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The Cretaceous and Cenozoic tectonic evolution of Southeast Asia

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Abstract

Tectonic reconstructions of Southeast Asia have given rise to numerous controversies which include the accretionary history of Sundaland and the enigmatic tectonic origin of the Proto South China Sea. We assimilate a diversity of geological and geophysical observations into a new regional plate model, coupled to a global model, to address these debates. Our approach takes into account terrane suturing and accretion histories, the location of subducted slabs imaged in mantle tomography in order to constrain the opening and closure history of paleo-ocean basins, as well as plausible absolute and relative plate velocities and tectonic driving mechanisms. We propose a scenario of rifting from northern Gondwana in the Late Jurassic, driven by northward slab pull, to detach East Java, Mangkalihat, southeast Borneo and West Sulawesi blocks that collided with a Tethyan intra-oceanic subduction zone in the mid Cretaceous and subsequently accreted to the Sunda margin (i.e. southwest Borneo core) in the Late Cretaceous. In accounting for the evolution of plate boundaries, we propose that the Philippine Sea Plate originated on the periphery of Tethyan crust forming this northward conveyor. We implement a revised model for the Tethyan intra-oceanic subduction zones to reconcile convergence rates, changes in volcanism and the obduction of ophiolites. In our model the northward margin of Greater India collides with the Kohistan-Ladakh intra-oceanic arc at ~53 Ma, followed by continent-continent collision closing the Shyok and Indus-Tsangpo suture zones between ~42 and 34 Ma.

We also account for the back-arc opening of the Proto South China Sea from ~65 Ma, consistent with extension along east Asia and the emplacement of supra-subduction zone ophiolites presently found on the island of Mindoro. The related rifting likely detached the Semitau continental fragment from east China, which accreted to northern Borneo in the mid Eocene, to account for the Sarawak Orogeny. Rifting then re-initiated along southeast China by 37 Ma to open the South China Sea, resulting in the complete consumption of Proto South China Sea by ~17 Ma when the collision of the Dangerous Grounds and northern Palawan blocks with northern Borneo choked the subduction zone to result in the Sabah Orogeny and the obduction of ophiolites in Palawan and Mindoro. We conclude that the counterclockwise rotation of Borneo was accommodated by oroclinal bending consistent with paleomagnetic constraints, the curved lithospheric lineaments observed in gravity anomalies of the Java Sea and the curvature of the Cretaceous Natuna paleo-subduction zone. We complete our model by constructing a time-dependent network of continuously closing plate boundaries and gridded paleo-ages of oceanic basins, allowing us to test our plate model evolution against seismic tomography. In particular, slabs observed at depths shallower than ~1000 km beneath northern Borneo and the South China Sea are likely to be remnants of the Proto South China Sea basin.

1 Introduction

Southeast Asia is an accretionary mosaic of continental fragments, seamounts, exotic terranes and intra-oceanic island arcs that were welded to the Asian continent, presently delineated by suture zones and remnants of ancient Tethyan and proto-Pacific ocean basins that once separated them (Şengör et al., 1988; Metcalfe, 2011; Veevers, 2004; Stauffer, 1983) (Fig. 1). The tectonic framework of Southeast Asia is inherited from the long-term convergence between the Australian, (proto-) Pacific and Eurasian plates and the cyclical Gondwana-derived terrane detachment and subsequent accretion onto Eurasia and the Sundaland core (Acharyya, 1998; Golonka, 2004; Stampfli and Borel, 2002; Hall, 2002; Metcalfe, 2006; Veevers et al., 1991). The northern Gondwana margin, as the origin for many of the Asian continental fragments, was a passive boundary for much of the Mesozoic, with periodic rifting events that carried continental slivers on the Tethyan conveyors to be accreted to the Eurasian margin (Audley-Charles, 1988; Veevers et al., 1991; Seton et al., 2012).

The Sundaland core, forming much of the Sunda shelf and continental promontory in Southeast Asia (Fig. 2), is largely comprised of the Cimmerian terranes that rifted from Gondwana at early Permian times (Metcalfe, 2011) and accreted diachronously along the Eurasian margin during the Triassic and Jurassic (Golonka, 2007; Metcalfe, 1999; Seton et al., 2012; Stampfli and Borel, 2002) to open the MesoTethys at the expense of the PaleoTethys (Table 1). A Late Jurassic rifting episode along northern Gondwana likely detached continental fragments including West Sulawesi, Mangkalihat, East Java, parts of Borneo (Hall, 2011; Metcalfe, 2011; Wakita, 2000) and other potential micro-continents such as Sikuleh, Natal, Lolotoi and Bengkulu (Acharyya, 1998; Metcalfe, 1996), to open the NeoTethys. However, the origin of these blocks on the northern Gondwana margin is controversial, in particular whether they all originated from the Argo Abyssal Plain, hence the "Argoland" name applied to blocks originating here, on the northwest Australian shelf, or whether some of these blocks originated from the New Guinea or even Greater Indian passive margin. In addition, the nature of the micro-continents on Sumatra has been disputed and recent studies have argued that these are more likely to be accreted intra-oceanic island arcs with no continental basement or affinity (Barber, 2000; Barber and Crow, 2003, 2009).

Although oceanic crust adjacent to the northwest Australian shelf records NeoTethyan seafloor spreading, only dismembered fragments of obducted oceanic crust in suture zones gives a glimpse of the older Meso- and Paleo- Tethyan oceanic domains (Seton et al., 2012). For example, the only remnant of the latest Jurassic seafloor spreading is contained in the obducted basement of the Irian ophiolite, likely preserved in an embayment along New Guinea (Hill and Hall, 2003). The lack of preserved seafloor spreading histories results in uncertain origins of many terranes presently found in Southeast Asia. As a result, we flag instances where alternative tectonic scenarios can explain the piecemeal data coverage in the absence of conclusive pre-breakup fits. This region, as the link between the Tethys and (proto-) Pacific, is complex also because of the uncertain nature of plate boundaries that accommodated generally westward subduction of (proto-) Pacific oceanic crust beneath east Asia and the overall northward subduction of Tethyan seafloor beneath southern Eurasia. Much of the accretionary events and convergence histories between the Indo-Australian, Pacific and Eurasian plates are recorded in the tectonic fabric of Sundaland. In addition,

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a large portion of Sundaland is submerged and remote (Fig. 2), resulting in uncertain tectonic histories of accreted blocks – including their origin, tectonic stability and accretionary chronology. In particular, the development of Borneo since the Late Cretaceous is intricately linked to the opening and closure of the Proto South China Sea and its successor, the South China Sea (Hutchison, 1996), as well as the collision of micro-continental fragments and island arcs from the south and east.

