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Key Points:

- The South China Sea rift system experienced a wide rift mode of deformation with multiple extension centers interacting in 3D
- Extensional deformation formed thick continental crust boudins laterally thinning to narrow interboudin necks with ultrathin continental crust
- Breakup probably resulted from seafloor spreading center propagation rather than entirely from progressive continental lithospheric thinning

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Understanding the 3D Formation of a Wide Rift: The Central South China Sea Rift System

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Abstract Rifted margins result from continental lithosphere extension, breakup, and transition to seafloor spreading by modes typically described by end-member conceptual models. However, current geophysical data challenge these archetypes showing a more complex spectrum of rifting styles. Here, we integrate geophysical and geological observations to constrain the time and space evolution of the central South China Sea (SCS) rift system. We provide new insights into the continental extension mechanisms and continent-ocean transition (COT) formation from a seismic transect parallel to the extensional direction of the central SCS rift system. We present 850-km-wide region of continental crust where distributed extensional deformation formed a pattern of lithospheric boudinage defined by seven 100- to 200-km-long structural segments. Each segment is formed by an 18- to 24-km-thick crust sector laterally thinning into an interboudin neck with ≤ 10 -km ultrathin crust (β factors ~ 3.3 – 6.5). Drill and stratigraphic information support that extension continued at all six interboudin necks in the central SCS until ~ 23 Ma, when breakup by seafloor spreading propagation reached one of them. We propose that the seven segments evolved as discrete subsystems from early rifting to breakup. Structurally equivalent ultrathin crust grabens occur NE and SW of both SCS conjugate margins, supporting a 3D wide rift mode of deformation across the SCS rift system. The six ultrathin crust contemporaneous necks and the abrupt nature and location of the COT support that the breakup was not controlled by further continental lithospheric thinning but rather was determined by the seafloor spreading propagation toward the SW.

1. Introduction

Conceptual models explaining the mechanisms controlling the crustal architecture, the distribution, and nature of the continent-ocean transition (COT) or the degree of along-strike segmentation at rifted margins rely heavily on a few natural examples. Most models are based on the Iberia–Newfoundland and East Greenland–mid-Norwegian conjugate rifted margins and have been used to explain most other rift systems. However, modern, regional geophysical studies have uncovered a more complex spectrum of styles of rifting—e.g., Gulf of California (Lizarralde et al., 2007), the Tyrrhenian Basin (Prada et al., 2014, 2015), or the South China Sea (SCS) (Cameselle et al., 2017)—that challenges the end-member model interpretations.

In this paper, we examine the evolution of the central SCS rift system (Figure 1) from geophysical and geological observations. In recent years, the SCS has become a focus region for the study of rift formation as a result of the acquisition of new seismic data, deep-sea drilling results from the International Ocean Discovery Program (IODP) (Ding et al., 2016; Larsen et al., 2018; Li et al., 2014, 2015; Sun et al., 2018) and publication of special issues and reviews (Li et al., 2015, and references therein; Pubellier et al., 2014; Wang et al., 2014). The relative youth of the SCS promotes the preservation of its original nature, and its small size compared with many classic, Atlantic-type continental margins allows conjugate rifted margins to be readily matched.

To assess the spatial and temporal evolution of the central SCS rift system at a large scale, we integrate recently published calibration by boreholes of the syn-rift age and new seismic images of the tectonic structure of both conjugate rifted margins. The $\sim 1,100$ -km-long seismic transect acquired parallel to the direction of extension of the central SCS rift system (Figure 1) reveals the top of the basement, fault blocks, syn-rift strata, and clear Moho reflections across most of the line, allowing estimation of lateral variations in crustal thickness. The tectonic structure and crustal architecture provide information

Figure 1. Bathymetric map of the South China Sea showing the major topographic structures. The subbasins forming the SCS are labeled: northwest (NWSB), east (ESB), central (CSB), and southwest (SWSB) subbasins. Thick black track corresponds to SO49-23 seismic profile in Figure 3. Thick dark-brown track corresponds to BGR84-127 seismic profile at the top of Figure 4 and thick light-brown track to BGR84-128 seismic profile at the bottom of Figure 4. Red segments correspond to the close-up images showed in Figures 5–7, 9, and 10. Numbered brown arrows locate the axis of the interpreted interboudin necks in Figures 3–8. See enclosed legend for additional information: (1) wide-angle seismic profiles: (a) Ding et al. (2011); (b) Guo et al. (2016); (c) Lü et al. (2016); (d) Pichot et al. (2014); (e) Qiu et al. (2001); (f) Qiu et al. (2020); (g and h) Wei et al. (2012, 2016); (i) Zhang et al. (2016); (2) 2D and 3D MCS data: Ding et al. (2015); Lei and Ren (2016); Qiu et al. (2013); Steuer et al. (2013); (3) magnetic anomalies from Barckhausen and Roeser (2004) and Barckhausen et al. (2014); (4) boreholes used for stratigraphic calibration: In the northern margin, boreholes CC4-1-1 and CC1162 (Lei & Ren, 2016) projected in Figures 3 and 5; in the southern margin, boreholes Sampaguita-1 and Aboabo A-1x (Steuer et al., 2013) projected in Figure 4; (5) location of boreholes in the Paracel Islands used to time constraints (Yubo et al., 2011), see the text; (6) high thin-crust regions reported by Huang et al. (2005), Pang et al. (2018), Wang et al. (2018), Zhao et al. (2015), and Zhou et al. (2018); (7) study area in the Zhu-3 Depression where detailed stratigraphic works constrained by ~30 boreholes (black dots) interpreted the end of the main extensional phase at ~23 Ma (Fengjun et al., 2001); (8) direction of opening of the CSB (Briais et al., 1993; Udo Barckhausen et al., 2014).

about the mechanisms governing the evolution of the extension. The observations yield new insights on continental extension modes and can be checked against previous conceptual and numerical models of rifted margin evolution.

2. Geological Background

The SCS is a Tertiary Basin located at the junction of the Eurasian, Pacific, and Indo-Australian plates (Figure 1). It is bounded on the north by the South China continental block, on the east by the Luzon Arc, on the south by the Palawan-Borneo contractional folded belt, and on the west by the Indochina Peninsula. The SCS deep water region is traditionally divided into the northwest (NWSB), the east (ESB), the central (CSB), and the southwest subbasins (SWSB) (Figure 1). The continental crust extended during the Tertiary opening of the SCS was accreted to Asia during the Mesozoic subduction of the paleo-Pacific Plate (Zhou et al., 2008; Zhou & Li, 2000). The geodynamic drive of the Cenozoic extension is debated: (1) extrusion tectonics related to the collision of Indochina into South China (Lunt, 2019; Replumaz & Tapponnier, 2003; Tapponnier et al., 1982); (2) rifting caused by slab pull during subduction of the proto-SCS under Borneo (Hall, 2002; Hutchison, 2005; Pubellier & Morley, 2014; Taylor & Hayes, 1983); or (3) extension related to the uplift caused by the Hainan mantle plume (Yan et al., 2014; Zhou et al., 2009).

Models of extension and thinning of the SCS rift system include classical symmetrical models (Brune et al., 2017; Ding et al., 2011; Gao et al., 2016; Nissen et al., 1995; Su et al., 1989), simple shear asymmetrical models (Hayes et al., 1995; Lü et al., 2016; Savva et al., 2014; Zhou et al., 1995), or combination of both pure- and simple shear mechanisms (Franke et al., 2014; Schlüter et al., 1996; Wu et al., 2004, 2016; Zhu et al., 2016). Alternatively, an asymmetric rift model where spreading center propagation caused final breakup has been proposed for the NWSB (Cameselle et al., 2017). Most models were based on data from only one conjugate margin or studied a reduced region.

Continental extension resulted in several subbasins bounded by tilted fault blocks that dominate the structure of the northern and southern conjugate margins of the SCS (e.g., Cameselle et al., 2017; Franke et al., 2011, 2014; Hayes et al., 1995). Integration of 2D and 3D seismic data and industry boreholes from hydrocarbon exploration in the northern (Clift & Lin, 2001; Lei & Ren, 2016; Qiu et al., 2013) and southern (Aurelio et al., 2014; Franke et al., 2011; Ilao et al., 2018; Steuer et al., 2013, 2014) SCS margins (Figure 1) and recent IODP drilling (Sun et al., 2018) support that major rifting started in Late Eocene and continued until Late Oligocene-Early Miocene (Figure 2). The stratigraphic unconformities analysis suggests a southwestward decreasing age of the continental breakup inferred from a southwestward younger oceanic plate (Franke, 2013; Morley, 2016).

