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Continental rifting in the South China Sea through extension and high heat flow: An extended history

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ABSTRACT

We present a new extensional tectonic model for the Cenozoic history of SE Asia and the opening of the South China Sea (SCS), proposing a feedback mechanism by which intracontinental rifts initiate and propagate without invoking mantle plumes.

Four principal tectonic models have been proposed for SCS opening: 1) Slab pull from subduction of a Proto South China Sea (PSCS); 2) Extrusion tectonics from the India-Asia collision; 3) Basal drag from a mantle plume; and 4) Backarc rifting. Each model was developed around different particular data, and all tend to perpetuate independently through selective data prioritisation. We present a new GPlates model, showing that the geological and geophysical correlations between the opposing SCS conjugate margins best agrees with a common initial development on the South China Margin, and that regional development via protracted extension since the Mesozoic is in agreement with available paleomagnetic data for Borneo.

The geodynamic mechanism for protracted lithospheric extension in SE Asia is via the development of progressive feedback processes, initiated by Mesozoic slab rollback and migration of the subduction zone beneath South China, leading to intracontinental thinning and extension. This in turn drove passive asthenospheric upwelling, increasing heat flow and crustal ductility, and enhancing further extension as a wide rift rather than narrow crustal neck. Subsequently, following sufficient continental extension, SCS oceanic spreading occurred. This feedback mechanism (involving shallow, not deep mantle processes) may enhance and enable intracontinental rifting elsewhere.

1. Introduction

Our understanding of the geological history and complex tectonic framework of SE Asia has advanced considerably (Hall, 1996; Hutchison, 2014) since early work (Haile, 1973, 1968; Hamilton, 1979). Outcrops are scant and deteriorate rapidly in the tropical climate. Biostratigraphic data on age and paleogeography are improving, but are still incomplete (Lunt, 2020). Widespread areas have a rugged, deeply dissected topography that imposes limitations on both geological and onshore geophysical surveys. Numerous borders and territorial claims are disputed, which hinders cooperative international studies and developing a unified stratigraphic nomenclature. Lastly, although several companies have published regional studies (Daly et al., 1991; Longley, 1997), the actual industry data (borehole and seismic) remains largely out of the public domain. Despite these challenges, the scientific community has built a solid geological framework that reflects the knowledge from persistent field-based studies, paleomagnetic data (Fuller et al., 1999; Haile et al., 1977), regional 2D reflection seismic data (Franke et al., 2008), and marine magnetic data from the South China Sea (Barckhausen and Roeser, 2004; Li et al., 2014; Taylor and Hayes, 1983). Software development has enabled internally consistent kinematic reconstructions of the regional tectonic evolution (Advokaat et al., 2018; Hall, 2012; Replumaz and Tapponnier, 2003; Zahirovic et al., 2014), and tomographic imaging of the region's deep mantle structure continues to improve (Hall and Spakman, 2015; Rangin et al., 1999; Wu and Suppe, 2018). However, with this expansion of data, understanding the region's geological history has become akin to solving a distorted Rubik's Cube in which everything relates to everything else.

This paper addresses various alternative tectonic models for the widespread rifting that culminated in Oligocene to Early Miocene

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seafloor spreading in the South China Sea (SCS), including the evolving interpretations of the proto-South China Sea (PSCS). The SCS is arguably the region's most prominent bathymetric and tectonic feature (Figs. 1 and 2a). There are four principal models for the opening of the SCS (Fig. 3): 1) Backarc extension (3a); 2) Extrusion tectonics from the India-Asia collision (3b); 3) Slab pull from subduction of a Proto South China Sea (3c-1 and 3c-2); and 4) Basal drag from a mantle plume. Of these, the PSCS slab pull model is the most widely accepted, although proponents for all four continue to publish arguments in their favour. The slab pull model has two further variants (Figs. 3c-1 and 3c-2): 1) single-sided PSCS subduction under Borneo and Palawan (Hall, 2012, 2002, 1996) and 2) double-sided PSCS subduction under the Dangerous Grounds and Borneo-Palawan (Daly et al., 1991; Wu and Suppe, 2018). Further complicating matters are two different interpretations of the origin of the PSCS lithosphere: 1) old Paleo-Pacific oceanic lithosphere (implied by Holloway, 1982, but named by Hinz et al., 1991; Lee and Lawver, 1994; Hall, 2012;) or 2) rifted Southeast Asia continental lithosphere (Ye et al., 2018; Zahirovic et al., 2014).

In this manuscript, we summarise the evolution and key features of each tectonic model before discussing their shortcomings; particularly in light of recent studies (e.g. Advokaat et al., 2018; Lin et al., 2020). We present flaws in all the currently debated models and propose an alternative kinematic model for South China Sea rifting favouring the development of long-lived back arc extension (driven by slab roll back) that evolves into a wide rift, enabled by enhanced heat flow and a ductile upper mantle and lower crust.

2. Key geological tectonic elements

The diverse geology of SE Asia records continental margin processes from the Precambrian to present (Fig. 1). We divide the greater South China Sea region into 5 geological / geographic domains (Fig. 2a), using the term "domain" to reduce the impression of rigid, singular blocks, and to avoid confusion with prior definitions of regional blocks. The composite units of each domain share a similar geological history (stratigraphic and structural) that is sufficiently distinct from adjacent domains to warrant treating each domain as a coherent entity within the context of the region's tectonic evolution; especially as pertaining to Cenozoic rifting and opening of the South China Sea (SCS). The two conjugate continental margins represent the rift phase that preceded the drift phase (sea floor spreading) of the SCS.

Some domain boundaries are well-established fault zones (e.g. the Red River-Ailao Shan Fault system). Other domain boundaries are poorly constrained, owing to concealment under thick, younger sedimentary cover sequences and rugged rainforests (e.g. the south-eastern limit of the Southern Conjugate Margin in Kalimantan). Collectively, these domains occupy a large part of the "Sunda Plate" (Fig. 2b), as defined by GPS data showing significant relative motions between SE Asia and Eurasia (Bird, 2003; Simons et al., 2007; Tingay et al., 2010).

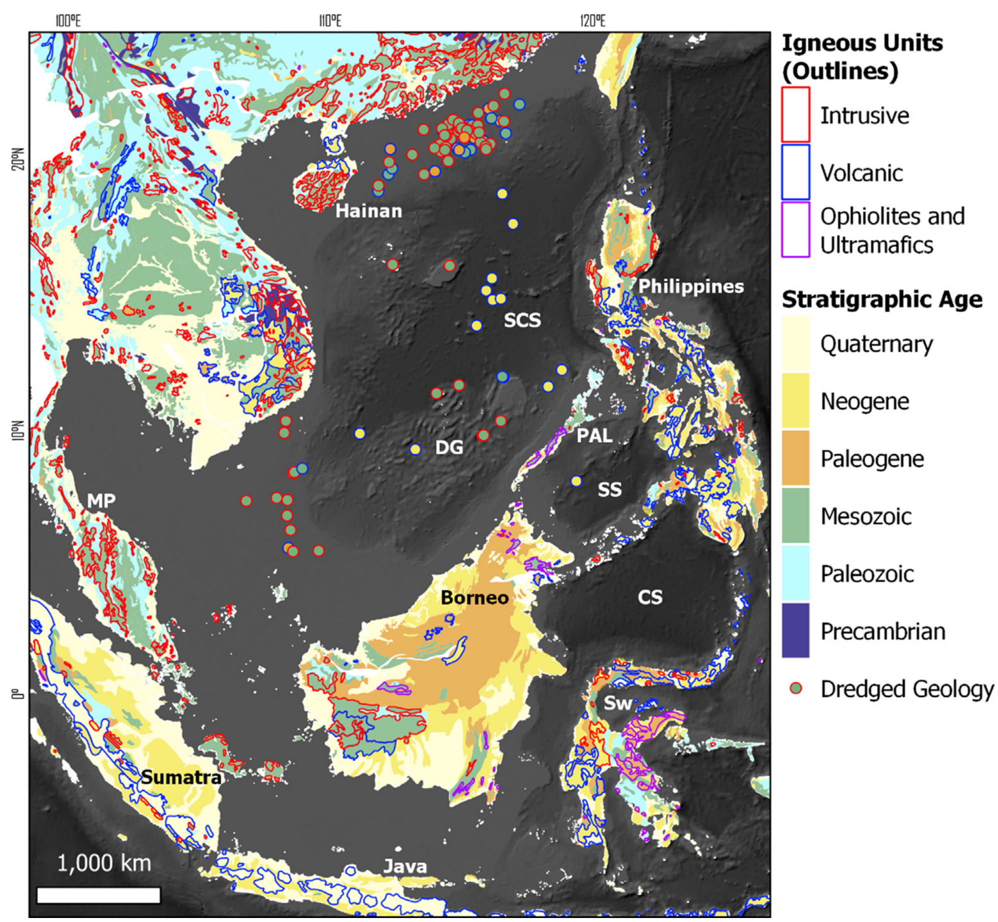

Fig. 1. Geological map of SE Asia, modified from Steinshouer et al. (1999) using regional studies (Aurelio et al., 2014; Balaguru and Nichols, 2004; Galin et al., 2017; Keenan et al., 2016; Shao et al., 2017; Witts et al., 2012). Circles show dredged and drilled bedrock geology using same colour scheme as terrestrial geology (Li et al., 2018; Yan et al., 2006). Bathymetry from ETOPO1 (Amante and Eakins, 2009). CS – Celebes Sea; DG – Dangerous Grounds; PAL – Palawan; MP – Malay Peninsula; SCS – South China Sea; Sw – Sulawesi; SS – Sulu Sea.

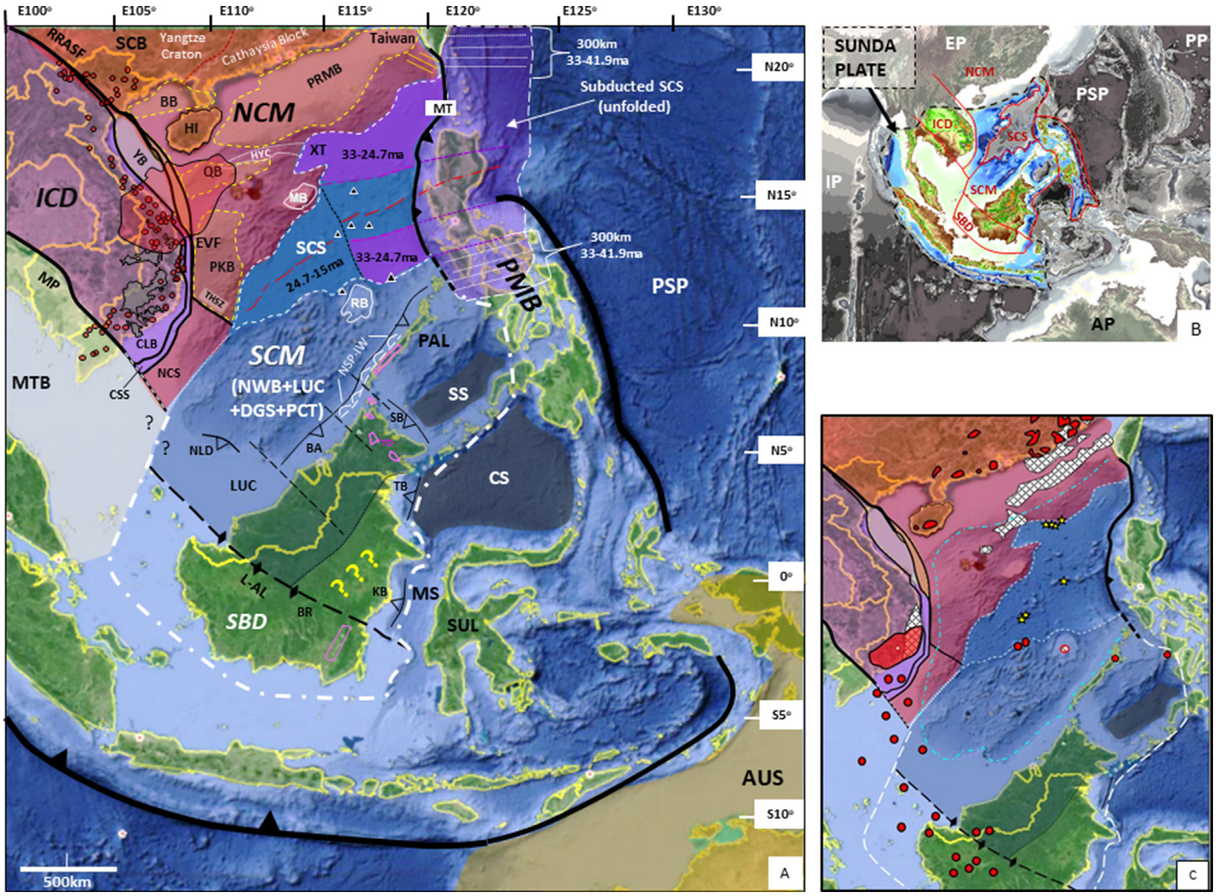

Fig. 2. a) Regional Tectonic Domain Map with key structural features and basins discussed in text. Figure is modified from Cullen (2010), Hu et al. (2013), Schmidt et al. (2019), and Wang et al. (2021). Solid lines with filled black triangles denote upper plate at subduction zones, open black triangles note frontal thrusts of Neogene deepwater basins, open purple polygons of northern Borneo and Palawan outline large ophiolitic bodies. AUS-Australian continental crust; BA-Baram Basin; BB-Biebu Basin; BR-Barito Basin; CL-Cu Long Basin; CS-Celebes Sea; CSS-Con Son Swell; ICD-Indochina Domain; HI-Hainan; KB-Kutei Basin; LUC-Luconia; L-AL-Lupar Andang Line; KB-Kutai Basin; MC-Macclesfeld Bank; MS-Makassar Straits; MT-Manila Trench; MTB-Malaysian-Thai Basin; MP-Mae Ping (Wang Chao) Fault; NCS-Nam Con San Basin; NCM-Northern Conjugate Margin; PAL-Palawan; PCT-Palawan Continental Terrane; PKB-Phu Khanh Basin; PMB-Philippine Mobile Belt; PSP-Philippine Sea Plate; QB-Qiongdongnan Basin; RB-Reed Bank; RRASF- Red River-Ailao Shan fault zone; SB-Sandakan Basin; SBD-South Borneo Domain; SCB-South China Block; SCS-South China Sea oceanic crust; SCM-Southern Conjugate Margin; SS-Sulu Sea; SUL-Sulawesi; TB-Tarakan Basin; THSZ-Tuy Huy Shear Zone; To- Telupid Ophiolite; XT-Xisha Trough; YB-Yinggehai Basin. On the Indochina Domain, the small red circles are hot springs (>50 °C), and grey shaded areas are Cenozoic basalts. Small triangles in the SCS are post-spreading volcanic sea mounts. b) Inset map showing tectonic domains of this study (red lines) in relation to the Sunda Plate (black dashed line; Bird, 2003) and regional bounding plates. AP-Australian Plate; EP-Eurasian Plate; IP-Indian Plate; PP-Pacific Plate. c) Map of Cretaceous-age Yanshanian granitic rocks (red polygons), and volcanic rocks (black and white hachured polygons) (Li et al., 2018; Nguyen et al., 2004). Yellow stars mark IODP sites summarized by Sun et al. (2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.1. Northern Conjugate margin (NCM)

The Northern Conjugate Margin (NCM) is continental crust of Cathaysia; part of the larger South China block that includes the Yangtze Craton. To the southwest and west, the NCM is bounded by the Red River-Ailao Shan Fault system (RRASF) and the East Vietnam Fault. The continent-ocean transition of the SCS oceanic crust marks the southeast boundary (Fig. 2a). The NCM has a core of Proterozoic crystalline basement and Early Paleozoic sediments (Fig. 1) that were originally part of Australian Gondwanaland (Metcalfe, 2013). The South China block was sutured to China in the Late Triassic Indosinian Orogeny (Metcalfe, 2013). The South China block was relatively stationary through the Cretaceous and Cenozoic (Hall, 2012). A belt of Late Mesozoic continental arc granitoids and volcanic rocks, referred to here as the Yanshanian Arc, intrude and overlie this accreted terrane and extend to the Indochina Domain, the Dangerous Grounds, and Palawan (Fig. 2b). These igneous rocks become progressively younger to the east owing to rollback of the Paleo–Pacific plate and eastward retreat of its subduction zone (Deng et al., 2017; Hall, 2012; Li et al., 2018; Li and Li, 2007; Wang et al., 2018; Zhang et al., 2020). Similar igneous rocks are present in the South Borneo Domain, with the younger Cretaceous granites attributed to post-subduction extension (Breitfeld et al., 2020).

The hallmark feature of the NCM is a set of intracontinental rift basins from a protracted episode of regional lithospheric extension (Fig. 4). This protracted history includes minor structural overprinting of the initial rift basins related to changes in the regional stress field driven by ridge jumps and impingement of the Indochina Block (Cullen et al., 2010; Zhao et al., 2021). This led to reactivation of Indosinian and Yanshanian fault systems and a transition from pure shear to simple shear dominated strain (Suo et al., 2022). Early studies of the rifting history of the NCM based on inversion of gravity data and seismic data (expanded spread profiles, refraction profiles, and 2D and 3D seismic data) concluded that it underwent spatially varied depth-dependent stretching and only minor magmatic activity prior to the onset of SCS rifting (Clift et al., 2001; Nissen et al., 1995). However, subsequent IOPD

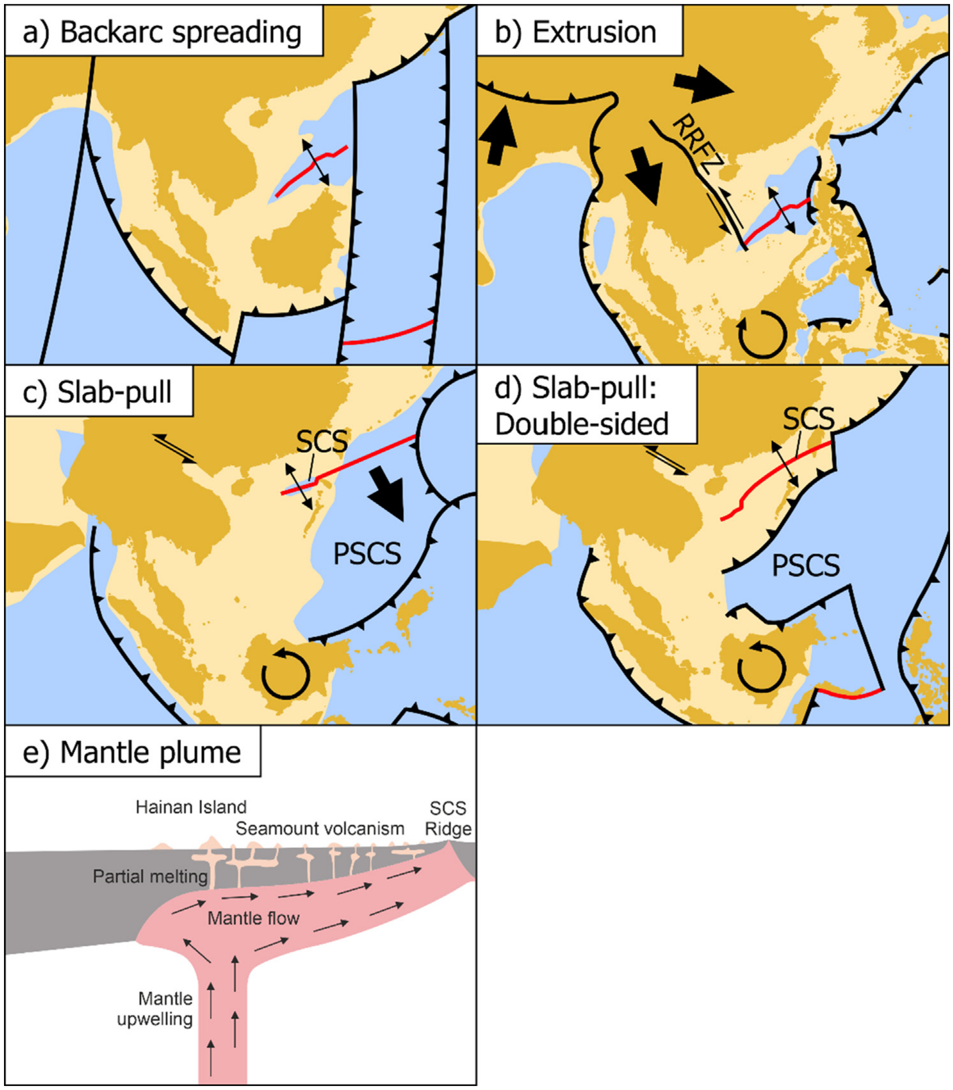

Fig. 3. Tectonic models of the South China Sea (SCS). a) Opening of the SCS via backarc spreading, initiated by northwards subduction of a transform fault-bounded ocean segment of the Indian-Australian Plate (modified from Stern and Bloomer, 1992). b) Extrusion model for South China Sea (SCS) extension (modified from Tapponnier, 1982) RRFZ – Red River Fault Zone. c) Slab-pull model for SCS extension, driven by subduction of the Proto South China Sea (PSCS) beneath a CCW-rotating Borneo (shown for 30 Ma, modified from Hall, 2012). d) Alternative slab-pull model involving double-sided subduction of the PSCS (shown for 34 Ma, modified from Lin et al., 2020). e) Mantle plume model, opening the SCS via mantle flow from a plume beneath Hainan (modified from Zhang et al., 2020). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

expeditions (summarised in Sun et al., 2018) and 3D seismic data analyses have shown considerable lateral and vertical variability in the strain distribution, and that localised *syn*-rift magmatism along the NCM represents a hybrid model between the magma-rich and magma-poor end member models of continental rifting (Larsen et al., 2018; Zhao et al., 2021). Ding et al. (2020) interpret rift-related magmatic activity along the NCM as driven by adiabatic decompression melting during rapid extension focused on a narrow continent-ocean boundary.

