



Rift–drift transition in the Dangerous Grounds, South China Sea

Xi Peng¹ · Chuanbo Shen¹ · Lianfu Mei¹ · Zhigang Zhao² · Xiaojun Xie²

Received: 1 December 2017 / Accepted: 2 April 2018 / Published online: 24 April 2018
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Abstract

The South China Sea (SCS) has a long record of rifting before and after subsequent seafloor spreading, affecting the wide continent of the Dangerous Grounds, and its scissor-shape opening manner results in the rifting structures that vary along this margin. Some 2000 km of regional multichannel seismic data combined with borehole and dredge data are interpreted to analyze the multistage rifting process, structural architecture and dynamic evolution across the entire Dangerous Grounds. Key sequence boundaries above the Cenozoic basement are identified and classified into the breakup unconformity and the rift end unconformity, which consist of the rift-related unconformities. Reflector T70 in the east of the Dangerous Grounds represents the breakup unconformity, which is likely corresponding to the spreading of the East Subbasin. T60 formed on the top of carbonate platform is time equivalent to the spreading of the Southwest Subbasin, marking the breakup unconformity of the central Dangerous Grounds. The termination of the spreading of the SCS is manifested by the rift end unconformity of T50 in the southwest and the final rift occurring in the northwest of the Dangerous Grounds is postponed to the rift end unconformity of T40. On the basis of the stratigraphic and structural analysis, distinct segments in the structural architecture of the syn-rift units and the ages of rift–drift transition show obvious change from the proximal zone to the distal zone. Three domains, which are the Reed Bank-Palawan Rift domain, the Dangerous Grounds Central Detachment domain and Nam Con Son Exhumation domain, reflect the propagation of the margin rifting developed initially by grabens formed by high angle faults, then large half-grabens controlled by listric faults and detachments and finally rotated fault blocks in the hyper-extended upper crust associated with missing lower crust or exhumed mantle revealing a migration and stepwise rifting process in the south margin of the SCS.

Keywords South China Sea · Seismic imaging · Dangerous Grounds · Breakup unconformity · Segmentation · Rifting

Introduction

Rifting resulting breakup of continent is governed by plate boundary stresses or mantle convection (Honza 1995; Ziegler and Cloetingh 2004). The location of the South China Sea (hereafter SCS) at the junction of first-order plates (the Pacific, Eurasian and Indian-Australian plates), thus provides an outstanding opportunity to better study rift processes in conjugated continental margins. From the late Cretaceous into Cenozoic, the SCS experienced an abnormally long transition from a convergent to a divergent margin,

and subsequently seafloor spreading and then oceanic crust subduction (Briais et al. 1993; Holloway 1982; Taylor and Hayes 1983). Until now, intensive surveys have been carried out to research the Dangerous Grounds area, including continental rifting (Hinz and Schlüter 1985; Kudrass et al. 1986; Schlüter et al. 1996), deep crustal structure (Franke et al. 2008, 2011; Pichot et al. 2013; Vijayan et al. 2013), sedimentation and deformation (Clift et al. 2008; Cullen et al. 2010; Cullen 2010; Hutchison 2004; Hutchison and Vijayan 2010; Yan and Liu 2004), with the increase in the acquisition of geological and geophysical data. However, the limited number of industrial drill sites and seismic profiles across the full Dangerous Grounds area which is a key region to cast light on the evolution of the SCS, have prevented the detailed study of the rift architecture and tectonic framework.

Globally, numerous models stemmed from geophysical and field observations are applied to highlight the processes

✉ Chuanbo Shen
cugshen@126.com

¹ Key Laboratory of Tectonics and Petroleum Resources of Ministry of Education, China University of Geosciences, Wuhan 430074, China

² CNOOC Research Institute, Beijing 100028, China

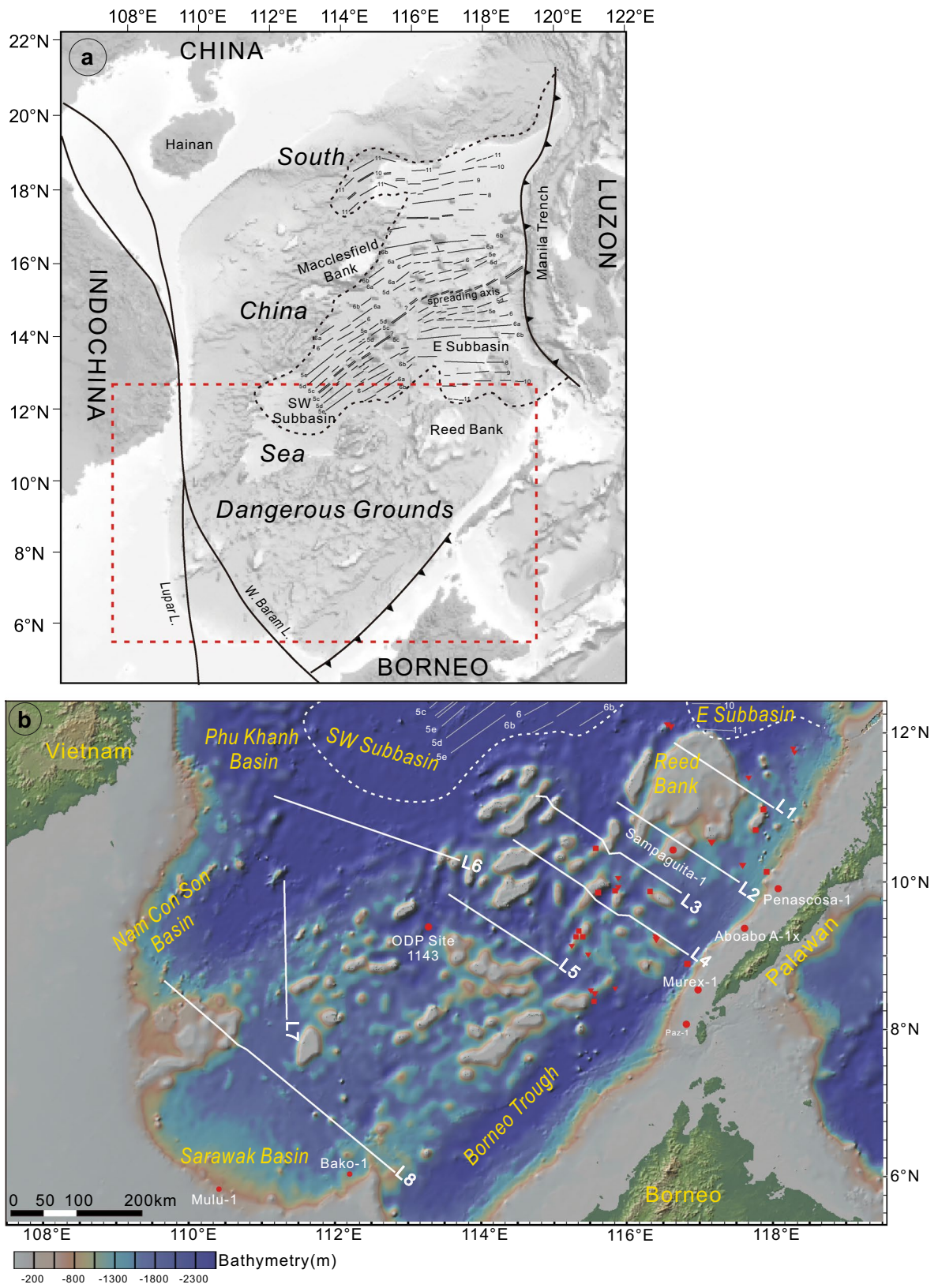


Fig. 1 a The study area in the South China Sea and its adjacent region. **b** Regional setting map of the study area. Color bathymetry and topographic map of the southern South China Sea shows the locations of the data set illustrated in this study. The map shows the major features of the region including the Borneo Trough, Dangerous Grounds, and the sedimentary basins. Bold white lines show seismic profiles presented in this paper. Dashed bold white line indicates approximate location of the continent-ocean boundary (COB) (Briaïs et al. 1993). The grey dashed lines mark the magnetic anomalies (Briaïs et al. 1993). Red triangles (so-23 samples) and squares (so-27 samples) are dredges sites (Kudrass et al. 1986). Trace of black fault lines are from Clift et al. (2008). Well locations (red circles) are from ODP Shipboard Scientific Party (2000) and Steuer et al. (2013)

of crustal extension (Boillot et al. 1980; Lister et al. 1991; Péron-Pinvidic and Manatschal 2009; Wernicke 1985; Whitmarsh et al. 2001), particularly in magma-poor or moderately volcanic margins. The incipient age of continental rifting seems to become younger from NE to SW instead of a ubiquitous cessation of extension after seafloor spreading in the SCS and adjacent areas (Franke et al. 2014; Morley 2016; Sibuet et al. 2016). Strata package records the complex evolution of continental margins in rift basins, as well as offers critical information on the crustal processes leading to continental break-up (Ding et al. 2016; Gawthorpe and Leeder 2000; Song and Li 2015). Nonetheless, the detailed evolution of continental rifting for the different crustal segments of the Dangerous Grounds area has not yet been clearly documented. Also, the timing of continental rifting and the significance of syn-rift and post-rift tectonics along the southern margin are the key issues not yet fully accomplished, posing serious problems to the correct assessment of its resources potential (Hall 2009; Longley 1997). Thus, the Dangerous Grounds area is revealed here as a perfect province to address the intricate rift to drift evolution of the southern margin of the SCS.

In this research, we integrate the new information with existing geological and geophysical data from the Dangerous Grounds and establish a relatively uniform tectostratigraphic framework. All these results will help us (a) understand the transition process from rifting to drifting in the whole Dangerous Grounds, (b) analyze the discrepant syn-rift geometry and thickness of the rift sequences revealing a relative rift locus migration among the major rifting segments in continental extension, (c) reconstruct the dynamics model of the Dangerous Grounds in a magma-poor extensional setting.

Regional geological setting

The Dangerous Grounds area

The Dangerous Grounds, which is underlain by the attenuated continental crust rifted from the South China continent with the onset of spreading in the SCS Basin, consists of the

largest component of the southern continental margin of the SCS (Clift et al. 2008; Hall 2012; Holloway 1982; Taylor and Hayes 1983). It lies north of Borneo from which it is separated by the Northwest Borneo-Palawan Trough (Fig. 1). The SW end of the trough is truncated by a transform fault known as the West Baram Line (Morley 2002; Hutchison 2004), but this fault is also considered as a boundary of continental crust that underwent differential extension in the early Tertiary (Cullen 2014; Sapin et al. 2012). The Reed Bank adjacent to the East Subbasin lies in the northeastern part of the Dangerous Grounds, attached to the South China continent and probably linked to the Macclesfield Bank during the Paleogene (Cullen et al. 2010; Barckhausen et al. 2014), and moving southwards with the Dangerous Grounds in the seafloor spreading period.

The pre-rift sedimentation is likely related to the Mesozoic South China continental margin and is marked by the T100 unconformity which shows a high amplitude reflection on the top (Figs. 2, 3). The syn-rift strata in Early Tertiary are composed by fluvial to middle neritic interbeds of siltstones and sandstones of Late Eocene to Oligocene age (Schlüter et al. 1996; Williams 1997). The sedimentation during Late Oligocene to Early Miocene is coeval with the drifting stage of the Palawan-Mindoro microplate (Franke et al. 2011). The most distinguishable stratigraphic sequence is the Nido carbonate sequence (Steuer et al. 2013) (Fig. 2), which is composed of the carbonate platforms in shallow marine environment. This Nido carbonate sequence is cover on top by limestones, wackestones, and packstones, deposited in an open marine of shallow shelf to bathyal environment. Since Middle Miocene, the sedimentation is linked to the collision of the micro-continental blocks with the Philippine Mobile Belt and Borneo (Arfai et al. 2011). The sedimentation of this period is predominantly filled by turbidite deposition in the southeastern margin. In deep water Sarawak basin southwest of the Dangerous Grounds, the collision resulted in the change of the environment from the coastal plain to outer neritic and bathyal (Madon 1999).