Seafloor spreading started at 33–32 Ma (Figure 2) in the easternmost part of the ESB and reached the CSB at 25–23 Ma after two southward ridge jumps (Barckhausen et al., 2014; Barckhausen & Roeser, 2004; Briaies et al., 1993; Li et al., 2011, 2014, 2015; Taylor & Hayes, 1983). Seafloor spreading stopped synchronously in the ESB, CSB, and SWSB due to the subduction of the ESB at the Manila Trench (Arfaei et al., 2011) and the collision of the Dangerous Grounds and the Reed Bank along the NW Borneo Trough (Wang et al., 2006). The end of seafloor spreading is debated between 20.5 Ma (Barckhausen & Roeser, 2004; Udo Barckhausen et al., 2014) and 15–16 Ma (Briaies et al., 1993; Li et al., 2011, 2014, 2015; Taylor & Hayes, 1983).

3. Data Set and Methodology

The multichannel seismic (MCS) reflection data used in this study (Figure 1) were acquired during cruises Sonne49 in 1989 and BGR84 in 1984 by the Federal Institute for Geosciences and Natural Resources (BGR). Seismic profile SO49-23 extends over ~770 km from the South China continental margin into the deep water of the CSB (Figure 1). The acquisition used an AMG 37-43 streamer composed of 48 channels with 50-m group intervals, resulting in an active length of 2,400 m. Data were sampled at 4 ms and recorded to 12 s two-way travel time (TWT). The source was designed by Prakla-Seismics (Hannover) and consisted of two 5-air-gun well-tuned subarrays with 25.6 L of total volume fired at 140 bars. Shots were fired on time, roughly every 50 m, with distance recalculated for binning. Profiles BGR84-127 and BGR84-128 were acquired by Seismic Vessel Explora chartered from Prakla-Seismos. They extend continuously more than 380 km across the southern margin of the CSB, from the deep water basin to the Palawan-Borneo Trough

Figure 2. (a) Tectonic stages and rift evolution of the CSB (after Aurelio et al., 2014; U. Barckhausen & Roeser, 2004; Briais et al., 1993; Dieter Franke et al., 2014; Ding et al., 2015; Fengjun et al., 2001; D. Franke et al., 2011; Lei & Ren, 2016; C.-F. Li et al., 2014; J.-B. Li et al., 2011; Morley, 2016; N. Qiu et al., 2013; Steuer et al., 2013; Udo Barckhausen et al., 2014; Yubo et al., 2011). Key unconformities are as follows: Tg (~45–40 Ma); T70 (~32–29 Ma); T60 (~23 Ma). Sea floor spreading terminated between 20.5 Ma (Udo Barckhausen et al., 2014) and 15–16 Ma (Briais et al., 1993; C.-F. Li et al., 2014, 2015). (b) Seismic stratigraphy along profile 06e286 (Lei & Ren, 2016) across the Xisha Trough. See Figure 1 for location; (c) seismic stratigraphy of line SO49-23 across the Xisha Trough with unconformities after Lei and Ren (2016) and Qiu et al. (2013). Yellow line marks the intersection with line 06e286; (d) seismic stratigraphy from Reed Bank (after Ding et al., 2015). See Figure 1 for location; (e) seismic stratigraphy across Reed Bank with unconformities after Ding et al. (2015), located 23 km to the north (Figure 1).

(Figure 1). The signal was recorded on a 60-channel streamer with 50-m group interval and a total of 3,000 m of active length. Data were recorded at 4-ms sampling rate to 12-s TWT. The source consisted of a 31-air-gun array with a total volume of 57.6 L at 140 bars. Shots were fired on time, roughly every 50 m, with distance recalculated for binning.

About 1,150 km of MCS field data have been reprocessed up to poststack time migration: ~770 km from profile SO49-23 (Figure 3) and ~380 km from BGR84-127 and BGR84-128 seismic profiles (upper and

lower panel in Figure 4, respectively). The three seismic profiles form together a transect parallel to the opening direction of the central SCS rift system (Figure 1). Prestack processing includes trace edition, predictive deconvolution, velocity analysis, spherical divergence correction, and prestack multiple attenuation. Prestack deconvolution filters used a 24-ms TWT prediction length and 360-ms TWT operator length statistically designed in two overlapping windows, following geological structure. Radon filtering was used for prestack attenuation of water-layer multiples. A hand-picked inner trace mute further removed multiple remnants at near offsets. Semblance-based velocity picking was performed at least twice—once before and once after multiple removal—with analysis every 5 km or closer in areas of rough basement topography. In areas where Moho reflections were indistinct, we selected the velocity using constant-velocity stacks. Poststack processing included manually designed FK filters to remove strongly dipping multiple remains and other coherent noise particularly problematic for migration. Poststack time migration was performed using a finite difference algorithm on the time-space domain and a smoothed 2D velocity model modified from the stacking velocities that followed geological structures. Finally, we applied a space- and time-variant band-pass filter over a four-window design and a double median automatic gain control over a 3-s TWT running window that locally preserves amplitude relationships.

4. Interpretation of Seismic Images

4.1. Seismic Stratigraphy

The seismic images display syn-rift and post-rift strata geometry and tilted basement fault blocks (Figures 3–7). We used crossing and nearby modern 2D and 3D MCS data calibrated with industry boreholes (Figure 1) on the northern (Lei & Ren, 2016; Qiu et al., 2013; Yubo et al., 2011), and southern rifted margins (Ding et al., 2015; Steuer et al., 2013, 2014) to define three regional unconformities (Tg, T70, and T60) that can be readily extended across the entire continental domain and bound three distinct sedimentary units (Figure 2).

Because our seismic transect is parallel to the direction of continental extension and opening of the CSB (Figure 1; Barckhausen et al., 2014; Briaies et al., 1993) and the 2D cross section does not cross any major margin-perpendicular boundary that may be bounding the subbasins, we can consider that the imaged tectonic structure and the seismic units developed in a single tectonic sector. Through this sector, the breakup occurred only in one place (Figure 1). However, in the northeast and southwest tectonic sectors at both sides of our seismic transect, early works have suggested likely variations in the breakup age. These works based on magnetic anomalies (Barckhausen et al., 2014; Briaies et al., 1993) and tectonics of the conjugate margin pairs (Ding & Li, 2016; Franke, 2013; Huchon et al., 2001; Morley, 2016; Sibuet et al., 2016) have observed a southwestward decreasing age of the breakup unconformity associated with the southwestward propagation of the spreading center. Assuming that the continental extension stopped when seafloor spreading reached any particular sector of the SCS basin (i.e., the breakup moment), the ages presented below—based on seismic stratigraphy and industry boreholes located nearby or coincident with our seismic transect—constrain the timing of the main extensional phase in the central sector of the SCS rift system.

4.1.1. Seismic Unit 1 (Late Eocene to Middle Oligocene)

Seismic Unit 1 (Figures 3 and 4) contains low-frequency, variable-amplitude, discontinuous to moderate continuous reflections that overlie continental basement (Tg; black dots), and it is bounded at the top by the T70 angular unconformity. The unit's thickness changes laterally, filling the relief created by tilted fault blocks, forming wedge-shaped strata packages strongly dipping toward the faults, indicating syntectonic deposition during the main extensional phase (e.g., Figures 5 and 6). Under the SW Reed Bank, Unit 1 was deposited into a growing half-graben bounded by a major fault that thins the basement from ~22 km in the east to ~10 km in the west. Unit 1 is not present on the footwall, supporting its syn-rift deposit (Figures 4 and 6). Their internal facies are complex and may indicate a combination of sediment dynamics and tectonic rotations. The 1-s TWT thick deepest sediment of Unit 1 shows a more chaotic character and lower frequency and amplitude than sediments above (Figures 4 and 6). These reflections probably represent deep marine clastic sediments (Aurelio et al., 2014; Ding et al., 2013, 2015), forming the syn-rift turbiditic sequences exposed in the central and south Palawan as the Eocene Panas Formation (Aurelio et al., 2014). All large normal faults cutting the basement also cut Unit 1 to terminate at T70 or T60 (Figures 3–7).