2.2. Indochina Domain (ICD)

The Indochina Domain (ICD; Fig. 2a) is bounded by the Mae Ping (Wang Chao) fault zone to the southwest, which cuts through the larger Indochina Terrane of Metcalfe (2002). The eastern ICD boundary follows the East Vietnam Fault through the Tuy Huy shear zone, then down along the Con Son Swell to the offshore projection of the Mae Ping fault zone (Schmidt et al., 2019). The Red River-Ailao Shan fault system (RRASF), which defines the northeast boundary between the ICD and the South China Block, runs along the Permo-Triassic Song Chay suture (Faure et al., 2014) that records the amalgamation of the South China / Indochina Super Terrane (also referred to as Cathaysia; Metcalfe, 2002). The Indochina Domain has a Precambrian metamorphic core (Kontum Massif) overlain by Paleozoic sediments intruded by Mesozoic granites, and is locally overlain by Neogene to Quaternary basalts (Carter et al., 2000). In Vietnam, widespread plateaus of Late Cenozoic basalt and numerous hot springs (greater than50 °C) attest to a youthful thermal disturbance along the ICD boundary (Fig. 2a). The Indochina Domain was tectonically extruded to the southeast along the RRASF as India collided with Asia (Tapponnier, 1982). The amount of left-lateral lateral displacement along the RRASF is a source of controversy, with estimates ranging between 700 km (Leloup et al., 1995), 500 km (Briais et al., 1993) and 200 km (Hall, 2002). Correlations of the Da Lat Province (Vietnam) with similar rocks on the Northern Conjugate Margin (Fig. 2c; Nguyen et al., 2004) favours a displacement at the lower end of the various estimates; an important consideration for tectonic reconstructions.

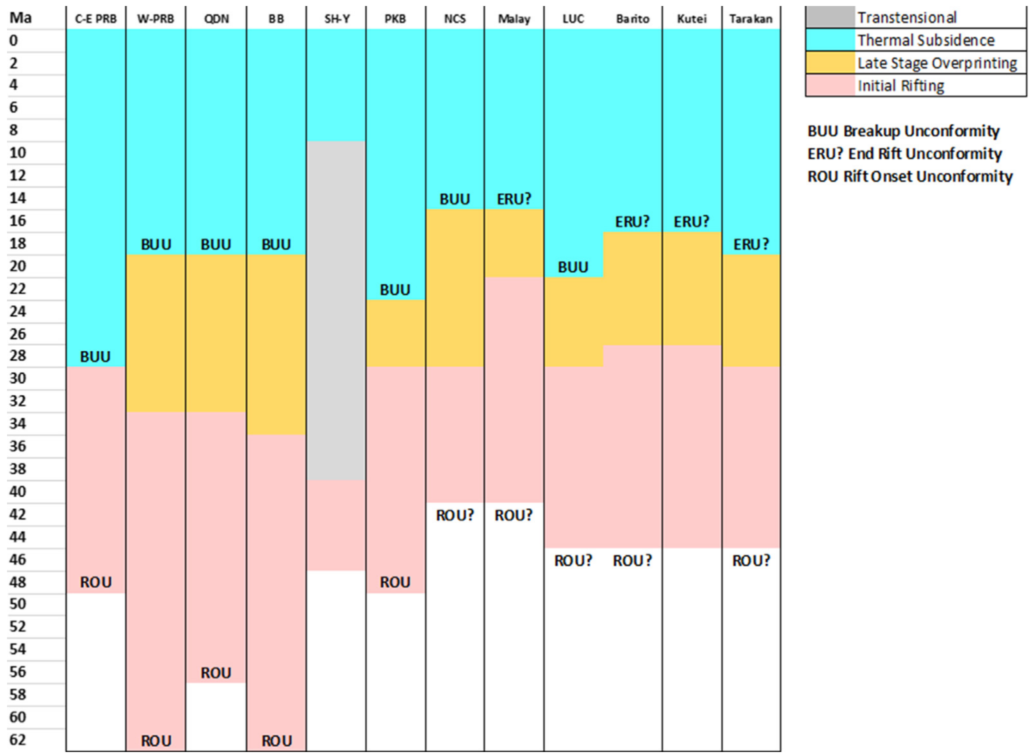

Fig. 4. Summary diagram of regional rifting history for basins in the greater South China Sea Region (compiled and simplified from Cullen et al., 2010; Franke et al., 2014; Lunt, 2019; Ru and Pigott, 1986; Zhang et al., 2020). BUU - breakup unconformity, ROU - rift onset unconformity, ERU- end of rifting unconformity for Borneo rift basins that are not associated with South China Sea oceanic spreading.

2.3. South China Sea oceanic crust (SCS)

The South China Sea (SCS) oceanic crust is a triangular region bounded to the northwest by attenuated continental crust of the South China Margin, to the southeast by the attenuated continental crust of the conjugate Dangerous Grounds, and to the northeast by the Manila Trench subduction zone (Fig. 2a). A narrow continent-ocean transition is sharply defined by the 3000 m isobath and regional gravity data (Braitenberg et al., 2006; Briais et al., 1993). Marine magnetic data establish that the SCS opened as a propagating rift in several distinct phases between 32 and 15.5 Ma (Briais et al., 1993; Taylor and Hayes, 1983). Although Barckhausen et al. (2014) concluded sea floor spreading at the SW tip ceased around 20.4 Ma, subsequent studies utilising deep tow magnetometer data support the younger, 15.5 Ma age for cessation (Li et al., 2014; Sibuet et al., 2016). The eastern SCS boundary is placed at the Manila Trench, where oceanic lithosphere and the extinct spreading centre have been subducting from the late Oligocene to middle Miocene and continue at the present day (Hayes and Lewis, 1984). Implications of this subducted lithosphere are discussed in Section 4.2.

The continental rifting early in the extensional history of the SCS was asymmetric. Extreme thinning of the continental crust generated MORB (Mid-Ocean Ridge Basalt) magmatism prior to continental rupture, with final continental extension accommodated by a low angle extensional fault on the SE China margin (Nirrengarten et al., 2020). The SCS initially opened from east to west as it propagated into the present-day Xisha Trough (Qiu et al., 2001). This early phase of N-S spreading aligns with Eocene intracontinental rifting directions on the Northern Conjugate Margin (Deng et al., 2020). The earliest extension of the SCS conjugate margins was asymmetric, with a lower half spreading rate on the southern margin than the north, during which the spreading centre migrated southward until symmetric steady-state ocean spreading developed after ~ 28.7 Ma (Nirrengarten et al., 2020).

Whilst previously classified as a magma-poor rift, with limited magmatism associated with rifting (Franke et al., 2014), seismic, passive geophysical, and IODP data indicate that the northern passive margin of the SCS transitioned from a magma-poor to magma-rich margin in response to passive asthenospheric upwelling during lithospheric extension (Sun et al., 2019; Zhang et al., 2021). Geophysical data also indicates extensive mafic lower crustal underplating occurred beneath both conjugate margins during early extension (Peng et al., 2020).

The SCS experienced ridge jumps at 25.5 and 24.7 Ma. The second, more significant jump reoriented rift propagation to the southwest, splitting the Macclesfield and Reed Banks (Barckhausen and Roeser, 2004). Magnetic anomalies south of Taiwan were interpreted as 37 Ma oceanic crust (Hsu et al., 2004), but subsequent work showed this area to be highly attenuated continental crust (McIntosh et al., 2014).

Following cessation of SCS extension, there is a scattered yet considerable amount of post-rift intraplate magmatism with wide ranging ages along the margins and within the SCS oceanic crust (Fig. 1, Fig. 2, and Fig. 5e).

2.4. South Borneo Domain

The South Borneo Domain is composed of three terranes (Fig. 6) that were rifted from northern Australia in the Jurassic and were sutured to Southeast Asia in the Cretaceous to complete the assembly of greater Sundaland (Hall, 2012; Hennig et al., 2017; Metcalfe, 2011). These Gondwanaland-derived terranes are: 1) South Borneo (Banda), 2) North Sulawesi (Inner Banda), and 3) East Java-South Sulawesi (Argo). Paleomagnetic data indicate that relative to Sundaland, Borneo underwent strong Cenozoic counter-clockwise

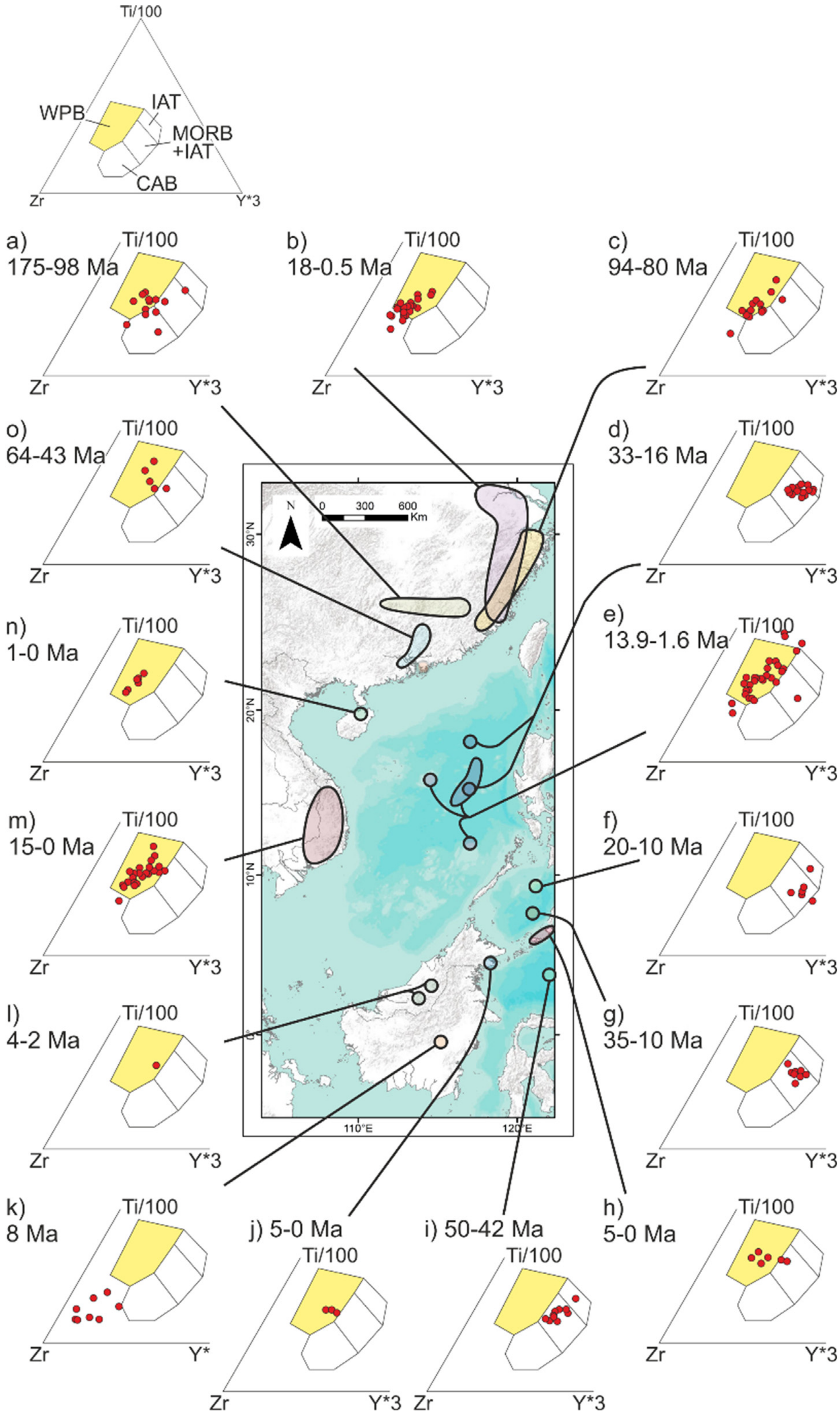

Fig. 5. Tectonic discrimination diagrams of basaltic (<52% SiO_2) magmatism in the South China Sea region since the Jurassic, showing the prevalence of within plate magmatism. Ti-Zr-Y basalt discrimination diagram from Pearce and Cann (1973). WPB – Within Plate Basalt; IAT – Island Arc Tholeiite; MORB; Mid-Ocean Ridge Basalt; CAB – Continental Arc Basalt. Localities: (a) Cathaysia Folded Belt (Chen et al., 2008); (b) Cenozoic SE China basalts (Zou et al., 2000); (c) Southeast China Coast Magmatic Belt (Chen et al., 2008); (d) SCS spreading ridges (Yu and Liu, 2020; Zhang et al., 2018); (e) SCS post-spreading seamounts (Tu et al., 1992; Yan et al., 2008); (f) Cagayan Ridge (Kudrass et al., 1990; Spadea et al., 1996); g) Sulu Sea (Roeser, 1991; Spadea et al., 1996); (g) Sulu Archipelago (Castillo et al., 2007); Celebes Sea (Silver and Rangin, 1991; Spadea et al., 1996) (h) Semporna Peninsula (Macpherson et al., 2010); (i) Linhaisai minettes, Kalimantan (Bergman et al., 1988). (j) Usun Apau and Linau Balui (Cullen et al., 2013); (k) Vietnam (Nguyen et al., 1996); (l) Hainan (Zou and Fan, 2010); (m) South China Paleogene magmatism (Chung et al., 1997).

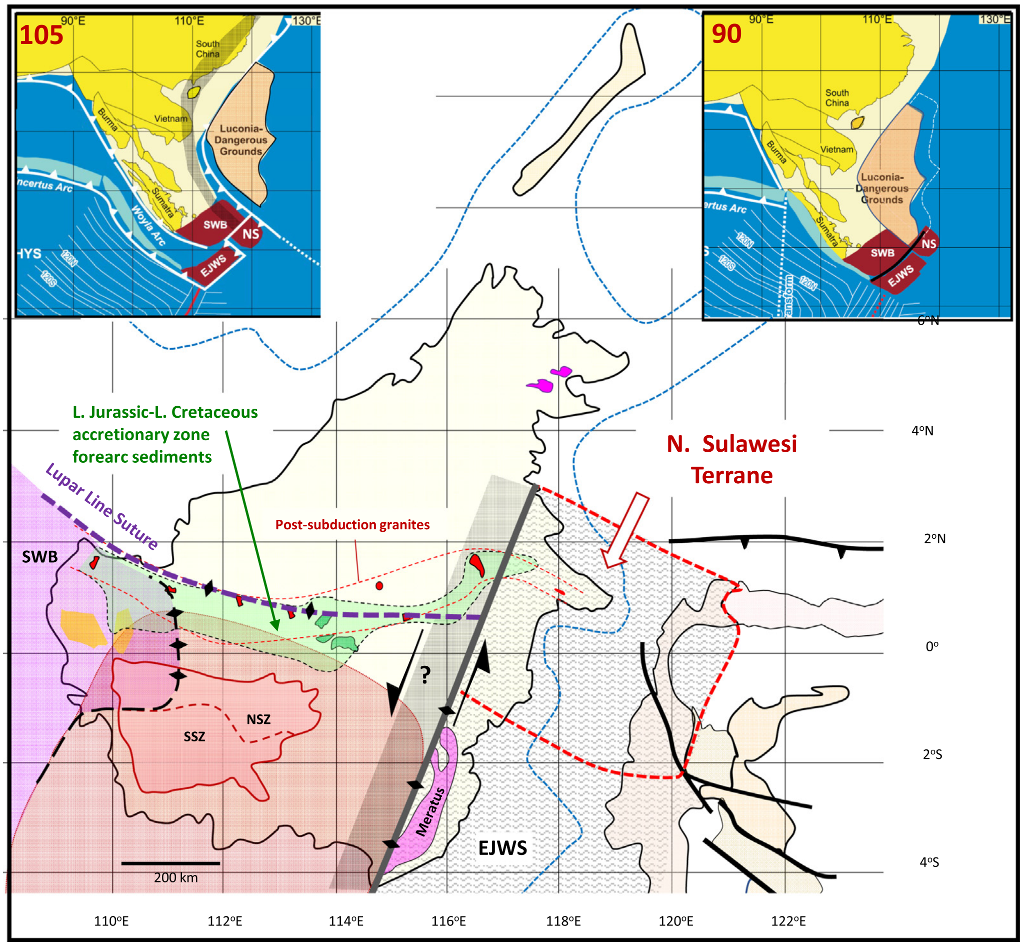

Fig. 6. Main geological and structural features of the South Borneo Domain in relation to its assembly and docking of the Greater Luconia Block at 105 Ma and 90 Ma. Modified from Hennig et al. (2017) and Breitfeld et al. (2017). current 200 m isobath shown by a blue dashed line. EJWS - East Java Sulawesi, SSZ- Southern Schwaner zone, NS- North Sulawesi Terrane, NSZ – North Schwaner zone. SWB – Southwest Borneo. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

rotation as a relatively coherent block with some possible complications from regional shear zones (Advokaat et al., 2018; Fuller et al., 1999; Wood, 1985). The structures to accommodate this relative rotation have yet to be confidently identified.

The northern boundary of South Borneo is a complex suture zone along the ESE trending Lupar Line. The suture zone is intruded by post-subduction Late Cretaceous granites. Illites from the Lubok Antu tectonic mélange have K-Ar ages clustering around 60 and 36 Ma, indicating subduction in Sarawak could have continued until ca. 60 Ma and that a second thermal event possibly reflects uplift of the Rajang Group (Zhao et al., 2021). The Lupar suture zone is cross-cut by the NNE-trending Meratus Mountains complex, which includes a suite of metamorphosed arc and ophiolitic rocks recording oblique collision and accretion of the East Java-West Sulawesi and North Sulawesi terranes to Sundaland (Hall, 2012). The Mesozoic arc rocks are unconformably overlain by the Cenozoic formations in the Barito Basin (Witts et al., 2014). Reconstructions indicate a complex structural history, including left-lateral displacement along the Meratus suture and a poorly defined docking history of the Luconia-Dangerous Ground block to the north (Fig. 3).