The previous stratigraphic schemes in the Dangerous Grounds

Until now, the strata of the Dangerous Grounds were only penetrated by industrial wells that mostly localize in the petroliferous basins of various countries. On top of Cretaceous basement, five unconformities were recognized by the SONNE composite investigation in offshore Palawan, and the ages of the seismic unconformities were further verified by wells in the Reed Bank (Hinz and Schlüter 1985). The exploration in Sarawak basin established eight stratigraphic cycles from Oligocene to Pliocene, while the tectonic movements had a much bigger effect than sea-level changes in the Early Miocene (Hageman 1987). The Middle Miocene

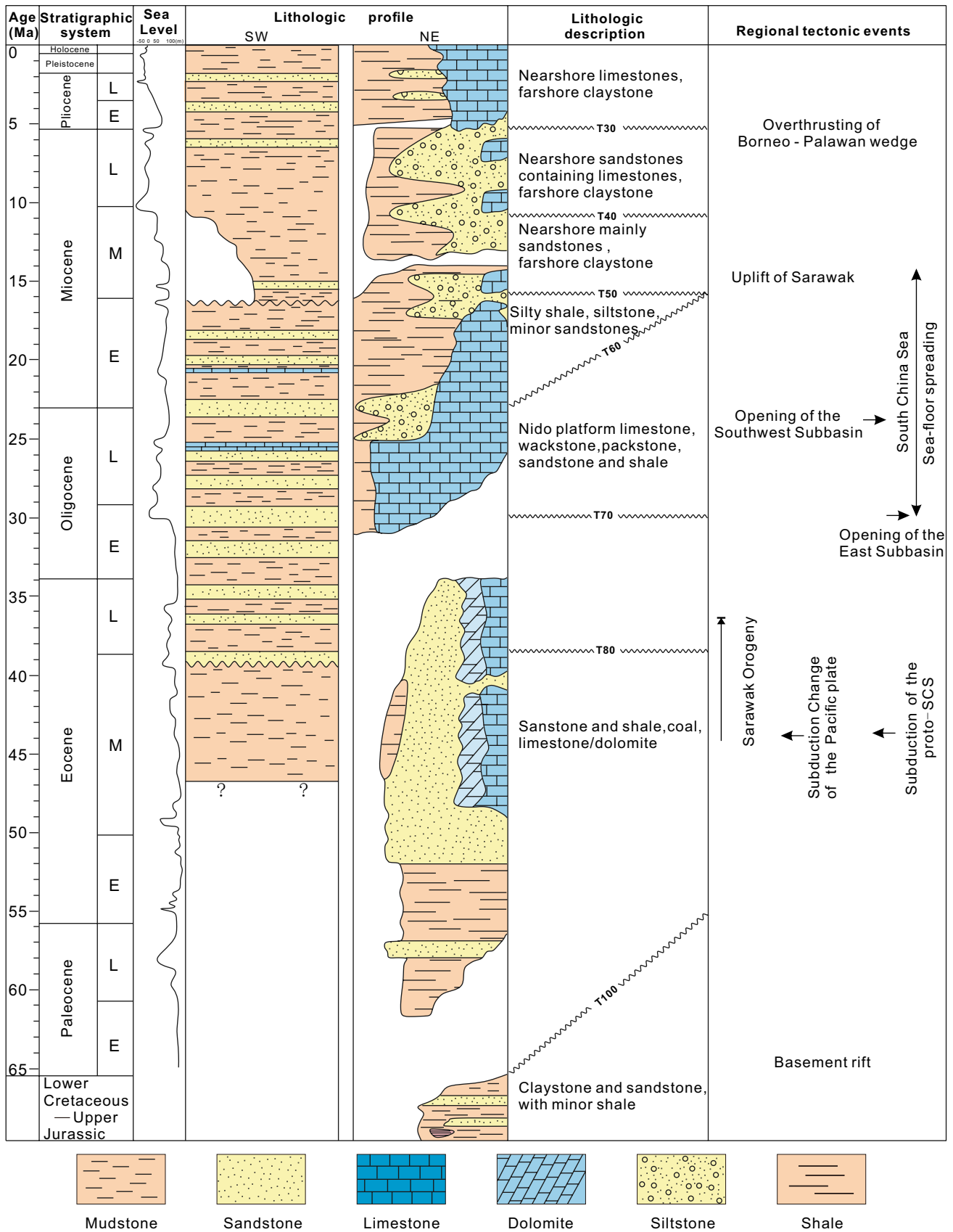


Fig. 2 Simplified Cenozoic column of the Dangerous Grounds with lithostratigraphy (from Franke et al. 2011 and Madon 1999), seismic reflectors, relative change of eustatic curve (from Franke et al. 2011) and key tectonic events

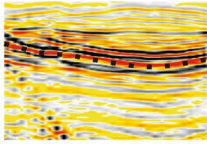
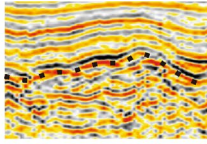
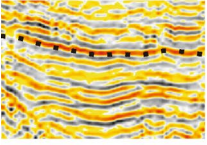
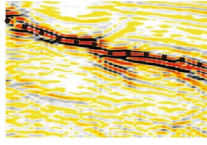
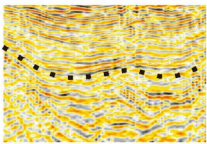
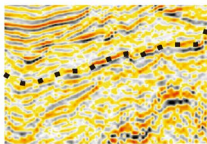
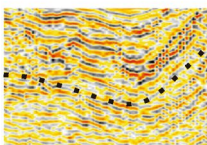
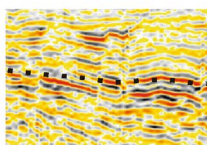
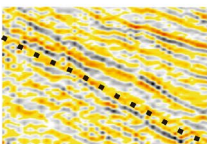
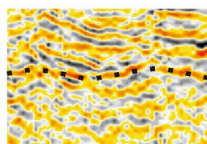
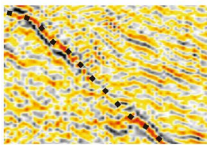
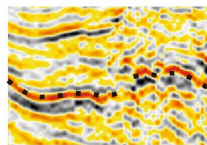
Horizon and age	Location	Typical seismic image		Main reflection feature
T40 (~10.5 Ma)	L6 L7			Middle to strong amplitude, high lateral continuity, parallel above and truncation below
T50 (~16 Ma)	L5 L8			extreme strong amplitude, middle continuity, onlap above and truncation below
T60 (23~16 Ma)	L4 L5			Middle to weak amplitude, general continuous, onlap above and truncation below
T70 (~31 Ma)	L7 L2			Middle to strong amplitude, continuous - interrupted continuity, onlap above and truncation below
T80 (~38 Ma)	L1 L2			Middle amplitude, good continuity, onlap above and truncation below
T100 (basement of Cenozoic)	L1 L3			Middle to strong amplitude, patchy-continuous continuity, onlap above and truncation below

Fig. 3 Seismic reflection patterns of the main unconformities with inferred ages

Unconformity (MMU) seems to be prevalent especially in the western study area, representing the cessation of the sea-floor spreading in the SCS and the collision of the Dangerous Grounds with Borneo (Hutchison 2004; Madon 1999, 2013). Furthermore, a compressive belt oriented NE where folded paleo-anticlines are overlain by undeformed sediments is mapped from Nanwei (East Nan Con Son Basin) to Liyue (Reed Bank) by tectono-stratigraphy analysis (Wang et al. 2016; Yan and Liu 2004), but alternatively, the unconformity dividing the two distinct structures is similar to the MMU or the SCSU (South China Sea Unconformity) (Cullen 2014). The relative accurate ages of some unconformities are still uncertain and Franke et al. (2014) firstly summarized the timing of the rift-related unconformities around the SCS, indicating a diachronous system coherent with the regional plate kinematic (Sibuet et al. 2016). Since the late Cretaceous, the Dangerous Grounds have been in the center of sequential tectonic event, and discrimination of

key interfaces compatible with reasonable causes in seismic lines is useful for illustrating these extension events (Morley 2016). Hence, the construction of a relative uniform stratigraphic framework is not only vital to the hydrocarbon exploration, but also for the understanding of the evolution of this complex region. The comparison about these schemes will be carefully analyzed in the discussion.

Data and methods

The multichannel seismic database presented in the study consists of industrial data collected several times over 10 years, made available by courtesy of China National Offshore Oil Corporation (CNOOC). The data were recorded in SEG-D format at 13 m of trace spacing and recorded up to 9–12 s (two-way travel time, hereafter TWT). Details of the seismic processing techniques and flows were not available

to our study. All the data were interpreted with Geoframe 4.5™ (Schlumberger Company).

The Reed Bank Basin covered by 2D seismic profiles includes five seismic profiles (L1, L2, L3, L4, L5), and the other data (L6, L7, L8) are scattered in western basins. In this paper, we used more than 2000 km of the high-quality seismic data and the latest geological interpretation (Figs. 4, 5, 6, 7, 8, 9, 10, 11) to build the sequence stratigraphic framework and carried out a qualitative study through unconformity analysis (Fig. 13). Furthermore, previous dredging data distributed in the Reed Bank area and log data from the shallow ODP well were used for constraining the interpretation of seismic sequences (Kudrass et al. 1986; Shipboard Scientific Party 2000; see Fig. 1 for locations). Besides, relative reliable stratigraphic schemes in the nearby area were taken as a reference and compared in the discussion (Fig. 13) (Clift et al. 2008; Cullen 2010; Ding et al. 2013; Hinz and Schlüter 1985; Hinz et al. 1989; Hutchison 2004; Steuer et al. 2013) to crosscheck interpretation of several unconformities (T100, T80, T70, T60, T50, T40) in the Cenozoic sequence over the entire seismic lines. For better understanding the deep crustal architecture in the northwest of the Dangerous Grounds, line L6 was synthetically interpreted by using of the magnetic and velocity data (Fig. 9).

A set of comparable architectural elements have been proposed to characterize the rifted margins, such as their

partitioning into proximal and distal zones mainly depending on variation of bathymetry and topography. The relevant terminologies applied in the rifted margins are quoted from Péron-Pinvidic et al. (2013). Although their study is limited to the Iberia-Newfoundland margins, the described evolution is probably comparable and applicable in other rifted margins. Based on the thickness of the continental crust and stratigraphic patterns, we define the outline of distinct seaward arrangement zones along the strike of the Dangerous Grounds (Fig. 12).

Interpretation and results

Rifting related unconformities and sequences architecture

Seismic lines close to the existing drillings have been chosen to establish the new stratigraphic scheme (Figs. 5, 8, 11), and several key unconformities have been identified to provide good age constraints for the development of the strata. Sequences formed in the rifting of the Dangerous Grounds can be classified into the syn-rift sequence and the rift transition sequence based on the unconformities. Furthermore, the different styles of strata package in these sequences have also been analyzed.