Figure 3. Poststack time migration of SO49-23 line running from the South China continental margin into the CSB (see Figure 1 for location). The tectonic structure defines four structural segments: Xisha Trough, Parcel Islands, Macclesfield Bank, and Zhongjian Massif Segments. Yellow vertical lines mark intersection with seismic profiles 11e335 and 06e286 (Lei & Ren, 2016) and L1 and L3 (N. Qiu et al., 2013) used for stratigraphic correlation. Position of boreholes (red-filled circles) from Qiu et al. (2013) are projected (see Figure 1 for map location). The image displays lateral changes in the crustal domains across the margin and deep water basin: continental domain (green), continent-ocean transition (red), and oceanic domain (blue). The Moho is displayed as a set of strong, subhorizontal, low-frequency reflections typically at 8- to 10-s TWT. Dark green dots mark the interpreted Moho under the continental domain and blue dots under the oceanic domain from this work. Moho depth has been constrained from nearby or coincident WAS data (Qiu et al., 2001, dashed white line; Qiu et al., 2020, dashed pink line). The basement thickness is indicated at locations by green/blue vertical lines and corresponding values (in seconds TWT). The Tg unconformity (black dots) marks the top of the continental basement, and the T60 unconformity (light green dots) marks the top of the syn-rift sediment. The COT (red) is identified as an ~20-km-wide area where the change between the continental and oceanic domains occurs. Labeled purple ticks (e.g., 6AA) locate chrons of seafloor spreading after Barckhausen et al. (2014). Black dashed rectangles demarcate close-ups in Figures 5, 7, and 9. Vertical exaggeration at the basement is ~1.2.

Figure 4. Poststack time migration of lines BGR84-127 (top) and BGR84-128 (bottom) across the southern margin of the CSB (BGR84-127 dark brown, BGR84-128 light brown tracks in Figure 1) showing the NW Reed Bank, SW Reed Bank, and Palawan Trough Segments. Horizontal yellow line marks the overlap with profile from Ding et al. (2015) used for stratigraphic calibration (see Figure 1 for location and Figures 2d and 2e for interpretation). Red circle plus black dashed line locate boreholes used for stratigraphic correlation from Steuer et al. (2013, 2014) (location in Figure 1). The extend of crustal domains across the basin is indicated by a thick line under the images (continental in green, COT in red, and oceanic in blue). The Moho is imaged as a set of strong, subhorizontal, low-frequency reflections typically at 9- to 11-s TWT, delineated by green dots under the continental domain and blue dots under the oceanic domain. The basement thickness is locally indicated in seconds TWT by green/blue vertical lines. The top of the basement (Tg marked by black dots), T70 unconformity (purple dots), and T60 unconformity (light green dots) are main stratigraphic boundaries. The COT occurs abruptly (~10 km wide) between continental and oceanic domains. Black dashed boxes demarcate close-ups of Figures 6 and 10. Vertical exaggeration at the basement is ~1.2.

Figure 5. Image of the interboudin neck between the Xisha Trough and Paracel Islands Segments (see Figures 1 and 3 for location). Yellow vertical lines mark ties with profiles 11e335 and 06e286 (Lei & Ren, 2016) and L1 and L3 (N. Qiu et al., 2013) used for stratigraphic correlation. Boreholes CC1162 (N. Qiu et al., 2013; location in Figure 1) is projected. The top of the basement (=Tg) is offset and rotated in a series of tilted blocks of up to 10-km width by faults with offsets ≤ 4 -s TWT. The syn-rift sequence is bounded at the top by the T60 unconformity, and shows the maximum thickness (~ 2 -s TWT) in the continental domain. Purple dots mark the T70 unconformity. Green-filled circles delineate the Moho, and dashed white line marks the Moho from a coincident WAS profile (X.-L. Qiu et al., 2001). The continental basement thins from 6-s TWT (~ 18 km assuming 6 km s^{-1} velocity) to 6 km under the trough axis, where its continental nature is supported by seismic velocity (X.-L. Qiu et al., 2001). Vertical exaggeration at the basement is ~ 1.2 .

Figure 6. Image of the interboudin neck between the SW Reed Bank and the Palawan Trough Segments (see Figures 1 and 4). The top of the basement (Tg) is segmented by >10 km wide tilted blocks associated to faults with offsets ≤ 1 -s TWT. Syn-rift sediments (top marked by light green dots) infill the accommodation space created by extension. Purple green dots represent the T70 unconformity. At about km 1,100, the top of the basement is cut by an ~5-s TWT offset normal fault producing the maximum thinning in the area, with syn-rift sediment (top bounded by T60) filling the accommodation space. Moho (delineated by green dots) reflects crustal thinning toward the southwest from ~25 to ~9 km (assuming 6 km s^{-1} basement velocity) over a distance of 120 km. Vertical exaggeration at the basement is ~1.2.

Figure 7. Interboudin neck between Paracel Islands and Macclesfield Bank Segments (location in Figures 1 and 3). Large northward-dipping faults with ≤ 2 -s TWT offsets bound 20-km-wide tilted basement blocks (top of the basement marked by Tg unconformity), with syn-rift sediments (top T60 unconformity) filling the accommodation space. The continental basement thins from ~20 to 10 km over a <25-km distance (assuming 6 km s^{-1} basement velocity). Vertical exaggeration at basement is ~1.2.

On the northern conjugate margin, we have correlated our transect with coincident and nearby modern 2D/3D seismic and borehole data displaying very similar fault-block structures (green lines and red diamonds in the northern margin in Figure 1) from the Xisha Trough (Lei & Ren, 2016; Qiu et al., 2013), and we have identified the key horizons (Figures 2b and 2c). Based on the drill-calibrated data, Unit 1 is Late Eocene ($T_g \sim 45\text{--}40$ Ma) to Middle Oligocene ($T_{70} \sim 32\text{--}29$ Ma) in age (Figure 2a). In the neighboring Paracel Islands, segment basement is shallower, and syn-rift is thinner (Figures 3 and 7), but drilling (starry circles in Figure 1) supports our interpretation (Yubo et al., 2011). Basinward interpretation of the T_{70} unconformity is locally restricted by syn-rift basement topography so that it is mapped across the entire line through several jump correlations, which prevent tight constraints on its age away from drill sites.

On the southern conjugate margin, our interpretation was correlated (e.g., Figures 2d and 2e) with published works in the area (green lines in Figure 1) and drilling in the Palawan Trough and the Reed Bank (red diamonds in Figure 1 and projected boreholes in Figure 4) (Aurelio et al., 2014; Ding et al., 2015; Steuer et al., 2013). The age interpreted for the T_{70} unconformity in the SW Reed Bank basin is ~ 30 Ma (Ding et al., 2015). The T_{70} unconformity can be readily traced across the fault blocks into the NW Reed Bank Segment, where syn-rift sediment gradually thins seawards.

4.1.2. Seismic Unit 2 (Late Oligocene)

Unit 2 consists of subparallel reflections of high-intermediate continuity and medium amplitude between T_{70} and T_{60} horizons (Figures 3 and 4). Unit 2 laps on the basement with a wedge-shaped geometry and strata fanning attitude, indicative of syn-rift deposition in grabens (e.g., Figures 5 and 6). Unit 2 shows comparatively limited expanding geometries toward the main faults, which have offsets commonly smaller than across Unit 1 (e.g., 90–110 km in Figure 5), though a few faults have large displacement until T_{60} (e.g., 115 km in Figure 5) or younger (e.g., 975 km in Figure 4). The comparatively smaller fault offset in Unit 2 interval indicates time-decreasing fault activity and, therefore, in extension rate or strike-slip deformation. Unit 2 thickness is ≤ 1.5 -s TWT throughout the seismic transect and typically much thinner.