We present a plate motion model of the evolution of Sundaland in the context of terrane accretions, island arc collisions and the opening and closure of marginal seas. We assimilate a diverse range of geological and geophysical data, and draw on previously-published kinematic models, to reconcile the chronology and tectonic evolution of the latest Jurassic rifting event from northern Gondwana and the subsequent accretion and growth of Sundaland since the Cretaceous. In addition, we use seismic tomographic constraints to estimate paleo-locations of subduction zones in the region. The model we present invokes long-lived north-dipping subduction along Eurasia during the Jurassic and Cretaceous, with micro-continental slivers detaching from northern Gondwana and accreting to Sundaland. We provide the digital files (rotations, tectonic elements including digitized ophiolite belts, volcanic and tectonic features) and tools in order to test and improve the model (plate reconstruction software, *GPlates*, http://www.gplates.org).

2 Methodology

We assimilate geological data and previously-published models of extensional tectonic settings, shallow marine paleobiogeography, basaltic volcanism and the emplacement (crystallization) of ophiolites to constrain rifting events along northern Gondwana. Proxies of convergence including subduction-related volcanics and metamorphic belts (Fig. 3) are used to infer subduction polarities, and collisional events are inferred from the spatio-temporal distribution of ophiolite obduction episodes, high pressure-temperature metamorphism and orogenies. Our base global plate motion model in-

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cludes relative plate motions for Southeast Asia based on the syntheses of Lee and Lawver (1994, 1995), Hall (1996, 2002, 2012), Metcalfe (1994, 1996, 1999, 2011), Golonka (2004, 2007), Golonka et al. (2006) and other data and models described in Seton et al. (2012). We incorporate a range of datasets and models specific to Southeast Asia, and in particular the development of evolution of Sundaland, the South China Sea, the Philippine arcs and the accretionary history of northern New Guinea (Table 2).

We supplement geological evidence and previously-published models with additional criteria of convergence rate thresholds, geometric rules of triple junction closure and evolving plate boundaries (Fig. 4). Firstly, no part of a plate is allowed to have velocities exceeding 25 $\mathrm{cm\,yr^{-1}}$, following the velocity threshold used by Stampfli and Borel (2002). Secondly, mid-ocean ridge triple junctions in an RRR configuration (as in our eastern Tethys model) must accommodate seafloor spreading on all three arms following McKenzie and Morgan (1969). Thirdly, changes in relative plate motions can alter the type of plate boundary, for example, the predecessor to the (Proto) Izu-Bonin-Mariana Arc is a transform that eventually becomes a west-dipping subduction zone consuming Pacific crust, following the model of Casey and Dewey (1984) and Stern and Bloomer (1992). In the eastern Tethys we invoke the conversion of transform boundary to a spreading center following a change in relative plate motions from strike-slip to extensional, following the analogue of the San Andreas strike-slip boundary in the Gulf of California between ~ 6 and 2 Ma to an oblique extensional plate boundary, resulting in seafloor spreading and the transfer of the Baja Peninsula from North America to the Pacific (Karig and Jensky, 1972). Lastly, plate boundary configurations must be consistent with relative plate motions – for example, convergence between two plates must be accommodated by subduction or orogenesis, extension along rifts or mid-oceanic ridges, and conservation of crust along transforms.

We implement a new model for the intra-oceanic subduction in the NeoTethys, based on the models of Ali and Aitchison (2008), Zahirovic et al. (2012), Burg (2011) and recent data and interpretations from Bouilhol et al. (2013) to link the intra-oceanic subduction in the central NeoTethys involving the Kohistan-Ladakh arc system (i.e. ac-

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commodating India–Eurasia convergence) eastward to the Woyla back-arc along West Burma and Sumatra (Fig. 1). The Late Jurassic age of shallow marine sandstones from the Bantimala Complex on Western Sulawesi (Fig. 3), along with the Late Jurassic-Early Cretaceous (158–137 Ma) mafics on Western Sulawesi (Polvé et al., 1997), are assumed to indicate rifting from the Gondwana margin and the emplacement of ophiolites (i.e. crystallization ages). Accretion events are interpreted from the onset of ultra high pressure and temperature metamorphism indicative of collision, changes in the style of volcanism and the obduction of ophiolites (i.e. metamorphic ages). For Sundaland, the Meratus Suture in southeast Borneo and the Luk-Ulo Suture on Java (Fig. 3) record a mid- to late-Cretaceous accretion event, accompanied by ophiolite obduction and high pressure-temperature metamorphism (Wakita, 2000). The present-day geometry of this suture zone is delineated regionally using the distribution of ophiolites, previously-identified suture zone outcrops, gravity anomalies and high vertical gravity gradients that represent lithospheric-scale structures, mapped from the 1 min Sandwell and Smith (2009) gravity model (Figs. 5 and 6).

To determine the biogeographic affinity of Borneo with either Gondwana or Asia, we use the global open-access community Paleobiology Database, and extract all fossil occurrences in the Triassic and Jurassic. The sampled fossil collections are situated approximately within the Semitau block as described by Metcalfe (1996) (Figs. 2 and 7). A simplified oroclinal bending model of Sundaland was constructed interactively in *GPlates* (Fig. 8) by approximately reversing the opening of the Java Sea, following the 50 Ma onset of Makassar Strait rifting (Lee and Lawver, 1994), and assuming this rifting propagated westward to open the Java Sea (Doust and Sumner, 2007). The counter-clockwise rotation of Borneo ceases by 10 Ma as determined by the paleomagnetic study undertaken by Fuller et al. (1999). Although we acknowledge that there was a larger Cretaceous rotation of Sundaland, we confine our oroclinal bending between 50 and 10 Ma to produce the curved lineaments observed in the gravity anomalies of the region (Figs. 5 and 6). Present-day reference points are digitized where the curved lineaments intersect the Borneo coastline and assigned the motions of Borneo while

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Sumatra is held fixed. Borneo is then rotated so that the reference points follow the curvature of the lineaments to take the effects of crustal stretching during the opening of the Java Sea into consideration. Although such an approach utilizes the geometric constraints from the onshore structural fabric, future work would benefit from estimating stretching factors and numerical modeling of crustal deformation.

Our plate motion model, using the Seton et al. (2012) global model as a starting point, is constructed interactively in open-source and cross-platform plate reconstruction software, *GPlates* (http://www.gplates.org). The absolute reference frame underlying our global plate motions is a combination of a true-polar wander-corrected reference frame from 200 to 100 Ma and a moving Indo–Atlantic hotspot reference frame since 100 Ma. Tethyan spreading history has been revised following a re-interpretation of magnetic anomalies off the northwest Australian shelf (Gibbons et al., 2012) and the incorporation of rotations that account for full-fit reconstructions and continental deformation during rifting of Australia from Antarctica from ~ 160 to 83 Ma (Williams et al., 2011). Intersecting plate boundaries are created following Gurnis et al. (2012) at 1 Ma intervals to model the continuous evolution of the plate boundary system and enable global sampling of plate velocities. Resolved topological plate boundaries, block outlines and model rotation files, along with animations of a hemispherical and regional view and digitized regional geological features are included in the Supplement (Appendix B).