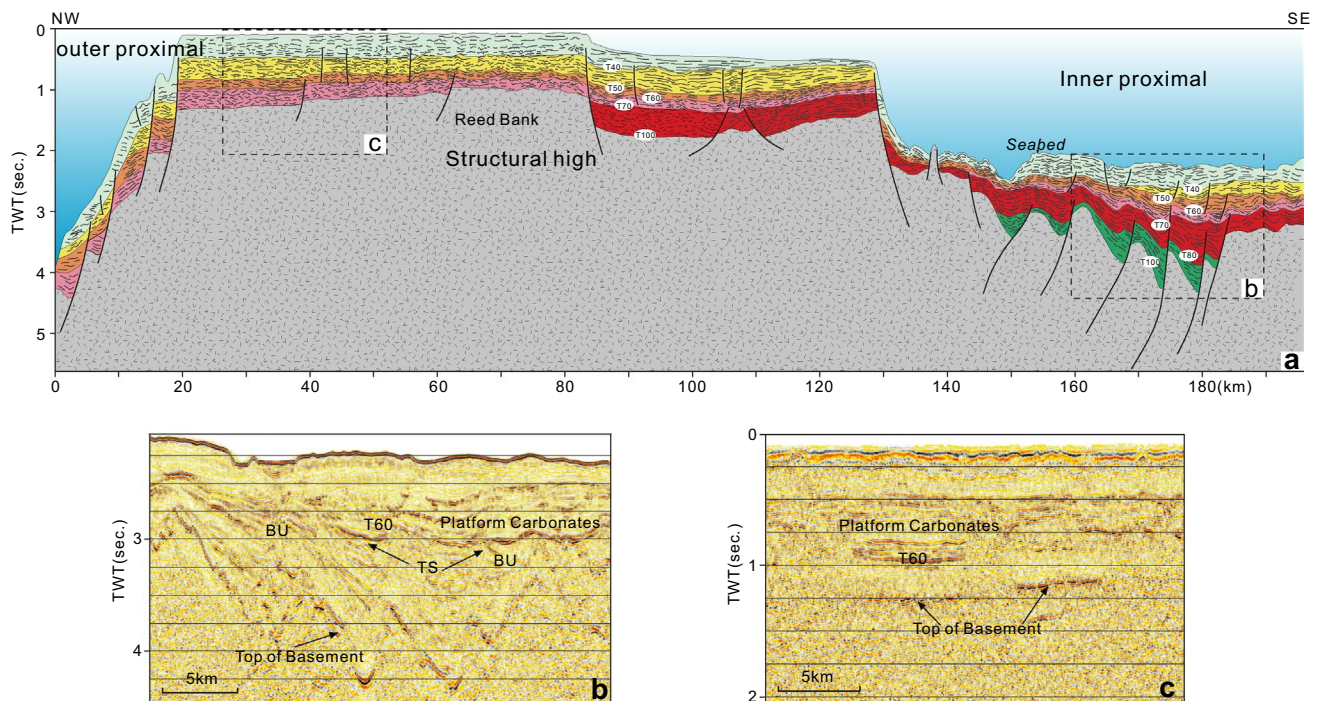


Fig. 4 **a** Line drawings of 2D seismic line L1 from the Reed Bank. **b** Typical half-graben structure in the inner proximal zone. A series of half-grabens of the master faults dipping northwest control the early Oligocene and older sequence below the BU. Late Oligocene/

Early Miocene Nido carbonates are obvious, covering the syn-rift sequences. **c** The structural high shows considerably thinner syn-rift sequences and weaker deformation. BU breakup unconformity, TS transition sequence. For location see Fig. 1

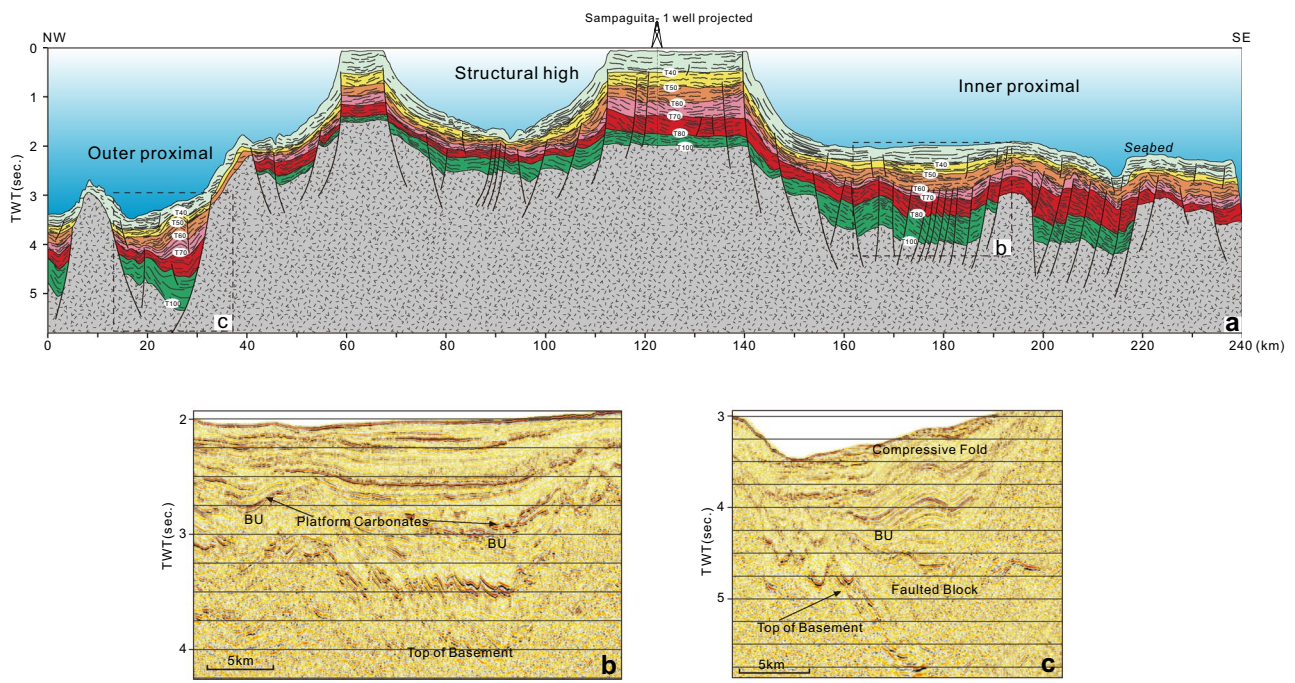


Fig. 5 **a** Line drawings of 2D seismic line L2 from the Reed Bank. **b** Seismic section in the inner proximal zone shows a series of half-grabens. Late Oligocene/Early Miocene Nido carbonates are above the BU, covering the syn-rift sequences. **c** The structure of the outer

proximal zone is a wide half-graben and the post-rift strata are obviously deformed into the compressive fold. *BU* breakup unconformity; for location see Fig. 1

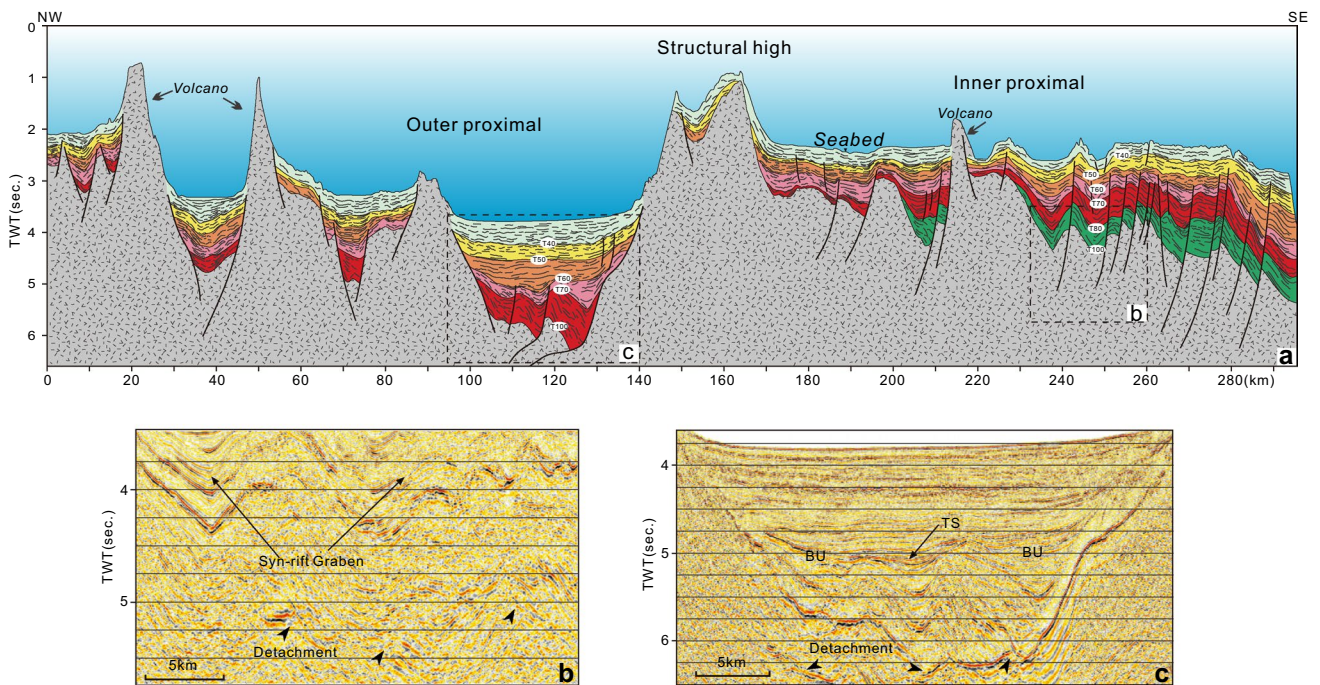


Fig. 6 **a** Line drawings of 2D seismic line L3 from west of the Reed Bank. For location see Fig. 1. **b** The basement structure in the inner proximal zone. Note that arrows indicate the detachment development below the early syn-rift grabens. **c** The structure in the outer proximal zone. An abrupt drop of the basement topography is separated

by the structural high. The master faults sole out at a detachment at about 7 s (TWT) depth. The TS are saucer-shape and thicken towards outer proximal zone. The BU is presented by the T60 boundary. *BU* breakup unconformity, *TS* transition sequence

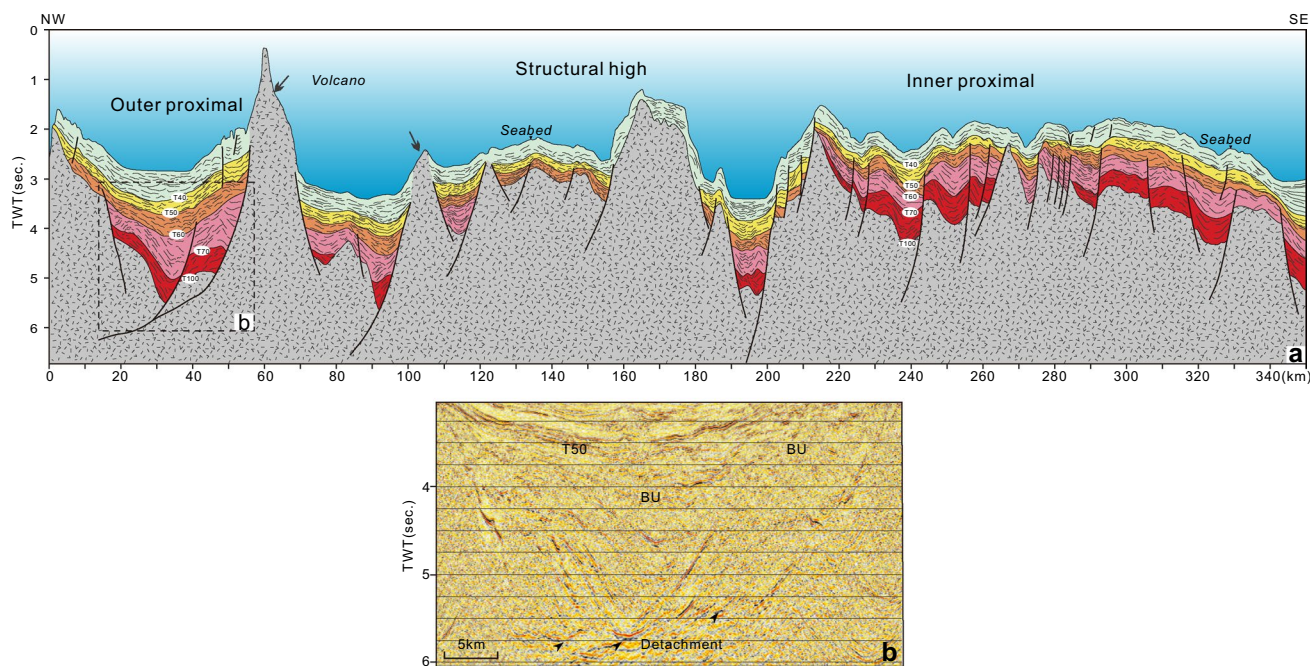


Fig. 7 **a** Line drawings of 2D seismic line L4 from west of the Reed Bank. For location see Fig. 1. The scale of the individual rift gradually becomes larger to NW. **b** The wedge-shape half graben below the

