Rifting of the South China Sea: new perspectives

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ABSTRACT: The Cenozoic evolution of SE Asia records a diverse array of tectonic processes with rifting, subduction, terrane collision and large-scale continental strike-slip faulting occurring in spatially and temporally complex relations. Oligocene seafloor spreading and rift propagation in the South China Sea are critical tectonic events that overprint an earlier phase of regional extension. Two end-member models proposed to explain the opening of the South China Sea differ in the relative importance of extrusion versus subduction as the driving mechanism. This paper treats the South China Sea region as a large multi-phase continental rift basin. Synthesizing recently published studies and using filtered Bouguer gravity data, we make a series of observations and possible interpretations to advance the notion that a hybrid tectonic models need to be proposed and tested. We present an example from the Phu Khanh Basin where flexural backstripping supports our interpretation that an 'out-of-sequence' rifting event was of sufficient magnitude to completely attenuate the continental crust in the ultra deep water part of the basin. The complex rift history of the region leads us to believe that future frontier hydrocarbon exploration will carry large uncertainties from basin to basin.

KEYWORDS: *South China Sea, rifts, tectonics*

INTRODUCTION

The Cenozoic evolution of the South China Sea region encompasses a broad spectrum of tectonic processes including rifting, seafloor spreading, subduction, terrane collision, and large-scale continental strike-slip faulting. Although this plethora of processes makes the region an ideal natural laboratory for tectonic studies, their close association in time and space clouds our vision when attempting to distinguish cause from effect. Drawing heavily on new filtered Bouguer gravity data, this paper examines tectonic models for rifting of the South China Sea in relation to the region's geological features incorporating the results of recent studies that post-date those tectonic models. The greater South China Sea is a prolific petroleum province with numerous productive basins that have been studied largely on a case-by-case basis. This study treats the region as a single oceanic basin with conjugate margins containing multiple sub-basins. Our approach is primarily inquisitive, as we place our observations in the context of different tectonic models in an attempt to highlight areas on which further research should be focused.

REGIONAL GEOLOGICAL OVERVIEW

The South China Sea (hereafter SCS) rift is expressed as an irregularly shaped triangular area of Oligocene to Early Miocene oceanic crust with a SW pointing apex (Fig. 1). The 3000 m isobath approximately outlines the continent–ocean boundary ((COB; Briais *et al.* 1993; Braitenberg *et al.* 2006). Removing the longer wavelength components (500 km high pass filter) from the Bouguer gravity signal improves resolution of shorter wavelength features of the SCS rift. Further enhancement of the shorter wavelength features is achieved using a 150 km high pass filter rendered semi-transparent and draped over the 500 km high pass filter (Fig. 2). The axis of the rift is expressed as a narrow Bouguer gravity low. A series of volcanic seamounts that rise from rift axis and associated transform faults record a younger, post-rift, episode of igneous activity that is attributed to the Hainan mantle plume (Tu *et al.* 1992; Lie *et al.* 2009). Beyond the COB, two wide areas of attenuated continental crust define the conjugate margins of the SCS rift. In the deeper water areas, horsts and graben of the brittle upper crust are bathymetrically well expressed, e.g. Dangerous Grounds. A series of petroleum-rich pull-apart rift basins underlying the shallow shelf on the NW side of the rift (China and Vietnam), have little bathymetric expression owing to burial by Neogene deltaic successions. These basins record a complex history that includes episodes of extension, wrenching and inversion. To the SE, the Dangerous Grounds and Reed Bank are the expression of attenuated continental crust. Attenuated continental crust also underlies the NW Borneo trough and Baram–Balabac foreland basin (Cullen 2010).

Since the Late Cretaceous at least three episodes of Cenozoic extension have affected the SCS region (Ru & Pigott 1986). In the Cenozoic we recognize two main episodes of rifting. The older Paleocene to Eocene episode is very widespread; recognized in the Dangerous Grounds (Thies *et al.* 2005), the Phu Khanh Basin (Fyhn *et al.* 2009*a*), Luconia (Mat-Zin & Swarbrick 1996), the Pearl River Mouth Basin (Ru & Pigott 1986), onshore Kalimantan (Barito, Kutei, and

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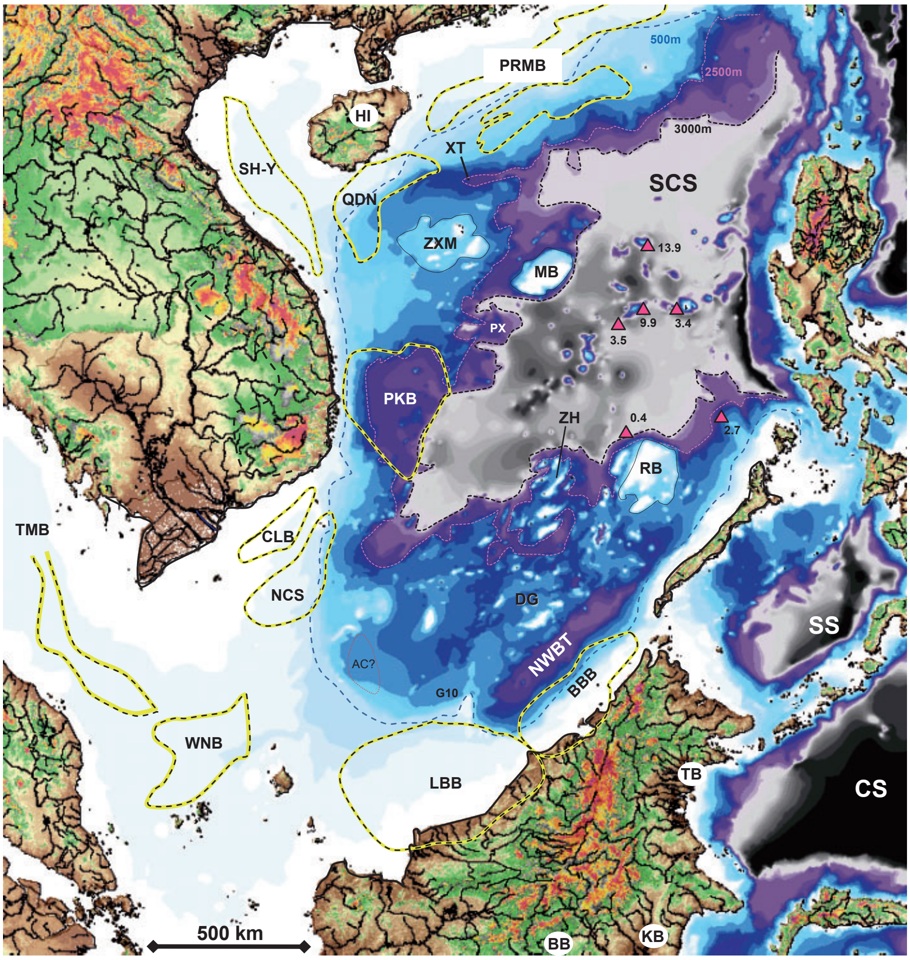