2.5. Southern Conjugate margin (SCM)

The Southern Conjugate Margin (SCM) comprises three regions (Fig. 7a) that constituted the outboard, southern conjugate to the Northern Conjugate Margin (NCM) prior to opening of the South China Sea. The common origin of these margins is demonstrated by traversing around the SW tip of the extinct SCS spreading ridge. The SCM domain is comprised of: 1) The Greater Dangerous Grounds (including Luconia, used herein in the collective sense of Madon, (1999) and Lunt, (2019); 2) Northwest Borneo (Sibu Zone, Miri Zone, Brunei and Sabah as used by (Hutchison, 2005); and 3) the Palawan Continental Terrane (Dimalanta and Yumul, 2013; Yumul et al., 2020). Collectively, this diverse assemblage is broadly equivalent to the Luconia Block of Fyhn et al. (2010) and the Luconia-Dangerous Grounds block of Hall (2012). These respective lithosphere-scale fragments have been interpreted to have much different sizes and to have been sutured to SE Asia at different times (Fig. 7c): a smaller size with Paleocene collision (Fyhn et al., 2010), or a larger block with a Late Cretaceous collision (Hall, 2012).

Before discussing its individual elements, several aspects of the SCM need highlighting. The first is the poorly constrained extent, age, and nature of the outboard oceanic crust that was part of the Panthalassa / paleo-Pacific plate, which in various tectonic reconstructions became the PSCS (reviewed by Hall and Breitfeld, 2017). Secondly, the regional Bouguer gravity data (Fig. 7c) indicates the presence of smaller embedded microblocks, such as Central Luconia (Madon et al., 2013) south of the West Baram Line and the Reed and Macclesfield Banks on the Dangerous Grounds. Areas of broad strong gravity highs, such as the SCS, Xisha Trough, Sulu Sea, and Celebes Sea (Fig. 7b), correspond to oceanic to hyper-thinned continental crust (Fig. 8; Gozzard et al., 2019; see

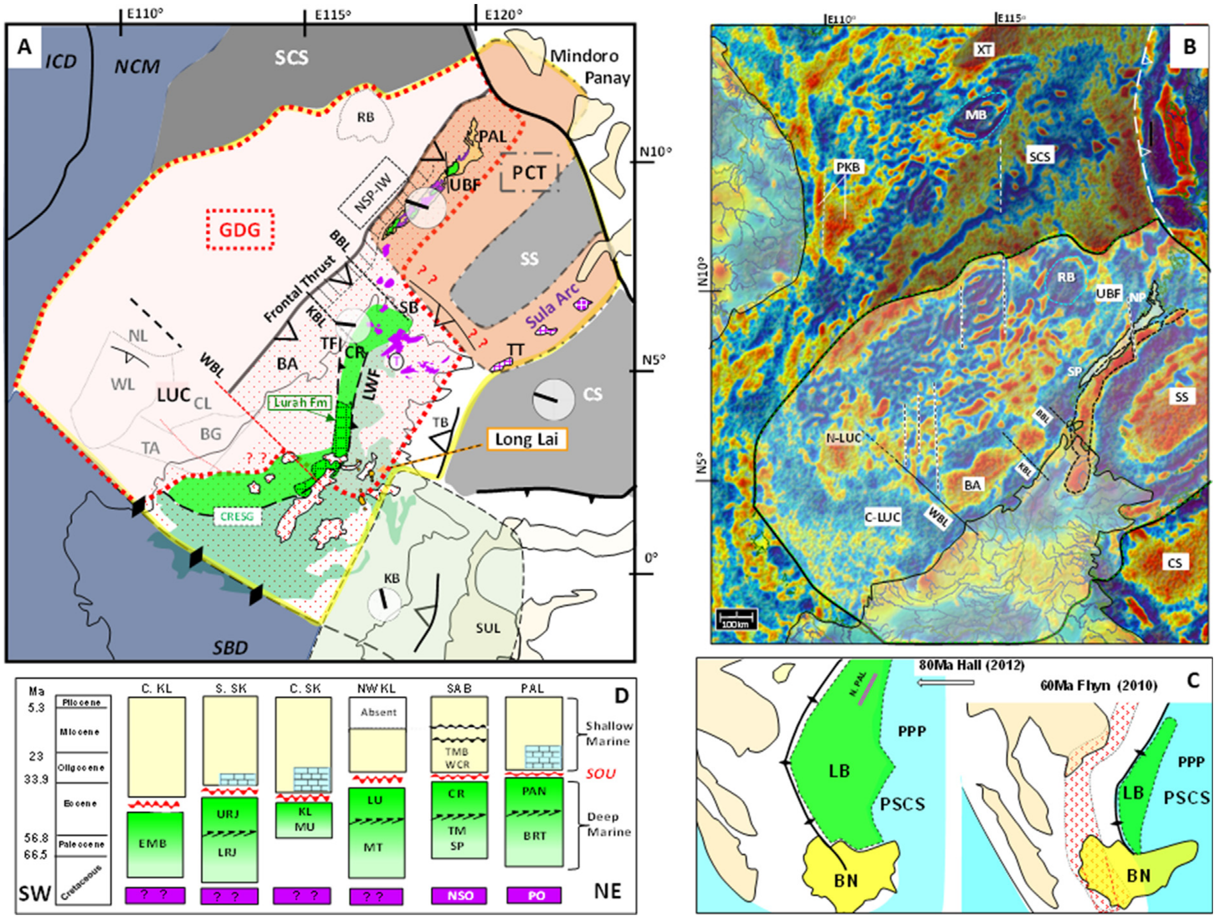

Fig. 7. Main geological and structural features of the Southern Conjugate Margin (SCM); abbreviations as in Fig. 2. a) Dark green polygon is the Eocene-age Crocker-Rajang Group outcrop; light green polygon is the Embulah-Menterang Group outcrop; purple polygons indicate ophiolitic rocks; semi-transparent circles with lines show paleomagnetic regional rotations. BBL - Balabac Line; BG - Balingian Province; CL - Central Luconia; CR - Crocker Formation; KBL- Kebabangan Line; LWF - Lurah - Witti Fault; NSP-IW - North Sabah Palawan Imbricate Wedge; PCT - Palawan Continental Terrane (light orange) SB - Sandakan Basin; T - Telupid; Ophiolite TA - Tatau Province; TF - Tenom Fault; TT - Tawi - Tawi Island UBF - Ulugan Bay Fault; WBL- West Baram Line. b) Regional Bouguer gravity data, blended with a first derivative filter, showing correspondence to major geo-tectonic features. Red-orange areas are high gravity anomalies, and dark blue areas are low gravity anomalies. SCS is shaded light grey (adapted from Cullen et al., 2010, who used the data of Sandwell and Smith, 1997). c) Two different docking scenarios for the Luconia Block from Fyhn et al. (2019) and Hall (2012). d) Regional stratigraphic correlation columns showing ophiolitic rocks (purple), Cretaceous–Paleogene deep marine sediments (green) and Neogene shallow marine sediments (light yellow), SOU is the Sarawak Orogeny Unconformity; formation abbreviations are: BRT - Babuyan River Turbidites; EMB - Embulah; LU - Lurah; LRJ - Lower Rajang; URG - Upper Rajang; KL - Kelan; MU Mulu; MT - Menterang; PAN - Panas; SP - Sapulut; TM - Trusmadi; TMB - Temburong; WCR - West Crocker. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

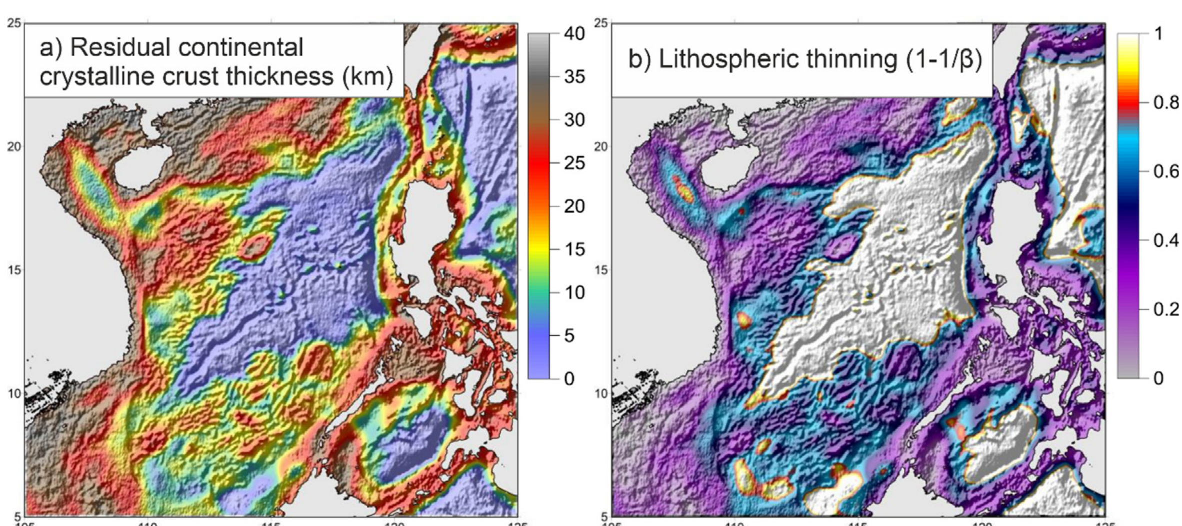

Fig. 8. Crystalline crustal thickness (a) and lithospheric thinning (b) of the SCS predicted by gravity inversion incorporating a lithosphere thermal gravity-anomaly correction (from Gozzard et al., 2019). β = initial thickness/final thickness. Initial crustal thickness assumed to be 37.5 km.

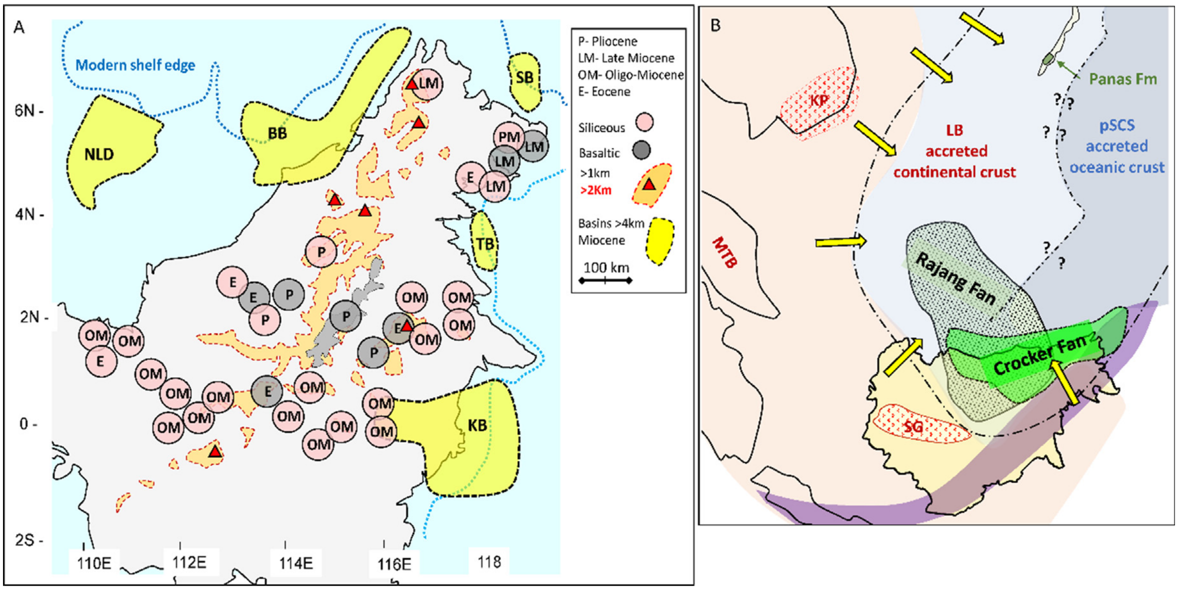

Fig. 9. NW Borneo Features a) Key geologic units and Neogene basins (BB- Baram Basin, KB- Kutai Basin, NLD- North Luconia Delta, SB- Sandakan Basin, TB- Tarakan Basin). Distribution of igneous rocks modified from Cullen et al. (2013). Central Highland greater than 1,000 m height in red polygon. b) Paleogene depositional systems. Rajang Fan (Galin et al., 2017), Crocker Fan (van Hattum et al., 2013), KG- Kontum Granites, MTB- Malay Tin Belt, SG- Schwaner Granites. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

also Supplement_1 Fig. S1a), whereas areas that correspond to outcrops of ophiolite assemblages are expressed as narrow, sharp-edged, gravity highs (South Palawan-North Sabah). Lastly, we note that where the post-breakup sedimentary cover is thin, the horsts and graben of the Dangerous Grounds continental rifting are clearly expressed as sets of closely spaced gravity highs and lows (Fig. 7b).

2.5.1. Greater Dangerous Grounds (GDG)

The Greater Dangerous Grounds (GDG) is a region of continental crust that records protracted rifting prior to the onset of SCS oceanic spreading. The Dangerous Grounds *sensu stricto* comprises a series of islands, atolls, and shallow reefs built upon horst blocks of the rifted Indochina continental margin. Our understanding of the GDG geology is informed by a limited number of exploration wells (Reed Bank and deepwater Northern Luconia), several ODP dredging and drilling sites (Fig. 1), and regional 2D seismic grids. Rifted continental crust is present underneath Luconia, but is not well understood owing to poor geophysical imaging and the lack of borehole penetrations. We tentatively extend the southeast limit of the GDG past the inversion anticlines of the Balingian fold belt (Lunt, 2019) and the Balingian Shear Zone (Tate, 1995) to the contact with Paleogene deepwater clastic rocks of the Rajang Group across the Tatau-Bukit Mersing Line. Northeast of the West Baram Line, GDG crust is imaged on seismic lines beneath the Northwest Borneo fold and thrust belt at least as far as the shoreline (Cullen, 2014, 2010; see Supplement_1 Fig. S1b). Offshore west of Palawan, small rift basins filled with Eocene-age deepwater clastics are imaged below the footwall of the Palawan thrust beneath the Pagasa accretionary wedge (Aurelio et al., 2014). The Pagasa accretionary wedge is correlative with the Lower Tertiary thrust sheet and Domain D of Hazebroek and Tan (1993) and Cullen (2010); an allochthon of Miocene age clastic rocks. These correlatives respectively comprise the North Sabah-Palawan Imbricate Wedge, NSP-IW (Fig. 2, and Supplement_1 Fig. S1c). Along its SW boundary, the NSP-IW has been thrust over the fold belt of the Baram Basin along a feature we informally call the Kebabangan Line (Supplement_1 Fig. S1d).

3D P- and S-wave tomography and teleseismic inversion suggest that Dangerous Grounds crust extends underneath the Crocker Range in Sabah, Malaysia (Rawlinson et al., 2019). Tin-bearing Oligocene–Early Miocene adamellites at Long Mai, Kalimantan (Tate, 1995, referencing Bambang and Le Bel, 1988) indicate derivation from underlying continental crust. We show the GDG as extending beneath most of Sabah so that it abuts the southeast side of the Palawan Continental Terrane (Fig. 7a). This is consistent with Milsom and Holt's (2001) suggestion that onshore gravity data indicate much of northern Sabah could be underlain by crust of continental affinity; albeit as heterogeneous in its rift architecture and crustal thickness as observed in the attenuated continental crust of the Dangerous Grounds.

2.5.2. Northwest Borneo

The geology of NW Borneo can be simplified into three broad tectonostratigraphic units: 1) dismembered intraplate Mesozoic ophiolitic rocks overlain by largely Paleogene deepwater clastic rocks (Fig. 7a); 2) largely shallow marine Neogene to recent basins that extend offshore (Fig. 9a); 3) widely scattered, small volume Eocene to Pleistocene-age igneous rocks with a scattered geographic and temporal distribution (Fig. 9a). Units 1 and 2 are separated by the Sarawak Orogeny Unconformity, a major unconformity that developed in response to the Sarawak Orogeny near the end of the Eocene (Fig. 7d). Note that the Sarawak Orogeny extends beyond Sarawak through Sabah and into Palawan.

Unit 1 dominates Borneo's rugged interior highlands. In Sabah and southern Palawan, Unit 1 is floored by scattered small to modest-sized outcrops of Mesozoic ophiolite. The ophiolite comprises structurally disrupted ultramafic, gabbroic, and basaltic units, overlain by chert, and is dominantly Cretaceous in age, although the oldest units are intruded by Triassic island arc felsic plutons (Burton-Johnson et al., 2020) (intrusions previously interpreted to represent windows of an underlying crystalline basement; Leong, 1974).

Tsikouras et al. (2021a) interpret the Telupid Ophiolite in central Sabah (Fig. 7a) to be Late Miocene in age and related to propagation of the Sulu Sea spreading centre into northern Borneo. However, Cullen and Burton-Johnson (2021) highlight the geological and geophysical evidence for a Cretaceous age, and argue that the younger U-Pb zircon ages represent the crystallisation of metasomatic Miocene zircon during magmatic-hydrothermal alteration of the Cretaceous basement. Regional crustal thickness maps (Bai et al., 2020; Gozzard et al., 2019, Fig. 8 herein; Pilia et al., in review), do not support extending the Sulu Sea spreading ridge through Sabah as shown by Tsikouras et al. (2021a, their Fig. 3). Recent shear wave tomography utilising a dedicated dense seismic network covering north Sabah shows several zones of crustal thickening and thinning, including a thin area (25 km) in central Sabah (Linang et al., in review; Pilia et al., in review). However, Greenfield et al. (2022) estimate a small crustal thinning factor in this region (β = 1.2 to 1.3), *"well-below that expected for crustal breakup and onset of seafloor spreading*". Additionally, there is no evidence for exhumation-related core complexes that should be present if the Telupid Ophiolite is of Late Miocene age, and Kirk (1968) notes the Miocene basalts in the Telupid area are not associated with any chert. Despite the morphological features highlighted by Tsikouras et al. (2021b), metasomatic zircon cannot be distinguished from magmatic zircon based on morphology alone, and the presence of zircon in low-SiO_2 rocks implicitly implies secondary crystallisation (Schaltegger, 2007). There is therefore no evidence for Cenozoic ophiolitic magmatism in Sabah.

In addition to its ophiolitic rocks, Unit 1 is composed predominantly of a thick succession of strongly deformed Cretaceous to Eocene deepwater turbiditic sandstones that generally have faulted contacts with the underlying ophiolites. This succession's complicated stratigraphic nomenclature reflects name changes across national and international borders, poor biostratigraphic control, complex structure, and difficult access to remote outcrops in Borneo's heavily vegetated highlands. Departing from Moss (1998), who assigned the name Rajang-Embaluh Group to this succession, we informally apply the name Crocker-Rajang-Embaluh Super Group (CRESG) to include coeval units in Sabah (Fig. 7d). The Cretaceous units of the CRESG (Embulah, Kapit, Menterang, and Sapalut Formations) are interpreted to be in the hanging wall of major thrust faults, such as the Long Aran and Witti, faults (Fig. 7a; see also Hutchison, 2007, Fig. 5.22). The CRESG was originally interpreted as a series of accretionary prisms related to eastward-direct subduction beneath Borneo (Haile, 1973; Hamilton, 1979). Subsequent studies indicate the CRESG, particularly the Eocene-age Crocker and upper Rajang Formations, were deposited on trapped crust of a remnant basin (Moss, 1998) on the Luconia block after its accretion to Indochina.