BU (T60). Note the master faults sole out at a detachment at about 6 s (TWT) depth. BU breakup unconformity

The rift onset unconformity

The base of the Cenozoic rift infill is marked by T100 with middle-strong amplitude and patchy-continuous continuity, representing a prominent angular unconformity between the Mesozoic and the Cenozoic sequences and indicating erosion beneath it (Figs. 3, 4). The wedge sediments of pre-T100 imply the rifting may initiate earlier such as in the South China margin (Chan et al. 2010). Dredge samples from the Dangerous Grounds basins and the Reed Bank indicate Upper Triassic to Lower Cretaceous strata (Schlüter et al. 1996), whereas Upper Cretaceous strata are absent. In deep-water Sarawak, the base of the syn-rift unit is underlain by the reflector T100 (Fig. 11b, c) that is probably no more than 43 Ma (Madon et al. 2013). Therefore, the T100 boundary is characterized as a widespread erosional surface with remarkable onlap sequence in seismic facies and its age is between late Mesozoic and Early Eocene (Fig. 2). The T80 is an internal unconformity with middle amplitude and good continuity in upper Lower Paleogene, penetrated by Sampaguita-1 well located in the east of the study area (Figs. 1, 5).

The breakup unconformities

The T70 boundary associated with the opening of the East Subbasin of the SCS is obvious over the eastern Dangerous Grounds with seismic reflection of middle-strong

amplitudes and intermediate continuity (Fig. 3). In the northeastern Dangerous Grounds and Reed Bank area, the breakup unconformity (BU) is directly overlain by a widespread carbonate platform sequence (Nido carbonates) with reef complex occupying its top part (Figs. 4b, 5b). The top of these limestones at the central and south Palawan shelf is of Lower Miocene age (ca. 22–17 Ma) (Hinz and Schlüter 1985; Schlüter et al. 1996). The truncations below the unconformity indicate erosion which was linked to the rising asthenosphere at the initiation of the continental breakup and seafloor spreading. So we propose that a late Early Oligocene age is suitable for T70.

Widespread dredging samples from the carbonate platform developed in the southwest of the Reed Bank were dated from Late Oligocene to Early Miocene (Kudrass et al. 1986; Schlüter et al. 1996; Steuer et al. 2013). Most faults cut through the whole Paleogene strata, with the tilted and faulted syn-rift sequences beneath this obvious high amplitude reflector (Fig. 6a, c). So the T60 boundary may indicate this surface forms the top of a carbonate sequence with middle-weak amplitude and general continuous (Fig. 3). We estimate the age of this identified regional breakup unconformity in the central Dangerous Grounds is about 23 Ma, around the Oligocene/Miocene boundary with a few millions years variation, corresponding to the diachronous age of the top of the limestone or the result of diachronous spreading in the Southwest Subbasin.

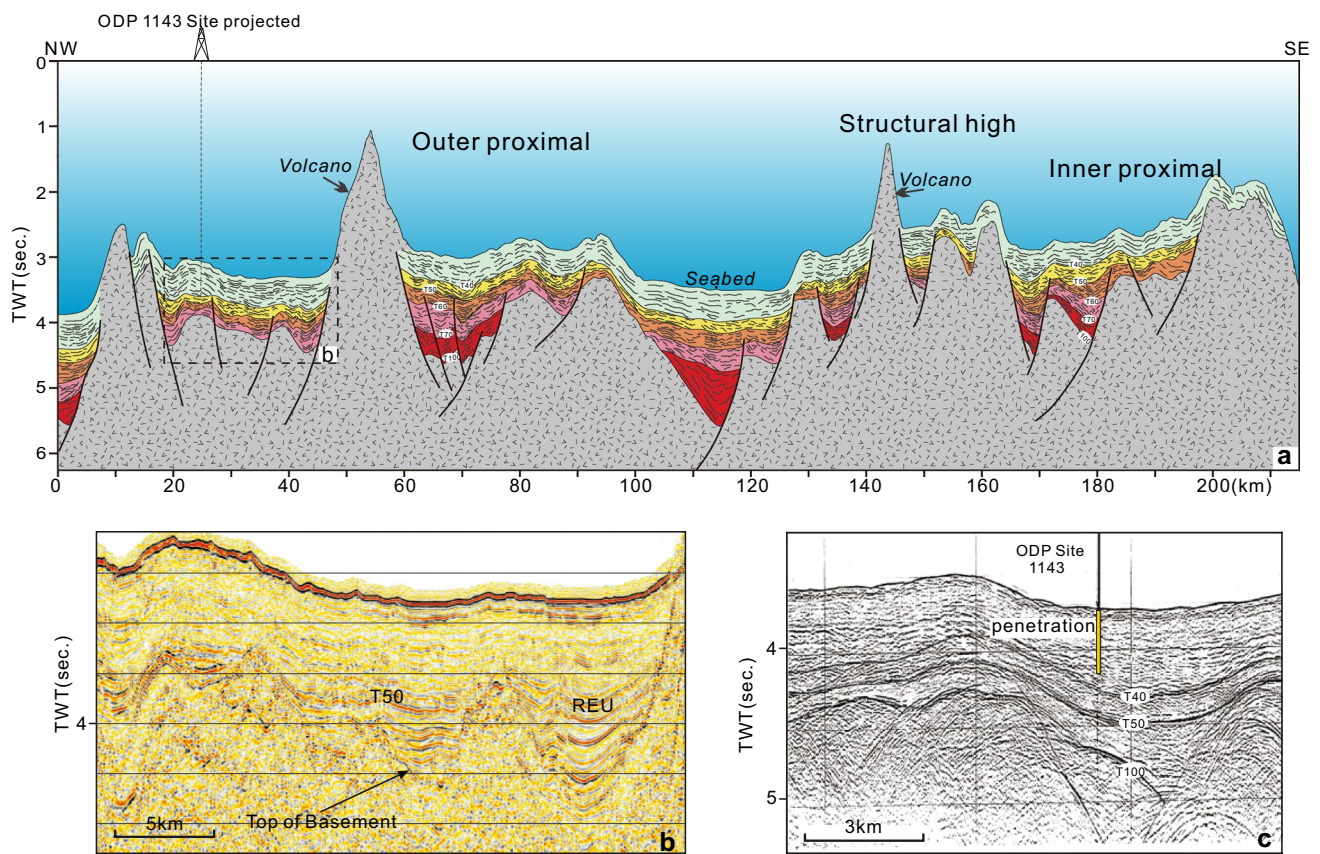


Fig. 8 **a** Line drawings of 2D seismic line L5 from west of the Dangerous Grounds. The rift structure is larger in the outer proximal zone and is modified by the late volcanic event. **b** The syn-rift sequences are sealed by the REU of T50. **c** Seismic section of the ODP Site

1143. The approximately 500 m drill is of Upper Miocene to recent. REU rift end unconformity; see Fig. 1 for location Modified from Shipboard Scientific Party (2000)

The syn-rift sequences

The syn-rift sequence is well developed in the Dangerous Grounds, filling the wedge-shape half-grabens. In the Reed Bank area, the syn-rift sequences below the BU are characterized by chaotic and low frequency discontinuous-moderately internal reflections above the basement, indicating clastic sedimentation filling the half-grabens in the extension period. They are related to strongly rotated blocks bounded by the high-angle faults (Figs. 4b, 5b, 6b), and are cut by a series of closely spaced planar faults. In the west of the Dangerous Grounds, the highly faulted basement and rift unit beneath the T50 or T40 unconformity is clearly different of seismic character from the overlying hemipelagic drape sediments. These half-grabens are bounded by both normal faults and large-scale listric faults, which is responsible of the wedge deposition of the strata and often appear to sole out at depth and in this case continue upward, subdivided into multiple fault block compartments by the synthetic and antithetic faulting (Figs. 10, 11).

The rift end unconformities

The rift end unconformity (REU) is usually located above the BU boundary, with local erosion and angular unconformity that mark the termination of rifting. T50 boundary shows very strong amplitude, with middle continuity and onlap above and truncation below (Fig. 3). The age of youngest strata directly below the unconformity is dated at 16 Ma (Mulu-1), which represents the latest time of the tectonic event giving rise to the unconformity (Madon et al. 2013). ODP Site 1143 drilled the continuous hemipelagic sedimentation from late Miocene to present (Fig. 8b, c), showing the bottom of the hole with an age greater than 9.6 Ma (Shipboard Scientific Party 2000). Therefore, we tentatively define the T50 boundary to around the base of Middle Miocene.

T40, another rift end unconformity in northwest of the Dangerous Grounds, with middle-strong amplitude and high lateral continuity (Fig. 3), is adjacent to the tip of the propagation of the Southwest Subbasin, and normal faults cut through up to this horizon, indicating younger extension