Subduction polarities are inferred from subduction-related volcanism on the overriding plate. Additionally, seismic tomographic models of the mantle are used to infer subduction histories for the Philippine Sea Plate and the New Guinea margin for the Cenozoic, due to the ambiguities in the geological data and the dominant influence of subduction on these margins during this time. Depth slices of slab material are age-coded using constant sinking velocities following Hafkenscheid et al. (2006) and Zahirovic et al. (2012), and assuming near-vertical sinking of slabs following Van Der Meer et al. (2010). Two end-member slab sinking scenarios are applied, with a stratified mantle with 3 and 1.2 $\mathrm{cm\,yr^{-1}}$ sinking rates in the upper and lower mantle,

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respectively, compared to a whole mantle sinking rate of 1.4 $cm\,yr^{-1}$ (Fig. 9). Although the assumptions of constant sinking velocity and vertical sinking of slabs are an over-simplification, the age-coding technique offers a first-order insight to the subduction history, which we limit to the Cenozoic due to the complexity of slab sinking and advection in the mantle. The *P* wave model of Li et al. (2008) incorporates stations from the Chinese Seismograph Network with global data collated by Engdahl et al. (1998), resulting in well-resolved slabs related to circum-Asian subduction zones. In addition, the GyPSuM *S* wave model from (Simmons et al., 2009) was used to aid observations of 3-D mantle structure and vertical cross-sections due to the better sampling of the mantle beneath oceanic regions and the Southern Hemisphere in order to avoid the land-coverage bias of *P* wave models (Figs. 10 and 11). Positive seismic velocity anomalies exceeding 0.2 % in *P* wave models are assumed to represent thermally-perturbed mantle resulting from subducted slabs following Van der Voo et al. (1999).

3 Plate tectonic model

Major terrane boundaries in southern Eurasia and SE Asia are marked by sutures (Fig. 1) where consecutive Tethyan ocean basins were consumed (see reviews by Şengör et al., 1988; Acharyya, 1998; Hutchison, 1989 and Metcalfe, 1994). The cyclicity of Gondwana terrane detachment is complemented by the cyclicity of intra-oceanic subduction preceding many of the accretion events, including the Permian back-arc basin forming the Sukhothai Zone (Metcalfe, 2011; Sone et al., 2012) associated with the closure of the PaleoTethys, and the Kohistan-Ladakh (Burg, 2011) intra-oceanic subduction systems of the Meso- and Neo-Tethys (Aitchison et al., 2000). That is why the present-day intra-oceanic subduction systems in the west Pacific (including the Izu-Bonin-Mariana and Tonga-Kermadec arcs) are often invoked as analogues for the intra-oceanic history of the Tethyan realm. On the Sundaland continental promontory, the Borneo core has previously been invoked as an extension of the Sibumasu and Sumatran terranes with Paleozoic and Mesozoic metamorphosed basement intruded

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by melts derived from subduction originating from the proto-Pacific in the Cretaceous (Katili, 1981; Charvet et al., 1994). However, the recent models of Metcalfe (2011) and Hall (2011, 2012) argue for a Late Jurassic–Early Cretaceous origin of the Borneo core from northwest Australia. We present an alternative scenario for the evolution of the Sundaland core in the context of plate reconstructions linking the transfer of terranes and the evolution of intra-oceanic subduction zones in the Tethyan and proto-Pacific domains.

3.1 Latest Jurassic rifting of terranes from northern Gondwana

Both Metcalfe (2011) and Hall (2012) propose that the latest Jurassic–Early Cretaceous rifting from northern Australia and New Guinea consisted of the Southwest Borneo core, East Java and West Sulawesi (i.e. Argoland), with the NeoTethys opening through back-arc spreading along northern Gondwana. The models invoke a north-dipping intra-oceanic subduction zone in the India–Eurasia segment as the "Incertus Arc" with simultaneous south-dipping subduction to form a back-arc along northern Gondwana that initiated the latest Jurassic rifting event that detached Argoland from the NW Australian shelf (Hall, 2012). In these models, and the model of Morley (2012), the Southwest Borneo core docks to Sundaland along a transform margin, presently the Billiton Depression (Figs. 2 and 5), to the east of Sumatra by ~ 110 Ma. The driving mechanism for anchoring Southwest Borneo to Sunda along a transform rather than accreting to eastern South China is not explained. In these models, East Java–West Sulawesi accrete to the Southwest Borneo core by ~ 90 Ma through short-lived south-dipping subduction along northern West Sulawesi. In the models of Metcalfe (2011) and Hall (2012), the Luconia–Dangerous Grounds continental block (presently underlying the Sarawak Basin) accretes to northern Borneo soon afterwards in the Cretaceous, which is disputed by Morley (2012).

Our preferred scenario invokes the onset of rifting along northern Gondwana in the latest Jurassic to Early Cretaceous, to open the NeoTethys and the Proto Molucca Sea (Table 1, Fig. 13b), propagating westward along New Guinea and into the NW Australian shelf (Figs. 12, 13 and 14). South Sulawesi, easternmost Borneo, Mangkalihat and portions of East Java are considered to be fragments that likely originated on the New Guinea or Argo Abyssal Plain margin. We model seafloor spreading along northern Gondwana (New Guinea and Northwest Australian shelf) from ~ 155 Ma (Fig. 13), as supported by a basaltic dyke and microgabbro associated with nearby pillow basalts on West Sulawesi (Figs. 1–3) that have an age range of 158–137 Ma (Polvé et al., 1997). Shallow marine sandstones of Late Jurassic age in the Bantimala Complex on West Sulawesi (Wakita, 2000), along with Jurassic-age ammonites, gastropods and brachiopods (Fig. 14) in the Paremba Sandstone (Sukamoto and Westermann, 1992; Wakita, 2000), indicate that West Sulawesi was an allochthon with Gondwana affinity. We acknowledge that the rifting may have initiated as early as 187 Ma along northern New Guinea (Cullen and Pigott, 1989), determined from the oldest passive-margin sediments, however, we rely on the West Sulawesi mafics that are likely direct indicators of the onset of seafloor spreading. East Java and Borneo are treated as a continuation of this continental fragment, as indicated by the present-day geometry of the Meratus and Luk-Ulo sutures on Sundaland. We infer that the rifting was initiated by the northward slab-pull of the Meso-Tethyan seafloor subducting northward along the Sundaland core leading to micro-continent detachment from northern Gondwana, following the mechanisms described by Müller et al. (2001).