There are two contrasting depositional models for the Crocker and upper Rajang sandstones. On the basis of heavy mineral and detrital zircon data, van Hattum et al. (2006) favour Crevello's (2002) mega-fan, largely sourced from the South Borneo Block (Schwaner Mountains). Lambiase et al. (2008) make the case for deposition in a series of coalesced smaller fans with multiple sources. These models are not mutually exclusive, as shown in van Hattum et al.'s (2013) revised depositional model showing multiple source areas wrapping around the eastern side (present-day geography) of a large deepwater basin. Shallow marine and coastal plain sediments (including coals) in the Lurah Formation (a correlative of the Crocker Formation; Fig. 7a and Fig. 7d) indicate source areas to the east, which is supported by the near ubiquitous presence (75% of the 40 samples) of minor amounts of chrome-spinel (supplementary material of van Hattum et al., 2006). Galin et al. (2017) show the Rajang Fan as a different system than the Crocker Fan (Fig. 9b). The Rajang Group sandstones are richer in tourmaline (27% tourmaline) than the Crocker Formation (19% tourmaline), but are relatively impoverished in chrome spinel (present in only 25% of the samples). Eocene-age deepwater sediments also occur in the rift basins of offshore Palawan, and crop out on southern Palawan as the Panas Formation (which was derived from the Northern Conjugate Margin, NCM; Cao et al., 2020; Shao et al., 2017; Suzuki et al., 2000). Although much work remains to be undertaken, it is clear that a large Latest Cretaceous to Eocene-age deepwater embayment developed on the Luconia Block following its accretion to the Indochina Domain and NCM (Fig. 9b).

Unit 2 of the Northwest Borneo domain is represented by a set of Neogene to Recent sedimentary basins that are filled with more than 4 km of largely shallow marine and coastal plain sediments derived from the uplifted and strongly deformed Unit 1 deepwater clastic rocks. These basins extend from onshore, across the present-day shelf, to well beyond the 200 m isobath into bathyal water depths (Fig. 9a). The shelf areas are characterised by growth faulting, whereas the slope and deepwater areas are deformed by down-dip, toe thrust anticlines and detached folds. There is a progressive 180° swing in the sense of vergence in the deepwater fold-thrust belts that wrap around three sides of the island (Fig. 2), indicating that most of the deformation is not tectonically driven but represents a gravity-driven system balanced by up-dip extension. The exception to this generalisation is north-western Sabah (the Miocene thrust sheet of Hazebroek and Tan, 1993, and Domain D of Cullen, 2010) where down-dip contraction exceeds up-dip extension by more than 4 km (Hesse et al., 2009). The Baram Basin, estimated to have more than 10 km of Neogene sediment (Morley and Back, 2008), has strongly aggradational clastic depositional systems, with the shelf edge prograding about 100 km in 10 Myr. Here, high sedimentation rates are balanced by high subsidence rates, a circumstance that can be attributed to isostatic sediment loading on the weak, low elastic thickness, GDG crust (Cullen, 2014, 2010); as documented on the NCM (Clift et al., 2002).

Hall and Nichols (2002) estimated that an average of 6 km of overburden has been removed from the central highlands since the end of the Oligocene, with observable effects on isostatic rebound, further uplift, and deeper incision by drainage networks. They attribute the high denudation rates (300 m/Myr) to the high annual rainfall characteristic of the tropics. The central highlands are outlined by the 1000 m topographic contour and have six peaks with > 2000 m elevation (Fig. 9a), and are characterised by a rugged topography formed by multiple deeply incised drainage networks with deep valley floors (Fig. 10).

Unit 3 represents Eocene to Pleistocene igneous activity. However, individual bodies are volumetrically small, compositionally varied, widespread but sparsely distributed, and lack a strong spatial pattern (Fig. 9a). Arc-like adakitic and andesitic igneous rocks of the Sintang Suite in Sarawak (Prouteau et al., 2001) and on the Semporna peninsula (Macpherson et al., 2010) reflect melting of previously modified subcontinental lithosphere (Breitfeld et al., 2019), and so are not direct products of subduction produced andesitic magmas (SPAMs). This observation is consistent with basalt trace element geochemistry, which indicates an intra-plate setting for Cenozoic magmatism in the greater SCS region (Fig. 5). Even the prominent Mt Kinabalu granitic intrusion, commonly attributed to crustal melting in an arc or lithospheric delamination setting (Pilia et al., in review; Vogt and Flower, 1989), is an extensional low-degree mantle melt; albeit a melt that has assimilated sedimentary crust during ascent and emplacement (Burton-Johnson et al., 2019a,b). Its topographic prominence attracts a tendency to draw tectonic cross sections through the ~ 12 km wide intrusion (e.g. Hall, 2013; Hutchison, 2000; Pilia et al., in review). However, this over emphasises what is an anomalous and isolated, small volume magmatic event.

2.5.3. Palawan continental Terrane (PCT)

The concept of the Palawan Continental Terrane (PCT) dates to Holloway's (1982) recognition that the southwest Philippines (Reed Bank, northern Palawan and Mindoro) were part of Cathaysia prior to rifting and opening of the SCS. On the basis of the detrital modes and chemistry of the sandstones in the Eocene to Cretaceous Babuyan River Turbidites, Suzuki et al. (2000) included

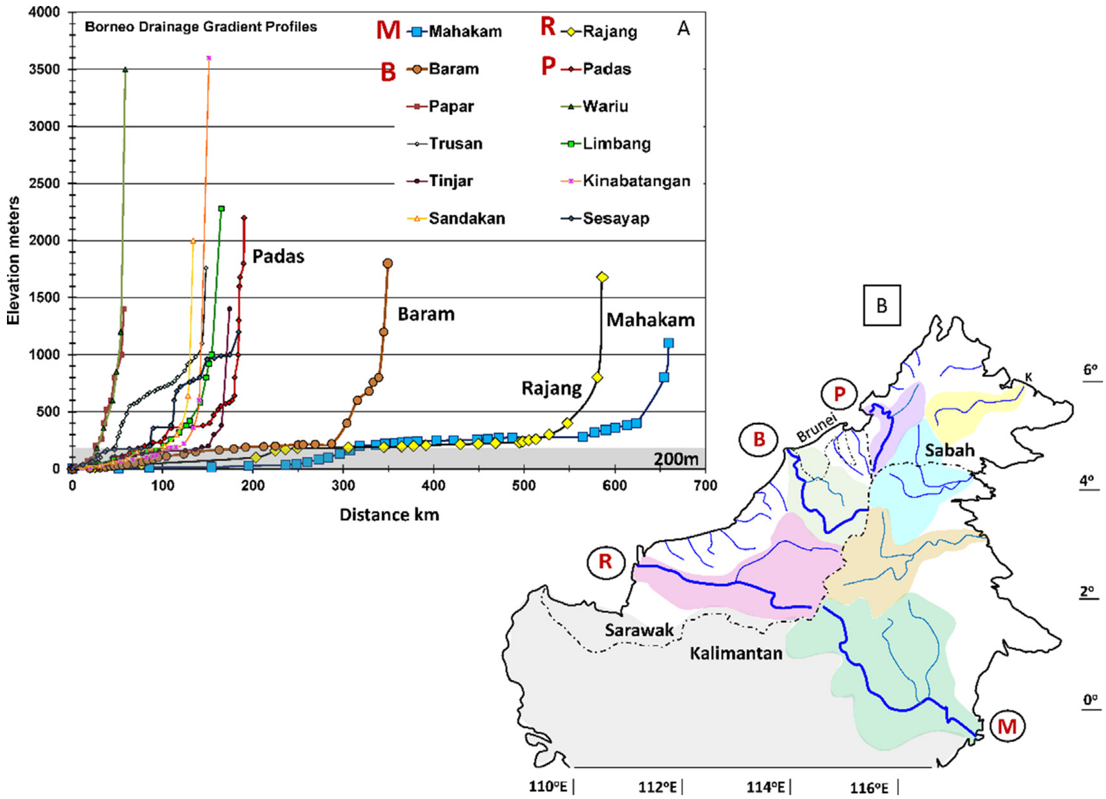

Fig. 10. Drainage gradient profiles for rivers in NW Borneo. These were constructed by measuring elevation above mean sea level along the path of each drainage. b) Lightly shaded polygons depict the catchment areas for the 4 major rivers (Rajang, Baram, Padas, Mahakam) in heavy blue lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

all of Palawan in the PCT. However, because that study did not include samples south of the Ulugan Bay Fault, the argument for treating Palawan as a single block is inconclusive. Utilising sedimentary rock major element geochemistry, Dimalanta and Yumul (2013) not only showed all of Palawan as part of the PCT, but also expanded the PCT to include part of Sabah and what is now the Sulu Archipelago. Suggate et al. (2014) confirm a southern China provenance for Eocene sandstones from northern Palawan, but were only able to sample the Miocene section from southern Palawan. Subsequent to these studies, Shao et al. (2017) and Cao et al. (2020) concluded that the deepwater sandstones from the Eocene-age Panas Formation on southern Palawan and the Lasala Formation on Mindoro have heavy mineral assemblages and detrital zircon ages consistent with a South China Provenance (the Northern Conjugate Margin).

Deepwater turbidite sandstones of the Panas Formation unconformably overlie the Cretaceous-age South Palawan Ophiolite, similar to the Cretaceous–Eocene tectonostratigraphic Unit 1 in northern Sabah (Rhamat et al., 2020; Jasin and Tongkul, 2013) and on intervening small islands. A pronounced Bouguer gravity high is associated with these Cretaceous–Eocene units and supports linking South Palawan with northern Sabah (Fig. 7b; Cullen, 2010), as shown by Wakita and Metcalfe (2005). The PCT and northern Sabah share a similar Cretaceous–Eocene lithostratigraphy, and both record large amount of CCW rotation, as does the Celebes Sea (Fig. 7a). Thus, the preponderance of evidence favours treating northwest Borneo and the PCT as a relatively coherent tectonic block with a probable structural contact along the Balambac Fault Zone (Fig. 7a and 7b). Although the history of the suturing of Luconia, Greater Dangerous Grounds, and the Palawan Continental Terrane is not fully resolved, our view of a large, relatively coherent tectonic block is consistent with the interpretation of Jamaludin et al. (2021). They interpreted long-wavelength E-W regional aeromagnetic anomalies in Luconia as reflecting deep crustal structural features related to amalgamation of the Luconia crustal block and the southern boundary of the Palawan block.

Deformation, metamorphism, stratigraphic relationships, and magmatism in the central Philippine Mobile Belt (PMB) indicate collision of the PCT with the PMB in the Early Miocene (Dimalanta et al., 2009; Yumul et al., 2009), contemporaneous with the Miocene deformation in NW Borneo (the "Sabah Orogeny"; Hutchison, 1996).

2.6. Philippine Mobile Belt (PMB)

The Philippine Mobile Belt (PMB) incorporates the Philippine archipelago east of the Manila and Negros Trenches, and west of the Philippine Trench, bounding the belt with oppositely-dipping subduction systems. The PMB remains volcanically and seismically active. Multiple parautochthonous ophiolite sequences (ultramafic rocks, gabbros, dykes, pillow lavas, and a volcaniclastic–sedimentary cover) were emplaced from the Jurassic to Oligocene (Cretaceous ages being the most extensive) in episodic back-arc, forearc, and intra-arc supra-subduction zone extensional settings, generally younging from the east to the west (Encarnación, 2004; Yumul, 2007; Yumul et al., 2020). The ophiolites are pre-dated by Permian to Jurassic accretionary complexes SW of Mindoro (Zamoras and Matsuoka, 2004, 2001), and post-dated by Cenozoic volcanic, carbonate, and clastic rocks (Rangin, 1991).

Geochronology, geochemistry, and lithological similarities correlate the Cretaceous magmatism with rocks in Indochina, northern Palawan, and the South China margin (Faure et al., 1989; Gong et al., 2021; Yumul et al., 2004), despite Mesozoic and Cenozoic paleomagnetic data indicating a more southerly, equatorial origin for the PMB (McCabe et al., 1987; Queano et al., 2007).

The Cathaysian affinity of north Palawan and the correlation of chaotic Jurassic-Cretaceous mass transport deposits (olistostromes) between north Palawan and the PMB (Mindoro, Tablas, Romblon, Sibuyan, and Carabao islands) led Faure et al. (1989) to correlate the PMB with Cathaysia. Similarly, Yumul et al. (2004) noted the geochemically continental affinity of the Zamboanga Peninsula (the PMB presently adjacent to the Sulu Archipelago; Tamayo et al., 2000) and correlate metamorphic, and ophiolitic suites to link the PMB with Cathaysia via Palawan; albeit with the Zamboanga Peninsula representing an oceanward continuation of the continental shelf environment recorded by the Palawan carbonates. Gong et al. (2021) found abundant Permian-Triassic zircon xenocrysts in Cretaceous, Eocene, and Miocene arc volcaniclastic rocks from Cebu and Bohol Islands (PMB), with Hf isotope chemistry supporting the presence of a continental granitic basement (or its eroded products) within the PMB. The age distribution correlates with geochronological data from eastern Indochina, but not New Guinea or Sulawesi, indicating an Asian origin for the PMB rather than the Australian margin (from where New Guinea and the Sula Spur of Sulawesi rifted in the Mesozoic; Hall, 2012).

3. Summary of SCS tectonic models

Various authors have synthesised and discussed the competing models for SCS opening (e.g. Cullen et al., 2010; Sun, 2016; Zhang et al., 2020). The following are the five primary hypotheses (Fig. 3).

3.1. Backarc spreading

It has been proposed that the SCS opened via extension in the overriding plate in a supra-subduction zone setting, in response to either northward subduction of the Indo-Australian Plate (Hilde et al., 1977; Mai et al., 2018; Stern and Bloomer, 1992; Sun, 2016), or westward subduction of the Pacific and Philippine Sea Plates (Karig, 1971; Li et al., 2012; Schellart and Lister, 2005). In the latter scenario, SCS extension was a continuation of extension on the South China continental margin, where backarc strain during slab retreat is the accepted driving mechanism (Li et al., 2012; Northrup et al., 1995; Zhou et al., 2006).

3.2. Extrusion

In the extrusion model for SCS opening, the India-Eurasia continental collision extruded the Indochina Peninsula via > 700 km of sinistral strike-slip displacement along the Red River-Ailao Shan fault (Leloup et al., 1995; Tapponnier et al., 1990). Initial ages placed this displacement at $\sim$ 35–17 Ma (Leloup et al., 1993); approximately contemporaneous with earlier estimates of the SCS spreading ages (32–15.5 Ma; Briais et al., 1993). In this model, the Red River-Ailao Shan fault terminated as a rift (akin to a transform fault), which developed into the SCS spreading centre and accommodated the strike-slip displacement. The extrusion model for SCS opening was based on physical modelling experiments (Briais et al., 1993; Tapponnier, 1982; Tapponnier et al., 1990), as well as structural data from the fault, and apparent synchronicity between the fault movement and SCS spreading. These experiments also showed how SCS spreading would cease as the Red River-Ailao Shan fault was overtaken by India, migrating active extrusion tectonics northwards (Tapponnier, 1982).

3.3. Slab-pull from Proto-SCS subduction

Currently the most broadly accepted hypothesis is that the SCS opened through slab-pull during subduction of older ocean crust (the Proto-South China Sea, PSCS). The subduction driven model (Hall, 2017, 2002, 1996; Holloway, 1982; Taylor and Hayes, 1983, 1980) invokes the complete southward subduction of a PSCS beneath Borneo and Palawan during the Eocene to Miocene. In this model, eastward subduction of the PSCS (outboard Luconia Block, section 2.5) was forcefully initiated by counter-clockwise rotation of Borneo, driven by the arc-continent collision of the Australian margin with the Philippine Sea plate. Once subduction was established, the slab-pull force on the down-going plate drove extension and rifting of the attenuated continental crust to the north (similar to the subduction-driven extension along intra-oceanic Pacific ridges). The continuing arc-continent collision of Australia and Indonesia drove further counter-clockwise rotation of Borneo, until its Miocene collision with the attenuated continental crust of the Dangerous Grounds, at which point subduction and consequent spreading of the SCS ceased (Fig. 3c). The past existence of a PSCS was first proposed as an interpretation of the stratigraphic relationships in the "NW Borneo Geosyncline" (Haile, 1968), and subsequently supported by paleomagnetic data from NW Borneo indicating that Borneo underwent $\sim 45^{\circ}$ counter-clockwise rotation since $\sim$ 50 Ma (Advokaat et al., 2018; Fuller et al., 1999). Rotating Borneo about a point close to its northwest corner meets this paleomagnetic constraint (Hall, 1996), requiring subduction of a PSCS to bring Borneo to its present position.

A variant of this model has been proposed involving double-sided subduction (Wu and Suppe, 2018, refined in Lin et al., 2020), with the PSCS subducting beneath Palawan and the southern SCS conjugate margin in the north as well as beneath Borneo in the south (Fig. 3d). This hypothesis was based on seismic tomography models showing slab-like low velocity anomalies beneath the SCS at 450–700 km depth as well as beneath Borneo.

Hybrid models have been also proposed, in which SCS extension via slab pull from subduction of a PSCS of variable proposed width is supported by strike-slip faulting, either from extrusion along the Red River-Ailao Shan fault (Cullen, 2010; Wang et al., 2021), or via transtension during oblique subduction of the oceanic crust to the east (Huang et al., 2019).

3.4. Mantle plume

Various examples of continental rifting have been attributed to the upwelling of mantle plumes (e.g. Storey, 1995). Multiple potential hotspots were initially proposed under SE Asia (Burke and Wilson, 1976), and isotopic data identified the extensive basaltic lavas of Hainan island (post-dating SCS spreading) as enriched OIB-type magmatism (Ocean Island Basalts; Tu et al., 1991). In the absence of geophysical evidence for a deep source, the OIB magmatism was initially attributed to a shallow source in entrapped subcontinental mantle (Tu et al., 1991), upper mantle convection (Smith, 1998), or mantle extrusion associated with the India-Asia collision (Flower et al., 1998). Identification of a low velocity seismic zone under the SCS, extending to at least the lower transition zone (Lebedev and Nolet, 2003) or lower mantle (Montelli et al., 2006) under Hainan, supported the presence of a deep-mantle plume. It was consequently proposed that, given the coincidence of crustal extension and the local arrival of a mantle plume, SCS extension was driven by upwelling divergent mantle flow (Fig. 3e; Chen et al., 2017); similar to that proposed in the north Atlantic.

4. Problems with the existing models.

4.1. Backarc spreading

Backarc extension of the SCS in response to westward subduction of the Philippine Sea Plate is not compatible with the NNW-

SSE extension direction of the SCS (Sun, 2016). The alternative proposal of extension in response to Indo-Australian Plate subduction originally proposed SCS extension commenced at ~ 100 Ma (Stern and Bloomer, 1992), far earlier than the Oligocene seafloor spreading of the SCS, so the backarc extension model was subsequently refined (Mai et al., 2018; Sun, 2016). However, given Eocene backarc extension began opening the Java Sea ~ 400 km from the Sunda Trench, the backarc extension model does not explain why SCS rifting occurred so distal to the trench. This is particularly questionable given that other backarc basins of East Asia (e.g. the Andaman Sea, South Java Basin, East China Sea, and the Sea of Japan) occur ~ 100–800 km from the trench, yet during rifting the SCS ridge was over 2000 km from the Sunda Trench.