The northern margin has borehole information that constrains Unit 2 age. In the Xisha Trough Segment, Unit 2 deposited during the final rifting stage of decreasing fault activity, estimated at $\sim 30\text{--}23$ Ma (Lei & Ren, 2016; Qiu et al., 2013). In the Paracel Islands, borehole data constrain the T_{60} unconformity to the Oligocene-Miocene boundary (~ 23 Ma; Yubo et al., 2011) (Figure 1). Unit 2 in the Macclesfield Bank and the Zhongjian Massif segments occurs in isolated grabens, and its age is not directly constrained (Figure 8). We infer that T_{60} , marking the end of continental extension here, cannot be younger than the oldest nearby ocean crust identified as chron 6b (~ 23 Ma) (Barckhausen et al., 2014; Biais et al., 1993).

On the southern conjugate margin, Unit 2 has been drilled on structural highs, where it is primarily made of carbonate reefs (Aurelio et al., 2014; Ding et al., 2015; Franke et al., 2014; Steuer et al., 2013, 2014). Seismic and borehole data support that carbonate growth terminated at ~ 23 Ma in the SW Reed Bank (Figure 2). In

Figure 8. Line drawing from the interpretation of the top of the basement, Moho, faults, syn-tectonic (yellow), and posttectonic (white) sediment along the continental and COT domains of the transect. Basement structure displays a crustal-scale boudinage across all the central SCS rift system. Interboudin necks indicated by arrows have the corresponding β values and end-of-extension age (location in Figure 1). Interboudin neck 4 corresponds to location of the CSB. The onset of seafloor spreading is constrained to ~ 23 Ma based on IODP drilling and magnetic seafloor spreading lineations vertical exaggeration is ~ 2.3 at the basement and ~ 3.5 at the syn-rift.

the NW Reed Bank basin, Unit 2 age is not constrained by drilling, but its age, marking the end of rifting, cannot be younger than the oldest seafloor spreading magnetic anomaly at the breakup, identified as chron 6b (~23 Ma; Barckhausen et al., 2014; Briaies et al., 1993; Figure 1).

4.1.3. Seismic Unit 3 (Early Miocene to Recent)

Seismic Unit 3 includes the youngest sediment in the continental domain and the entire sediment in the oceanic domain in our transect (Figures 3 and 4). Unit 3 displays parallel or subparallel reflections that fill in or drape at deep water distal areas, underlying relief, indicating deposition without significant tectonism. Average thickness is relatively constant along the continental domain, ~1- to 1.5-s TWT, although it may locally thin against relief (e.g., 160 km, Figure 3). Borehole data in the Xisha Trough, the Paracel Islands area, and the SW Reed Bank Basin (Figures 1, 3, and 4) indicate that Unit 3 deposits are $\lesssim 23$ Ma (Aurelio et al., 2014; Ding et al., 2015; Lei et al., 2020; Lei & Ren, 2016; Qiu et al., 2013; Steuer et al., 2013; Yubo et al., 2011). At the deep water basin, Unit 3 thins toward the center of the basin (~0.4-s TWT). IODP leg 349 indicates that Unit 3 is $\lesssim 23.6$ Ma (Li et al., 2015).

4.2. Tectonic Style and Crustal Architecture

The ~1,150-km-long transect reveals three basement domains with distinct characteristics (Figures 3 and 4). Our interpretation of domains follows the rationale of our previous work in the NWSB using similar seismic data (Cameselle et al., 2017), and integrating other available basement information. The nature and extension of the domains are supported by previous geophysical works (Figure 1) including wide-angle seismic (WAS) data (Ding et al., 2011; Guo et al., 2016; Lü et al., 2016; Pichot et al., 2014; Qiu et al., 2001; Wei et al., 2012, 2016; Wu et al., 2011; Zhang et al., 2016), gravity data (Hao et al., 2013), magnetic data (Barckhausen et al., 2014; Barckhausen & Roeser, 2004; Briaies et al., 1993; Li et al., 2014; Taylor & Hayes, 1983), dredging and coring (Kudrass et al., 1986; Yan et al., 2010), and IODP drilling results (Larsen et al., 2018; Li et al., 2015; Sun et al., 2018). Two sectors form the continental domain, from 0 to 490 km and from 795 to 1,150 km. Two (narrow) sectors form the COTs between 490 and 515 km and between 785 and 795 km, which constrain the oceanic domain between 515 and 785 km (Figures 3 and 4). The domains along the seismic transect can be extended into a 3D lower resolution interpretation of the central SCS using the available bathymetry (Figure 1).

The continental basement is characterized by tilted blocks bounded by normal linear or sometimes listric (in time, not in depth) faults. The largest faults predominantly dip away from the basin, except between 390 and 480 km where basement blocks appear bounded by quasi-vertical faults (~80° dip) and between 880 and 920 km where tilted blocks are bounded by both basinward- and landward-dipping normal faults (Figures 3 and 4). Rotated strata form wedge geometries indicating syntectonic infill of the half-grabens and are overlain by subhorizontal post-rift strata (Figures 3 and 4).

On the northern rifted margin, we interpret a set of strong, subhorizontal, low-frequency reflections at 8- to 10-s TWT as the Moho (dark green dots in Figure 3). The TWT of these reflections is consistent with the crust-mantle boundary modeled from coincident and nearby WAS data (dashed white line in Figs 3 and 5 from Qiu et al., 2001; pink dashed line in Figs 3 and 7 from Qiu et al., 2020). We extended the Moho interpretation throughout the entire line SO49-23, mapping similar—albeit often weaker—reflections (green dots in Figure 3). On the southern margin, Moho reflections appear as a band of subhorizontal, sometimes strong, fairly continuous events at 9- to 11-s TWT in profile BGR84-127 and 10 to >12 s TWT in profile BGR84-128 (Figure 4). Assuming average velocities of 3.0 km s^{-1} for sediment and 6.0 km s^{-1} for basement from nearby WAS profiles (Liang et al., 2019; Pichot et al., 2014), Moho depth ranges from 15 to 23 km in BGR84 lines, in good agreement with results from WAS data (Pichot et al., 2014) and 3D gravity inversion models (Wu et al., 2017).

The continental-crust architecture of the central SCS rift system consists of seven structural segments that define a 100- to 200-km-long boudinage geometry of the crystalline basement (Figure 8). Each segment is formed by a sector of 6- to 8-s TWT (~18–24 km) thick basement tapered at each end in an interboudin neck of 1.6- to 3.2-s TWT (~5–10 km) thick basement, with comparatively more intense faulting and thicker syntectonic sediment packages. We describe the tectonic structure of each segment below.

4.2.1. The Xisha Trough Segment

The Xisha Trough Segment extends from the continental shelf to the Xisha Trough (0–102 km; Figures 3 and 8), between the Pearl River Mouth Basin and the NE end of the Qiongdongnan Basin (Figure 1).

Normal fault intensity increases and basement thins toward the center of the trough (Figure 3). From 0 to 70 km, most faults show vertical offsets <0.5 -s TWT, and the basement is 18–25 km thick. From 70 to 102 km, extensional strain increases: basement thins abruptly from 18 to 5–6 km by large landward-dipping normal faults with vertical offsets of ≤ 3.5 -s TWT (Figure 6) that bound tilted blocks ≤ 10 km wide. Moho is interpreted as a subhorizontal group of reflections at 8- to 9-s TWT (green dots in Figure 3), matching the Moho from a coincident WAS line (white dashed line from Qiu et al., 2001). The lower crust under the trough contains a package of reflections that thins toward the region of intense thinning of the interboudin neck 1 axis (Figures 3 and 5).

4.2.2. The Paracel Islands Segment

It extends from 105 to 290 km (Figures 3, 7, and 8). From 150 to 250 km, the basement is 5.4- to 7.2-s TWT (~ 16 –21 km) thick, cut by large faults (~ 1.5 –1.8 s TWT offset) spaced >20 km apart. Smaller offset fault arrays cut the hangingwall of the major fault blocks (e.g., 190 km in Figure 3). Basement thins toward the interboudin neck 2 from 20 to ~ 9.5 km between 270 and 290 km, associated with an increase in large fault density (Figure 7).