As the strike of the NW Australian shelf and the New Guinea margin are approximately 120° to one another, we infer that a triple junction is likely necessary to accommodate the rifting westward into the Argo Abyssal Plain. It is difficult to determine the longevity and exact nature of this triple junction as the seafloor has been completely subducted. However, we invoke the simplest tectonic scenario to propagate rifting from the New Guinea to the NW Australian margin. We model the eastern boundary of the MesoTethys as a transform that accommodates extension and progresses to seafloor spreading to become the third arm of the NeoTethyan triple junction (Fig. 13). Instead of the West Burma block rifting to open to Argo Abyssal Plain as portrayed in the Seton et al. (2012) model, we invoke the separation of micro-continental fragments (potentially now in the Mawgyi and Woyla Nappes) using the seafloor spreading model of Gibbons et al. (2012). Although the Mawgyi Nappe obscures the basement rock, we assume that a Gondwana-derived terrane that supplied Timor with sediment from the northwest as interpreted by Metcalfe (1996) underlies this sedimentary cover, and is a westward extension of the contemporaneous, although controversial, micro-continental fragments found in the Sikuleh, Natal and Bengkulu areas on the Sumatra margin (Barber and Crow, 2003; Morley, 2012). We follow the model of Gibbons et al. (2012) that invokes continental block detachment in the Argo Abyssal Plain at ~ 155 Ma (Figs. 12 and 13), and we assume that these blocks collide with the Woyla intra-oceanic arc to drive the closure of the associated back-arc basin by the Late Cretaceous (Metcalfe, 2006). However, we acknowledge that East Java, West Sulawesi and Mangkalihat may have originated from the NW Australian margin rather than northern New Guinea (Fig. 13), as discussed in more detail below. Our kinematic model implies largely continuous subduction along the Sumatra and Java–Sunda trenches, with a ~ 10 Ma magmatic gap between ~ 75 and 65 Ma that can be accounted for assuming impeded subduction during the accretion of the Woyla arc and obduction of ophiolites onto Sumatra (Fig. 13b).

Perhaps through their shared pedigree, the models of Metcalfe (2011), Hall (2012) and Morley (2012) argue for a leaky transform plate boundary (i.e. "I-A Transform") approximately coincident with the continuation of the Ninetyeast Ridge (Fig. 1) in the NeoTethys to accommodate India–Eurasia convergence between 90 and 45 Ma without requiring subduction of the Australian plate along the Java–Sunda margin, which they argue does not record any significant volcanism during this time interval. Importantly, Hall (2012) rejects the possibility of any ridge intersections (namely the Wharton Ridge, Figs. 1 and 13b) with the Java–Sunda subduction zone and rejects the possibility of subduction along the eastern segment in the NeoTethys between 90 and 45 Ma. Instead, the model of Hall (2012) requires that up to 500 km of the Australian plate subducts beneath the Indian plate, or vice versa, between 75 and 55 Ma. This is likely a result of the choice of Euler rotations representing Australia–India–Antarctica breakup, as well as the effects of plate circuits and absolute reference frames. The Hall (2012) model uses motions of India and Australia based on the model of Royer and Sandwell (1989) that did not have the benefit of marine magnetic anomaly data collected over the last two decades, while our model is based on compilations of more modern data and re-interpretations of magnetic anomalies (Gibbons et al., 2013; Müller et al., 2008) and the consideration of continental stretching and deformation during initial Australia-Antarctica rifting (Williams et al., 2011). As a result, our model does not require any convergence between the Indian and Australian plates between 75 and 55 Ma, and instead seafloor spreading is accommodated on the now-extinct Wharton Ridge rather than convergence as required by the Hall (2012) model along the leaky I-A Transform that cuts across the pre-existing tectonic grain of oceanic lithosphere. The model of Seton et al. (2012) and earlier incarnations such as those presented by Gurnis et al. (2012) and Whittaker et al. (2007) portray continuous subduction of NeoTethyan oceanic crust along Java–Sunda, with the Wharton Ridge intersecting this margin in the early Eocene (Fig. 13b). Volcanic arc rocks on Sumatra have been documented by Cobbing (2005) with an age-range of 264 to 75 Ma (namely the Sibolga Batholith in north Sumatra), with a subsequent population with an age range of ~ 65 Ma to recent by Bellon et al. (2004), consistent with the synthesis of Sumatran volcanics by McCourt et al. (1996) when taking into account the errors in the radiometric ages. Such data suggests that a magmatic gap along the Sumatra and Java–Sunda margin may have existed between ~ 75 and 65 Ma (Fig. 14), but not for the entire duration between 90 and 45 Ma as argued by Hall (2012). Post-Cretaceous subduction along the Java–Sunda trench has established a volcanic arc, leading to the accretionary growth of eastern Java since the Eocene (Smyth et al., 2007).

3.2 Cretaceous plate boundary configurations linking the Tethys and proto-Pacific

Reconstructing the proto-Pacific is notoriously difficult due to the lack of preserved seafloor with reconstructions relying on assumptions of symmetrical seafloor spread-

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ing where single flanks of the spreading system are preserved (Seton et al., 2012) or evidence of compression or extension that may be recorded in the geology of the overriding plate (Hilde et al., 1977; Johnston and Borel, 2007; Li et al., 2012; Ruban et al., 2010). Linking the motions of the Pacific plate to the remaining plate circuit has also been a considerable challenge due to the added complexity of moving hotspots (O'Neill et al., 2005), ridge capture of plumes and the deflection of plume conduits resulting from mantle advection (Christensen, 1998; Tarduno et al., 2009), and the lack of preserved seafloor spreading linking the Pacific to the Indo–Atlantic plate circuit (Seton et al., 2012).

Two end-member scenarios exist that describe the link between the easternmost Tethys and western Panthalassa. The model of Seton and Müller (2008) and Seton et al. (2012) requires a westward-dipping subduction zone that defines the boundary between Panthalassa and the Junction Plate, an isolated seafloor spreading system forming the easternmost Tethyan domain. Alternative scenarios propose a continuation of the proto-Pacific mid-ocean ridge system (Audley-Charles, 1988; Hilde et al., 1977; Ben-Avraham, 1978). However, the westward-dipping subduction in the Cretaceous along eastern Asia (Seton et al., 2012; Hall, 2002; Hilde et al., 1977), implying westward motion of the Panthalassan seafloor, is kinematically-incompatible with northward-directed subduction of Tethyan seafloor along southern Eurasia without requiring a stable mid-oceanic ridge triple junction or a convergent boundary between the two tectonic domains. A mid-oceanic ridge triple junction would require numerous southward ridge jumps to maintain seafloor spreading across the Panthalassa–Tethys oceanic gateway. We follow the model of Seton et al. (2012) where convergence between the proto-Pacific and the MesoTethys is accommodated largely by westward dipping subduction along the Late Jurassic Junction Plate in the eastern Tethys (Fig. 13).