4.2. Extrusion

Implicit in the extrusion model for opening the SCS is the clockwise (CW) rotation of Borneo, which is at odds with paleomagnetic data that indicate ~ 35° counter-clockwise (CCW) rotation from the Eocene to Early Miocene (Advokaat et al., 2018; Fuller et al., 1999). Kinematically, the extrusion model requires a geometry whereby the Ailao Shan-Red River Fault (ASRRF) extends offshore to link with series of faults (including the East Vietnam and West Baram Faults) that pull the Southern Conjugate Margin (SCM) away from the Northern Conjugate Margin (NCM) as Borneo rotates CW. Regional industrial seismic coverage over these faults does not support such linkages. Moreover, linking the left-lateral ASRRF with the East Vietnam Fault would result in a major restraining bend and substantial shortening. Some shortening has been documented: basement-involved thrusting in the Cuu Long Basin (Cuong and Warren, 2009) and partly inverted Eocene rifts in the Kutai Basin (Cloke et al., 1999) and on the Dangerous Grounds (Supplement_1 Fig. S1d). However, the amount of shortening appears insufficient to add up to the hundreds of kilometres of shortening implicit in the extrusion model. Lastly, the extrusion model proposes that the ASRR Fault opens the SCS via its termination at the SCS spreading ridge. If so, this would predict initial and maximum extension in the western extent of the basin. Instead, seafloor spreading initiated and reached its maximum extent at the eastern end of the SCS, propagating westward later.

Although the extrusion model for SCS opening originated from physical modelling experiments (Briais et al., 1993; Tapponnier, 1982; Tapponnier et al., 1990), the effect of extrusion in analogue modelling is dependent on the boundary conditions imposed. Recent modelling of India's collision coupled with slab roll back does not generate SCS extension via the India-Asia collision alone, requiring slab rollback from Sunda and Western Pacific subduction (Schellart et al., 2019).

A core tenant of the extrusion model is synchronicity of initial SCS spreading and motion along the Ailao Shan-Red River Fault (ASRRF). Updated age constraints place the timing of seafloor spreading at 33–16 Ma (Li et al., 2014), whilst the initiation of ASRRF displacement was approximately 36 Ma (Liang et al., 2007). We contend that this timeline is debatable. Although the present-day eastern boundary of the SCS follows the Manila Trench (Section 2.3), this does not consider the subducted portion of the SCS lithosphere. After geometric restoration of the high-velocity seismic anomaly representing the SCS slab beneath the Manila Trench, Wu and Suppe (2018) estimated that 400–500 km of lithosphere has been subducted, and that the SCS slab extends further to the north and south than the present extent of the Manila Trench (Fig. 2). Given its initial north to south spreading direction, parallel to Eocene extension on the Northern Continental Margin (Deng et al., 2020), the additional lateral extent on either side of the subducted SCS spreading centre (ca. 300 km north and 300 km south) requires that the subducted lithosphere is older than that lithosphere presently at the trench. Applying a half spreading rate of 2.8 cm/y for this older phase of sea floor spreading (Barckhausen et al., 2014) yields a Middle Eocene (~41.9 Ma) estimate for the onset of SCS seafloor spreading. Although this predates onset of ASRRF motion, our estimated initial SCS spreading age has a wide uncertainty. Direct linkage of these two events implies nearly instantaneous propagation of the ASRRF. Whilst we acknowledge there is uncertainty of our estimate, we note that it resembles the onset of CCW rotation of Borneo at 41.7 Ma (Advokaat et al., 2018). Moreover, we note coincidence with the Eocene global reorganization of plate motions documented by the bend in the Hawaii-Emperor Seamount chain (47.4 ± 1.0 Ma), the smooth-rough transition along the Carlsberg Ridge (associated with onset of the collision of India with Eurasia), and the onset of rapid divergence of South America and Australia from Antarctica (Gaastra and Gordon, 2021; Whittaker et al., 2007). This indicates a possible association of initial SCS spreading with the global plate reorganisation event.

4.3. Slab-pull from Proto-SCS subduction

The PSCS, slab-pull model does not explain why Eocene PSCS subduction postdates some areas of rifting, and why during early PSCS subduction, when slab-pull force would be limited, there was a rapid transition from SCS rifting to breakup (Ding et al., 2020; Larsen et al., 2018). The proposed PSCS-Borneo subduction zone also lacks an associated Eocene–Miocene volcanic arc. Contemporaneous arc magmatism is absent from Sabah (north Borneo), and the sparse Neogene magmatism of Sarawak (west Borneo) was derived by remelting of existing hydrous mafic rocks driven by intraplate processes (Bergman et al., 1988; Breitfeld et al., 2019). Evidence in SE Asia for the high pressure, low temperature rocks associated with subduction zones is also ambiguous (Hall and Breitfeld, 2017).

As with the extrusion model, eastward slab-pull of the PSCS does not account for Eocene to Early Oligocene north–south extension and sea floor spreading, ridge re-orientation, and ridge jumps during the SCS spreading history. Additionally, if South China remains stationary, then SW propagation of the SCS ridge tip requires the PSCS to rotate CW with the SCS spreading centre. This would produce: 1) progressive NE to SW collision of the Dangerous Grounds (Fig. 11), inconsistent with plate reconstructions that indicate that triple junction migration and deformation of Sabah and Palawan proceeded from SW to NE (Aurelio et al., 2014; Hall, 2002; Yumul et al., 2009; Zahirovic et al., 2014); and 2) compression along the Northern Conjugate Margin (South China) or right-lateral strike slip faults in the SWCM contemporaneous with SCS spreading (Fig. 11).

Lin et al., (2020) geodynamically modelled the predicted Vp tomography from single-sided and double-sided PSCS subduction (Fig. 12a–b) and compared these models with four different tomographic models of observed seismicity (Fig. 12c–f). However, the geodynamic models do not reproduce the regional seismic tomography models. Single-sided PSCS subduction reproduces the ~ 400–1,000 km depth high velocity anomalies beneath Borneo, but results in higher than observed shallow (<400 km) low velocities beneath Borneo, and fails to reproduce the 400–1000 km high velocity anomalies beneath the SCS (Fig. 12c–f). Although double-sided subduction, with simultaneous PSCS subduction beneath Borneo and South China, has a better statistical fit (Lin et al., 2020), there is scant geological evidence to support the model. Moreover, the convergent setting this would require on the Palawan Continental Terrane (adjacent to a northern subduction zone) is inconsistent with its observed Eocene and Oligocene strata (Zhang et al., 2020).

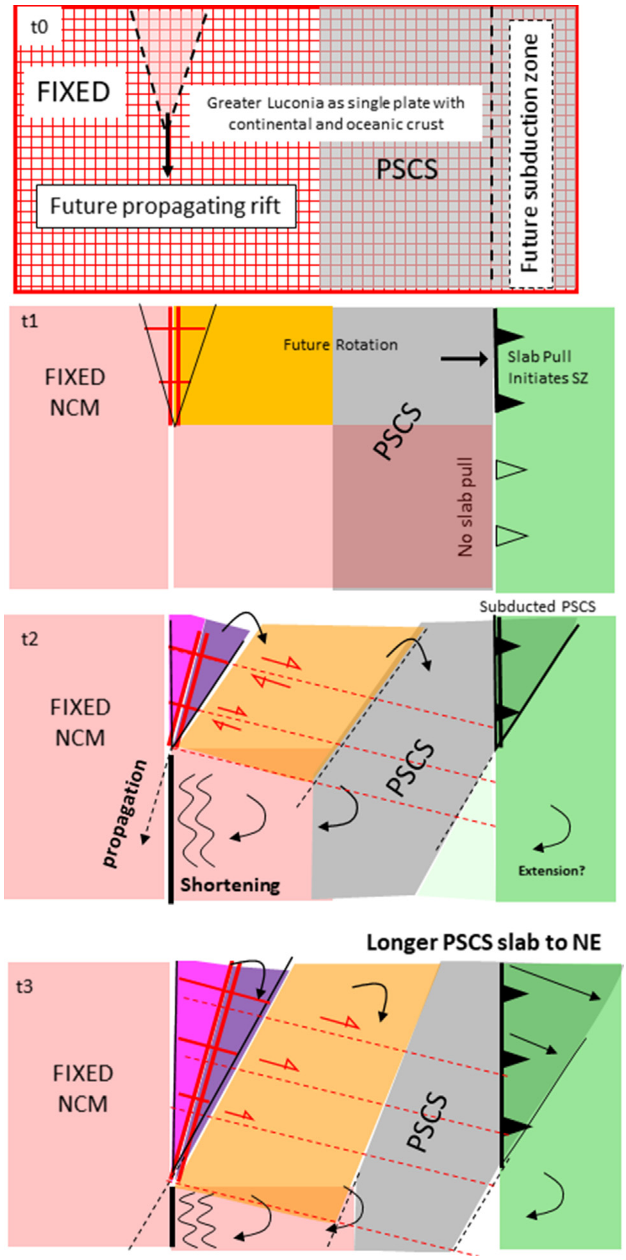

Fig. 11. Illustration of the kinematic implications of SCS opening via PSCS subduction. Without CCW rotation of the Northern Conjugate Margin (Fixed NCM), then the SCS spreading center must rotate CW with PSCS or have through-going right-lateral strike slip faults extending from the SCS transform faults. Also note the crustal shortening required west of the propagating SCS tip.

Proposing PSCS subduction and slab-pull as the driver for SCS spreading requires rotation and SCS spreading to be synchronous, as is shown by Hall (2009). However, although early data indicated that ~ 50° CCW rotation of Borneo occurred between ~ 30–10 Ma (Fuller et al., 1999), an updated data compilation (including new data from Kalimantan) indicates instead that ~ 35° CCW rotation occurred in the Eocene–Oligocene between 50 and 30 Ma, preceding SCS spreading, and that only minor (~10°) CCW rotation occurred since the Early Miocene (Advokaat et al., 2018). If rotation and consequent PSCS subduction occurred prior to SCS spreading, this precludes slab pull as the geodynamic mechanism for SCS extension.

Additional considerations also favour the proposed earlier rotation of Borneo: 1) An earlier rotation yields a good fit to the apparent polar wander path (Advokaat et al., 2018). 2) The Eocene–Oligocene CCW rotation of Borneo is consistent with Eocene–Oligocene CCW rotation (~60°) of the Cretaceous-age Espina Basalt of the Palawan ophiolite (Almasco et al., 2000), CCW rotation of the Celebes Sea (Shibuya et al., 1991), and CCW rotation of Cretaceous sediments of Cebu in the Philippine Mobile Belt (McCabe et al., 1987). 3) Red mudrocks of the Crocker Formation (N = 3; Fuller et al., 1991) near Kota Kinabalu carry a primary magnetic signal showing a strong CCW rotation (73.9° / σ 11.3°) that is similar to Palawan and the Celebes Sea (Fig. 7a). 4) An earlier period of rotation accounts for the earliest episode of deformation in northern Sabah (Tongkul, 1994), and development of the major Late Eocene unconformity (Fig. 7d), which we attribute to the broader extent of the Sarawak Orogeny. And finally, 5) An isopach of Oligocene–Early Miocene sediments overlying the West Baram Line do not show significant offset (Cullen, 2014), which requires a pre-Oligocene age for the West Baram Line. An Eocene age for deformation along the West Baram Line, possibly during the Sarawak Orogeny, is a plausible interpretation.

Although the PSCS model explains the ~ 45° CCW rotation of Borneo, it fails to explain the evidence for ~ 15° CW rotation of North Borneo since remagnetisation of the Crocker sandstones (15–35 Ma, see Section 4.3.1; Cullen et al., 2012), or the ~ 16° southward paleomagnetic migration of Borneo since 50 Ma (Advokaat et al., 2018). Rotation about a pole NW of west Borneo requires ~ 320 km of shortening between Borneo and Indochina (Fig. 11; Advokaat et al., 2018). With little evidence for shortening of this magnitude in this region (Section 4.2); ambiguous and diffuse regional shortening has to be invoked (Advokaat et al., 2018; Hall, 2002). Given the large area with relatively ductile crust, distributing some regional shortening via penetrative stain is likely, but again it is the magnitude that becomes difficult to reconcile.

The slab-pull model proposes that Palawan and Borneo originated on opposing margins of the PSCS. However, a prominent Bouguer gravity high can be traced between Palawan and northern Sabah (Fig. 7b; Cullen, 2010). This suggests that the underlying geology is one coherent body, and correlates the Cretaceous ophiolites of northern Sabah (Jasin and Tongkul, 2013; Rehmat et al., 2020) with those of the southern Palawan ophiolite (as proposed by Rangin et al., 1990, and Schlüter et al., 1996). The implication is that since their Cretaceous emplacement, the ophiolites of northern Sabah and southern Palawan have a common kinematic history, thus favouring extending the Palawan Continental terrane into northern Sabah (Dimalanta and Yumul, 2013).

The Eocene–Miocene sandstones of the Crocker Formation (Sabah) were derived predominantly from the continental crust of the Schwaner Mountains (SW Borneo) and the Malay Peninsula (van Hattum et al., 2013). However, older sediments are more ambiguous. The Triassic zircons of Borneo's extensive Cretaceous–Eocene Rajang Group only have a minor constituent of the brown zircons diagnostic of the Malay Peninsula "Tin Belt" granites. SE China is a potential alternative source, only disregarded due to the distance between SE China and Borneo in the PSCS model (Galin et al., 2017). Prominent ~ 1.8 Ga detrital zircon populations in the Triassic Sadong Formation (Sarawak) also imply a South China source, requiring more complex models of allochthonous blocks moving between China and Sundaland to be invoked (Breitfeld et al., 2017). However, similar Proterozoic detrital zircon ages in the Palawan continental terrane supported the development of Palawan on the South China margin (Fig. 13; Cao et al., 2020).

4.3.1. Neogene rotation history of Borneo

The issue of Late Oligocene–Early Miocene rotation is not fully resolved. Advokaat et al. (2018) budget only ~ 10° CCW rotation since the Early Miocene and interpret an average of 5.4°CW

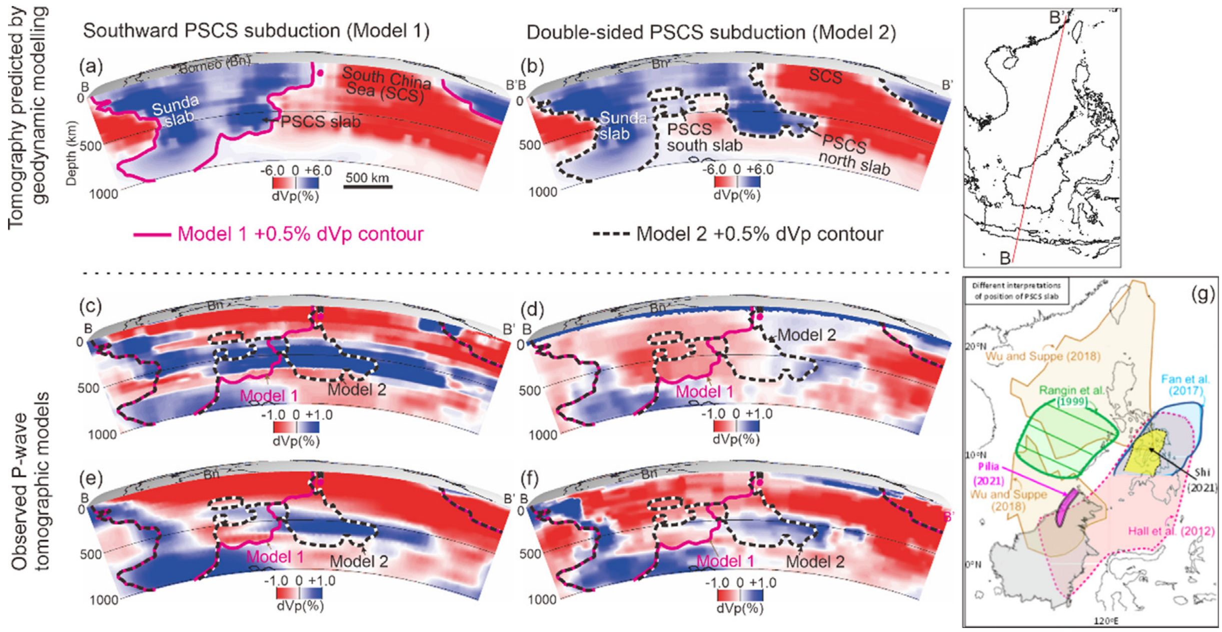

Fig. 12. Adapted from Lin et al. (2020). Comparison of seismic tomography models of the SCS mantle (c–f) with tomographic models predicted by geodynamic modelling of single-sided (a, Model 1) and double-sided (b, Model 2) PSCS subduction. + 0.5% dVp (P-wave velocity) contour from both geodynamic models overlain on each seismic tomography model. Global P-wave seismic tomography models from (c) LLNL-G3D-JPS (Simmons et al., 2015), (d) MITP08 (Li et al., 2008), (e) GAP_P4 (Fukao and Obayashi, 2013), and (f) UU-P07 (Amaru, 2007). Note the extensive high velocity anomaly at 400–700 km depth and the low velocity anomaly at shallower depths underlying Borneo and the SCS (Fig. 17b–d), neither of which is predicted by the geodynamic models (particularly single-sided subduction). Inset figure at lower right (g) shows different interpretations of the current position of the subducted proto-South China Sea slab (Fan et al., 2017; Hall, 2012; Pilia et al., in review; Rangin et al., 1999; Shi et al., 2021; Wu and Suppe, 2018).

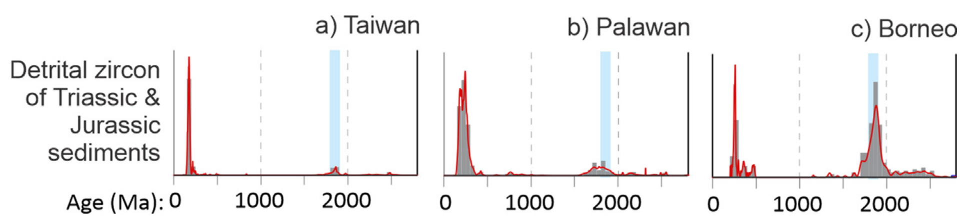

Fig. 13. Detrital U-Pb zircon ages from Triassic and Jurassic sedimentary rocks on the opposing margins of the SCS. The highlighted the ~ 1.7–1.8 Ga Proterozoic ages were used to support the development of Palawan (b) on the South China margin (a) (Cao et al., 2020). The prominent Proterozoic peak in the Triassic Sadong Formation (c) of Sarawak (NW Borneo) indicates the same argument applies to Borneo. PRMB – Pearl River Mouth Basin. Data from Breitfeld et al. (2017) and Cao et al. (2020).

rotation from four sites (N = 60 of 400 samples) in a 4 km section of Middle Miocene sandstones from Samarinda, Kalimantan, as "showing no significant rotation has occurred in the Samarinda area since ~ 17 Ma." The individual Samarinda sites, however, record discrete CW and CCW rotations that appear to be bimodal (Fig. 14a), which suggests there may be unaccounted local deformation.