Fig. 1. Regional setting and features map with ETOPO2v2 bathymetry and Shuttle Radar Topography Mission Digital Elevation Model models as an underlay. The bathymetric map has a non-linear colour bar to assist in highlighting certain features. Dark grey to black areas are marginal basins and oceanic crust. Offshore Cenozoic sedimentary basins outlined in yellow and black dashed lines. White to light blue areas correspond to the continental shelf and upper slope, respectively. BB, Barito Basin; BBB, Baram Balabac Basin; CLB, Cuu Long Basin; CS, Celebes Sea; DG, Dangerous Grounds; HI, Hainan Island; KB, Kutei Basin; LBB, Luconia Balingian Basin; MB, Macclesfield Bank; NCS, Nam Con Son Basin; NWBT, NW Borneo Trough; PKB, Phu Khanh Basin; PRMB; Pearl River Mouth Basin; PX, Penxi Seamounts; QDN, Quiondongnan Basin; RB, Reed Bank; SCS, South China Sea; SS, Sulu Sea; SH-Y, Song Hong-Yengeahai Basin; TB, Tarakan Basin; TMB, Thai Malay Basin; WNB, West Natuna Basin; XT, Xisha Trough; ZH, Zenghe Massif (e.g. Spratley Islands); ZXM, Zongsha-Xisha Massif. Red triangles show location of age dates (reviewed by Yan *et al.* 2006). AC, possible attenuated crust; G10 marks prominent north-trending structurally-controlled carbonate build.

Tarakan basins; Satyana *et al.* 1999) and the Makassar Straits (Guntoro 1999; Hall *et al.* 2009). Owing to overprinting by subsequent tectonic events, as well as poor exposures in the heavily vegetated onshore areas, well constrained tectonic models for Paleocene to Eocene extension remain to be worked out. This early episode of extension has been attributed to back-arc spreading induced by slab role back around greater SE Asia (Doust & Sumner 2007). Hall (2009) suggests that a component of this older event reflects extension perpendicular to the maximum tectonic stress in what became the upper plate following re-initiation of subduction of the Indo-Australia plate beneath Java and Sumatra *c.* 45 Ma.

A second episode of regional extension occurred from the Late Eocene to Early Miocene. Although not as regionally widespread as the earlier episode, the amount of crustal thinning in the second episode was of sufficient magnitude to result in wholesale rifting of Asian continental crust and seafloor spreading in the SCS. Volcanism contemporaneous with rifting and seafloor spreading is minimal and the South China Sea is regarded as a non-volcanic margin to weakly volcanic margin (Yan *et al.* 2006; Clift & Lin 2001). Although we treat the extensional history of the SCS in terms of two episodes, we recognize that these episodes are not independent events, but stages of a protracted process. To the extent that heterogeneities in the rheology, thermal gradient, composition and thickness of the upper mantle and crust are fundamental boundary conditions that influence rifting (Huismans *et al.* 2005; Gueydan *et al.* 2008), rifting in the SCS was strongly influenced by lithosphere-scale perturbations resulting from the first episode of extension.

SEAFLOOR SPREADING HISTORY

The timing and kinematics of the seafloor spreading in the SCS rest largely on the interpretation of marine magnetic data acquired in multiple cruises over the several decades. The early work of Taylor & Hayes (1983) and Briais *et al.* (1993) established that SCS opened in several phases during the Oligocene and Early Miocene, *c.* 32 Ma to 16 Ma and that at least one major ridge jump occurred. The main tectonic models for the region's evolution (e.g. Lee & Laver 1995; Hall 1996, 2002; Replumaz & Tapponnier 2003) rest on this earlier work.

Additional ship-borne magnetic data acquired specifically to address a data gap near Taiwan and uncertainties between the Reed and Macclesfield banks introduce two important refinements to the spreading history that must be considered within a regional tectonic context. First, additional magnetic anomalies identified south of Taiwan across a Luzon transform fault suggest that SCS oceanic crust could be as old as 37 Ma, magnetic anomaly C17 (Hsu *et al.* 2004). Second, Barckhausen & Roeser (2004), in a paper reviewed by Hayes and Briais, conclude that seafloor spreading at the SW rift tip ceased at 20.5 Ma, anomaly 6A1; approximately 4 Ma earlier than interpreted in the seminal models for the SCS. Reconstructing the opening history for the SCS from seafloor magnetic anomalies is complicated by several factors that include difficulty with magnetic measurements at equatorial latitudes, the presence of younger igneous rocks, and post-spreading transpressive deformation of the magnetic anomalies (Barckhausen & Roeser 2004; Yan *et al.* 2008). Taking these potential complications into