4.2.3. The Macclesfield Bank Segment

It extends from 295 to 395 km (Figures 3 and 8). Between 310 and 350 km, the basement is 13–16 km thick, where a few faults cut the top of the basement with offsets of ≤ 0.5 -s TWT, smaller than in segments to the NW. Basinward from 350 km, Moho reflections (dark green dots) rapidly rise, and the basement thins from ~ 16 to ~ 6 km under the wide graben at the interboudin neck 3, with little evidence of block faulting (Figure 3). In this area, Moho's position is constrained by a nearby WAS line (line f in Figure 1 and dashed pink line in Figure 3). The seafloor of the interboudin neck deepens rapidly to the NE (Figure 1) possibly indicating further thinning. We speculate that the thinning could be caused by large-scale detachment faulting creating the smooth graben basement relief (Figure 3). The smooth geometry would correspond to the exhumed portion of the fault, which ends to the NW in a breakaway geometry. The fossil detachment may laterally penetrate into the basement to the SE, with the fault delineated by a series of indistinct reflections (Figure 3).

4.2.4. The Zhongjian Massif Segment

It is the basinward-most segment of the northern margin (400–490 km; Figures 3 and 9). It contains an area of complex structure with large subvertical faults ($\sim 80^\circ$ dip) with ~ 2 -s TWT offsets rotating ~ 15 -km-wide basement blocks that form prominent half-grabens (405–480 km in Figure 3). Strata overlaying the two largest half-grabens are gently tilted but thick considerably toward the fault plane (e.g., 420 and 440 km in Figure 3). Since the fault dip can only be equal or steeper to the angle imaged on the seismic line, the steep fault wall associated to a thick deposit of moderately deformed sediment indicates significant extension with minor rotation (from the imaging angle of the line) that collected hundreds of meters of moderately tilted syntectonic strata. The basement and strata geometries support steep faulting with a strike-slip component.

In areas, the top basement of the footwall block is rough and poorly defined (e.g., 430 or 455 km; Figure 3). We interpreted these features as posttectonic volcanic buildups based on the seismic character and disturbance of the overlain deposits (450 km, Figure 3). A volcanic nature is also proposed by Yan et al. (2006) from a parallel seismic profile located ~ 10 km to the northeast, proposing an age of 14–3.5 Ma for all the seamounts in the sector. The Moho boundary is identified as discontinuous subhorizontal reflections between 9- and 10-s TWT. The basement thins laterally from ~ 16 to ~ 9 km thick and across a narrow COT to clear oceanic-crust structures (Figures 3 and 9).

4.2.5. The Continent-Ocean Transition

The COT of the northern margin (~ 490 –515 km; Figure 9) is ~ 25 km wide, extending between the outermost rotated fault block interpreted as continental crust (~ 8 km thick) and the oceanic crust characterized by a basement with a highly reflective little faulted top, and fairly constant thickness of ~ 6 –6.5 km. The top of the basement is little rotated and overlain by 0.9- to 1.3-s TWT thick subhorizontal strata (Figure 9). The gentle attitude of the strata supports a posttectonic deposition. Approaching the northern COT, the basement abruptly thins across two faults from ~ 4 - to 2.7-s TWT, indicating a crustal thinning from ~ 12 to ~ 8 km over ~ 10 -km distance (Figure 9). A volcano sits at ~ 500 –510 km at the change from continental to oceanic character. The onlapping geometry of the oldest sediments suggests a latest syn-rift early post-rift emplacement of the high.

Figure 9. The southern end of the Zhongjian Massif Segment and an ~20-km-wide COT defined between the outermost rotated fault block associated with unambiguous stretched continental crust and the little faulted constant-thickness oceanic crust (location in Figures 1 and 3). Moho reflections rise fairly abruptly under the COT, from ~4- to 2.7-s TWT below the top of the basement, indicating a thinning from ~12 to 8 km over 10 km distance (using 6 km s^{-1} velocity). Vertical exaggeration in basement is ~1.2.

The southern COT has a simpler structure extending from ~788 to ~798 km (Figures 4 and 10). Moho appears as 1- to 2-km-long high-amplitude reflections deepening from ~8.2- to ~9.2-s TWT. The basement thickens from 2.1- to 2.8-s TWT or from 6 to 9 km over an ~10-km distance. The top of the basement changes from a series of 3- to 4-km-long smooth segments gently tilted by faults in the oceanic domain to a rugged complex reflective pattern in the interpreted continental domain. Here, the top of the basement is characterized by 0.3- to 0.5-s TWT thick tilted layering and some fainter-dipping reflections underneath that delineate a series of faults dipping away from the basin (Figure 10).

4.2.6. The Oceanic Crust Domain in the CSB

Oceanic crust extends between 515 and 785 km (Figures 3 and 4). The top of the basement is comparatively a brighter and simpler structure than the one at the continental domain. It is formed by 1- to 3-km-long reflections creating 0.3- to 0.6-s TWT thick packages (Figures 3 and 4). Two sets of small offset normal faults with opposite dipping directions are observed at either side of the abandoned spreading center (Figure 3). Sediment strata overlay subhorizontally the top of the igneous basement, indicating very limited faulting or posttectonic deposition for the entire column (e.g., 660–680 km).

Moho reflections of moderate continuity occur between 9- and 10-s TWT (Figure 3), delineating the base of an ~2.2- to 2.6-s TWT thick basement, with gentle lateral variations (Figure 3). These Moho reflections are comparatively less continuous and subtler than those in the NWSB, where they are more conspicuous (Cameselle et al., 2017). This change in reflective pattern might be associated with an increase in the SCS's spreading rate with time. A poorer continuity of Moho reflection has been described when comparing Atlantic intermediate spreading rate crust to NW Pacific fast-spreading crust (Mutter & Carton, 2013; Ranero et al., 1997). Assuming a 6 km s^{-1} as the average basement velocity (Zhang et al., 2016), crustal thickness ranges between 6.6 and 7.8 km. Our interpretation of the oceanic domain and thickness of the oceanic crust agrees with results from nearby WAS profiles (Pichot et al., 2014; Zhang et al., 2016), drilling results from IODP (Li et al., 2014, 2015), and identification of seafloor spreading magnetic anomalies (Barckhausen et al., 2014; Barckhausen & Roeser, 2004; Biais et al., 1993).

Figure 10. The southern COT is defined as an ~10-km-wide area where the structures change from clear continental to the oceanic crust (location in Figures 1 and 4). Under the continental domain Moho reflections shoals basinward from 3.4- to 2.8-s TWT under the top of the basement. The crust thins from ~10 to 8 km (using 6 km s^{-1} velocity) and to 2.1-s TWT into the oceanic crust over an ~10-km distance. Vertical exaggeration in the basement is ~1.2.

A series of 1- to 2-s TWT tall basement highs occur mainly close to and on either side of the spreading center (Figure 3). Most of these basement highs (e.g., 545, 600, 610, 655, and 715 km in Figure 3) can be correlated in the bathymetry map with ridges typically observed in the oceanic crust (magenta segments in Figure 1). Some others correspond to conical volcanic structures, as the high located at the abandoned spreading center (640 km, Figure 3).

4.2.7. The NW Reed Bank Segment

It extends between ~800 and 925 km (Figure 4). The complex fault structure may include a transfer zone of two large NE-SW aligned graben systems visible in the bathymetry to the NE and SW of the seismic line (Figure 1) and in satellite gravity inversion maps (Gozzard et al., 2018). However, in the seismic image, the transfer zone is shown as a single graben with pronounced thinning (Figure 4). A graben from 835 to 870 km is bounded by ~1-s TWT offset conjugate faults, with the intervening hanging wall basement intensely cut by two sets of conjugate faults (Figure 4). The tectonic structure from 870 to 925 km was formed by complex fault kinematics. Faults of considerable dimensions dip away from the center of a graben so the hanging wall to a large fault appears the footwall to another large fault (Figure 4). The two sets of opposite dipping normal faults possibly formed in the area of linkage between two grabens. The 1-s TWT offset faults rotate ~20-km-wide basement blocks away from the graben center, and their hanging wall is cut by smaller (offset <0.3-s TWT) arrays of faults (Figure 4). The complex fault architecture of this segment may indicate the temporal interaction of evolving fault systems that cut each other as grabens enlarge and extend laterally. However, the geometry of well-developed syn-rift strata supports that both sets of faults worked either simultaneously or with a little delay between their activity. Subhorizontal Moho reflections at 9- to 10-s TWT (Figure 4) define a transition from the ~16- to 17-km thick basement at 830–875 km to the thinnest basement (9–10 km thick) at 920–925 km associated with two subvertical faults (Figure 4).