Our Meso-Tethyan triple junction in the easternmost Tethys remains active between 155 and 115 Ma, with the north-south striking spreading arm abandoned when the West Sulawesi–East Java terrane collide with the fore-arc of an eastward continuation of the intra-oceanic Woyla subduction zone. This collision timing is determined from the

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onset of high P/T metamorphism related to the closure of the Barito Sea (Wakita, 2000) (BAS, Fig. 13b). Rather than invoking the accretion of the Southwest Borneo core to Sundaland at this time as argued by Hall (2012), we prefer the accretion of easternmost Borneo, South Sulawesi, Mangkhalihat and East Java following the K–Ar dated ∼ 120–110 Ma metamorphic belts, associated with dismembered ophiolites, stretching along the southern Cretaceous paleo-margin of Sundaland (Parkinson et al., 1998) that outcrop in the Luk-Ulo and Meratus sutures (Figs. 1 and 2). The Meratus Ophiolite was likely obducted between ∼ 100 and 93 Ma, in the Cenomanian (Yuwono et al., 1988), and final closure and suturing of the Barito Sea along the southeastern margin of the Borneo core occurs by 80 Ma based on the U–Pb dated zircons in fore-arc sandstones (Clements and Hall, 2011; Wakita, 2000). The collision of the Gondwana-derived terranes with the Southeast Asia margin is asynchronous, with progressive accretions westward. Intra-oceanic collisions occur by 100 Ma in the Woyla (Fig. 13b), associated with the obduction of the Chin Hills and Naga Ophiolites (Morley, 2012), with renewed subduction and forearc emplacement likely forming the Andaman Ophiolite at 95 ± 2 Ma in a supra-subduction zone setting (Pedersen et al., 2010). We invoke continuous north-dipping subduction of Tethyan oceanic crust following Guntoro (1999), to produce the large mid-mantle slabs observed in tomography (M/N-T, Figs. 10 and 11a and b) and previously described by Van der Voo et al. (1999). However, Morley (2012) invokes south-dipping subduction of Woyla back-arc beneath Tethyan oceanic crust prior to collision of the continental fragments. We prefer continued north-dipping subduction of Tethyan crust resulting in slab-pull necessary for the northward motion of the Indo-Australian plates, following the trend of subduction polarities in the central Meso- and Neo-Tethys (Aitchison et al., 2000; Ali and Aitchison, 2008; Van der Voo et al., 1999).

3.3 Intra-oceanic subduction in the Meso- and Neo-Tethys

The evolution of the NeoTethyan subduction zone along southern Eurasia has been a source of continued controversy as to whether this margin was a long-lived Andean-type margin or whether it included back-arc opening and intra-oceanic subduction episodes (Aitchison et al., 2000, 2007; Zahirovic et al., 2012). Recent fieldwork has revealed remnants of Cretaceous intra-oceanic subduction in the Indus-Tsangpo suture zone (Aitchison et al., 2000; Davis et al., 2002; Ziabrev et al., 2004). However, plate motion models tend to differ in key areas, including (1) the subduction polarities, (2) the number of active subduction zones bounding southern Eurasia, and (3) the tectonic driving forces related to the opening and closure of the proposed back-arc basins. Previous studies argued for Shyok Suture (Karakoram-Kohistan) closure in the Late Cretaceous, between 102 and 75 Ma, well before the approach of India to the Eurasian margin (Molnar and Tapponnier, 1975; Petterson and Windley, 1985; Beck et al., 1995; Rowley, 1996; Bignold and Treloar, 2003) based on the review of Rehman et al. (2011). Subduction beneath Kohistan was interrupted between ~ 95 and 85 Ma, and was replaced by arc rifting (Burg, 2011), suggestive of a new pulse of back-arc generation in the NeoTethys at this time, much like the multi-phase back-arc generations in the Mariana arc system on the eastern margin of the Philippine Sea Plate (Sdrolias and Müller, 2006; Sdrolias et al., 2004). The cessation of magmatism by ~ 61 Ma and paleo-latitude estimates from paleomagnetic data on Kohistan led Khan et al. (2009) to conclude that India first collided with the Kohistan arc. Such a scenario would require the Shyok Suture to be closed sometime in the Early Eocene (Burg, 2011; Heuberger et al., 2007), much later than the established argument for Late Cretaceous suturing. A recent isotopic study by Bouilhol et al. (2013) of granitoids on Kohistan and Ladakh indicate that the leading edge of Greater India likely collided with this island arc at 50.2 ± 1.5 Ma, while the Shyok Suture closed much later than previous estimates at 40.4 ± 1.3 Ma rather than Cretaceous times.

The ~ 85 Ma event in the central NeoTethys is contemporaneous with other collisional events in the eastern Tethys, namely the collisions of Argoland (Mawgyi, Sikuleh and related blocks?) with the Woyla intra-oceanic arc, and the accretion of Eastern Java and West Sulawesi terranes to Sundaland (Hall, 2011, 2012; Metcalfe, 2011; Morley, 2012). The Woyla terranes (Fig. 13b), which sutured to Sumatra in the Late Creta-

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ceous displays both intra-oceanic subduction (Wajzer et al., 1991; Barber and Crow, 2003) and Gondwana-derived affinities (Metcalfe, 1996) and therefore suggests that intra-oceanic subduction extended further east of the India–Eurasia convergence zone in the Meso- and Neo-Tethys. It has previously been suggested that the intra-oceanic subduction and related back-arc were closed as a result of the collision of a number of micro-continents, including the Sikuleh, Natal, Lolotoi and Bengkulu blocks, with subsequent suturing to Sumatra (Acharyya, 1998; Metcalfe, 1996). However, the continental nature of these blocks has been disputed to instead suggest an intra-oceanic island arc origin for these blocks (Barber and Crow, 2003; Wajzer et al., 1991). Existing models of northern Gondwana rifting episodes depict the detachment of Argoland in the Late Jurassic to close the Woyla (or Incertus) back-arcs in the Late Cretaceous (Hall, 2012; Heine et al., 2004; Metcalfe, 2011). However, these models disagree both on the block's origin and destination (Table 3), with contrasting present-day candidates including West Burma (Heine and Müller, 2005) or Southwest Borneo and East Java (Hall, 2012; Metcalfe, 2011). Although it is possible that West Burma originated from the NW Australian shelf, we prefer that it accretes to Eurasia in the Triassic (Metcalfe, 2011). Following the model of Gibbons et al. (2012), we implement the detachment of Argoland micro-continental fragments that result in accretion along the West Burma and Sumatra portion of the Woyla intra-oceanic arc. However, as discussed below, East Java and easternmost Borneo may be alternative candidates for the enigmatic Argoland block.