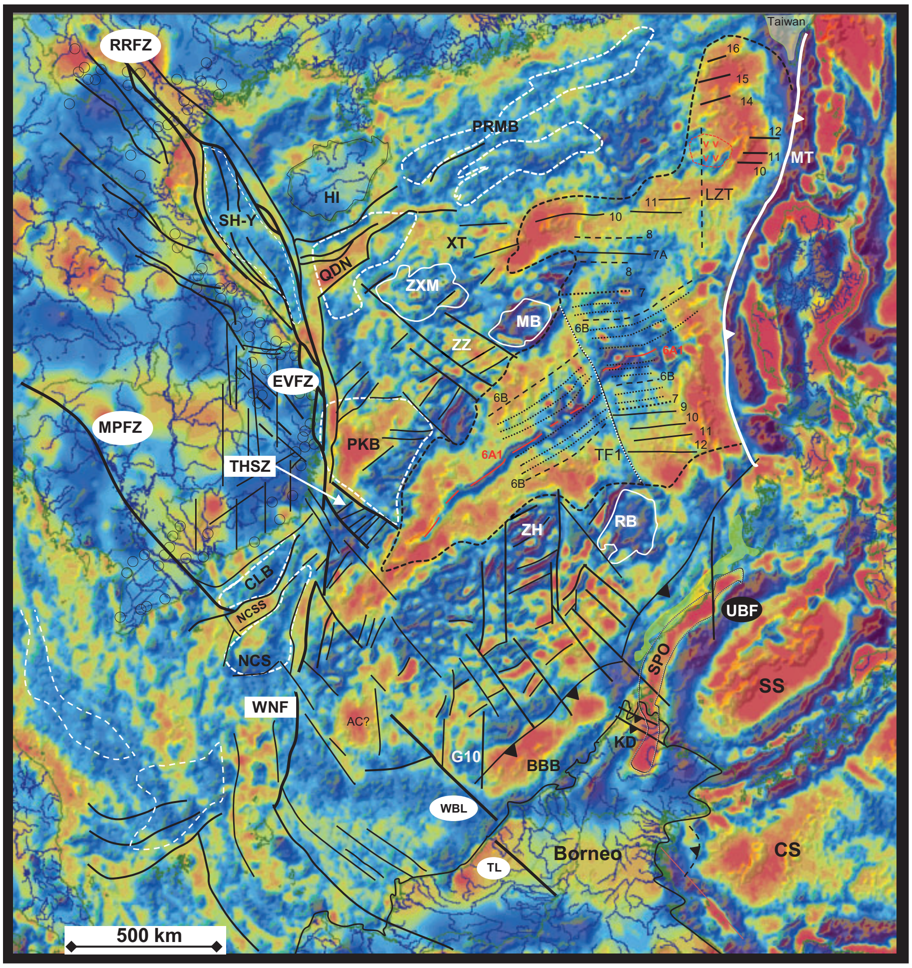

Fig. 2. 150 km high pass Bouguer gravity map draped over a 500 km high pass Bouguer gravity map. Dashed line around SCS marks approximate limit of oceanic crust. Magnetic anomalies are from Barckhausen & Roeser (2004). Solid black lines show faults and fault relays are from Fyhn *et al.* 2009; Liu *et al.* 2004; Morley 2002; Pubellier *et al.* 2006; Rangin *et al.* 1995*a*; Tongkul 1994, 2006; Zhu *et al.* 2009. Abbreviations as in Figure 1. EVFZ, East Vietnam Fault Zone; KD, Kudat Peninsula; LZT, Luzon Transform; MPFZ, Mae Ping Fault Zone; MY, Manila Trench; NCSS, Nam Con Son Swell; RRFZ, Red River Fault Zone; SPO, Sabah-Palawan Ophiolite; THSZ, Tuy Huy Shear Zone; TL, Tinjar Line; TF1, transform fault; WBL, West Baram Line; UBF, Ulugan Bay Fault; WNF, Wan-Na Fault; ZZ, Zonghsah Zone. Open circles show Vietnam hot springs with waters > 50°C (Quy 1998). Fine black line with filled triangle marks modern NW Borneo-Palawan collision zone.

account, Figure 3 is a diagrammatic reconstruction that depicts three phases of seafloor spreading in the SCS.

37 Ma to 25.5 Ma (anomalies 16 to 7A)

Spreading segments strike east–west and are linked to north–south striking transform faults. The restriction of anomalies 14–16 to the east side of the Luzon transform fault, relative to younger anomalies, suggests that rifting progressed from east to west. Evidence for east–west propagation comes from the Xisha Trough; a narrow east–west trending bathymetric low on the northern side of the Zhongsha-Xisha Massif (Paracel Islands) that is marked by a modest Bouguer gravity high and deep bathymetry (Figs 1 & 2). On the basis of these features

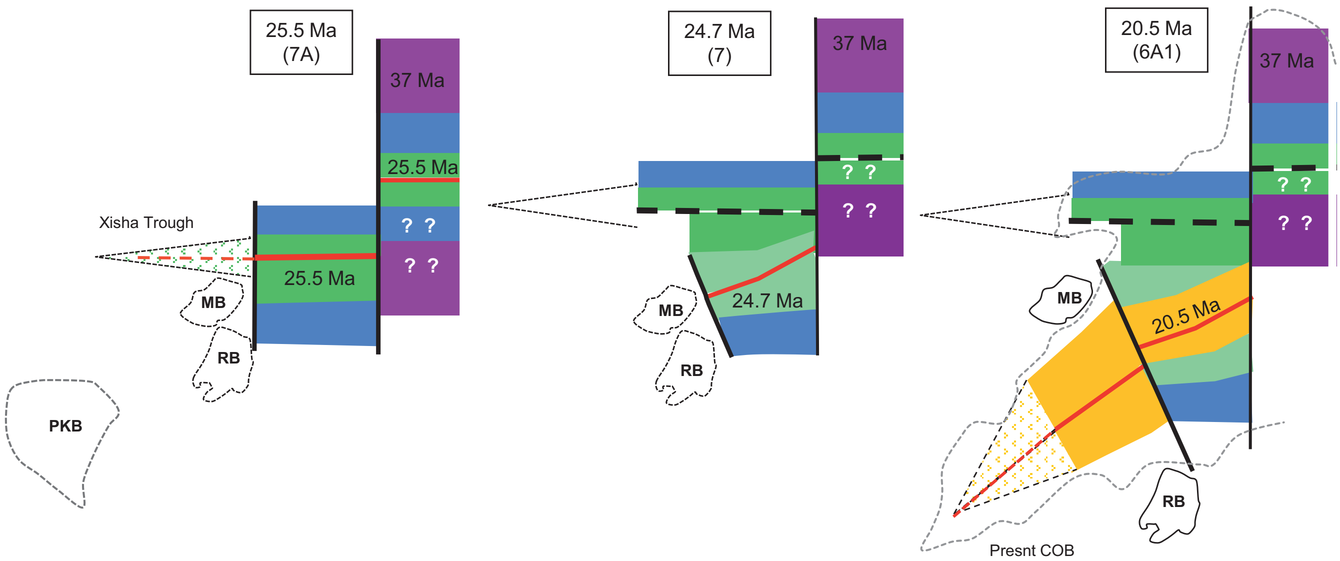

Fig. 3. Schematic opening history of the South China Sea oceanic spreading system at Magnetic Anomalies 7, 7a and 6A1. Redrawn from Barckhausen & Roeser (2004) and Hsu *et al.* (2004).