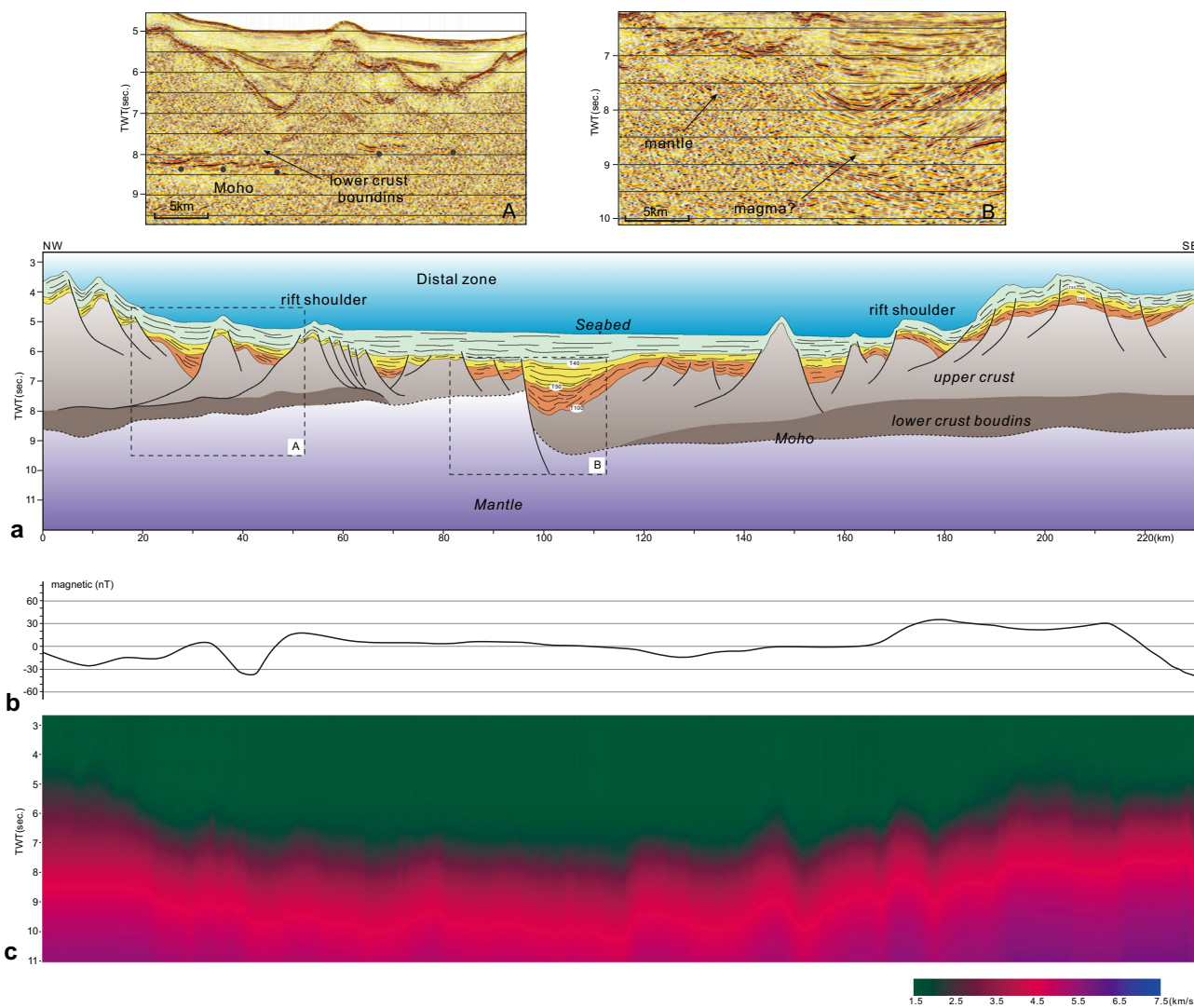


Fig. 9 Cross-section of line L6 in the northwest of the Dangerous Grounds. **a** Line drawings display a series of highly tilted fault blocks on both sides of the rift, representing the distal zone deformation. Note that fragment reflectors show a fairly continuous Moho (9aA) and the lower crust may miss in a relative wide region (km ca.

70–110, in 9aB). **b** Magnetic data recorded along seismic line L6. **c** P-wave stack velocity TWT section of L6. High velocities seem to be under the contact of sediment and mantle, indicating the rising mantle. See Fig. 1 for location

(Figs. 10b, 11d). Therefore, the age of the T40 horizon is approximately the base of Late Miocene.

The rift transition sequences

The rift transition sequence is the strata package between the BU and REU, representing the sediments from late rifting to post-rifting (Fig. 14). In the Reed Bank and offshore NW Palawan, this sequence between T70 and T60 is restricted to the rift associated half-grabens, with the thinner unit than the syn-rift one. The internal reflection of saucer-shape structures is characterized by the intermediate-high continuity and subparallel reflections (Fig. 4b). When the rifting propagated to the west until

the spreading of the Southwest Subbasin at about 23 Ma (Li et al. 2014a), another transition sequence between T60 and T50 is formed. The internal reflectors are moderately to highly continuous reflections, locally transparent with various frequencies (Fig. 6c). In the west of the Dangerous Grounds, the transition sequence between T50 and T40 shows the obvious different geometry from south to north. In deep-water Sarawak, the unit infills the lower position of the faulted blocks above the T50 boundary, with reflectors onlap above it and truncation below the T40 (Fig. 11a, b). But in the COB of the Southwest Subbasin, the unit is characterized by the wedge-shape and is sealed by the T40 (Fig. 10c).

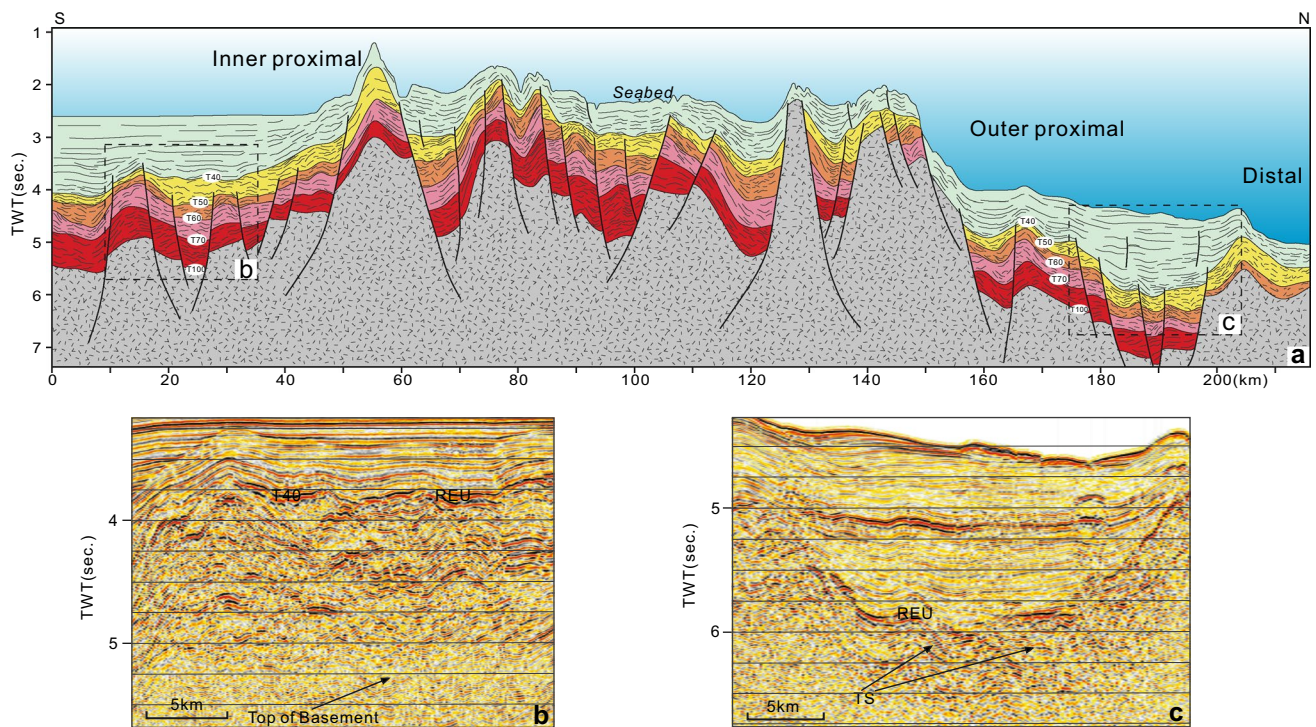


Fig. 10 **a** Line drawings of 2D seismic line L7 from northwest of the Dangerous Grounds. **b** Huge thick of post-rift sediments drape over the faulted blocks above the REU of T40. **c** The highly tilted fault

blocks dipping oceanward are dominated in the outer proximal zone. TS are still controlled by faults. REU rift end unconformity, TS transition sequence; for location see Fig. 1

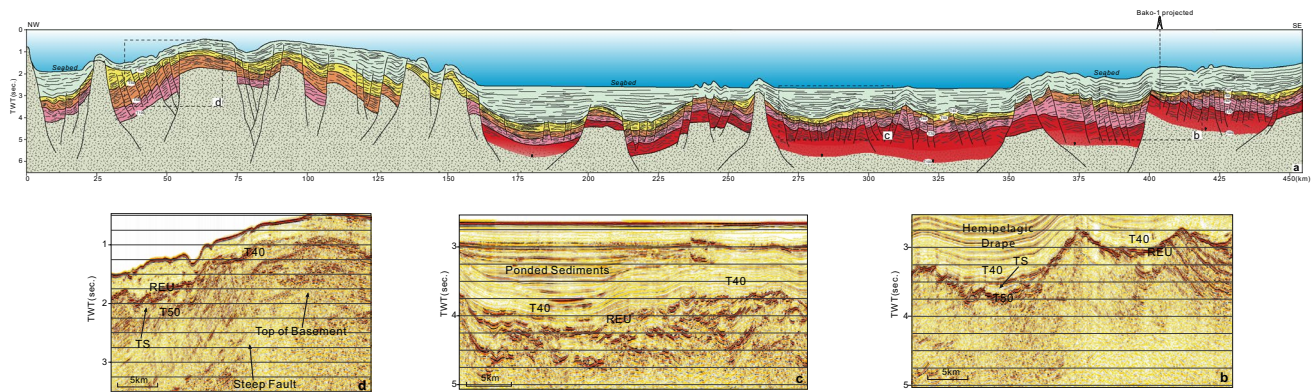


Fig. 11 **a** The interpreted cross-section of line L8 across the western margin of the Dangerous Grounds. Two different tectostratigraphic units are separated by a structural high (km ca.250). Note that the REU of T50 in the southeast is highly erosional in **b** and **c**. **d** The

Middle Miocene strata obviously thicken towards the NW to the Nam Con Son Basin, indicating the northwest rift locus migration. REU rift end unconformity; TS transition sequence; for location see Fig. 1

Structure segmentation of the Dangerous Grounds

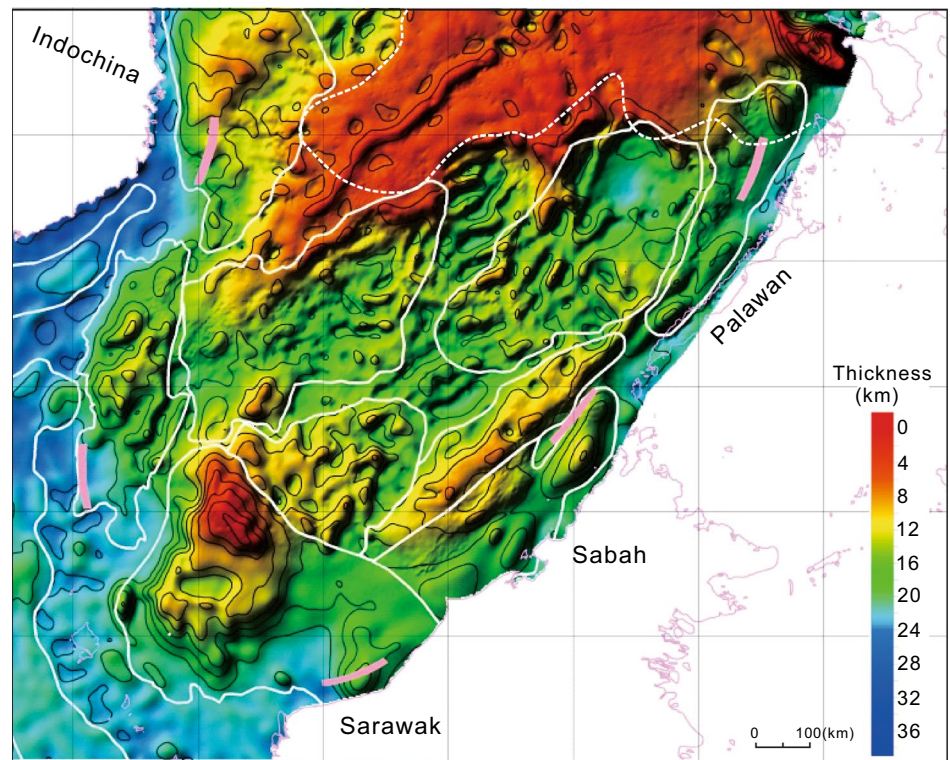
By analysis of seismic reflection boundaries and the sequences from the Dangerous Grounds, three major domains characterizing the rift structure have been revealed (Figs. 12, 14). These characteristics include morphology, fault style and crust configuration. The

boundaries of the domains approximately correspond to the transform faults by Liu et al. (2009) (Fig. 12b).