Middle to Late Miocene remagnetisation and CW rotation of the Late Eocene Crocker Formation sandstones in the area of Kota Kinabalu, Sabah, (Cullen et al., 2012; see also Supplement_2) is an important dataset to consider regarding Borneo's rotation history. In their compilation, Advokaat et al. (2018) dismissed these data noting the wide range of inclinations (-84.5° to + 48.7°), but erroneously cited the structurally corrected data and thus missed the key point: the Crocker sandstones were remagnetised after most deformation occurred. Moreover, data from a parasitic fold on the eastern limb of the Bukit Sepanger anticline shows the Crocker sandstones were remagnetised prior to the Middle Miocene, not to the modern field as suggested by Fuller et al. (1999). We have high-graded the data reported by Cullen et al. (2012) by accepting only sites with more than four cores, and that have at least 50% of those cores carrying a ChRM signal. We also excluded three additional sites (Fig. 14b): 1) the Kudat site is a single, isolated, location within the Balabac fault zone of deformation; 2) and 3) the Tenom and Keningau Valley sites may have been affected by younger normal faults and offset of the Tenom and Keningau valleys during related gravitational collapse of the Crocker-Trusmadi anticlinorium (Menier et al., 2017; Tongkul, 2017). Lastly, we treat the Nexus (NX), Kota Kinabalu Industrial (KI), and Bukit Sepanger (BS) sites as single sites rather than a composite site. The NX, KI, and BS sites cover a distance (Fig. 14b and Fig. 14c) comparable to the previously discussed Samarinda sites (Advokaat et al., 2018). The high-graded in-situ data (Table 1) have much lower range of inclinations (-11.4° to 22.3° with a mean = 5.16° and σ = 5.4°). The resulting robust dataset comprises 6 sites with 87 cores having a valid ChRM signal, covers more than 1500 km^2, and shows an average of 13.5°CW rotation with a low standard deviation of 8.8°.

4.4. Mantle plume

Although the arrival of a mantle plume has been attributed to continental rifts elsewhere, the ability for plumes to progress continental rifting into complete breakup is debatable (Niu, 2020).

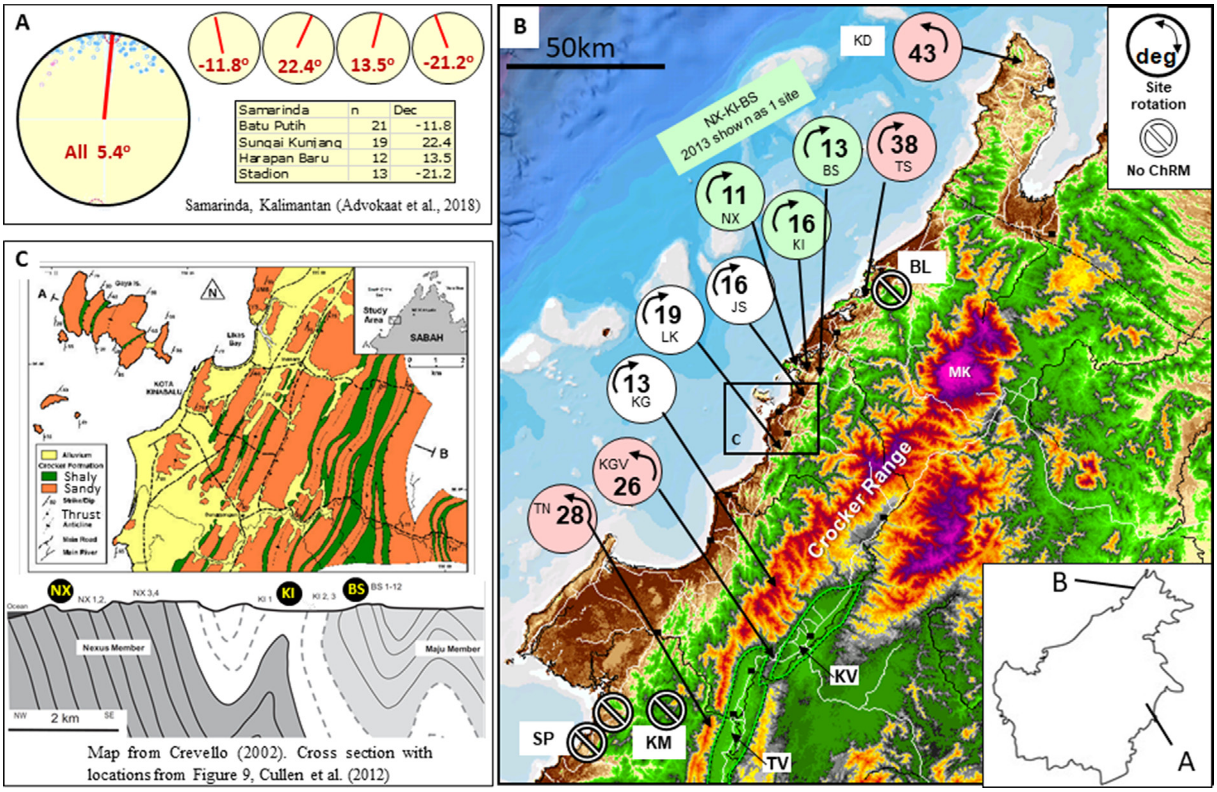

Fig. 14. Neogene paleomagnetic data of Borneo. a) Bimodal orientations of the Middle Miocene sandstones of Samarinda, Kalimantan (Advokaat et al., 2018). b) Revised paleomagnetic data of the Crocker sandstones, Sabah, which were remagnetised prior to the Middle Miocene. c) Structural relationship of the Nexus (NX), Kota Kinabalu Industrial (KI), and Bukit Sepanger (BS) sites, now treated as single sites rather than a composite site.

Table 1
High-graded paleomagnetic data, revised from Cullen et al. (2012) by accepting only sites with more than four cores, that have at least 50% of those cores carrying a ChRM signal, and excluding three sites of structural ambiguity (see text).

Site	Formation	Lat. N	Long. E	Strike	Dip	In-Situ Dec	In-Situ Inc	In-Situ a95	N/N0	N/N0 %
JS1	Crocker	6.0381	116.1417	199	94	15.6	−0.4	19.3	5/6	83%
LK1	Crocker	5.8339	116.0433	5	71	19	13.9	14.8	4/5	80%
NX1	Crocker	6.1048	116.1341	55	85	10.9	13	7.9	7/8	88%
NX2	Crocker	6.1150	116.1170	47	66	11.4	2.5	9.2	6/6	100%
KI1	Crocker	6.0829	116.1600	35	100	16.7	5	16.4	4/6	67%
KI2	Crocker	6.0805	116.1576	237	88	0.4	−5.7	8.9	4/6	67%
KI3	Crocker	6.0805	116.1576	237	88	31.2	−0.6	13.9	4/6	67%
BS1	Crocker	6.0670	116.1549	35	58	3.5	13.9	15.5	5/8	63%
BS2	Crocker	6.0670	116.1549	35	58	9.7	5.5	14.3	4/7	57%
BS3	Crocker	6.0670	116.1549	27	66	19.4	9.2	10.7	4/7	57%
BS5	Crocker	6.0670	116.1549	30	58	8.8	−2.8	15.4	4/4	100%
BS6	Crocker	6.0670	116.1549	30	58	3.1	2.6	15.3	4/4	100%
BS7	Crocker	6.0667	116.1563	31	86	11.8	18.4	18.4	4/5	80%
BS8	Crocker	6.0667	116.1563	31	86	3.2	16.3	11.5	4/5	80%
BS9	Crocker	6.0667	116.1563	46	129	24	−9.5	18.9	4/6	67%
BS10	Crocker	6.0667	116.1563	44	133	12.8	−9.1	12.5	5/7	71%
BS11	Crocker	6.0667	116.1563	45	124	30	−11.4	15.4	4/6	67%
KG1	Crocker	5.4381	116.1061	25	45	19.2	13.1	16.3	6/8	75%
KG2	Crocker	5.4381	116.1061	25	45	6.2	22.3	16	5/8	63%
					Mean	13.5	5.1			
					StDev	8.8	10.1			

Although the post-spreading seamounts of the SCS have an OIB chemistry, the initial seafloor magmatism of the SCS have MORB chemistries from a depleted mantle source (Yu et al., 2018). The initial MORB magmas have calculated melting temperatures (~1380 °C) similar to those of global MORB, and lower than those of the Iceland or Hawaii hotspots (1558 ± 32 °C and ~ 1530 °C respectively; Yu and Liu, 2020). This indicates there was no plume-related thermal anomaly when SCS rifting began.

Rather than commencing contemporaneously with the opening of the SCS or the initiation of Hainan magmatism, OIB magmatism is prevalent across SE Asia and China through the Cenozoic and Mesozoic; mostly post-dating SCS rifting (Fig. 5; Tu et al., 1992; Yan et al., 2008). However, this magmatism is in relatively small volumes rather than the LIP magmatism associated with the arrival of a plume, and is not the source for the seafloor basalts of the SCS. These widespread OIB signatures led Burke and Wilson (1976) to propose multiple hotspots, although the mantle density distribution this implies would contradict the geoid distribution (Smith, 1998). It should also be noted that whilst the deeper (200 km to at least 600 km) mantle thermal anomaly underlies Hainan, the most prominent upper mantle (<100 km) thermal anomaly underlies Borneo; ~2000 km south of the proposed plume location (Lebedev and Nolet, 2003).

Consequently, although seismic tomography shows a broad area of warm asthenosphere under the region, and geochemistry shows temporally and geographically (if not volumetrically) extensive OIB magmatism, there is no clear evidence for the arrival of a mantle plume associated with rifting of the SCS. The scattered low-volume OIB melts and the shallow low-velocity seismic anomaly, disconnected from deeper thermal anomalies, are in better agreement with shallow processes of passive mantle upwelling and low-degree adiabatic mantle melting driven by tectonic extension and subduction processes in the overlying lithosphere (Smith, 1998).

5. New kinematic model: A history of extension

As highlighted above, no model for the Cenozoic history of SE Asia and the opening of the SCS agrees with the complete regional geological, geochemical, and geophysical data, instead preferentially treating certain data whilst negating other observations. We propose that tectonic reconstructions can agree with the paleomagnetic constraints without invoking subduction of an expansive PSCS, whilst also addressing the discrepancies discussed above between observations and the different models for SCS opening. Using GPlates (Boyden et al., 2011), a global plate rotation model (Matthews et al., 2016), and previous regional reconstructions (Hall, 2012, 2002) as a basis, we present a new 50 to 0 Ma tectonic model of SE Asia using minimal moving components, focussing on the kinematics of Borneo, the Sunda arc, and the South China Sea (Fig. 15). As discussed below a key feature of our model is a repositioning of Borneo's pole of rotation to a position northeast of the SCS rather than to the southwest. The GPlates rotation file and shapefiles of the coastlines and basins of SE Asia used for the reconstruction are included in the Supplementary Material (Supplement_4), along with enlargements of the Fig. 15 reconstructions (Supplement_3).

5.1. Borneo

In the PSCS/slab-pull model for SCS opening, the rotation pole to the NW of Borneo "*allows Borneo to remain part of a Sunda block while permitting the rotational movement to be absorbed within the north Borneo accretionary complexes by closing a PSCS*" (Hall, 1996). We propose moving the CCW rotation pole to NE Borneo from 50 Ma until SCS opening (33 Ma; Li et al., 2014), rotating the declination of Borneo about this pole according to the Apparent Polar Wander (APW) calculated compiled paleomagnetic data by Advokaat et al. (2018; Fig. 16). The required CCW rotation was accommodated by Eocene to Oligocene lithospheric extension of the thinned continental crust between Borneo and Indochina (Gozzard et al., 2019). At 50 Ma, we locate Borneo 5°W and 3°S of its APW (Fig. 15), and by 33 Ma it was close to its present-day position relative to Palawan (Fig. 15). Even since the Miocene, only SW Borneo has behaved in a rigid way (Hall, 2017), so between 50 and 33 Ma we treat the Mesozoic continental crust of SW Borneo as its only rigid block. Cenozoic sedimentary rocks dominate the rest of Borneo, lacking > 40 Ma paleomagnetic constraints (Advokaat et al., 2018). Between 50 and 33 Ma, sediments of the Crocker-Rajang-Embaluh Super Group were deposited in active submarine fans overlying extending crust, rotating and extending relative to the rigid continental crust of SW Borneo (Fig. 15; Section 2.5.2). Our proposed treatment of Borneo as a composite domain, with SW Borneo acting as a rigid block whilst northern Borneo deforms as composite domains, has been previously proposed (Cullen, 2014, 2010). This previous work used seismic, stratigraphic, gravity, and paleomagnetic data to show how Borneo is segmented into NW-SE trending structural domains, and how these domains influenced the development of NW Borneo's offshore sedimentary and structural systems. The principal boundaries of these domains are the West Baram and Balabac Lines (Fig. 7a and Fig. 7b), which we suspect are related to lithospheric blocks within the ancestral Mesozoic arc complexes.

During SCS opening (33–16 Ma; Li et al., 2014), Borneo and Palawan migrated southwards and slightly CW (Fig. 16), fixed to the southern conjugate margin of the SCS (Fig. 7). During the later stages of SCS spreading (23–16 Ma), Borneo and Palawan rotated slightly CCW relative to the south SCS margin. The resultant contraction deformed and uplifted the Crocker Group sediments in north Borneo (van Hattum et al., 2013).

Our proposed model invokes extension between Borneo and Indochina by 1.3x between 50–32 Ma, and 1.5x between 50 and 0 Ma. Fig. 14-L9 of Gozzard et al. (2019) indicates average crustal thicknesses between Borneo and Indochina (excluding overburden) of ~ 40 km at the margins, thinning to 20–30 km beneath the western SCS. Assuming an average 27 km present crustal thickness (excluding overburden) and a fixed cross sectional area since 50 Ma, the equivalent beta factor (β = initial thickness/final thickness = 1.5) and crustal thinning ($1-1/\beta = 0.3$) of our kinematic model are comparable to Gozzard et al. (2019) (Fig. 8).

Completing CCW rotation of Borneo prior to SCS spreading, then moving Borneo with the southern SCS margin, explains why the sediments of northern Borneo record CW rotation after a remagnetisation event at some time between 35 and 15 Ma (Fig. 14 and Fig. 16; Cullen et al., 2012). Without an ocean separating Borneo from South China, the transparent Triassic zircons of the Cretaceous–Eocene Rajang Group (Galin et al., 2017), and the ~ 1.8 Ga zircon populations of the Triassic Sadong Formation (Breitfeld et al., 2017) of Borneo can be explained via a South China provenance without having to invoke complex models involving allochthonous crustal blocks.

5.2. Sundaland

Sundaland translates 350 km SE along the Red River-Ailao Shan Fault Zone between 35 and 17 Ma (Leloup et al., 1993; Matthews et al., 2016); intermediate to the 500 km and 200 km estimates of Briais et al. (1993) and Hall (2002) respectively. The northern Malay Peninsula moved south relative to Thailand between 50 and 30 Ma due to 300 km sinistral displacement of the combined Wang Chao-Three Pagodas fault system (Lacassin et al., 1997). Between 50 and 30 Ma, the southern Malay Peninsula moved SW in response to 150 km dextral displacement of the combined Ranong and Khlong Marui faults (Watkinson et al., 2011), and Oligocene–Miocene extension occurred in central Thailand (Matthews et al., 2016; Morley et al., 2011). Following Hall (2002), the West Burma Block was attached to the Malay Peninsula from 50 to 20 Ma, then became partially coupled to India and migrated north along the margin. Relative plate motions (Matthews et al., 2016) show convergence and subduction along the Sunda Arc throughout the period reconstructed.

5.3. Palawan and the Philippine Mobile Belt

Palawan developed as a Mesozoic accretionary complex on the SE Asian margin, closer to South China (its main source of detrital material; Cao et al., 2020). It was composed of Mesozoic

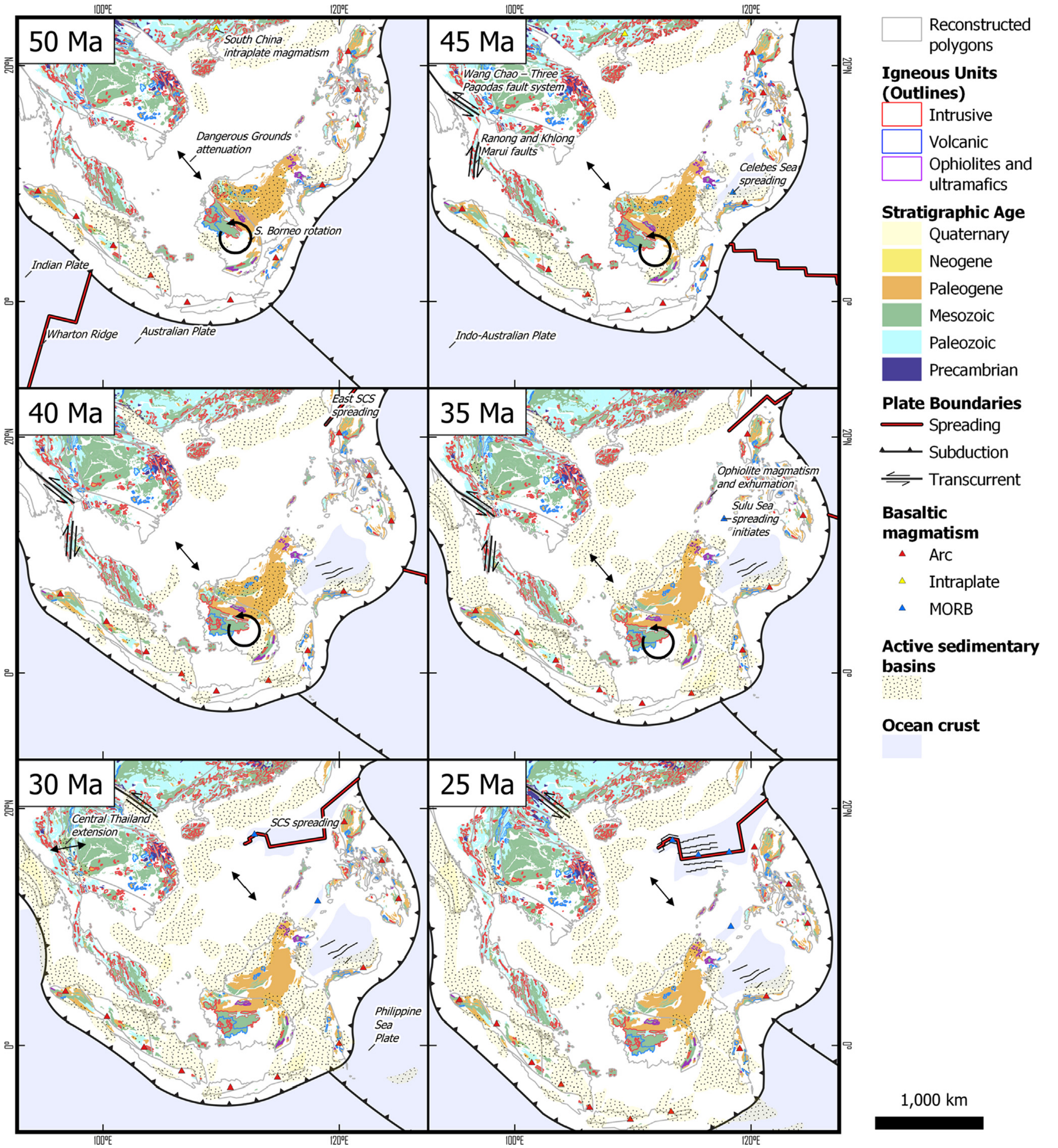

Fig. 15. Proposed extensional Cenozoic history of SE Asia, highlighting key tectonic elements. Coastlines, isochrons, and plate boundaries adapted from Matthews et al. (2016), Hall (2017, 2012, 2002), and Zahirovic et al. (2014). Sedimentary basins from Darman and Hasan Sidi (2000), Pubellier and Morley (2014), and Galin et al. (2017). Regional geology from Fig. 1. Regional basaltic magmatism from Fig. 5. Note that (as is typical in kinematic reconstructions) present-day coastlines are aids to geographic reference of past geological settings rather than implying the presence of similarly oriented past coastlines.

continental margin sedimentary rocks (the North Palawan Continental Terrane; Cao et al., 2020), and the Cretaceous backarc ophiolitic rocks of South Palawan (Labis et al., 2021).