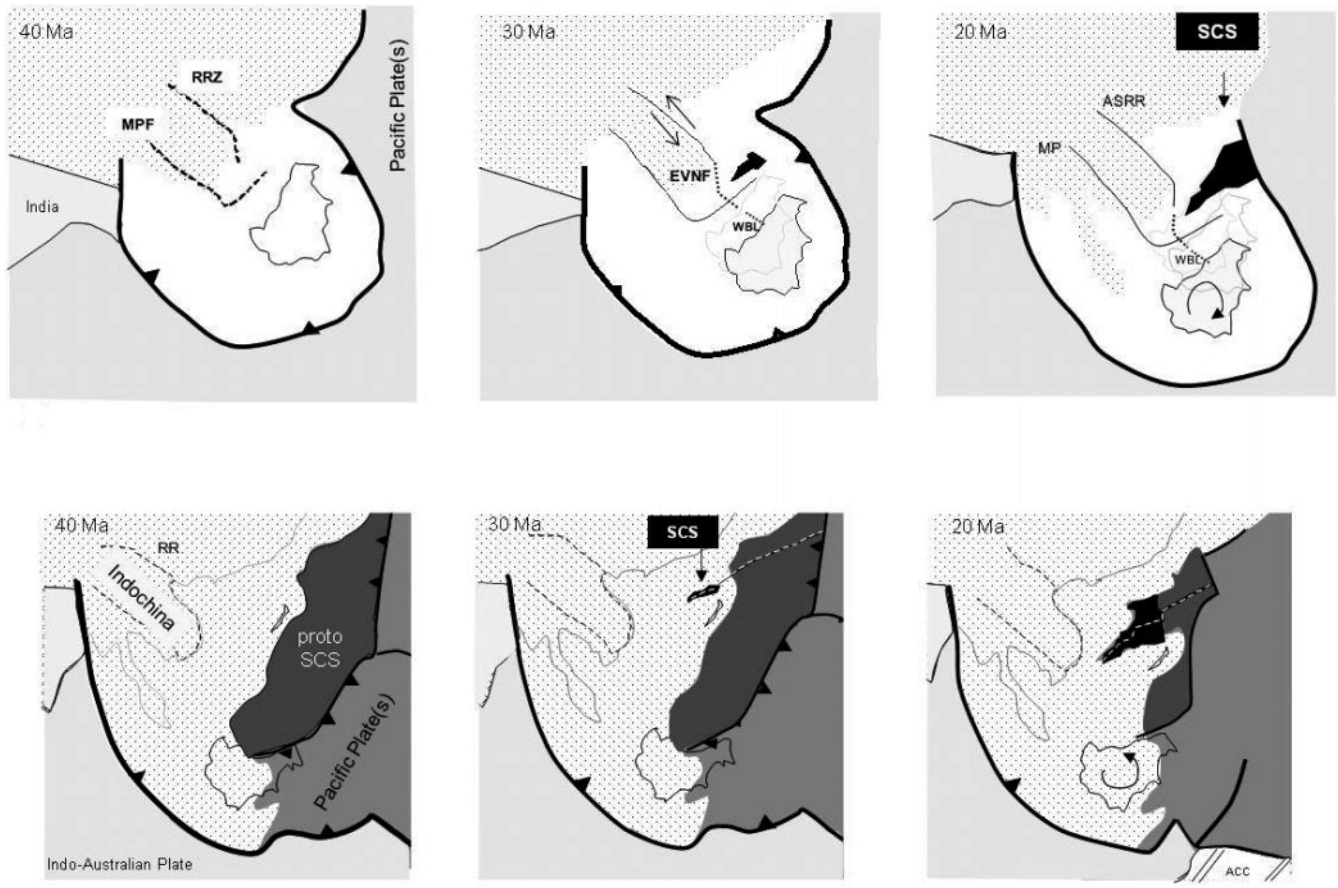

Fig. 4. Comparison of tectonic models for the region at 40 Ma, 30 Ma, and 20 Ma. (**a**) The extrusion model is adapted from Replumaz & Tapponier (2003). (**b**) The subduction model is modified from Hall (2002). Abbreviations as in prior figures, filled triangles are on the upper plate at active subduction zones. West Baram Line as transform fault after Morley (2002) is dashed line. Arcs with arrows on Borneo indicate sense of rotation predicted by different models.

and wide angle, multi-channel 2D seismic data, Qui *et al.* (2001) interpret the Xisha Trough as a failed rift arm that records thinning of the pre-rift continental crust from *c.* 25 km to 8 km.

25.5 Ma to 24.7 Ma (anomalies 7 to 6B)

Following a minor ridge jump from east of the Xisha Trough to a position approximately 50 km south, spreading segments were orientated WSW. This ridge jump is documented by juxtaposed magnetic anomalies 7 and 9 on the southern side of the rift and resulted in rifting of previously formed oceanic crust (Fig. 2). The Reed and Macclesfield banks are interpreted as representing an originally contiguous region of strong crust that inhibited propagation of the rift to the SW.

24.7 Ma to 20.5 Ma (anomalies 6B to 6A1)

An important ridge jump across a transform fault occurred at 24.7 Ma as the rift propagated SW into continental crust splitting the Reed and Macclesfield banks with seafloor spreading directed NW to SE. Magnetic anomalies related to seafloor spreading do not extend to the rift tip (Fig. 2) and it is not known whether the SW limit of the rift is underlain by oceanic crust or exhumed mantle. The SW limit of oceanic crust is taken from a study by Huchon *et al.* (2001) that documents dextral oblique faulting near the rift tip and that the rift is asymmetric with thicker continental crust on the southern (Dangerous Grounds) conjugate margin. Bouguer gravity data indicate that SE of the rift tip the Dangerous Grounds represents a much wider area of attenuated continental crust than is present on the Vietnamese margin. Although a wide area of attenuated continental crust may reflect a low strength ductile lithosphere (Guyedan *et al.* 2008), some of the observed faulting in the upper crust occurred during the earlier episode of regional extension (Thies *et al.* 2005).

TECTONIC MODELS

In considering the rifting history of the SCS within a tectonic framework there are two contrasting end-member kinematic-tectonic models: the collision-extrusion model (Fig. 4a) and subduction-collision model (Fig. 4b). Each of the models has strong points and resolution of their differences will probably require adaptation of components of each model. Extrusion-based models (e.g. Briais *et al.* 1993; Replumaz & Tapponnier 2003) show opening of the SCS as driven by the SE displacement of the Indochina block along the Mae Ping and Ailao Shan-Red River fault zones owing to India's collision with Asia. Subduction-based models (e.g. Hall 2002; Hall *et al.* 2008) suggest the SCS opened in response to slab pull during subduction of proto-South China oceanic crust. A variation on these models suggests additional lithospheric thinning related to the Hainan mantle plume is required to initiate seafloor spreading (Xia *et al.* 2006).

Collision-extrusion model

In the extrusion model, India's collision with Asia progressively displaces a series of blocks along inter-continental strike-slip