4.2.8. The SW Reed Bank Segment

This segment extends between 925 and 1,100 km characterized by an ~170-km-wide half-graben limited to the SE by a 20-km heave and 3-s TWT (~4–5 km) vertical offset fault (Figures 4 and 6). The basement is made of 10- to 40-km-wide fault blocks overlain by a comparatively thick ~1- to 2-s TWT (~1.5–3 km) syn-rift sequence cut by faults with ~0.1- to 1-s TWT offset. The largest faults may reach the Moho. The Moho boundary is delineated by strong, fairly continuous, undulating reflections deepening below 12-s TWT (field data record length) between 970 and 1,200 km and indistinct elsewhere (Figure 4). The basement ranges between 19 and 24 km thick between 935 and 1,040 km, thinning from ~19 to 9 km at the boudin's neck 6 (1,080–1,100 km) associated with the largest faults (Figure 6).

4.2.9. The Palawan Trough Segment

The southern part of the transect across the Borneo-Palawan Trough (Figure 1) extends from 1,105 to 1,150 km (Figures 4 and 6). Here, the rifted continental crust is overthrust by the Palawan-Borneo thrust belt, and the end of the segment with possibly thicker crust is not imaged. The basement forms a >30-km-wide half-graben cut by three basinward-dipping normal faults (Figure 4). The position of the top of the basement in the southernmost part is unclear due to the thick and deformed sedimentary cover. The basement is 19–21 km thick with Moho reflections deepening under the trough from 10- to 12-s TWT.

5. Discussion

5.1. Temporal Evolution of the Central SCS Rift System

The extent of continental and oceanic domains and the COT, their tectonic structure, and the seismic stratigraphy calibrated by drilling in both conjugate rifted margins (Figure 2) provide the information to interpret the major geodynamic events in the central SCS rift system. Extension stopped at interboudin necks 1, 2, and 6 at ~23 Ma, similar to breakup of neck 4 (Figure 8) (Arfaei et al., 2011; Ding et al., 2015; Franke et al., 2011; Lei & Ren, 2016; Qiu et al., 2013; Steuer et al., 2013; Yubo et al., 2011). The syn-rift of interboudin necks 3 and 5 is not directly constrained by drilling or stratigraphic correlation because continuity is interrupted by basement highs. However, as our seismic transect is parallel to the direction of continental extension and opening of the CSB and does not cross any major margin-perpendicular boundary (Figure 1), we can consider that the imaged tectonic structure and the seismic units developed in a single tectonic sector. This implies that extension on necks 3 and 5 should not continue significantly after breakup and seafloor spreading at neck 4 at ~23 Ma, as observed for necks 1, 2, and 6. Any other possibility would require to call for anomalous conditions to stop extension at different grabens at different ages. Even if segmentation of continental margins can occur with significant changes in the style of extension and even type of basement between segments, that may be bounded by major tectonic features (Franke et al., 2014; Pubellier et al., 2014; Rovere et al., 2004).

Similarly, the age of the initial extension is not constrained for each of the six interboudin necks. However, most of the industry boreholes constrain to Late Eocene (45–40 Ma) the rift initiation in the deep sedimentary basins (yellow shading in Figure 1) at both conjugate margins of our seismic transect (Haizhang et al., 2017; Zhou et al., 1995). Thus, we assume that the region mapped by our transect—keeping in mind the orientation parallel to the extension direction—was also affected by the initial extension, although the intensity of those initial phases across the different areas is unconstrained. Therefore, the age of the main continental extension across the central SCS rift system may extend from the Late Eocene (45–40 Ma) to the Late-most Oligocene (23 Ma) (Figure 2). This extensional and breakup timing is entirely compatible with the NE-SW variations in the ending age of rifting and breakup along the SCS rift system described in previous works (Ding & Li, 2016; Franke et al., 2014; Huchon et al., 2001; Morley, 2016; Sibuet et al., 2016). This change in age is related to the NE-SW progression of the seafloor spreading in the SCS (Figure 2a), causing continental extension to stop when seafloor spreading reached the different sectors of the SCS Basin (Cameselle et al., 2017). Therefore, our data constrain the temporal evolution of only the central sector of the SCS rift system.

Even if the available drilling information does not accurately constrain the age of the oldest syn-rift for each neck nor the extension climax for each large tilted block, a widely accepted age of rift initiation and end of extension is defined at locations north and south along the transect, which are the base for our model. Also, the asymmetry in fault distribution and crustal thinning of each neck might indicate that extensional strain evolved in time and space with the migration and focusing of faulting toward the center of each interboudin neck. Our seismic images show that the tectonic structure of the interboudin necks has increased faulting

and thinner basement (~5–10 km thick) compared with the boudin central sectors, where faults generally decrease in offset and/or increase in spacing and in crustal thickness to 18–24 km. Compared to an initial unstretched 33-km-thick continental crust (Nissen et al., 1995), β factors at these necks are 3.3–6.5 (Figure 8). The largest fault throws (up to 4-s TWT offset), some of which seem to reach Moho (Figures 5 and 6), are associated with the largest β factors. The deformation pattern of each interboudins neck includes asymmetric fault distribution, increasing in faulting intensity and decreasing block's dimension toward the necks, and β factors large enough for most of the lower crust to behave brittlely, which are akin to the sequential faulting model of conjugate magma-poor rifted margins (Ranero & Pérez-Gussinyé, 2010).

5.2. Tectonic Evolution of the Central SCS

The final wide-system crustal configuration (Figure 8) and inferred temporal evolution of the central SCS rift system described above share similarities with the “wide rift mode” of extension (Buck, 1991; Hopper & Buck, 1996). Wide rifts are related to regions of high heat flow and weak crustal rheology often associated with an initially thick crust (Bialas & Buck, 2009; Brune et al., 2017; Buck, 1991; Hopper & Buck, 1996; Kharazizadeh et al., 2016). Heat flux measurement at the SCS indicates a potentially high heat flow before rifting (Nissen et al., 1995) and associated to a phase of thickening during Andean-type orogeny, and magmatic additions related to a magmatic arc during the Mesozoic have also been speculated (Brune et al., 2017; Li et al., 2012).

Our work shares several fundamental characteristics of the wide rift systems: (1) extensional strain distributed over a ≥ 850 -km-wide continental area; (2) extension occurred distributed in space over the entire basement yielding six areas of <10-km-thick continental basement; (3) contemporaneous extensional deformation along the entire central SCS rift system from the initial rifting (Late Eocene) to breakup (Late-most Oligocene); (4) possible ductile deformation of the lower crust up to the latest phases of extension when entire crust becomes brittle at <10 km thick and faults cut deeper (see related discussion below); (5) narrow and abrupt COT with oceanic crust formation abutting stretched continental crust without mantle exhumation (Cameselle et al., 2017; Ding et al., 2019; Larsen et al., 2018), supporting relatively high flux during rifting; (6) predominance of rotational dip-slip faulting, with oblique-slip or wrench-style deformation potentially identified in isolated areas (Bosworth, 1989; Chapman et al., 1978; Wernicke & Burchfiel, 1982).

Previous works also pointed out to the similarity between the regional tectono-morphology of the Basin and Range province of North America—the paradigm of the wide rift mode proposed by Buck (1991)—and the rugged bathymetry of the broad area of extended continental crust across the Dangerous Grounds (Clift et al., 2001; Cullen et al., 2010; Franke, 2013; McIntosh et al., 2014). All these works propose a migration of extension over time from the proximal to the distal margin to explain crustal deformation, timing, and location of final breakup across the SCS. To that end, these authors invoked the processes described for the magma-poor Iberia margin model and proposed that breakup occurred during a final episode of crustal thinning (e.g., Lavier & Manatschal, 2006; Whitmarsh et al., 2001), responsible for the thinning of the distal continental crust and formation of the COT. In the SCS, the process leading to breakup and COT formation has been proposed to occur by low-angle detachment faulting (Ding et al., 2013), hyperextension of continental crust (McIntosh et al., 2014), or mantle exhumation (Ding et al., 2016; Franke et al., 2014).