Rifting at 35 Ma in a marginal ocean basin generated the MORB (Mid-Ocean Ridge Basalt) to transitional MORB-IAT (Island Arc Tholeiite) ophiolitic magmatism of central Palawan (Keenan et al., 2016). ∼ 1 km of metamorphosed mafic and sedimentary rocks are exposed at the ophiolite's northern extent, adjacent to mantle peridotite, and previously interpreted as a "metamorphic sole" (Keenan et al., 2016). The metamorphic units have identical ages to the ophiolite (34–35 Ma from hornblende and mica Ar-Ar, and U-Pb zircon chronology; Encarnación et al., 1995; Keenan et al., 2016). This was interpreted to represent immediate subduction-driven metamorphism, requiring magmatic crystallisation, subduction to 27 km, heating to 700–760 °C, and subsequent cooling to 400 °C, all within 1 Ma (Encarnación et al., 1995; Keenan

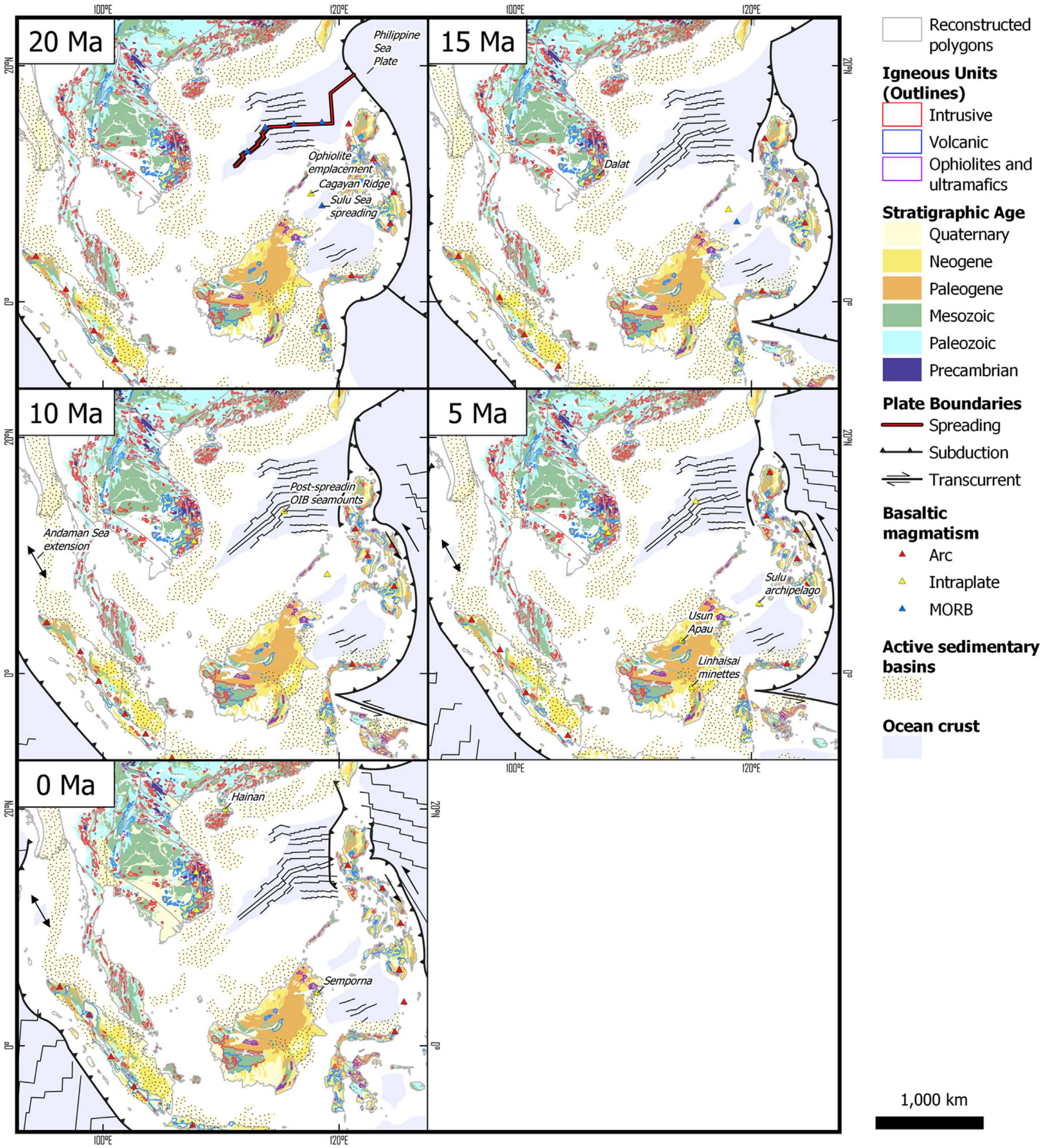

Fig. 15 (*continued*)

et al., 2016). A simpler solution, given the lithologies of lower crustal gabbros, amphibolites, and kyanite schists, is that these are all retrograde metamorphic ages, associated with extension and exhumation of lower crustal rocks during formation of the Palawan marginal basin and ophiolite magmatism. This implies that the prograde garnet zoning of these metamorphic rocks (Encarnación et al., 1995) developed prior to this period of extension and exhumation. Overlying sediments date ophiolite emplacement at ~ 23–16 Ma (Aurelio et al., 2014), contemporaneous with the regional deformation and unconformities in north Borneo (van Hattum et al., 2013) and compression between the Palawan Continental Terrane and Philippine Mobile Belt (PMB) (Dimalanta et al., 2009).

The extensional ophiolitic magmatism of Palawan was contemporaneous with the 35 Ma onset of Sulu Sea extension, which continued until 10 Ma (Roeser, 1991). Previous tectonic models interpret the Cagayan Ridge as arc magmatism associated with PSCS subduction (Hall, 2012), and the Sulu Sea extension as a back-arc basin associated with either PSCS subduction from the NW (Holloway, 1982), or Celebes Sea subduction from the SE (beneath

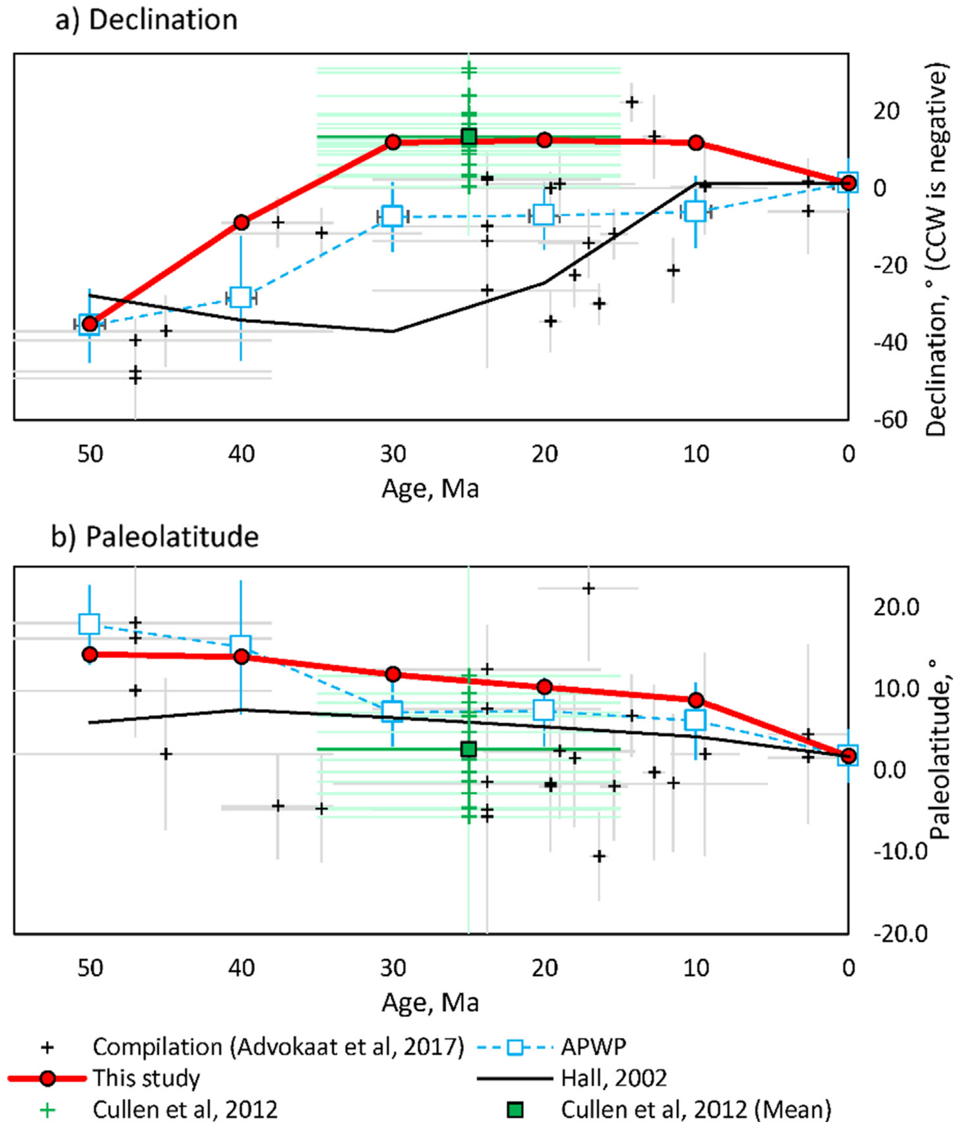

Fig. 16. Paleomagnetic constraints and history of Borneo, comparing the data compilation of Advokaat et al. (2018) with the predicted paleomagnetic wander of Borneo. *APWP* – Apparent Polar Wander Path of Borneo, calculated from the data compilation by Advokaat et al. (2018). *This study* – Paleomagnetic wander predicted by our proposed model for SW Borneo (Fig. 15). Hall, 2002 – Paleomagnetic wander of Borneo predicted by the Proto South China Sea model, digitised from the reconstructions of this paper. Cullen et al, 2012 – Paleomagnetic constraints of the Crocker Group sediments of north Borneo, remagnetised between 35 and 15 Ma. Calculated using paleomagnetism.org (Koymans et al., 2016) within the reference frame of Torsvik et al. (2012).

the Sulu Archipelago; Hall, 2012). However, the Cagayan volcanic rocks do not exhibit the Sr isotopic enrichment associated with arc magmatism, and do not show the expected isotopic relationship with the Sulu Sea whereby the arc magmatism should be more enriched in radiogenic Sr than the backarc (Spadea et al., 1996). Basalts of contemporaneous ages with Sulu Sea spreading have not been found in the Sulu Archipelago, and the 24.6–21.2 Ma ages from the Zamboanga Peninsula to the NE are metamorphic K-Ar ages (Tamayo et al., 2000), not igneous protolith ages (as presented by Lai et al., 2021). Basalts of the Sulu Archipelago and Zamboanga Peninsula that post-date Sulu Sea spreading have OIB signatures, as do those of the Semporna Peninsula of Sabah to the SW (Fig. 5h and 5j).

Therefore, the apparent arc signature of the Cagayan Ridge and Sulu Sea geochemistry (i.e. LILE/HFSE enrichment) may not represent active proximal subduction contemporaneous with the magmatism. Isotopic data indicates deviation from Pacific MORB values (Spadea et al., 1996), indicative of crustal contamination. Even minor contamination by crustal melts can impart LILE/HFSE enrichment, as they have done to the OIB magmatism of the Semporna Peninsula immediately to the SW (Macpherson et al., 2010). Alternatively, metasomatism of the lithosphere by subduction may have occurred tens or hundreds of millions of years previously and still impart this signature, as observed in the Sintang Suite of West Sarawak (Breitfeld et al., 2019). Similarly, migration of the lithosphere over metasomatised mantle (in this case, southward migration of the extending Sulu Sea) can also impart arc signatures tens of Myr after active local subduction (as observed in New Guinea; van Hinsbergen et al., 2020). Given the extensive subduction prior to extension, and the proximity to similar processes on the Semporna Peninsula (albeit 30–5 Myr later), these processes are all feasible. Consequently, the apparent arc signature of the Cagayan Ridge is not evidence for active proximal subduction of the SCS or Celebes Sea. Instead, we propose the Cagayan Ridge, Sulu Archipelago, and Sulu Sea are products of larger scale regional extension, within and overlying extended continental crust; microcosms of the broader SCS region. This is supported by shear wave tomography, which shows low seismic velocities in the upper mantle under the Sulu Archipelago (150 km depth, Fig. 17c; Schaeffer and Lebedev, 2013). This is comparable with other regions of extensional or strike-slip deformation in SE Asia (e.g. the SCS and the Wang Chao-Three Pagodas Fault; Fig. 17c), and dissimilar to the distinct high velocity anomalies associated with subduction (e.g. the Sunda and Manilla trenches; Fig. 17c).

Surrounded by transform faults and subduction zones, paleomagnetic evidence for the origin of the Philippine Mobile Belt (PMB) is ambiguous, developing at either local (Hall, 2012, 2002) or distal latitudes (Zahirovic et al., 2014). Given the correlation of the southern Philippines with Indochina, Palawan, and South China (Faure et al., 1989; Gong et al., 2021; Yumul et al., 2004), geological evidence supports development the archipelago proximal to Palawan (i.e. at local latitudes), which is where we locate it in our tectonic reconstructions (Fig. 15).

Mesozoic slab rollback of the Pacific ocean crust (Li et al., 2012; Zhou et al., 2006) generated transitional MORB (Mid-Ocean Ridge Basalt) to IAT (Island Arc Tholeiite) ophiolitic magmatism within marginal supra-subduction zone basins in what is now the PMB (Yumul et al., 2020; previously interpreted as PSCS crust). Without a PSCS, the Mesozoic units of the PMB were close to Taiwan and Palawan at 50 Ma (with the caveat that they were not contributing mafic material to the Palawan sediments, given their passive margin composition; Cao et al., 2020), and dispersed SE with NE Sulawesi as the Celebes Sea opened (50–42 Ma; Silver and Rangin, 1991). The archipelago moved south as the SCS opened, before partially coupling to the Philippine Sea Plate from 20 Ma, overriding and subducting a 400–500 km wide eastward extension of the original SCS ocean crust (Wu and Suppe, 2018). Convergence between Palawan and the PMB during this northward migration

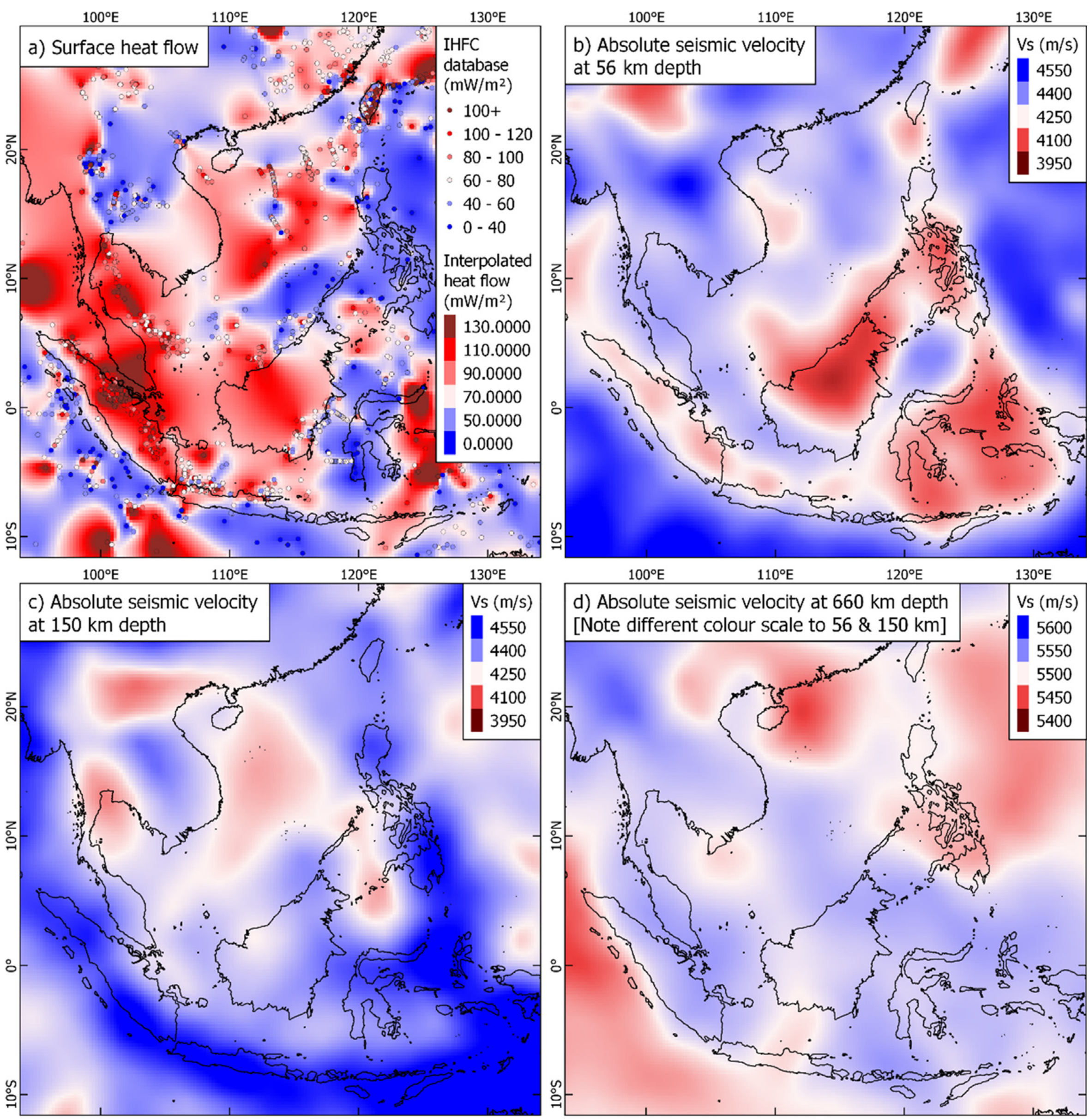

Fig. 17. a) Point data and interpolation of the Global Heat Flow Database of the International Heat Flow Commission (IHFC; Fuchs et al., 2021). For reference, the estimated average heat flow of continental crust is 67.1 mW/m^2, whilst for oceanic crust it is 78.8mWm^2 (Lucazeau, 2019). b–d) Absolute seismic velocity at 56 km, 150 km, and 660 km depth from the global shear wave tomographic model SL2013sv (Schaeffer and Lebedev, 2013), highlighting the shallow upper mantle thermal anomaly under Borneo. The 56 & 150 km sections highlight the upper mantle thermal anomaly under SE Asia and the active subduction zones, whilst the 660 km section highlights the extent of subducted material residing at the transition zone (compare with Fig. 12).

generated the compressional Miocene regime recorded by structural and metamorphic geology (Yumul et al., 2009), albeit over a more protracted period than a discrete Miocene event (which would be at odds with the evidence for continuing SCS subduction beneath the PMB; Wu and Suppe, 2018).

5.4. Extension vs compression

Our interpretation of SE Asian tectonics (Fig. 15), that the region was largely extensional throughout the Cenozoic, is in agreement with regional geological and geophysical data. Large scale data is all indicative of extensional tectonics, including: rifting of the SCS, Sulu Sea, and Celebes Sea basins; attenuation of the Dangerous Grounds continental crust; extensive sedimentary basins; regional within plate magmatism; exhumation of lower crustal rocks; supra-subduction zone ophiolites; high heat flow; and extensional faults in offshore seismic data. However, on the smaller scale, reverse faulting and regional unconformities indicate a compressional regime. This includes Eocene to Miocene reverse faulting (Tongkul, 1997) and multiple unconformities onshore and offshore of northern Borneo (Levell, 1987), the offshore fold-and-thrust belt of Borneo (Hesse et al., 2009), and Miocene reverse faulting during emplacement of the central Palawan ophiolite (~23–16 Ma, Aurelio et al., 2014).