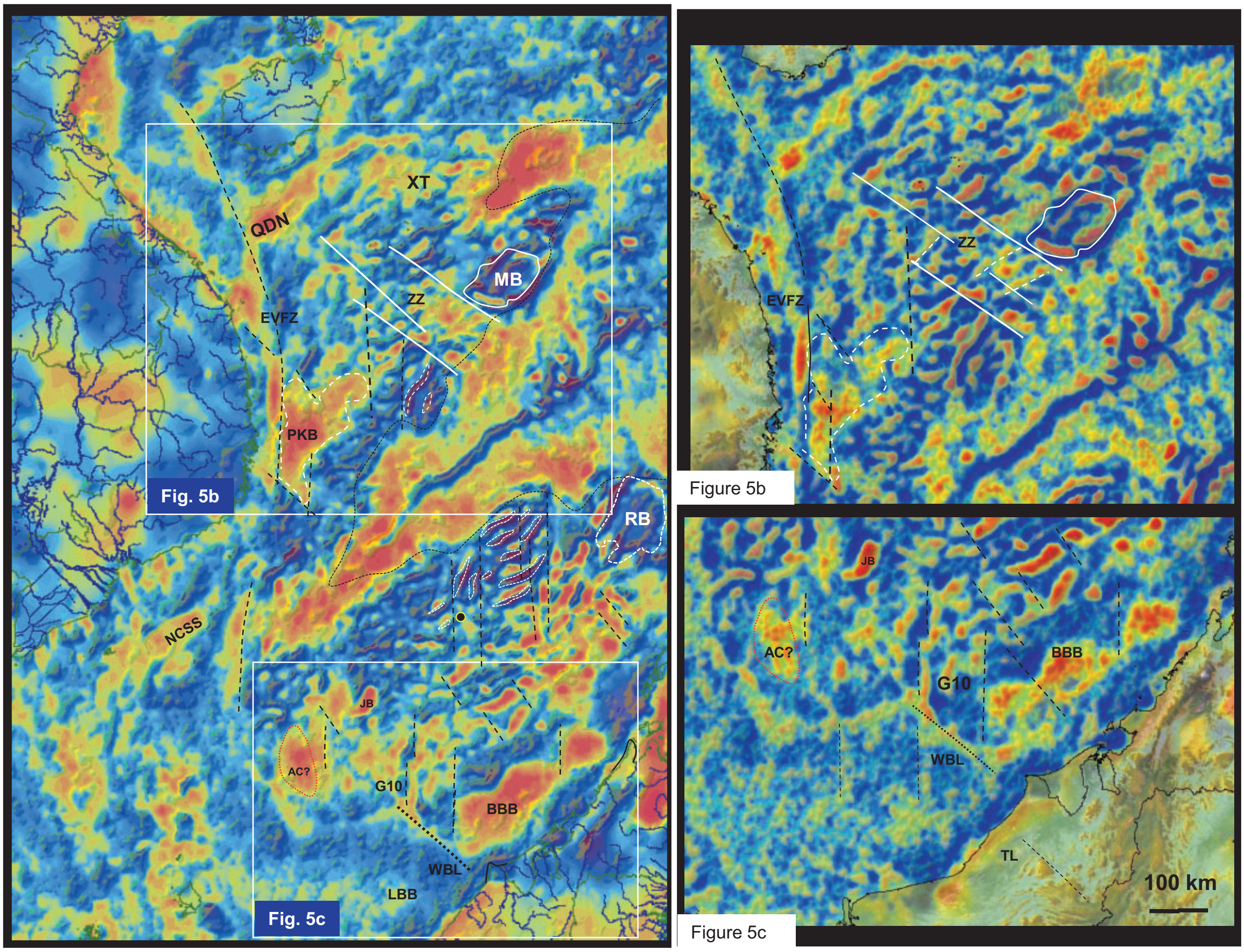

Fig. 5. 150 km high pass Bouguer gravity map draped over a 500 km high pass Bouguer gravity map. Abbreviations as in Figures 1 & 2; ZZ, Zongsha Zone. Dashed lines mark interpreted faults and dashed white lines outline gravity lows interpreted as narrow graben. Figures 5b and 5c (outlined in white on Fig. 5) show the 150 km high pass Bouguer gravity map draped over the 1st vertical derivative of the 150 km high pass Bouguer gravity data, which enhances edge effects related to faulting.

faults. Borneo and Palawan remain attached to Indochina and the SCS is pulled open by the left-lateral displacement of the Indochina Block along long intercontinental strike-slip, particularly the Ailao Shan-Red River fault zone (ASRR; Tapponnier *et al.* 1986). In the extrusion model, SCS seafloor spreading terminates when India penetrates far enough into Asia to no longer push Indochina aside. The extrusion model requires that the amount of seafloor spreading in the SCS is roughly equal to the lateral displacements along the intercontinental strike-slip and predicts *c.* 25° clockwise (CW) rotation of Indochina and Borneo. In the extrusion model there is no subduction under NW Borneo and mass is conserved by subduction in the Pacific Ocean. Although there are variants of the extrusion model, each requires that major transcurrent faults extend across the SCS essentially forming a giant hook. Briais *et al.* (1993) do not explicitly show how the ASRR fault zone extends into the SCS. LeLoup *et al.* (2001) link the Mae Ping fault with the West Baram Line; whereas Replumaz & Tapponnier (2003) show the ASRR linking with the East Vietnam Fault that in turn links to the SW side of the oceanic spreading ridge.

Whilst geometrically elegant, the extrusion model has been questioned on multiple grounds: the lack of palaeomagnetic evidence for clockwise rotation on Borneo (Fuller *et al.* 1999), the lack of evidence for through-going faults across the SCS and disagreement over the amount and timing of strike-slip displacement on the major fault zones relative to the age of seafloor spreading (Morley 2002; Searle 2006; Hall *et al.* 2008). The older, Eocene, magnetic anomalies in the NE part of the SCS (Hsu *et al.* 2004) are particularly problematic for the collision-extrusion, as these pre-date estimates for the earliest strike-slip motion on the ASRR (LeLoup *et al.* 1995). The extrusion model has difficulty in accounting for the wide area of attenuated continental crust on both sides of the continent–ocean boundary; as the Dangerous Grounds lies SE of the area being pulled away from Asia.

Subduction-collision model

Dating to the work of Hamilton (1979) and Holloway (1982), the subduction model, in sharp contrast with the extrusion model, features long-lived subduction beneath NW Borneo (e.g. Lee & Laver 1995; Hall 1997). Proposed variations of the subduction model generally show that subduction of the proto-SCS oceanic crust commenced between the Paleocene to Middle Eocene and ended (in the area of the Baram–Balabac Basin) in the Early Miocene with the arrival of buoyant attenuated continental crust of the Dangerous Grounds at the subduction (Hall 1997; Longley 1997; Murphy 1998; Morley

2002; Hall 2002). The Sabah Orogeny is attributed to collision of the Dangerous Grounds with NW Borneo *c.* 18 Ma (Hutchison *et al.* 2000).

There are several variants of the subduction theme with important differences. These differences arise from conflicting views on the roll of extrusion of Indo-China, the driving mechanism for opening the SCS, the rotation of Borneo, and the amount of proto-SCS that was subducted. In the models of Hall (2002, 2009) rifting in the SCS is driven by slab pull of the subducting proto-SCS, which is progressively consumed as the subduction zone tip line migrates SW–NE from Sarawak to Palawan from 45–15 Ma. In those models, the width of the proto-SCS outboard of Borneo remains little changed between 45 Ma and 30 Ma and nearly all of the subduction beneath Borneo occurs between 30 Ma and 15 Ma as the island is shown to rotate 50° counter clockwise (CCW); honouring palaeomagnetic data interpreted by Fuller *et al.* (1999). The consumption of relatively little proto-SCS crust under Borneo prior to 30 Ma appears to pose a geometric problem for invoking slab pull to open the SCS, as there appears to be relatively little subduction to pull apart the crust. A kinematic inconsistency arises from the observation that the rifting in the SCS progressed NE to SW opposite the direction of subduction tip line migration.

Hybrid models

Several hybrid models have been proposed to help resolve incompatibilities in the end-member models. Reconstructions by Longley (1997) and Murphy (1998), retaining elements of the extrusion model, show multiple CW rotating blocks (Luconia, Baram, Dangerous Grounds, Reed Bank) separated by transform faults colliding with NW Borneo and Palawan from 45–15 Ma. Rangin *et al.* (1999) suggest that extrusion was accompanied by subduction of a relatively narrow (*c.* 300 km) proto-SCS beneath NW Borneo along a SW migrating collision. Morley (2002), questioning the amount of young CCW rotation of Borneo, presents a subduction-collision model which links the ASRR to the West Baram Line using the East Vietnam Fault as a relay. Cullen (2010), in a study focused on NW Borneo, interprets new biostratigraphic and palaeomagnetic data to indicate minimal Oligo–Miocene subduction and suggests rifting in the SCS was accommodated over a wide zone by multiple mechanisms that included crustal shortening (including continental underthrusting) in Borneo and subduction in the Pacific Ocean.