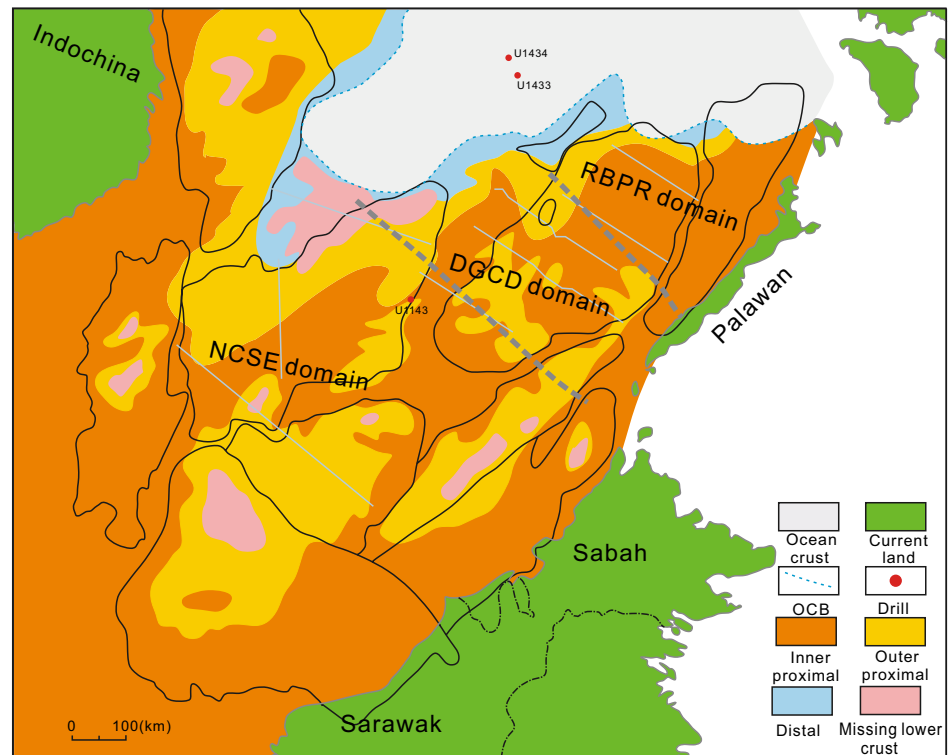
The Reed Bank-Palawan Rift (RBPR) domain

This domain is located in the northeastern part of the Dangerous Grounds, from the offshore NW Palawan to the

Fig. 12 **a** The map of the crustal thickness in the Dangerous Grounds. **b** The schematic representation of the structural elements in the southern rifted margin inferred from **a**. While the thickness of the crust gradually thin towards the ocean, the three domains still have the obvious structural discrepancy. Well location of red circles are from ODP Shipboard Scientific Party (2000) and Expedition 349 Scientists. Dash blue line is approximate location of the COB (Briais et al. 1993). Dash bold grey lines represent the boundaries of different domains and the ice blue lines are the seismic lines in Fig. 1. *RBPR* Reed Bank-Palawan Rift, *DGCD* Dangerous Grounds Central Detachment, *NCSE* Nam Con Son Exhumation



a



b

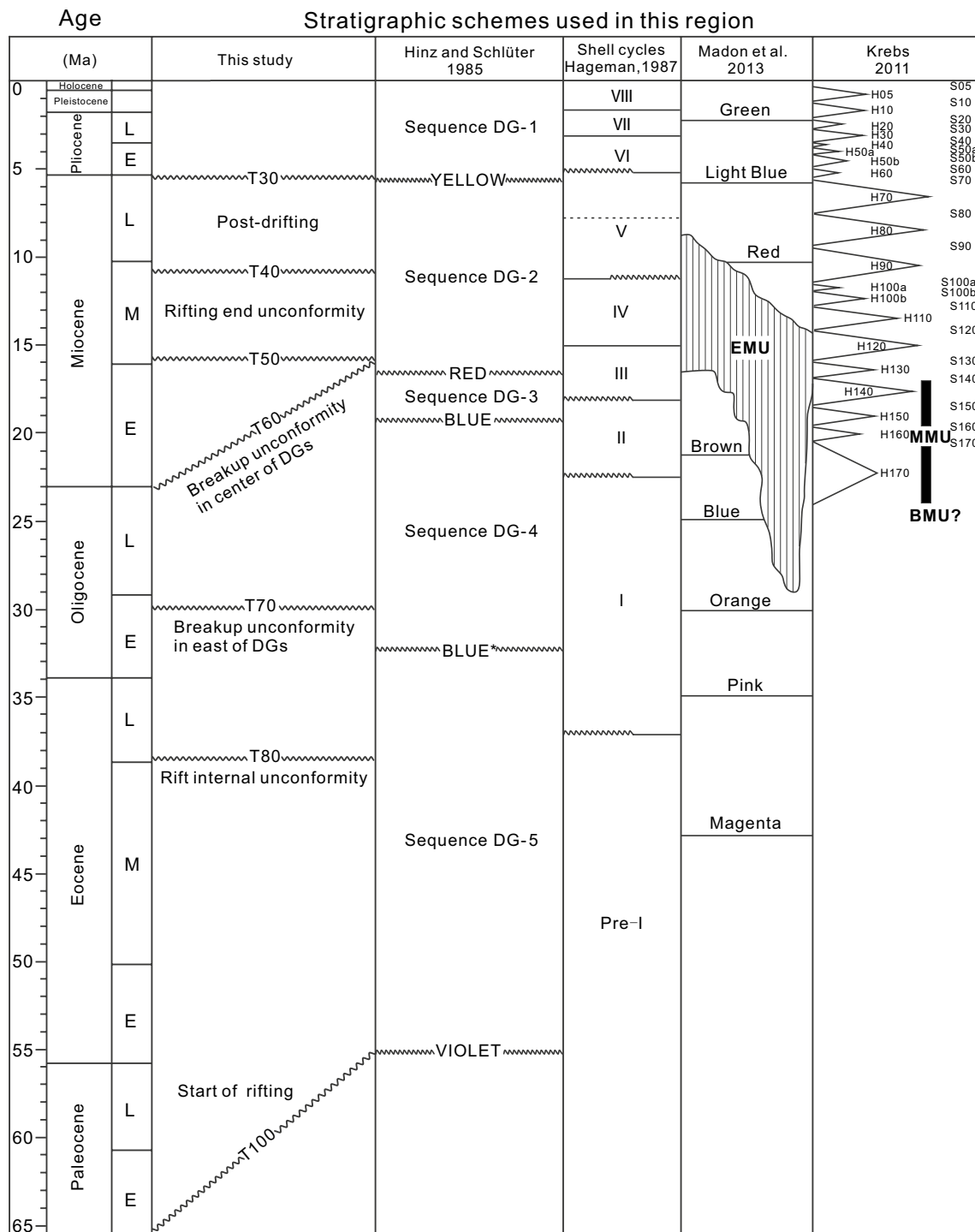


Fig. 13 A comparison of stratigraphic schemes in the Dangerous Grounds. The redefinition proposed in this study is based on the recognition of regional unconformities. Note that MMU is late Early

Miocene by Krebs (2011), time equivalent to the EMU in Madon et al. (2013). It is subdivided into the T60 which is younger towards west and merges into T50

western part of the Reed Bank. Multiple- channel seismic data reveal the continental crust underlain this domain underwent the stretching and thinning characterized by

half-grabens and grabens with steeply dipping border faults. The area is taken up by wide inner proximal zone and structural high (Figs. 4, 5, 12).

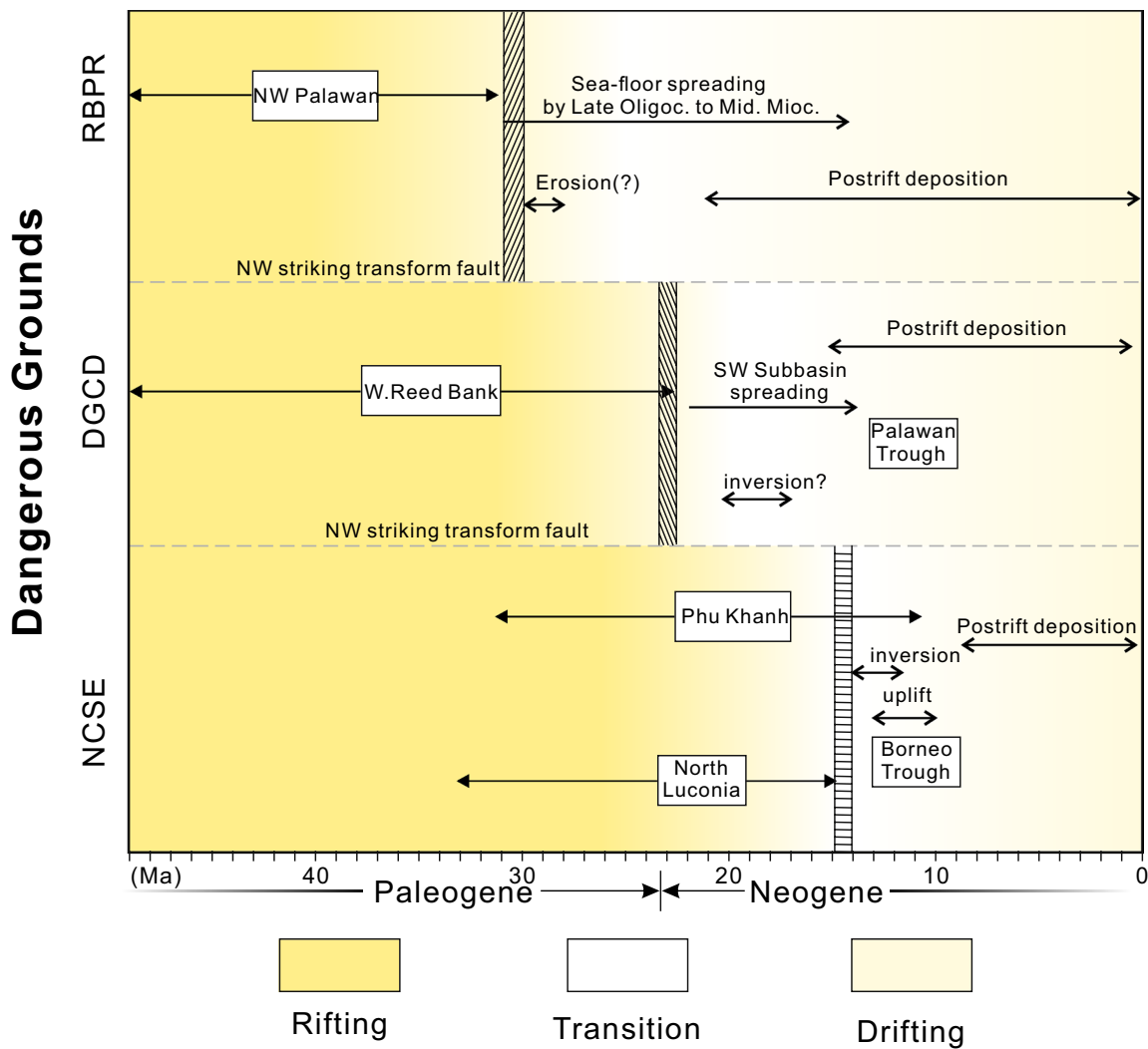


Fig. 14 Time sequence of different events during rift–drift transition along strike of the Dangerous Grounds, showing the temporal and spatial distribution of the deformation in three domains. The NW

transform faults mark the boundaries of these domains. *RBPR* Reed Bank-Palawan Rift, *DGCD* Dangerous Grounds Central Detachment, *NCSE* Nam Con Son Exhumation

In this sector, the thickness of the continental crust is approximately 20 km in the Reed Bank and is less than 10 km toward the narrow COT zone in East Subbasin of the SCS (Franke et al. 2011; Qiu et al. 2011). The total sediment thickness is up to 2 s TWT with the syn-rift unit approximately exceeding 1 s TWT. In the inner proximal zone, there are several half-grabens bounded to the east by oceanward dipping faults and filled by sediments overlapping to the west (km 140–180 in Fig. 4). The strata deposited in the structural high of Reed Bank are approximately horizontal layer with little deformation (Fig. 4c), indicating uniform subsidence in Late Tertiary and subsequent shallow water platform carbonate sedimentation. The outer proximal zone is relatively narrow and located in the abrupt change of topography, characterized by the younger Neogene

sedimentation. The overall thickness of the syn-rift shows a decreasing trend towards the ocean.