However, the stratigraphic correlation along our seismic transects supports that extension continued in all the six interboudin necks until the end of rifting, i.e., until ~23 Ma in the central SCS rift system. There is no evidence of systematic gradual migration of the extension over time from the proximal to the most distal basins on either of the two rifted margins. Even in the most proximal basins, landward of our seismic transect (gray-shaded box in Figure 1), detailed stratigraphic works of the oil industry also interpreted the end of the main extensional phase at ~23 Ma (Fengjun et al., 2001).

In contrast, we propose a model in which the evolution in the distribution of deformation leads to contemporaneous migration and focusing in multiple interboudin necks and did not focus only on the region where the final breakup occurred. Our model is fundamentally different from models proposed for magma-poor margins in which deformation progresses in just one direction from the most proximal continental shelf to the breakup region (e.g., Iberian-Newfoundland; Peron-Pinvidic et al. (2013) and references therein). Recently, 3D models of lithospheric extension have provided a new view of strain distribution and evolution of rifting basins, suggesting that wide rift margins and V-shaped oceanic basins, like in the SCS, can result at

the front and on the side of a seafloor spreading propagator when propagation stagnates by far-field compression (Le Pourhiet et al., 2018).

We interpret initial deformation occurring distributed on numerous faults that currently display limited offset. After some time, a subset of them gradually became dominant increasing in offset, i.e., the largest faults in the images (Figures 3–7). Similar time-space faulting evolution has been proposed for other regions with good age calibration and 3D constraints on the tectonic evolution (Cowie et al., 2005; Gawthorpe et al., 2003; Mattei et al., 2004; Walsh et al., 2003). Such evolution caused strain to migrate into each of those six interboudin necks where faulting focused, yielding localized crustal thinning similar to the sequential faulting model proposed for magma-poor margins (Ranero & Pérez-Gussinyé, 2010), but occurring coeval in six interboudin necks where final basement thickness is $\lesssim 10$ km (Figure 8). This model implies that the arrays of small offset faults stopped activity somewhat earlier than the larger faults that caused the greatest thinning and that the latter may have operated sequentially in time during the latest phases of extension (Ranero & Pérez-Gussinyé, 2010). The age calibration of the sediment units along our seismic transect is not accurate enough to determine individual fault activity, and each large fault possibly worked during a comparatively short period. However, we can infer that the initial suite of smaller faults was probably accompanied by ductile deformation in the lower crust during earlier phases of extension as they do not appear associated with significant relief in the Moho. In contrast, the largest faults operating during later stages of activity and causing the greatest thinning appear associated with Moho relief (Figures 5 and 6), which conceivably indicate that faults cut across the entire crust and that the entire crust was brittle at that time. Our interpretation agrees with recent stratigraphic studies with 3D seismic data from the nearby Baiyun Sag (Figure 1) reporting sequential faulting toward the subbasin's axis (Zhou et al., 2018).

The internal crustal reflectivity of the Xisha Trough may also support the transition from a two-layer crust, with a brittle upper crust and a ductile lower crust, during the early phases of extension to an entire brittle crust as extension progressed. The lower crust displays a lateral change in reflectivity characterized by an ~ 1 -s TWT package above the Moho that appears as the crust abruptly thins from under the shelf and upper slope (0–65 km, Figure 3) to under the lower slope (65–85 km). We speculate that the reflectivity corresponds to a tectonic fabric caused by ductile deformation and mineral reorientation, as the fabric does not correspond to a significant change in seismic velocity (Qiu et al., 2001) that could imply magmatic intrusions. The lower crustal fabric appears truncated and rotated by the largest faults at the center of the graben (Figure 3; 100–130 km), so these faults may have been formed after the crust thinned enough to become entirely brittle. A similar lower crustal reflectivity and relationship to faulting is observed at the central graben of the Galicia Interior Basin (Pérez-Gussinyé et al., 2003).

5.3. Structure and Formation of the COT

A fundamental difference with many previous models is that our images from both rifted margins support an abrupt COT, changing from typical continental to oceanic basement over a <10 - to 20-km section (Figures 9 and 10), similar to seismic images of the NWSB (Cameselle et al., 2017). In the northern conjugate margin of the CSB, the COT is an ~ 20 -km-wide transition between the outermost tilted fault block interpreted as continental and the subhorizontal, little-faulted oceanic crust that extends for hundreds of kilometers (Figures 3 and 9). In the southern conjugate margin, the COT occurs between a series of tilted fault blocks on ~ 9 -km-thick crust and the deep basin with ~ 6 -km-thick crust and small-scale faults interpreted as oceanic crust (Figures 4 and 10). There is no obvious structure resembling tens of km-long regional detachment fault that focuses the deformation on either side of the rift system neither in our data nor in published WAS data (Ding et al., 2011; Guo et al., 2016; Lü et al., 2016; Pichot et al., 2014; Qiu et al., 2001; Wei et al., 2012, 2016; Wu et al., 2011; Zhang et al., 2016). Similarly, drilling does not support the presence of exhumed mantle at the COT (Larsen et al., 2018). Our seismic data show the continental Moho reflections extending to a few kilometers from the oceanic Moho reflections, without a significant gap or an abrupt shoaling under the COT (Figures 4 and 10). In the northern COT, the transition between the continental to oceanic Moho is obscured by a large, possibly postsynthetic, volcano, but Moho reflections are visible on either side of the buildup, which rules out mantle exhumation (500 km, Figure 9). Similarly, the abrupt COTs imaged at the NWSB (Cameselle et al., 2017) are further extended by nearby IODP drilling and seismic images inferring the change from continental blocks to oceanic magmatism across one tilted block (Larsen et al., 2018). These observations support that the abrupt COT in the

central SCS rift system was formed by a sudden change in the rifting process, rather than by gradual variations associated with the progressive lithospheric thinning and asthenospheric upwelling as most magma-poor rifting models explain the SCS.

5.4. Three-Dimensional Basin Evolution

The central SCS rift system is characterized by an ~850-km-wide continental rift with multiple crustal-scale boudinage, created by the contemporaneous focus of extension at six interboudin necks, where the continental basement thinned to less than 10 km (Figure 8). To integrate our extensional model and the origin of the abrupt COT structure in the context of the evolution of the entire SCS rift system, we compare the margin architecture of the central SCS rift system with previous works NE and SW of our seismic transect (Figure 1). In the Pearl River Mouth Basin and Qiongdongnan Basin, several thin-crust areas similar to those imaged in our data have been described (Cameselle et al., 2017; Huang et al., 2005; Nirrengarten et al., 2020; Pang et al., 2018; Wang et al., 2018; Zhao et al., 2015; Zhou et al., 2018). At the axis of these stretched areas, continental crust is generally 8 km thick and even as thin as ~1 km at the Changchang Sag in the Qiongdongnan Basin (Gao et al., 2016). These areas form the so-called Depression Belts (Wang et al., 2013), defining along-strike large sedimentary basins under the continental shelf and slope of the northern SCS margin. In the ESB, Lester et al. (2014) and McIntosh et al. (2014) reported equivalent continental thin-crust areas ~150–200 km landward from the COT. The same occurs in the SWSB, where thin-crust areas occur in the Phu Khanh Basin (Cullen et al., 2010; Savva et al., 2013), the Nam Con Son Basin and the Dangerous Grounds (Franke et al., 2014), and the East Natuna Basin (Cullen et al., 2010). Similar continental ultrathin basement has been described at numerous magma-poor margins where they abut exhumed mantle of the COT (Prada et al., 2015). In the SCS, most ultrathin basement sectors did not experience breakup.

The numerous recent stratigraphic analyses by the oil and gas industry in most of these thin-crust areas support a Late Eocene onset of the main extension event across the region (Figures 2 and 11a) and a gradually younger end of rifting toward the SW (Ding et al., 2014; Hutchison, 2004; Lei et al., 2018, 2020; Lei & Ren, 2016; Qiu et al., 2013; Ren et al., 2014; Song et al., 2011, 2014; Su et al., 2014; Yao et al., 2012; Yuan et al., 2008; Zhang et al., 2018; Zhao et al., 2018; Zhou et al., 2018). The along- and across-strike distribution at both conjugate margins of the SCS of these ultrathin-crust areas, which appear equivalent of our interboudin necks, supports a wide rift mode of deformation across the SCS rift system (Figure 11a), creating a broad area of contemporaneous extension of continental crust (Figure 1).