Geodynamic considerations

Over the previous decade several papers have drawn attention to nature of the mantle beneath the greater Southeast Asia region and to the role that mantle upwelling and plumes may have played in rifting of the SCS. Age determinations, major and trace element concentrations, and isotopic ratios of the igneous rocks from the region suggest the widespread presence of Precambrian subcontinental lithosphere (under the Sulu Arc and Sabah (Castillo 1996; Macpherson *et al.* 2010), Mount Kinabalu in Sabah (Cottam *et al.* 2010), Dangerous Grounds (Yan *et al.* 2010; Kudrass *et al.* 1986), SE China (Xu *et al.* 2002)) that is underlain by mantle having a Dupal-like Indian Ocean to enriched ocean-island basalt composition (Tu *et al.* 1992; Castillo 1996; Macpherson *et al.* 2010). Petrological and geophysical evidence demonstrate a youthful mantle plume lies beneath Hainan Island (Zou & Fan 2010; Lei *et al.* 2009). Plume-related volcanism in the region could be as old as 60 Ma (Zhou *et al.* 2009) and ultimately be related to deep subduction slab dehydration (Zhao & Ohtani 2009). Geodynamic modelling suggests that neither the subduction model nor the extrusion model produce sufficient extension to trigger seafloor spreading and that additional thinning of the crust and lithospheric by asthenosphere upwelling is required to drive the opening and spreading of the SCS (Xia *et al.* 2006).

OBSERVATIONS / INTERPRETATIONS

The use of potential field data, such as Bouguer gravity, is an important tool for addressing and resolving tectonic models, especially in areas with minimal seismic and borehole information. Largely on the basis of gravity and bathymetric data, in light of the prior discussion of tectonic models and driving mechanisms for rifting in the SCS, we make several observations and propose interpretations of these data. Our interpretations are non-unique and our intent is to stimulate discussion by providing new ideas to be challenged with further research.

1. As a first order observation we note that there is an excellent correspondence between strong Bouguer gravity highs, bathymetric lows, and extremely attenuated continental crust in the Xisha Trough and at the SW tip of the SCS rift.
2. Attenuated continental crust can be traced 700 km across the Dangerous Grounds, the NW Borneo Trough and the Baram–Balabac Basin. Thus, the region can be classified as a wide rift (Buck 1991). A wide zone of attenuated crust beyond the COB implies a mechanically weak upper mantle prior to rifting (Gueydan *et al.* 2008). We propose that the earlier Eocene episode of extension is responsible for mechanically weakening the mantle prior to the second episode of extension.
3. The NW Borneo Trough is characterized by very deep water and a Bouguer gravity low, and thus shares characteristics with the Xisha Trough. Seismic data show that rifted continental crust extends beneath the Baram–Balabac Basin (Franke *et al.* 2008; Cullen 2010) and it is tempting to speculate that the basin is underlain by extremely attenuated crust. However, quantitative modelling indicates that Bouguer gravity low of the NW Borneo Trough is due to dynamic loading by the NW Borneo thrust belt which pushes the SCS crust below its level of isostatic compensation (Milsom *et al.* 1997) which exaggerates the contrast with adjacent areas. We propose that the Bouguer gravity highs beneath the Baram–Balabac Basin are the expression of small rift basins similar to those of the Dangerous Grounds. The 150 km high pass gravity data with enhanced edge detection indicates that the Baram–Balabac Basin is underlain by north–south, NE–SW and NW–SE striking basement faults similar to the fault orientations on the Dangerous Grounds (Fig. 5).
4. The West Baram Line which separates Luconia from the Baram–Balabac Basin is generally treated as a major tectonic feature that may have accommodated significant strike-slip motion during extrusion of Indochina. Luconia is an older block sutured to Borneo during the Middle Eocene Sarawak Orogeny (Hutchison 1996). On the filtered gravity data, Luconia has a distinctive character with subdued northerly-trending anomalies, one of which extends across the West Baram Line at the G10 high (Fig. 5). This subdued character in part reflects burial by a thick Pliocene sedimentary section and masking by Miocene platform carbonates and reefs. The observation that structural trends appear to extend across the West Baram Line from Luconia into the Dangerous Grounds is problematic for invoking major strike-slip motion (e.g. >100 km) across the West Baram Line.

5. The Sabah-Palawan Ophiolite is well expressed by a strong gravity high and displays an apparent left-lateral offset across the Ulugan Bay fault (Fig. 2). The Ulugan Bay fault, which has been interpreted as a right lateral transform fault (Ru & Pigott 1986), projects northward toward the Luzon Transform Fault on the northern side of the SCS rift. On the Kudat peninsula in northern Sabah thrust faults placing Eocene turbidites over Early Miocene shallow to deep-water clastics are interpreted to be related to opening of the SCS (Tongkul 1994, 2006). These observations and the relatively widespread north–south fabric expressed on the regional gravity lead us to concur that at least part of the opening of the SCS has been accommodated by shortening on Borneo (Tongkul 1994; Cullen 2010).
6. At the SW tip of the SCS oceanic crust near the Nam Con Son Basin, the rift is much wider on the SE (Borneo) side relative to the NW (Phu Khanh Basin) side (Figs 2&5). The basement structure map in the area of the rift tip shows a dominance of down-to-the-NW normal faults (Huchon *et al.* 2001, fig. 6). We suggest that this area may have experienced a greater component of simple shear (e.g. Wernicke 1985) extension.
7. South of the Zongsha-Xisha Massif and the Macclesfield Bank, the Penxi Seamounts lie along a NW–SE trending zone of high Bouguer gravity (Figs 1, 2, 5) that projects into a bend in the Qiongdongnan Basin (QDN). We informally refer to this feature as the Zongsha Zone (ZZ). On the 150 km high pass Bouguer gravity data (Fig. 5) the Zongsha Zone appears to be cut by a series of NE–SW striking gravity anomalies that can be interpreted as extensional fault blocks along a left-lateral shear, implying that the QDN Basin may have developed as a left-stepping releasing bend along an ancestral branch of the Red River Fault Zone, prior to its capture and relay into the East Vietnam Fault Zone, in a relationship similar to that proposed between the Mae Ping Fault and the Cuu Long Basin (Matthews *et al.* 1997; Morley 2002). The correspondence between the intersection of the ZZ with limit of well developed magnetic anomalies suggests the ZZ is an important tectonic feature (Fig. 2).
8. The Phu Khanh Basin lies athwart the East Vietnam Fault (EVF). East of a prominent bathymetric scarp that marks the trace of that fault, the ultra deepwater part of the basin is marked by a strong Bouguer gravity high (Fig. 5), which corresponds to region with an elastic thickness of less than 1 km (Braitenberg *et al.* 2006). Similar features are associated with the failed rift arm of the Xisha trough. We hypothesize that the eastern part of the Phu Khanh Basin is underlain by extremely attenuated continental crust.
9. We have highlighted an area (AC?) between the Nam Con Son Basin and Luconia-Balingian Basin that has a strong Bouguer gravity high associated with deep water (Figs 1, 2&5). Features similar to those are associated with strongly attenuated crust of the eastern Phu Khanh Basin. Fault patterns suggest that splays of the EVF, such as the Wan-Na Fault, extended further to the south than the Tuy Huy shear zone. Further work may reveal that area AC is also one of strongly attenuated crust.