The Dangerous Grounds Central Detachment (DGCD) domain

This domain is located in the central part of the Dangerous Grounds, adjacent to the Southwest Subbasin. It is characterized by less than 15 km thin continental crust identified as morphologic ribbons oriented NE (Fig. 12a), with a total syn-rift sediments thickness of up to 1 s TWT in the inner margin and more than 1 s TWT in the outer proximal zone (Figs. 6, 7). The syn-rift graben infilling beneath the T60 (BU) is thick as the tilted fault blocks developed during the continental crust thinning. In the inner proximal zone (km

ca.250 in Fig. 6), disconnected and high amplitude reflectors in the acoustic basement (Fig. 6b) can be identified at about 5.5 s TWT, fluctuating with the basement topography and probably representing the original detachment surface (Franke et al. 2014). The structure beneath the BU is a wide graben controlled by NW dipping faults and is subdivided by closely spaced secondary faults. The strata gradually thin towards the north until the structural high. In outer proximal zone, a half-graben bordered by a remarkable detachment structure (km ca.110 in Fig. 6), is located in the foot of major structural high. This listric fault seems to flatten and join the boundary (ca. 6.5 s TWT) of the lower and upper crust (Fig. 6c). The similar structure can be also seen in L4 line (km ca. 50 in Fig. 7b). The main detachments confined along large volcanoes seem to be active during the syn-rift period. These volcanoes are tentatively inferred to form around Middle Miocene by the obvious thickness difference above the T50 boundary at both sides of volcanoes. The structural highs dominated by volcanic basement structures probably formed along the large basement detachment faults (Fig. 6c), such as in the area of the southwestern margin of the SCS (Chang et al. 2017).

The Nam Con Son Exhumation (NCSE) domain

The domain is located in the western Dangerous Grounds, extending from the northern Sarawak Basin in the south to the Nam Con Son Basin and the tip of the Southwest Subbasin in the west and north respectively. The crustal thickness is usually less than 20 km (Figs. 9, 12), which underwent hyper-extension or even exhumation. The imaging clearly displays the pre-rift and the syn-rift sedimentary sequences affected by the detachment and the normal faults. The deep reflectors that sole out at the lower crust or even the Moho surface are interpreted as a large detachment system. Highly rotated tilt-blocks mostly extending towards ocean in the distal zone deeply root at detachment (Fig. 9aA) similar to the S reflector offshore Iberia (Reston et al. 1996). The conceivable magma basement is cut through by a huge fault down to the mantle lithosphere, probably dominated by exhumed mantle beneath the sediments and marked with numerous extensional faults (Fig. 9aB).

Furthermore, the aborted central sag characterizes an asymmetrical rift with the thickest deposits up to 2.7 s (TWT) accumulated in it. The strata below the T40 (REU) are controlled by the normal faults, forming the wedge-shape sediments. A strong wavelength crustal boudinage revealed in seismic data suggests lateral flow of the lower crust during the rifting (Li et al. 2014b) (Fig. 9a). Being located to the west of the crustal block, the domain is characterized by hyper-thinning or exhumation, corresponding to the last extension by a propagator breakup.

Discussion

The time of the rift–drift transition in the Dangerous Grounds

We make an attempt on a relative uniform stratigraphic framework in the whole Dangerous Grounds. It is a consensus that the margin of the SCS underwent the episodic rifting (Ru and Pigott 1986; Zhou et al. 1995; Savva et al. 2014) and at least three episodes of rifting have been documented. The last two episodes between Middle Eocene and Oligocene have a close-knit influence on the opening of the SCS (Ding et al. 2013; Zhou et al. 1995).

Episodic breakup unconformities

The rifting to drifting transition and the initiation of seafloor spreading is generally time-equivalent, characterized by the prominent breakup unconformity (BU) (Braun and Beaumont 1989; Falvey 1974). For comprehensively identifying the BU, Driscoll et al. (1995) presented following criteria. (1) Greater spatial persistence and more uniform thickness above the unconformity and sediment thickening into the hanging wall of faults below the unconformity. (2) Occurrence of the growth faults and igneous activity preferentially associated with the sediments below the unconformity and obvious diminishment of faulting and subsidence rate above the unconformity.

In our study, two breakup unconformity episodes associated with the seafloor spreading of the SCS have been verified. The deposition of Nido carbonates in NW Palawan and the Reed Bank were defined in Early Oligocene, depositing after the breakup unconformity at 31 Ma (T70) in the eastern part of the Dangerous Grounds. Most faults cut Lower Oligocene strata and terminate at this unconformity (Figs. 4, 5). The decreased speed of deposition and faulting after 31 Ma resulted in a relatively uniform strata between the T70 (~ 31 Ma) and T60 (~ 23 Ma) with smaller fault displacement (Figs. 4b, 5b), and this thinner strata is related to sediment supply as much as subsidence rate. Two main episodes of extension can also be identified and verified based on fault heave measure. In the early episode (Paleocene-Late Oligocene), the extension of the Dangerous Grounds exceeds half of the total extension (Ding et al. 2013). The weakness of the continental lithosphere might be contributive to continued extension (Clift et al. 2002). In the northern SCS slope, the delayed extension continued, following the start of seafloor spreading (Clift and Lin 2001; Dong et al. 2008; Sun et al. 2006). Although the earliest magnetic spreading anomaly is 6C (23.6–21.5 Ma) in the Southwest Subbasin (Li and Song

2012; Li et al. 2014a), it is obvious that the extension in the Dangerous Grounds continued with the spreading of the Southwest Subbasin. Given the magnetic anomaly age, the T60 unconformity formed the top of some carbonate platforms in the Dangerous Grounds is defined in our study to the BU in the central part of the Dangerous Grounds (Figs. 6, 7), according to the propagation of the spreading axis in the Southwest Subbasin.

Rifting cessation postdating the spreading of the SCS

In the southwestern Dangerous Grounds, the obvious T50 unconformity (Fig. 11) can be traced from offshore Sarawak across the Dangerous Grounds. Although it used to be genetically called the breakup unconformity, but its nature of simply marking the end of rifting has finally been recognized (Hutchison and Vijayan 2010). The unconformity used to be named “MMU” with Middle Miocene age (17–15 Ma) based on the Bako-1 well and Mulu-1 well (Madon 1999). However, a redefined age of Early Miocene (~ 16–19 Ma) was found through biostratigraphic correlation and seismic interpretation (Krebs 2011; Steuer et al. 2014) (Fig. 13). Hence, the Early Miocene Unconformity (EMU) seems to be more time-matchable (Madon et al. 2013). While the REU is time equivalent to the EMU in some places, it generally represents an unconformity separating rotated blocks below, and from unrotated blocks above, instead of showing the unconformity with time gap or obvious erosion (Fig. 8b). Hence, the multiple hiatuses or erosion in the Early Miocene (Krebs 2011; Madon et al. 2013) probably correspond to the BU (T60) caused by the opening of Southwest Subbasin, while the T50 unconformity is related to the termination of the spreading of the SCS and collision of the Dangerous Grounds with Borneo, although it laterally changes to the post-rift unconformity or conformity simply in the east of the region (Hinz and Schlüter 1985).

The amount of crustal extension indicated by present-day crustal thickness in the northern SCS is much less in the east than in the west during the rifting process (Hayes and Nissen 2005). The later initiation of seafloor spreading in the west is probably resulted from the more widely distributed extensional deformation, leading to a longer requisite time for the lithosphere to thin enough till the generation of the ocean crust along this portion of the continental margin. Although termination of the spreading of the SCS is 15 Ma (Li et al. 2014a), there is not too far apart the fact that rifting lasted for a few million years (T50–T40) in the adjacent area of the tip of the fossil spreading ridge of the Southwest Subbasin (Huchon et al. 2001; Morley 2016; Savva et al. 2013). An additional stretching period is expected in this area, as shown in the seismic data, by faults cutting through the Middle Miocene strata suggesting a continuous extensional activity (Figs. 9, 10). This may be an indication of the final

transition sequence occurring during Middle Miocene. The third phase extension of the Phu Khanh basin was mainly in the Middle Miocene, with the lower parts of reflectors onlapping the 15.5 Ma horizon, showing an obvious geometric variation in hyper-extended places, where thick Middle Miocene unit is accumulated in the synformal depocenters (Savva et al. 2013). A new Middle Miocene rifting of Mang Cau Formation ended in Late Miocene with the termination age of 10.4 Ma in the Nam Con Son Basin (Swiecicki and Maynard 2009).

Rift locus migration during diachronous breakup of the Dangerous Grounds

Through the identification of key unconformities and the distinct structural configurations in the study area, with the discrete distribution of Cenozoic sedimentary packages in the different sectors of the margin, we can conclude that the multistage rifting occurred on the southern margin of the SCS. Moreover, the different structural sectors divided on the Dangerous Grounds show a fairly continuous subsidence of tilt blocks in continental slope, denoting a multistage rifting during a long time.

The prominent structural domains existing in the Dangerous Grounds have an impact on the relative northwestwards rift locus migration during the syn-rift and the transition along the different parts of the margin (Fig. 14). During early syn-rift (e.g. T100–T80), extension on the attenuated continental crust, which is classified as the wide rift mode (Buck 1991; Clift et al. 2001; Cullen et al. 2010), has resulted in the generation of early sub-basins (Figs. 4, 5, 6, 7). When the extension continued during the late syn-rift (T80–T70), extensional stress migrated further and concentrated towards the outer proximal zone inducing increased subsidence (Fig. 6c), tilted block rotation and large sedimentation accommodation space for Late Eocene to Early Oligocene. Growth strata between T70 and T60 are observed on the transition period especially in the RBPR domain, and it is also coincident to a reduced subsidence rate after 32 Ma by the tectonic subsidence curves (Ding et al. 2015) as well as demonstrated on the northern margin (Clift and Lin 2001; Su et al. 1989). However, the contemporaneous deposition in the DGCD domain seemed to be continually controlled by the faults, with a relative thicker sedimentation than the eastern one (Figs. 6, 7). This is probably controlled by an advanced rifting phase which was coeval to the initial seafloor spreading in the Southwest Subbasin (Li et al. 2014a). The thickening of Lower Miocene strata towards the master faults, occurring mainly in the outer and inner proximal zone clearly contrasts to the counterpart in the RBPR domain.

In Middle Miocene, a recurrence of extension mainly focused on the northwest of the Dangerous Grounds,

reactivates existing faults and induces strong subsidence with a thick transitional period deposition from the syn-rift to post-rift (Figs. 9, 10). At the distal margin, the active faults in this phase predominantly dip north, typically depicting a transition to termination of seafloor spreading and draping sedimentation in the tip of the Southwest Subbasin. Nevertheless, at the southern part of the Dangerous Grounds, these structural styles described above are sparse. The primary rift geometry is largely overprinted by the compressive events (i.e. Fig. 5c) related to the termination of the spreading in the SCS (Hutchison and Vijayan 2010). The last extension strata filled in local depressions and pinched out at the structural high (Fig. 11a, b). From south to north, post-rift sequences of Late Miocene age covered the all transitional deposits (Fig. 9). Taken as a whole, the rift locus migration from SE to NW along the different domains probably indicates the various dynamic in deep (Fig. 12).