3.4 The evolution of the Philippine Archipelago and Philippine Sea Plate

The east and west Philippine Archipelago (EPA and WPA, Fig. 13a), forming the western boundary of the Philippine Sea Plate, is a mosaic of ophiolite exposures (Encarnación, 2004; Pubellier et al., 2004), active and extinct volcanic arcs and is dissected by a lithospheric-scale sinistral wrench Philippine Fault (Fig. 2) that has been active since at least ~ 4 Ma (Barrier et al., 1991). However, evidence for wrench faulting in the Late Cretaceous also exists, suggesting an older pre-existing feature (Encarnación,

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2004). To the east of the Philippine Fault, the archipelago and its northward continuation into eastern Luzon forms the active volcanic arc at which the West Philippine Basin is subducted along a west-dipping subduction zone (Lee and Lawver, 1995). To the west of the Philippine Fault, dismembered ophiolites show supra-subduction zone affinities in the south, while in the area of Mindoro and Palawan, the ophiolites indicate more-precisely Eurasian supra-subduction zone affinities (Encarnación, 2004). Therefore, the archipelago holds vital clues on the geodynamic evolution of the east Asian margin and western proto-Pacific, and their link to the Tethyan tectonic domain.

The synthesis of Philippine and Luzon ophiolites by Encarnación (2004) suggests that much of the archipelago is underlain by supra-subduction ophiolites emplaced in the latest Jurassic and Early Cretaceous (Fig. 15), with the Lagonoy Ophiolite yielding the oldest ages derived from a meta-leucodiabase of 156 ± 2 Ma amphibole $^{40}Ar/^{39}Ar$ plateau age and a meta-gabbro yielding a 151 ± 3 Ma age (Geary et al., 1988; Geary and Kay, 1989), representing the oldest rocks sampled from the Philippines Archipelago. The Calaguas Ophiolite is slightly younger, but the $^{40}Ar/^{39}Ar$ isochron age of $\sim 100 \pm 7$ Ma represents a minimum age (Geary et al., 1988), with pillow basalts of mid-oceanic ridge and back-arc basin affinities that may have formed as a back-arc to the Lagonoy Ophiolite (Encarnación, 2004). Further south, dolerite dykes found on Halmahera record a K–Ar age of 142 ± 4 Ma on Gag Island, wile arc rocks on Obi Island yield K–Ar ages of 100 ± 4 Ma, suggestive of continuous arc activity in the Early Cretaceous (Hall et al., 1995b), leading Encarnación (2004) to suggest that the archipelago formed through successive ophiolite emplacements through back-arc spreading along pre-existing Late Jurassic crust.

Other Late Cretaceous ophiolites, including the Dibut Bay (minimum age of 92 ± 0.5 Ma; plateau age of amphibolite metamorphism), Casiguran (87 ± 6 Ma; K–Ar) and Montalban (Late Cretaceous; biostratigraphy) ophiolites are comparable (Billedo et al., 1996) and may have formed as a result of subduction initiation and back-arc creation along the Calaguas ophiolitic crust (Encarnación, 2004). The Late Cretaceous ages of some Philippine ophiolites mark the onset of volcanism associated with the Daito

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Ridge, Minami-Daito Basin and the Oki-Daito Ridge with an age range of ~ 85 to 49 Ma and rocks in the vicinity of the Amami Plateau yield ages of ~ 85 to 60 Ma (Honza and Fujioka, 2004). Geochemical analyses of the rocks indicate that the Daito Ridge is a subduction-related arc feature, while the Oki-Daito Ridge has closer mid-ocean ridge basalt and seamount affinities (Honza and Fujioka, 2004; Matsuda, 1985; Tokuyama, 1995).

We follow the interpretation of Encarnación (2004) that eastern Luzon, the eastern Philippine Archipelago and at least Obi and Gag islands near Halmahera formed in a supra-subduction setting (i.e. back-arc) initiating in the latest Jurassic. We implement the origin of these fragments near the northeastern Gondwana margin, related to the northward transfer of eastern Borneo, Mangkalihat, West Sulawesi and East Java (Fig. 12). This "proto" Philippine Plate forms a back-arc resulting from proto-Pacific slab rollback, opening between ~ 155 and 115 Ma (Fig. 13b). The collision of the West Sulawesi continental fragments with an intra-oceanic subduction zone at 115 Ma ceases spreading in the proto Philippine Plate. By 85 Ma, the west-dipping subduction polarity reverses, resulting in the subduction of the proto Molucca and Philippine plates, resulting in the transfer of the embryonic fragments of Luzon, eastern Philippine Archipelago and Halmahera onto the Pacific Plate. North-east dipping subduction along this margin produces the Daito Ridge and Amami Plateau crust, and progresses to back-arc opening to produce the crust older than Anomaly 24 (~ 53 Ma) in the West Philippine Basin (Fig. 2), largely following the model proposed by Honza and Fujioka (2004) and Queano et al. (2007).

Intricately linked to the Cretaceous plate boundary between the Tethys and the Pacific is the subsequent formation of the West Philippine Basin in the earliest Cenozoic. Seafloor spreading in the Central Philippine Basin initiated at Anomaly 24 (Fig. 2, ~ 53 Ma), with a significant change in seafloor spreading direction at Anomaly 20 (~ 44 Ma) in the West Philippine Basin with active spreading continuing until ~ 35 Ma (Hilde and Chao-Shing, 1984). Seafloor spreading ceased in the West Philippine Basin at this time, and west-dipping subduction along its eastern margin initiated back-arc

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rifting in the Parece Vela and Shikoku basins along the Izu-Bonin-Marianas arc from ~ 30 Ma (Sdrolias and Müller, 2006). Whether Luzon moved with and developed on the Philippine Sea Plate has been controversial, with Hall (2002) implying an autochthonous origin on the east Asian margin while Deschamps and Lallemand (2002), Queano et al. (2007), Lee and Lawver (1995) and Milsom et al. (2006) prefer an allochthonous origin along a continuous Eastern Philippine Arc, growing on the southern margin of the West Philippine Basin resulting from northward-dipping NeoTethyan subduction. Onset of magmatism on Luzon is synchronous to magmatic episodes on Halmahera in the early Cenozoic (Queano et al., 2007), suggesting that Luzon was allochthonous to the east Asian margin. Although not entirely conclusive, paleo-latitudinal estimates suggest north-eastern Luzon was slightly south of the equator between ~ 50 and 30 Ma (Queano et al., 2007). In contrast, Mindoro and portions of Luzon and the western Philippine Arc indicate east Asian affinities and a formation autochthonous to the east Asian margin (Rangin et al., 1985; Yumul Jr et al., 2003).