ADDITIONAL WORK ON THE PHU KHANH BASIN

We tested the hypothesis regarding extreme crustal thinning in the Phu Khanh Basin by determining whole lithosphere thinning factors along a published cross-section (Fig. 6 is modified from Fyhn *et al.* 2009*a*, fig. 3). We assume an initial crustal thickness of 35 km (Holt 1998; Clift *et al.* 2002). The cross-

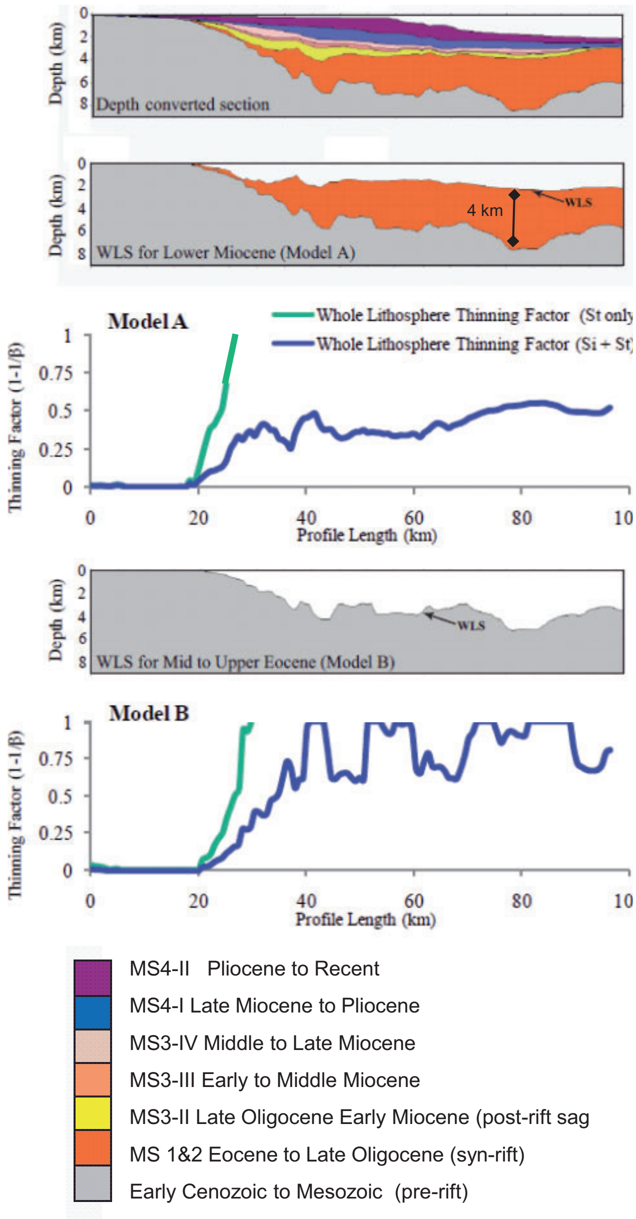

Fig. 6. Depth converted model with sediments flexurally backstripped to produce water loaded subsidence profiles. Model A & B results are from a McKenzie lithosphere extension model, modified to include volcanic addition at high thinning factors. Whole thinning factors for the lithosphere have been determined from the water loaded subsidence. Model A assumes a rift event in the Lower Miocene; model B assumes a rift event in the mid to Upper Eocene. Post rift thermal subsidence alone cannot account for the water loaded subsidence observed in both models; and results from model B suggests that the Phu Khanh basin consists of highly thinned continental crust with a large component of volcanic addition. Si, subsidence initial; St, subsidence thermal; WLS, water-loaded subsidence, b, stretching factor.

section was flexurally backstripped to the base of the Middle Miocene sediments (model A) and to the base of the Middle to Upper Eocene sediments (model B) to determine water loaded subsidence profiles using the lithosphere extension model of McKenzie (1978) modified to include volcanic addition at high thinning factors (White & McKenzie 1989).

Models A and B both show post-rift thermal subsidence (St-only) rapidly reaching a value of one, e.g. a beta factor approaching infinity. The numerical solution in both models

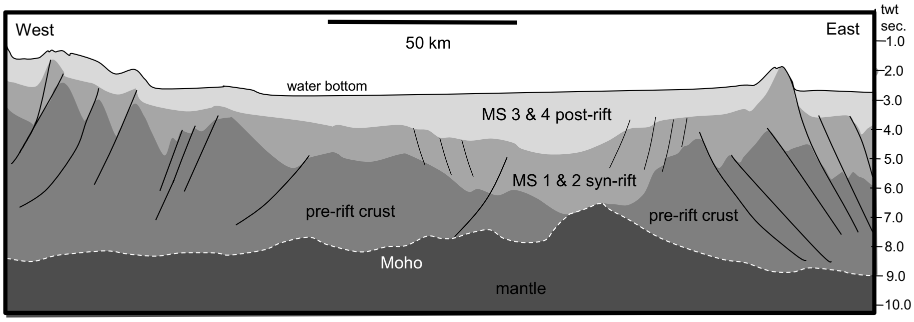

Fig. 7. Line drawing of interpreted 2D seismic line traversing eastern PKB. Sequence abbreviations are those used Figure 6. In central part of line pre-rift crust is completely attenuated and syn-rift sediments rest directly on the Moho.

requires whole lithospheric thinning factors exceeding one in order to account for the observed whole lithosphere subsidence. Such solutions are physically impossible and are not plotted. Therefore, additional initial (syn-rift) subsidence (Si) is required.

Model A predicts that the whole lithosphere has thinned to approximately half of its original thickness in the east since the Lower Miocene; less thinning has occurred in the west. Model B addresses the thinning required to account for accommodation space represented by the 3–4 km of Oligocene sediments following Middle to Late Eocene rifting. The lithosphere has thinned considerably. Assuming volcanism occurs when the thinning factor (γ) exceeds 0.7, there is volcanic addition of 6.5 km. Model B suggests that the crust and lithosphere have thinned substantially and the crustal basement under the eastern part of the Phu Khanh Basin is predominately highly thinned continental crust with a voluminous igneous component. Extreme Palaeogene crustal thinning in Model B is consistent with 2D gravity modelling along the line that shows rapid eastward thinning of the crust to a thickness of 2–6 km (Fyhn *et al.* 2009*a*). Recently available long-offset 2D seismic data in the ultra deep water Phu Khanh Basin appear to confirm the results of our flexural modelling (Fig. 7). We believe that part of the Phu Khanh Basin east of the East Vietnam Fault has Eocene to Lower Oligocene syn-rift sediments resting directly on oceanic crust or exhumed subcontinental mantle.