Multistage extension and transition mode of the southern margin of the SCS

Although many models have been established to depict the evolution of magma-poor rifts margin (Huisman and Beaumont 2011; Lavier and Manatschal 2006; Manatschal 2004), the complex rifting process involving the diachronous breakup and the rifting migration along the different domains of the Dangerous Grounds still needs to be discussed further. Wide and thorough researches about the crust structure and rheological behaviors during the rifting have been carried out on the northern margin after the formation of the conjugate margins (Clift and Lin 2001; Clift et al. 2001, 2002), hence the similarity of the crust property should also appear in the Dangerous Grounds before the spreading of the ocean. Here we adopt a conceptual model to describe the stepwise evolution in the three domains of the Dangerous Grounds and its vicinity.

By integrating the seismic interpretation and the geological setting, we can propose that an early rifting stage occurred during Late Cretaceous/Eocene to Early Oligocene in the micro-plates of the Dangerous Grounds and consisted in the northern margin of a Proto-SCS (Fig. 15a). This initial extension was a largely symmetric process on the crustal scale accommodated by high angle normal faults that sole out downwards at the upper-lower crustal transitional boundary and the largest crust-scale first faults cut through the basement along the uplifts. The RBPR domain underwent approximately the same degree extension like the conjugated Pearl River Mouth Basin in the north where extension in the crust exceeded that in the mantle lithosphere (Clift and Lin 2001). The doming of the Moho was inferred to compensate the more extended ductile lower crust (Franke et al. 2014). As time went on, extension continued until the rupture

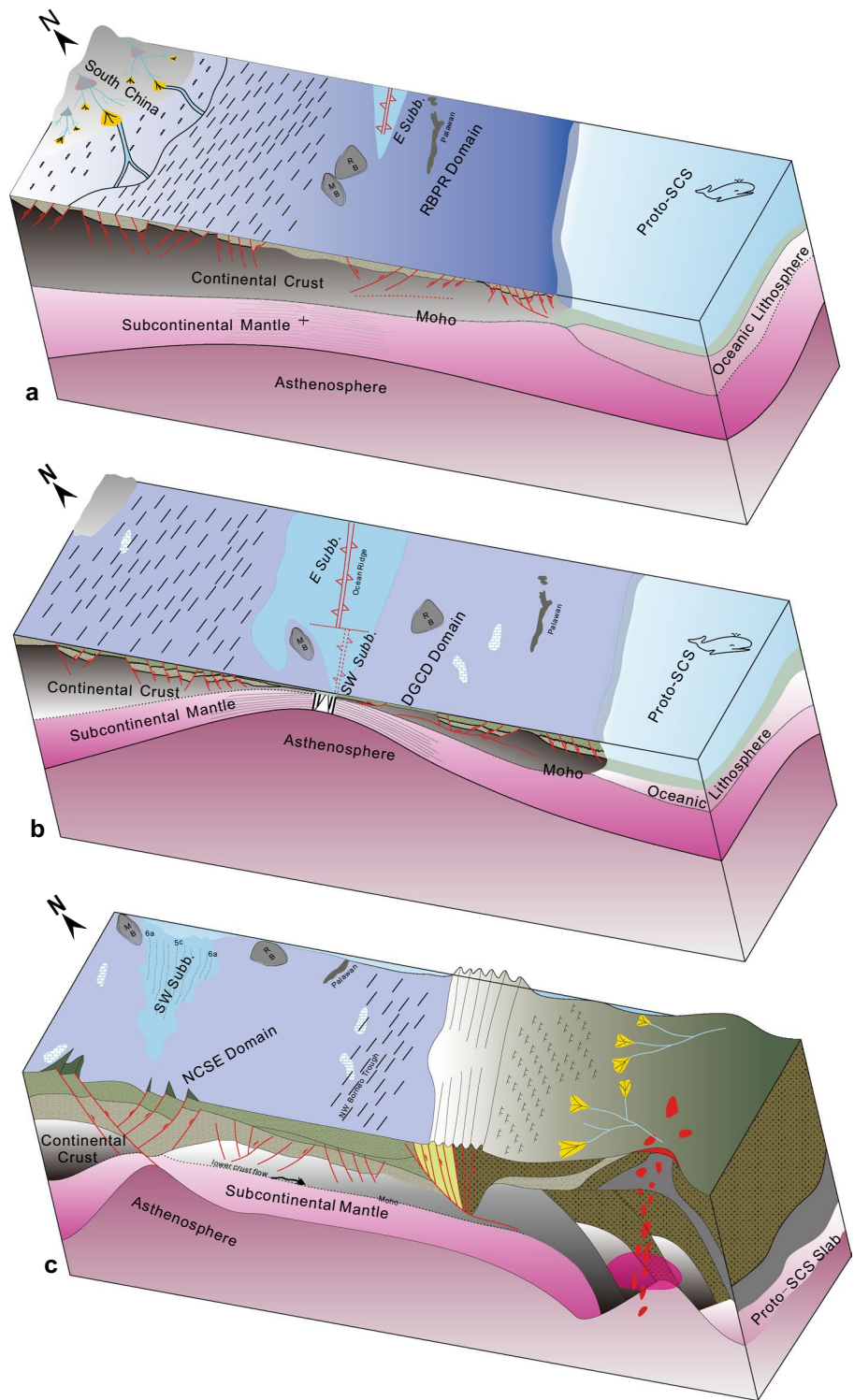
of continental lithosphere and gave rise to the opening of the SCS, corresponding to the first transition in the RBPR domain.

During the continuous extension and the rifting propagation into the Southwest Subbasin, the continental crust in the DGCD domain became brittle into the middle or lower crust as it thinned which is probably symbolic of the onset of asymmetric extension (Fig. 15b). The detachment fault horizontally transferred lithospheric extension between the crust and the deeper lithosphere (Lister et al. 1991), resulting in the DGCD domain made up of tilted basement fault blocks acted as the upper plate margin in the southern margin of the Southwest Subbasin. A noticeable detachment structure with listric detachment fault flattened and joined the Moho reflection is located in the COT of the DGCD domain (Ding et al. 2013). The structures of the outer proximal zone in this domain, where large listric faults root in ductile or semi-brittle detachment control the half-grabens (Figs. 6, 7), are consistent with our model.

At the end of Early Miocene, the southern continental margin started to collide with Borneo (Hutchison 2004; Hall 2013) and the terminal age of seafloor spreading is around 16 Ma (Briais et al. 1993; Li et al. 2014a). While the cessation of the rifting appeared in the RBPR domain and DGCD domain, the stretching system was still prevailing in the NCSE domain. The continued lithosphere extension resulted in the formation of the exhumed continental margin. Low amplitude magnetic anomalies in the tip of the Southwest Subbasin show that the basement magnetizations are much lower than the typical ocean basement (Fig. 9b), probably indicating the exhumed continental mantle as the southern Iberia abyssal plain (Whitmarsh et al. 2001). Extensional detachment faults accelerated the breakup of the continental mantle lithosphere with the ongoing rise of the asthenosphere (Fig. 15c). Sediments accumulated in the central sag were directly draped on the continental mantle lithosphere that is probably the embryonic oceanic basement. At the tip of the Southwest Subbasin offshore Vietnam, seismic evidence indicates hyper-extension crust, and the lower crust is absent in local areas and the upper crust rests directly onto the exhumed sub-continental mantle (Li et al. 2014b; Savva et al. 2013, 2014). This is also similar to the distal zone in the Southwest Subbasin (Fig. 9a), where breakup of crustal-necking occurred before the mantle lithosphere, corresponding to the model “Type I” rifted margin (Huisman and Beaumont 2011).

Although the uplift of Borneo in Late Miocene was attributed to isostatic rebound by the termination of subduction of the Proto SCS (Hutchison et al. 2000), a regional NNW–SSE-oriented extension for that period is revealed by Mt Kinabalu granite (Burton-Johnson et al. 2016). What’s more, the crust beneath the NW Borneo Trough is hyper-extended (Fig. 12a) in contradiction to a relatively thick one

Fig. 15 Schematic conceptual sketches of the stepwise extension modes depicting the evolution of the Dangerous Grounds (no scale implied). **a** In the early rifting period, brittle deformation in the upper crust results in basin formation while ductile extension in the middle or lower crust is compensated by doming of the asthenosphere. The Reed Bank-Palawan Rift (RBPR) domain was mostly covered by symmetrical rifts during the breakup of the continent. **b** Continuous extension and the rifting propagation into the SW Subbasin, the distribution of extension with time may lead to thinning of the crust. Large listric detachment ramped down to the boundary of brittle and ductile crust in the Dangerous Grounds Central Detachment (DGCD) domain. **c** Rifting migrated and concentrated on the Nam Con Son Exhumation (NCSE) domain after the termination of the spreading of the SCS. Continued extension induced by sediments load results in the mantle unroofing and flow of the lower crust



due to a collision of the Dangerous Grounds and the Sabah. In core complex and detachment mode, subsidence and uplift can occur in continental extension (Lister and Davis 1989). If the uplift of Borneo could also be linked to extension, thick sediments in the NCSE domain, whose provenance was fast erosion onshore, can accelerate subsidence as well as

induce flow of ductile crust towards continental interior after end of extension such as the mechanism on the northern margin (Clift 2015). At present we don't have enough data to prove it here, yet clay mineral composition of U1433 Site in the Southwest Subbasin shows a potential sediment flux that was from Palawan and Indochina in Middle Miocene

(Liu et al. 2017). In any case, just like the creeping lower crust wedging towards the rifting axis (Figs. 9a, 15c), a prolonged rifting corresponding to hyper-extension could be the production of rifting migration balanced through lower crustal flow (Brune et al. 2014).

Conclusions

The seismic imaging documents the long lasting rifting process of the Dangerous Grounds. Rifting related sequence boundaries have been identified from the multichannel seismic profiles and can be classified into the breakup unconformity and the rift end unconformity above the Cenozoic basement. In the most northeast of the Dangerous Grounds, the T70 unconformity which is coincident with the opening of the East Subbasin, representing the main break-up unconformity (BU), while in the central part of the Dangerous Grounds the BU corresponds to the top of the carbonate platform which is attributed to the T60 unconformity. This diachronism could be related to a southward ridge jump and the spreading of the Southwest Subbasin. The rift end unconformity of T50 is more clearly evidenced by an angular unconformity in the southwest and is related to the collision with the Borneo in Early Miocene. The final rifting episode took place in the northwest of the Dangerous Grounds and concentrated on the tip of the Southwest Subbasin, is marked by the T40 rift end unconformity.

Three domains of the Dangerous Grounds can be defined by the difference of structures. The RBPR domain is characterized by half-grabens bounded to the east by oceanward dipping faults with sediment infill onlapping to the west. The transitional sequence of Upper Oligocene thickens towards the ocean from the inner to outer proximal zones with a relative increased subsidence. The DGCD domain is characterized by thinning continental crust with the syn-rift unit below the BU of T60 controlled by large listric fault flattening and joining a deeply rooted detachment surface. The transitional sequence of the Lower Miocene is thicker towards the west compared the counterpart in the east. The NCSE domain is characterized by hyper-extended continental crust, with the half-grabens controlled by the crustal fault block rooting on the detachment or even the Moho in the distal zone. The three main structural domains of the Dangerous Grounds are associated with the relative northwards rift locus migration during the rift to drift transition, indicating a stepwise rifting evolution process.

Acknowledgements We appreciated CNOOC for their granting permission to obtain and use these data. This work was supported by the Key Project of National Natural Science Foundation of China (No. 91528303) and the Fundamental Research Fund for the Central Universities, China University of Geosciences Wuhan, (No. 201536), the

Outstanding Youth Funding of Natural Science Foundation of Hubei Province (No. 2016CFA055), the Wuhan Science and Technology Project (No. 2016070204010145). We want to express many thanks to the editor and two anonymous reviewers for their constructive suggestions that certainly improved the final manuscript.

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