Along our transect, rifting thinned the basement to <10 km in six interboudin necks. Toward the center of the necks, the tectonic structure supports that the entire crust was brittle and could potentially have been broken at any of the widely spaced necks during further extension. However, breakup and the establishment of stable seafloor spreading occurred only in one of the interboudin necks, forming the CSB (Figure 8). Thus, we interpret that the final breakup was not controlled by further lithospheric extension, but rather defined by the propagation of the spreading center that focused on one of similarly highly thinned necks. All other ultrathin basement areas in our seismic transect (yellow shading in Figure 1) evaded the breakup, which occurred in a sector that had experienced similar amount and tectonic style of extension (Figure 11).

In the NE South China margin, the breakup occurred ~150–200 km to the SE of an aborted rift with ultrathin basement (McIntosh et al., 2014), resulting in the onset of seafloor spreading in the northeastern sector of ESB at 33–32 Ma (cross section 1, Figure 11b). Further to the SW, several areas of ultrathin basement have been imaged in the Pearl River Mouth Basin, but final breakup occurred at 30–28 Ma in the NWSB (cross section 2, Figure 11c), and seafloor spreading continued in the SW area of the ESB after a ridge jump at ~25 Ma (Barckhausen et al., 2014; Briais et al., 1993) (cross section 2, Figure 11d). In the CSB, interboudin necks at both conjugate margins have continental ultrathin basement that did not breakup. Breakup occurred at ~23 Ma at interboudin neck 4, in the present CSB (cross section 3, Figure 11d). In the SWSB, thin-crust areas without breakup were also described at both conjugate margins, but breakup occurred at ~22 Ma in the present SWSB (cross section 4, Figure 11e).

Some interboudin necks in the SCS grew laterally to merge into longer structures, cutting each other's fault systems, possibly producing complex fault patterns like that imaged at the NW Reed Bank Segment (Figure 4). However, most of them are of a limited length, and the continental lithosphere in the intervening sectors is thus comparatively thicker and may have prevented full rupture, even after extreme local crustal

Figure 11. Cartoons illustrating the temporal and spatial evolution of the SCS rift system (not to scale). Red numbered lines in the map correspond to schematic cross sections depicted in rift stages shown in (a)–(e). Cross section 3 is the seismic transect presented in this work.

thinning. We speculate that the rising asthenosphere under those ultrathin basement areas had possibly not produced sufficient melt to promote lithospheric weakening via melt diking and subsequent rupture (Bialas et al., 2010).

The current paradigm establishes that progressive lithospheric extension and thinning lead to melting of the rising asthenosphere. However, thinning is not always accompanied by magmatism, which is explained by either the ascent of a depleted mantle or by slow extension/opening rates that permit asthenospheric cooling before crossing the melt adiabat (e.g., Pérez-Gussinyé et al., 2006). Most interboudin necks were thinned to a degree where melting might have played a role in the lithospheric strength profile and help focus breakup (Bialas et al., 2010), but there is no evidence in the seismic data of significant syn-rift magmatism in five unbroken-crust interboudin necks, which requires an explanation. The inferred relatively high initial sea-floor and abrupt COT in the CSB (Figures 9 and 10), similar to the COT along the entire NWSB (Cameselle et al., 2017) and the northern margin of the ESB (Larsen et al., 2018), appear at odds with the lack of (detected) significant syn-rift magmatism, which may indicate that rifting occurred in a region with a depleted mantle composition.

The narrow COTs, where oceanic crust abuts continental crust, support a rapid change in the extension process. The sudden establishment of a spreading center is necessarily associated with asthenospheric melting and intense magma migration in the mantle and diking in the crust. Thus, the differences in crustal structure imply either very distinct evolution for particular sectors of the west SCS, including the NWSB, ESB, and the CSB or that the current paradigm cannot satisfactorily explain the observations.

To reconcile the processes creating a lithosphere-boudinage geometry and the abrupt COT, we interpret the final architecture of the central SCS rift system resulting from the contemporaneous focus of extension toward several areas (i.e., interboudin necks) that interacted in a 3D rift system (Figure 11). Rifting ended when, after a ridge jump to the south (Barckhausen & Roeser, 2004; Udo Barckhausen et al., 2014), the spreading center propagated from NE to SW (Figure 1) cutting through the interboudin neck 4 (Figure 8 and cross section 3 in Figure 11d). The observations support that neither the location, nor the timing of breakup, nor the establishment of seafloor spreading are a direct consequence of the progressive lithospheric extension during rifting, which is similar for six different interboudin necks. The final breakup and locus of magmatism may have been controlled by the processes that governed the dynamics of the ridge jump and spreading center propagation. Our interpretation indicates that if 2D cross sections like ours (Figure 8) are analyzed without accounting for the 3D evolution described above (Figure 11), as it is often done for less well-surveyed systems, inferences of lithospheric thinning, thermal structure, asthenospheric upwelling, and potential melting may lead to conclusions that cannot explain the regional evolution, similarly to modeling studies (e.g., Le Pourhiet et al., 2018).

6. Conclusions

New seismic images provide new information on the tectonic style and crustal architecture of the central SCS rift system. The integration of geophysical data and available geological information constrains the time and space evolution of the rift system, providing new insights into the mechanisms of continental extension and COT formation.

The seismic images reveal variations in crustal thickness, internal basement reflectivity, morphology of the top of the basement, faulting style, fault-block geometry, and geometry of overlying sediment. Those changes provide constraints in distinguishing continental from oceanic domains in broad agreement with other regional data sets, and defining the COT accurately.

The central SCS rift system is characterized by an ~850 km wide region, where heterogeneously distributed deformation created a multiple crustal-scale (and thus lithospheric) boudinage. The tectonic structure defines seven segments, each one characterized by a boudin sector of ~18- to 24-km-thick continental basement (6- to 8-s TWT) that laterally thins to an interboudin neck of ultrathin <10-km thick basement (<3.2-s TWT). Extensional strain focuses toward the center of each neck associated with increased offsets (up to 4-s TWT) of the normal faults. At the axis of each neck, β factors range from 3.3 to 6.5, and the largest offset faults seem to reach the Moho. The final breakup occurred at one of these interboudin necks.

The basin stratigraphy mapped along our transect and calibrated with published modern seismic data and industry boreholes supports that continental extension continued at all the six interboudin necks of the central SCS rift system until breakup (~23 Ma). The tectonic structure of each neck supports that, within the wide central SCS rift system, each of the seven segments may be interpreted as a discrete subsystem evolving from early rifting to breakup.

The entirely brittle crust—and possibly a strong mantle—at the interboudin necks and the absence of magmatic syn-rift products support that the asthenosphere did not produce sufficient melt to rupture the lithosphere via diking. These facts, together with the structure and location of the COT, indicate that the breakup in the central SCS rift system was controlled by an abrupt change in the extensional process, possibly associated spreading center dynamics, rather than by a continuum of processes during progressive continental lithospheric thinning. We propose that the SCS rift system experienced a 3D wide rift mode of deformation from initial rifting to breakup. A series of contemporaneous and structurally equivalent ultrathin crust areas have been reported by seismic studies NE and SW of our seismic transect, supporting that simultaneously distributed deformation accommodated extension over a $1,000 \times 1,000 \text{ km}^2$ margin setting, creating numerous separated segments and grabens as those in our seismic images. Continuous extension resulted in a final lithosphere-boudinage structure of the continental domain, with interboudin necks where the crust is thinned to $\lesssim 10 \text{ km}$ alternated with boudins undergoing comparatively little extension. We interpret that final continental breakup was determined by the seafloor spreading propagation toward the SW and not primarily by continental lithospheric thinning during rifting.

Our interpretation explains the 3D spatial and temporal evolution of structures documented in wide rifted margins. We propose a strong link between the final architecture of the rift systems, the timing and location of the breakup, and the propagation of the oceanic spreading center. This interrelation can overcome the control that the progressive extension of continental lithospheric rheology exerts on the final architecture of magma-poor rifted margins.

Conflict of Interest

No conflicts of interest to declare.

Data Availability Statement

Images are available at the PANGAEA world datacenter (<https://doi.pangaea.de/10.1594/PANGAEA.911309>) (BGR, 2020).

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