An apparent dichotomy thus exists between the shallow structural fabric of the region and the large-scale geology. This was discussed by Hall (2013), who concluded that whilst the 20–19 Ma Top Crocker Unconformity (referred to here by its alternate name of Base Miocene Unconformity, BMU) was a product of Dangerous Grounds collision into Borneo, the ~ 16 Ma Deep Regional Unconformity (DRU), and ~ 10 Ma Shallow Regional Unconformity (SRU) represent extensional uplift driven by subduction and slab rollback of the Celebes Sea beneath Borneo. They proposed that this rollback also drove Sulu Sea extension. However, as noted above, basalts of contemporaneous ages with Sulu Sea spreading have not been found in the Sulu Archipelago, and those post-dating spreading have OIB signatures (including in eastern Sabah; Macpherson et al., 2010). There is also no tomographic evidence of a Celebes Sea slab beneath Borneo, and seismic lines show the Celebes Sea and Sulu Archipelago have an extensional contact of draped turbidite sediments and normal faults, with the only evidence for compression being a recent flower structure (Schlüter et al., 2001). Therefore, whilst we agree that these are extensional features, they are products of large-scale regional extension, not Celebes Sea subduction.

Levell (1987) and Cullen (2010) showed that offshore the different unconformities of NW Borneo become conformable (the BMU, DRU, and SRU can be traced into their respective horizons), and when traced shoreward each unconformity has been successively eroded to form a composite unconformity. This is indicative of a progressive common history of the three unconformities, grouping the BMU with the DRU and SRU as another product of progressive extension-driven uplift. Using seismic data from the Upper Miocene–Recent fold-and-thrust belt offshore of NW Borneo, Hesse et al. (2009) showed that whilst the 4–6 km deep water shortening to the South (offshore Brunei) was balanced with gravity-driven shallow water extension, towards the north of the belt (offshore Kota Kinabalu) the shortening exceeded landward extension by up to 5 km. They attributed this excess in shortening to basement-driven tectonic compression. However, Hall (2011) pointed out that this imbalance can be explained by onshore extension, not considered by Hesse et al. (2009), without invoking tectonic compression since the Late Miocene. Young intra-plate tectonic-driven shortening is difficult to reconcile with the fact that deepwater fold-thrust belts of the North Luconia Delta, Baram Basin, Sandakan Basin, Tarakan Basin, and Kutei Basin change their strike through 180° as they track around the island (Fig. 2 and Fig. 9a; see also Supplement_1 Fig. S1a to S1e).

However, whilst the above discussion attributes the regional unconformities and offshore fold-and-thrust belt to regional extension and uplift, the reverse faulting of northern Borneo and Palawan (including over-thrusting of the Palawan ophiolite onto the Palawan continental crust) does require a discrete compressional event in the Miocene. Deformation, metamorphism, overlapping sediments, and magmatic activity in the central Philippine Mobile Belt (PMB) indicate a compressive event between the PMB and northern Palawan in the late Early Miocene or early Middle Miocene (Yumul et al., 2009). Given its proximal location and contemporaneous timing, we propose that it was the distal effects of this transpressive deformation that were recorded in Palawan and Sabah; a discrete compressive event in an otherwise extensional system.

6. Geodynamic hypothesis: Continental breakup through enhanced heat flow

We have presented the regional geology of SE Asia, shown how the principal regional tectonic models do not agree with the available data, and have presented a new kinematic model showing how the observations better agree with an extended history of continental rifting. As in SE Asia, continental rifting globally has been variably attributed to tectonic and mantle processes; particularly in regard to the relationship between rifting and mantle plumes (e.g. Spohn and Schubert, 1982; Storey, 1995; Ziegler and Cloetingh, 2004). However, (as discussed in Section 4.4) although warm asthenosphere is present under SE Asia (Fig. 17b; Lebedev and Nolet, 2003), the timing, distribution, and chemistry of OIB magmatism in SE Asia disputes a mantle plume origin for the SCS. The region thus provides insight into the global processes of developing a continental rift without a plume.

The present effects of the warm mantle anomaly under SE Asia reveal how the region behaved in the past. Presently, the lithospheric effects of the thermal anomaly are most pronounced under the Gulf of Thailand (Malay Basin) and NW Borneo, where a pronounced low shear velocity zone extends to ~ 150 km depth (Fig. 17b; Lebedev and Nolet, 2003). Here it has enhanced the terrestrial and offshore heat flow and geothermal gradients: 47 °C/km (92 mW/m^2) under the Malay Basin, 45 °C/km (95 mW/m^2) under the Sarawak Shelf, and 34 °C/km (79 mW/m^2) under the Sabah Shelf (Fig. 17a; Madon and Jong, 2021). Lithospheric strength and rheological behaviour reflect its thermal properties (Gueydan et al., 2008), and the enhanced heat flow in SE Asia has weakened the lithosphere and affected the regional topography.

Onshore Borneo, the thermal effects are expressed as positive dynamic support of the regional topography, uplifting the region by up to 500 m (Roberts et al., 2018). In a quantitative geomorphic analysis, Mathew et al. (2016) proposed that Borneo has experienced rapid uplift and fault rejuvenation in the last 5 Ma, which is consistent with our analysis of river gradient profiles indicating about 200 m of uplift over a broad area of the island (Fig. 10). This uplift is too young by more than 15 Ma to be attributed to slab detachment and/or crustal delamination in subduction-collision models for Borneo (Hutchison, 2000), but does highlight the effect of regional dynamic topography.

Offshore, the thermally-enhanced ductility of the lithosphere has resulted in exceptional basement subsidence in response to sedimentary loading. In the Miocene–Present Baram-Balabac Basin (offshore NW Borneo), this is manifest by a strongly aggradational system, prograding horizontally only 50 km since the Early Miocene despite vertical deposition of up to 12 km of sediment (Cullen, 2010). The rheological effects of elevated heat flow and a weakened lower crust have been proposed to explain the coupling of anomalously rapid sedimentation and subsidence rates in the Bayun Sag. Clift (2015) termed this a "load-flow basin", proposing lower crustal flow beneath rapidly loaded basins toward the continent, in turn driving further uplift and sediment influx; supportive of the conceptual model of Hall (2011).

The regional magmatism provides evidence for a thin, ductile lithosphere and warm mantle upwelling during the initial stages of extension in SE Asia. The basaltic chemistry of continental magmatism is related to the lithospheric thickness and heat flow, with OIB magmatism indicative of thin lithosphere and high heat flow (Menzies, 1989). In South China, the Mesozoic Pacific arc retreated in the Late Cretaceous during slab roll-back (Li et al., 2012; Zhou et al., 2006); a result of rapidly diminished subduction convergence rates (Northrup et al., 1995). The generation of Mesozoic–Eocene intraplate magmatism in South China (Fig. 5a–c, and 5o); Chen et al., 2008; Chung et al., 1997) indicates that this upper-plate extension initiated the lithospheric thinning and enhanced heat flow of SE Asia, that this occurred distally to the active subduction zone, and that it may have begun as far back as the Jurassic. The distal location of extension and rifting from the subduction zone is in agreement with physical models for East Asia, and a correlation between the width of a retreating subduction zone and the distance into the overriding plate that extensional deformation propagates (Schellart and Lister, 2005). This shows that the active margin in East Asia could drive extension as far west as the Baikal rift (~3300 km from the margin).

Once lithospheric extension has initiated, a feedback loop is generated (Fig. 18) whereby the extension and thinning of the lithosphere is balanced by broad swells of passive asthenospheric upwelling. This upwelling and associated adiabatic melting enhances the heat flow of the overlying lithosphere (potentially

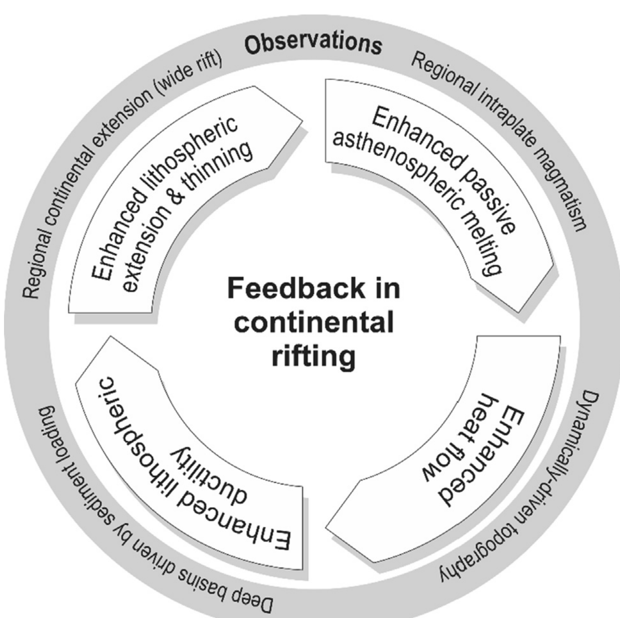

Fig. 18. Feedback processes involved in continental rifting and observations of these processes in this region. In SE Asia, initial lithospheric extension and thinning occurred in the Cretaceous via backarc extension and oceanward retreat of the subduction zone beneath South China (Li et al., 2012). However, as the subduction zone migrated southeast, this thinned lithosphere developed into a backarc rift of high heat flow and asthenospheric upwelling; evidenced by Paleocene–Eocene intraplate magmatism in South China (Chung et al., 1997). The upwelling asthenosphere enhanced the regional heat flow, developing a wide rift setting (rather than a narrow neck; Gueydan et al., 2008) over which SE Asia extended, attenuating the Dangerous Grounds continental crust until its eventual continental breakup generated the SCS ocean crust.

reducing its thickness further via thermal thinning), enhancing its ductility. This renders the lithosphere more responsive to further extension. Consequently, providing that a source of extension remains, the lithosphere will continue to rift. Wang et al. (2019) invoked basal drag via deep subduction and large-scale mantle convection as the driver for this extension. However, basal drag is an unsuitable driver for plate motion as insufficient shear resistance occurs at the lithosphere-asthenosphere boundary (Niu, 2020). This indicates that although the intraplate magmatism and SCS rift are distal to the backarc rifts proximal to the subduction zone, continued trench retreat and consequent passive motion of the overlying continental crust since the Mesozoic provided the source for this extension. Whilst NW-directed Pacific subduction was the driver of Mesozoic–Paleocene NW-SE extension (Li et al., 2012), the NNW-SSE extension of the SCS is neither parallel with the contemporaneous NW-directed subduction of the Philippine Sea Plate, nor the NE-directed subduction of the Indo-Australian Plate. Lying at the intersection of these two subduction zones during SCS spreading (Fig. 15), regional strain reflected a combination of these two distal sources.

We thus propose the following geodynamic history for SE Asia: Mesozoic subduction of old, heavy slabs of the West Pacific oceanic crust beneath South China and SE Asia and a rapidly diminishing convergence rate led to slab rollback, and upper-plate lithospheric extension and thinning (Li et al., 2012; Northrup et al., 1995). Warm fertile asthenosphere passively upwelled beneath the thinning lithosphere, enhancing the regional heat flow as it presently does under Borneo and the southern conjugate margin of the SCS (Madon and Jong, 2021; Roberts et al., 2018). This weakened the lithosphere sufficiently for distal extensional forces to drive OIB magmatism and within plate rifting. This crustal extension occurred distal to the back arc extension immediately behind the Sunda arc. Heat flow and resultant lithosphere ductility was high enough to develop a wide rift setting rather than a narrow neck (Gueydan et al., 2008). Numerical modelling shows that the development of a wide rather than narrow rift was also dependant on a wet, ductile upper mantle (Svartman Dias et al., 2015); a product of the protracted subduction history beneath East and SE Asia. Enhanced ductility of the lithosphere and upper mantle enhanced decoupling of the crust and mantle, distributing extensional strain over a wider area (Huismans and Beaumont, 2008; Svartman Dias et al., 2015). We consider the tectonic history of the Aegean Sea, (localised to distributed upper plate extension and the development of Neogene basins driven by slab rollback; Brun et al., 2016), to be a viable analogue to our proposed model.

Wide within plate rifting commenced with the attenuation of the South China continental margin from 60 Ma (Li et al., 2012), the extension of the Dangerous Grounds and Pearl River Mouth Basin, and eventual ocean spreading and MORB magmatism of the SCS. The transition from an active margin to a passive margin as the trench retreated in the Late Cretaceous-Early Cenozoic generated shearing and strike slip structures in the extending continental crust, which were inherited by the continued continental extension in the Paleocene-Eocene (Huang et al., 2019; Wang et al., 2019). In the Eocene, during the final 10 Myr prior to continental breakup, there was a rapid transition from a wide rift into a narrow continent-ocean-boundary (the "rift-to drift" transition). This triggered extensive MORB magmatism on what became the Northern Conjugate Margin via decompression melting of the asthenosphere, followed by steady-state seafloor spreading (Ding et al., 2020).

The long-lived subduction history beneath SE Asia generated an extensive area of relatively flat-lying slab material residing along the 660 km discontinuity (Fig. 17d; Fukao et al., 2001; Fukao et al., 2013; Schaeffer and Lebedev, 2013); the transition zone high velocity anomalies that geodynamic modelling of PSCS subduction failed to reproduce (Fig. 12; Lin et al., 2020). The passive warm mantle upwelling initiated during Mesozoic extension and slab rollback continues today, and is visible in the shallow upper mantle (<150 km) beneath Borneo in present day seismic tomography (Fig. 17b; Schaeffer and Lebedev, 2013), where it is enhanced by high erosion rates and resultant dynamic topography (Menier et al., 2017; Roberts et al., 2018).

Finally, linking geodynamic drivers to the kinematics of Cenozoic deformation of the greater South China Sea region requires considering global-scale processes. We thus return to the nature of the Sunda Plate (Fig. 2b), which represents an amalgamation of terranes with irregular boundaries and different inherited structural fabrics. The Sunda Plate is characterised by anomalously hot and therefore weak lithosphere that responds rapidly and locally to evolving stresses imposed by major bounding plates. This complex and localised response is manifested by the fact that whilst most plates show a relationship between the orientation and magnitude of their regional stresses with absolute plate motions, this is not the case for the Sunda Plate (Tingay et al., 2010). We suggest the interactions of the fragments and micro-blocks of the Sunda Plate resembles pieces of luggage jostled around in the overhead compartment of a train car with resultant short-lived spreading centres, stubby subduction zones (better characterised as lithospheric under-thrusting), and localised deep "load-flow" basins adjacent to small scale uplifts (e.g., the Sabah Orogeny).

7. Nature of the Proto-South China Sea (PSCS)

As discussed in Section 4.3 and Section 5, our model explicitly challenges the past existence of a large Proto-South China Sea (PSCS) and marginalises its role in the region's tectonic evolution. However, extensive Mesozoic ophiolites and associated lithologies of the Philippine Mobile Belt (PMB), Palawan, and Sabah (Northwest Borneo) provide abundant evidence for ocean crust and seafloor sediments preceding the SCS, and were interpreted as slivers of exhumed PSCS crust by Yumul et al. (2020). Ocean crust, including the SCS, typically display MORB (Mid-Ocean Ridge Basalt) chemistry (Yu and Liu, 2020; Zhang et al., 2018). In contrast, the Mesozoic ophiolites of the PMB (Yumul et al., 2020), Palawan (Labis et al., 2021), and Sabah (Burton-Johnson et al., 2020; Omang and Barber, 1996) exhibit the transitional MORB to IAT (Island Arc Tholeiite) chemistry associated with suprasubduction zone, marginal backarc basin magmatism. Therefore, we conclude that whilst the extensive PSCS crust shown in previous kinematic models did not exist, and its subduction was not the key driver for SCS extension, Mesozoic suprasubduction zone extension during slab rollback of Pacific Ocean crust did generate narrow marginal backarc basins floored by basaltic crust. The outcrops and Bouguer anomalies of the ophiolites that record these basins trace their past extent from the PMB, across, Palawan, and into Sabah (Section 4.3, Fig. 7b). However, whether we should name these narrow basins the "Proto-South China Sea" is debatable.

8. Conclusions

Four principal tectonic models (each with their own variants) have been proposed for the Cenozoic history of SE Asia and rifting of the South China Sea (SCS): 1) Slab pull from subduction of a Proto South China Sea (PSCS); 2) Extrusion tectonics from the India-Asia collision; 3) basal drag from a mantle plume; and 4) Backarc rifting. Each model developed around specific observations, and whilst providing good agreement with that data, each is challenged by other observations. Only by selective data incorporation have these different models perpetuated in parallel. We have summarised these models and their data disparities, and proposed an alternative tectonic and geodynamic history for the region. The shortcomings of previous models (discussed in this manuscript) and the agreement of our model with the various observations are summarised in Fig. 19.

We propose an autochthonous growth and continental rifting model of SE Asia, developing proximal to the South China margin (i.e. without invoking a Proto-South China Sea). Commencing in the Mesozoic along the long-lived South China continental arc, slab rollback and offshore migration of the subduction zone led to intracontinental thinning and passive extension and migration of the continental crust in response. This in turn drove passive asthenospheric upwelling. The enhanced heat flow and crustal ductility generated a feedback loop, enhancing further extension and developing SE Asia as a wide rift rather than a narrow crustal neck until, following sufficient extension, rifting of the South China Sea occurred. South China Sea extension ceased as the subduction zone and asthenospheric upwelling continued to migrate south. Currently this high heat flow underlies Borneo, where it dynamically elevates the regional topography and weakens the underlying basement of the surrounding basins.

Geological and geophysical observations are in closer agreement with this model than those previously proposed. Geological and geophysical correlations between the north and south conjugate margins of the SCS indicate a proximal common history prior to SCS rifting. By moving the rotation pole of Borneo's continental basement from NW to NE Borneo, the paleomagnetic evidence for CCW rotation of Borneo is met (unlike the extrusion model) without invoking a Proto-South China Sea (i.e. the slab pull model). The lithospheric extension and thinning generates the regional intraplate magmatism and upper mantle thermal anomaly without requiring a mantle plume, and developing an intracontinental rift via enhanced heat flow explains why the SCS developed distal to the active subduction zone (i.e. the backarc model).

In light of our conclusions, SE Asia provides a unique opportunity to study the development of intracontinental rifts. We propose

Observations	Backarc spreading	Extrusion	PSCS slab pull	Mantle plume	New rift model
35° CCW rotation of Borneo 50–30 Ma			✓		✓
14° CW rotation of Borneo <35 Ma	✓	✓		✓	✓
Synchronicity with SCS rifting	✓				✓
OIB magmatism across SE Asia				✓	✓
No PSCS arc in Borneo	✓	✓		✓	✓
Early SCS MORB magmatism	✓	✓	✓		✓
Low-volume continental magmatism	✓	✓			✓
Warm asthenosphere				✓	✓
Extensive 660 km slab material	✓				✓
Distal, intracontinental rifting		✓	✓	✓	✓
Detrital zircon correlations	✓	✓		✓	✓
Gravity anomaly correlations	✓	✓		✓	✓
Extension (not compression) between Borneo and Indochina	✓	✓		✓	✓

Fig. 19. Summary table of the various geological observations discussed, the agreements and disparities between these observations and the previously proposed SCS tectonic models, and the common agreement of these observations with our proposed model of intracontinental rifting in SE Asia.

that the feedback mechanism by which initial slab retreat and lithospheric extension leads to passive upwelling, enhanced heat flow and ductility, and thus further extension, is a workable hypothesis for intracontinental rifting without a plume elsewhere.

In this geologically complex region in which limited areas have behaved as rigid crustal blocks, much of the bedrock geology is not exposed, and large areas remain challenging to sample, there remains much research to be done; particularly via more extensive paleomagnetic sampling. However, providing a tectonic model that integrates the regional data provides a framework in which to operate and evaluate.

CRediT authorship contribution statement

A. Burton-Johnson: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **A.B. Cullen:** Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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