Fyhn *et al.* (2009*b*) interpret the Eocene to Middle Oligocene history of the Phu Khanh Basin as recording two phases of left-lateral transtensional rifting along the East Vietnam Fault Zone. Early rifting in the Phu Khanh Basin pre-dates and is spatially 'out of position' relative to seafloor spreading in the South China Sea (see 25.5 Ma on Fig. 3). Fyhn *et al.* (2009*b*) believe that Eocene to Early Oligocene rifting was terminated owing to a reversal of motion along the East Vietnam Fault that resulted in inversion during right-lateral transpression. The timing and kinematics of Middle Oligocene inversion in the Phu Khanh basin coincides with the propagation of seafloor spreading into the Xisha Trough (Briais *et al.* 1993; Qiu *et al.* 2001) leading us to suspect that there is a direct relation between these two events.

DISCUSSION & IMPLICATIONS FOR PETROLEUM EXPLORATION

From the observations and interpretations discussed above it is clear that the greater SCS has been affected by multiple processes during its protracted Cenozoic evolution. A restoration of the SCS to the Middle Oligocene (Fig. 8) shows a dominant north–south structural grain of wrench faults and/or relays linking smaller fault blocks that trend oblique to the wrench faults. Rangin *et al.* (1995*b*) noted a similar relationship in the Kontum Highlands, onshore Vietnam. Thus, suggests a regionally extensive event that may locally develop pull-apart basins with syn-rift sediments lying directly on the Moho. The north–south orientation of the major faults is consistent with a notion advanced by Hall (2009) that prior to re-initiation of subduction under Sumatra and Java, *c.* 45 Ma, the regional maximum stress was roughly north–south. The fact that extension also appears to be north–south, leads us to suggest that subsequent rifting also exploited the earlier extensional fractures but driven by slab roll back from Sumatra and Java, as well as extrusion of SE Asia following the collision of India with Asia (Briais *et al.* 1993; Fyhn *et al.* 2009*b*). We do not see evidence for this earlier phase of rifting being driven by slab pull beneath Borneo and the Philippines Hall (2009), which should produce east–west oriented extension. The relationship between early rifting in the SCS and initiation of the Tarkan, Kutei and Barito Basin on Borneo is not known, but is worthy of further investigation.

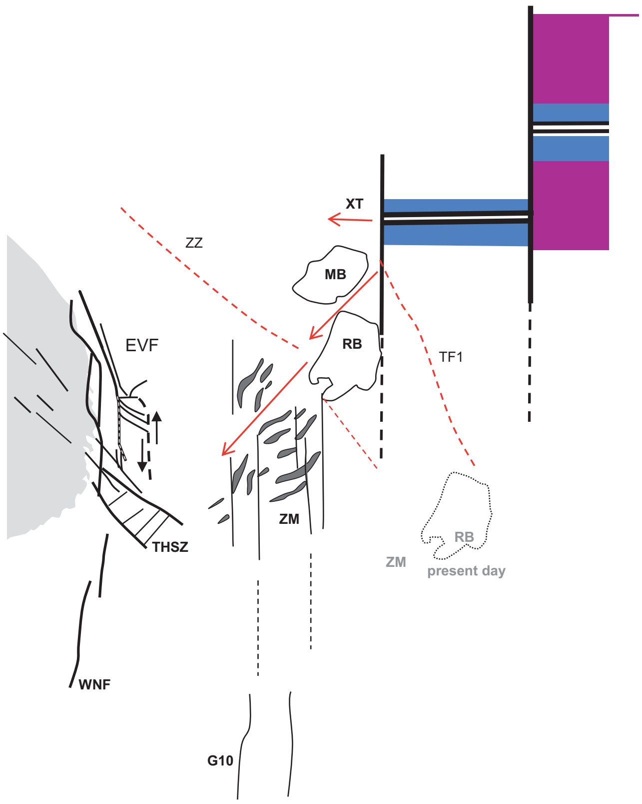

Fig. 8. Notional SCS restoration for 28 Ma (Chron 10). Abbreviations and faults are from those as in prior figures. Grey-filled polygons are graben outlined in Figure 5; solid red lines with arrows indicate future propagation of SCS spreading centre; red dashed lines strike-slip and future transform faults. Arrows on EVF show development of left-lateral pull-apart basin in eastern PKB.

The SCS rift shows a marked change in orientation in the post-25 Ma spreading geometry when it propagated to the SW through the older north–south system. Several NW–SE striking faults beyond the SCS spreading centre obscure the older faults. Neogene spreading in the SCS can be viewed as a consequence of a slab-pull associated with subduction of the proto-SCS following cessation of extrusion of the Indo-China Block (Hall 2002; Fyhn *et al.* 2009*b*). An alternate model proposed by Cullen (2010), interprets minimal Neogene subduction under Borneo and suggests a hybrid model of extrusion and crustal shortening needs to be considered (see also Zhu *et al.* 2009; Sun *et al.* 2009).

We note that reversals, left- to right-lateral motion along major fault systems, such as the Red River, represent relative motion between blocks and that from a regional tectonic perspective both blocks could still be 'extruding' away from Asia. From a geodynamic standpoint it appears that additional thinning of the lithosphere by asthenosphere upwelling is required to drive opening of the SCS (Xia *et al.* 2006). Given the complex subduction history around the region the concept of 'splash plumes' produced by instabilities at the edges of downwelling mantle (Davies & Bunge 2006) may prove useful in explaining some of the anomalous patterns in the SCS.

With respect to petroleum exploration in the frontier areas of the SCS, either deeper in presently productive basins or outboard towards the SCS spreading centre, our observations suggest complexity and surprises. Given the overprinting of multiple rift events, predicting age, depositional environments, and thermal history ahead of the drill bit will be challenging.

CONCLUSIONS

Multiple processes have contributed to the evolution of the SCS rift making this region an ideal laboratory to study the complexities of rifting. Earlier end-member tectonic models have been invaluable in providing a framework for subsequent studies to challenge. The use of filtered gravity data provides a useful tool for looking at potential tectonic features related to SCS rifting and the extrusion of Indochina. Our observations suggest that although rifting preceded collision-extrusion, the latter strongly influenced the former. Although rifts are a target-rich environment, frontier exploration in the South China Sea will be challenging because its complex evolution will limit inter-basin predictability for its petroleum systems. Improving our understanding of the region's tectonic evolution through development of hybrid models would greatly benefit from future multi-national, industry-academic-governmental joint studies.

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