We largely follow the model of Queano et al. (2007), Deschamps and Lallemand (2002) and Seton et al. (2012) for the evolution of the Philippine Sea Plate, with both north-dipping subduction consuming the Australian Plate and southwest-dipping subduction consuming the Pacific Plate, to open the West Philippine Basin between ~ 55 and 33 Ma. We invoke that a pre-existing transform fault on the eastern margin of the Philippine Sea Plate converts to a subduction zone resulting from a change in relative plate motions, triggering the onset of southwest-dipping subduction of Pacific crust at ~ 55 Ma. The initiation of this subduction zone (i.e. the Proto Izu-Bonin-Mariana Arc) may result in a plate reorganization event that is observed in the bends of volcanic island chains, notably the contemporaneous Louisville and Hawaiian-Emperor bends (Hall et al., 2003). Northeastern Luzon forms on the Philippines southern intra-oceanic arc, while westernmost Luzon develops on the east Asian margin in the vicinity of Mindoro. The relative positions of the Philippine Sea Plate with the Eurasian, Pacific and Australian plates is notoriously difficult to constrain resulting from the long-lived Cenozoic subduction on the margins of the Philippine Sea Plate (Hall et al., 1995b). Fuller et al. (1983), Haston and Fuller (1991) and Hall et al. (1995b) have used paleomagnetic data to constrain the latitudinal and rotational motion of the Philippine Sea Plate. However, the rotational history derived from scarce paleomagnetic data can indicate the rotation of individual blocks rather than whole-plate rotation, as is exemplified by the conflicting rotation histories from Luzon (Fuller et al., 1991). The study of Haston and Fuller (1991) suggested up to 80° of clockwise (CW) rotation of the Philippine Sea Plate since the Eocene, while the Hall et al. (1995b) model requires a whole-plate 50° CW rotation between ~ 50 and 40 Ma, no rotation between ~ 40 and 25 Ma, followed by 35° CW rotation between ~ 25 and 5 Ma. Additionally, the paleomagnetic data indicates largely Southern Hemisphere low latitudes in the Cenozoic (Hall et al., 1995a, b), however the data is confined to the southwestern extremity of the Philippine Sea Plate in the vicinity of Halmahera. It is questionable whether Halmahera and nearby Indonesian islands are part of the Philippine Sea Plate and therefore represent the rotational history of the entire plate. The synthesis of present-day plate boundaries using seismological evidence by Bird (2003) indicates active subduction zone west and east of Halmahera, isolating Halmahera from the Philippine Sea Plate. The eastern subduction zone along Halmahera (as the continuation of the Philippine Trench) likely initiated in the late Miocene (Lee and Lawver, 1995) and propagated southward to consume Philippine Sea crust, resulting in a west-dipping slab (PSP, Fig. 11f and g). In addition to the conflicting rotation histories, paleomagnetic data cannot be used to infer the longitudinal position of the Philippine Sea Plate due to the radially-symmetrical magnetic field (see Torsvik et al., 2008).

We use the paleomagnetic estimates from Hall et al. (1995b) and the seafloor spreading histories within the Philippine Sea Plate from Müller et al. (2008) and Sdrolias et al. (2004), and then calibrate the subduction zone locations on the periphery of the Philippine Sea Plate with age-coded slab material for the Cenozoic (Fig. 9). We age-code slab material based on an assumption of constant sinking velocities, as a first-order estimate, in the upper and lower mantle, of 3 and 1.2 $cm\,yr^{-1}$ vertical sinking, respectively, following Hafkenscheid et al. (2006) and Zahirovic et al. (2012).

This method is appropriate because the Philippine Sea Plate cannot be linked to the Eurasian, Indo-Australian or Pacific plate circuits as it is almost entirely bound by subduction zones during the Cenozoic. However, we acknowledge that age-coding of slabs is likely an oversimplification assuming vertical and constant sinking rates, where slab sinking rates are likely variable along-strike due to the oblique convergence vectors in this region (Sdrolias and Müller, 2006). We prefer the stratified mantle sinking scenario, with 3 and 1.2 $cm\,yr^{-1}$ sinking in the upper and lower mantle, respectively, compared to a whole-mantle sinking rate of 1.4 $cm\,yr^{-1}$ based on the reconstructed position of the Java–Sunda trench that we did not fine-tune using seismic tomography. In fine-tuning the absolute motion of the Philippine Sea Plate, we attempted to preserve the convergence with the Indo-Australian Plate, while simultaneously accommodating the opening of the Parece Vela and Shikoku basins from the rollback of the Pacific slab, resulting in a west-dipping slab observable in seismic tomography (PAC, Fig. 11d–g). Our resulting model invokes CW rotation of the Philippine Sea Plate between ~ 45 and 35 Ma, followed by little to no rotation between ~ 35 and 25 Ma. Our reconstructions invoke CCW rotation between ~ 25 and 15 Ma, followed by CW rotation to present-day, which is differs from the estimates from Hall et al. (1995b). Testing alternative rotation histories of the Philippine Sea Plate and the assumption of constant and vertical sinking rates can be achieved with global numerical models of subduction, where the present-day prediction of slab material can be validated using observations from a suite of seismic tomographic models.

3.5 The origin of the Caroline Plate

An independent Caroline Plate was first suggested by Weissel and Anderson (1978), with Bird (2003) identifying the nature of the plate boundaries using more recent data to infer relative plate velocities from seafloor spreading histories and present-day moment tensor solutions. To the west, the Caroline Plate is bound by the Ayu Trough (Figs. 1 and 15), representing a seafloor spreading system between the Philippine Sea and Caroline plates (Bird, 2003; Weissel and Anderson, 1978). The Sorol Trough, largely a

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transform boundary at present-day (Bird, 2003), accommodates the east-west relative motion with the Pacific and embryonic east-dipping subduction of the Caroline Plate along the Mussau Trench (Figs. 1 and 15). Interpretations of magnetic lineations in the Eastern Caroline Basin suggest active seafloor spreading occurred on the Kiilsgaard Trough between Anomalies 13 and 9 (~ 33.5 and ~ 27 Ma, respectively) based on the model of Weissel and Anderson (1978). Reinterpretation of the magnetic anomalies by Gaina and Müller (2007) identified Anomalies 8n to 15r (35 to 26 Ma, respectively) in the East Caroline Basin, and Anomalies 8r to 16n (36 to 26 Ma, respectively) in the West Caroline Basins, separated by the hotspot-modified Eauripik Ridge (Altis, 1999) that acted as a transform boundary between the eastern and western spreading systems. The model of Hall (2002) invokes Caroline Plate origin from rollback induced back-arc formation along the Palau-Kyushu Ridge (proto-Izu-Bonin-Mariana Arc) on the eastern boundary of the Philippine Sea Plate from ~ 40 Ma, while the model proposed by Altis (1999) suggests a Pacific origin. The Pacific origin model assumes that the Sorol Trough was originally a fracture zone (Altis, 1999), with slab-pull related tensile forces acting on the plate resulting in a tear of the Pacific plate and initiating seafloor spreading to accommodate Caroline Plate formation. The initial necking that led to rifting has also been suggested to be hotspot-related, resulting in the gravitational and topographic anomalies of the Sorol Trough and the Caroline Ridge. The initiation of Caroline Plate subduction in the north-west along the Palau Trench and Yap Trough (Figs. 1 and 15), bounding the Philippine Sea Plate, and the approach of the Caroline Plate with the leading edge of the Australian plate resulted in the counter-clockwise rotation of the Caroline Plate and the onset of seafloor spreading in the Ayu Trough from ~ 15 Ma (Gaina and Müller, 2007).

We largely follow the Hall (2002) and Gaina and Müller (2007) models for the Caroline Plate formation on the eastern boundary of the Philippine Sea Plate, but acknowledge that the Caroline Plate may have had a Pacific origin as proposed by Altis (1999). The Mussau Trench was originally a transform, accommodating the rollback and seafloor spreading within the Caroline Plate from ~ 45 Ma, and became a west-dipping subduction zone consuming Pacific crust from ~25 to 4 Ma to accommodate convergence between the Pacific and Caroline seafloor (PAC, Fig. 11e). In the last 1 Ma, the Mussau Trench reversed subduction polarity to consume Caroline Plate crust at an east-dipping subduction zone (Fig. 1, MUS in Fig. 11e). We model the origin of the intra-oceanic Torricelli-Finisterre arc on the southern margin of the Caroline Plate that collides progressively with northern New Guinea from ~6 Ma.

3.6 Post-Late Cretaceous accretion and rift histories of the north New Guinea margin

The New Guinea margin, as the leading edge of the Australian continent, has undergone collisional and extensional episodes related to the complex convergence of Australian, Eurasian and (proto-) Pacific plates. The arc-continent collisions and accreted terranes on northern New Guinea have uplifted margin-parallel mountain chains and obducted ophiolite belts (Baldwin et al., 2012; Abbott et al., 1994) (Figs. 1 and 15). Although no seafloor spreading history exists between the core of New Guinea and the accreted terranes, a number of Cretaceous and Eocene sedimentary units record oscillations between a convergent setting to an extensional passive margin, terminated by ophiolite obduction events (Cullen et al., 2012; Baldwin et al., 2012; Pigram et al., 1989). The youngest accretionary event is related to the arc-continent collision of the Finisterre–Torricelli terranes (Figs. 1, 13 and 15) with the New Guinean continental crust, beginning at ~3.7 Ma in the northwest Finisterre Ranges and propagating towards the southeast (Abbott et al., 1994). The Ramu-Markham Fault (Fig. 15) that is the remnant of the north-dipping subduction zone between the accreted arcs and mainland is largely a strike-slip system on land, while its oceanward continuation to the east forms the active New Britain Trench along which the (proto-) Solomon Plate is being subducted (Baldwin et al., 2012; Cullen and Pigott, 1989). The Finisterre–Torricelli arc likely formed at an intra-oceanic subduction setting on the southern margin of the Caroline Plate, with the Finisterre Volcanics yielding Oligocene to Early Miocene ages (Baldwin et al., 2012). In addition, Cretaceous-age plutons found in the Torricelli

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Mountains suggest that the arc system may be much older and overprinted by younger subduction-related volcanics (Cullen and Pigott, 1989). The Torricelli Intrusive Complex yields ages of 75 to 70 Ma based on K–Ar methods, followed by an Eocene episode of emplacement from between 42 and 18 Ma (Klootwijk et al., 2003). South of the Torricelli-Finisterre terranes, the Sepik terrane is the single largest accreted block representing an older collisional system with both continental and intra-oceanic island arc affinities (Klootwijk et al., 2003). Cooling histories derived from K–Ar thermochronology indicates that the Sepik terrane accreted to northern New Guinea between 27 and 18 Ma, while a later peak at 6 Ma likely represents the arrival of the Torricelli-Finisterre arc terrane onto the margin (Crowhurst et al., 1996). The paleomagnetic model from Klootwijk et al. (2003) suggests that the Sepik terrane was at $\sim 20^{\circ}$ S during the Mid–Late Eocene, along which Australian oceanic floor was subducting at a north-dipping subduction zone.

We model the rifting of embryonic portions of Sepik from New Guinea in the Late Cretaceous (from ~ 80 Ma), consistent with the Campanian–Maastrichtian (83.6 to 72.1 Ma) timing proposed by Hill and Hall (2003). The mechanism for this rifting is uncertain, with either slab-pull from north-dipping subduction of the Proto Molucca Plate at an Asia-Pacific subduction zone or south-dipping subduction along Sepik resulting in back-arc opening and detachment of continental material. We prefer north-dipping subduction of the Proto Molucca Plate (Fig. 13b and PMOL in Fig. 11d and e), consistent with the contemporaneous northward subduction of the NeoTethyan oceanic crust. We propose that the ophiolitic basement underlying the Sula Spur (east Sulawesi) may have originated from the Late Cretaceous seafloor spreading adjacent to the west of Bird's Head that connected the Sepik Plate mid-oceanic ridge to the NeoTethyan Wharton Ridge (Fig. 13b).

Our scenario requires that the Maastrichtian (72.1 to 66 Ma) Emo volcanics (Worthing and Crawford, 1996), and potentially the Late Cretaceous Torricelli Intrusive Complex, to be emplaced in a Pacific-derived back-arc (Fig. 16), southeast of the Philippine Arc, rather than a back-arc along Sepik. The northward advance of New Guinea and

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the southward rollback of Proto Molucca crust results in eventual accretion of the Emo volcanics and associated ophiolites onto the leading edge of New Guinea, which is supported by the north-dipping Owen Stanley Fault on the southern margin of the Emo metamorphics and volcanics. Published ^{39}Ar/^{40}Ar amphibolite ages for the Emo metamorphics of 35 to 31 Ma have been linked to a collision and the emplacement of the Papuan ophiolite (Worthing and Crawford, 1996) onto New Guinea. The seafloor separating Sepik from New Guinea is consumed along a north-dipping subduction zone from ∼ 50 Ma (Baldwin et al., 2012; Ryburn, 1980), with collision and suturing to New Guinea occurring diachronously from 27 Ma in the west and 16 Ma in the east based on cooling histories of exhumed blocks (Crowhurst et al., 1996). The obducted seafloor forms part of the April Ultramafic Belt in New Guinea (Baldwin et al., 2012). However, this north-dipping subduction polarity is also disputed, and may have been south-dipping. We implement north-dipping subduction in order to provide the necessary northward slab-pull on the Australian plate during this time to drive Antarctica–Australia seafloor spreading (Williams et al., 2011). By 23 Ma the leading edge of the Australian plate was interacting with the Sundaland margin, with the collision of Southeast Sulawesi and the Sula Spur with the Sunda trench and West Sulawesi (Hall, 2002, 2012). The Finisterre-Torriceli Arc is generated through Pacific slab-rollback along the Caroline trench during the Eocene. The intervening seafloor between the Sepik and Finisterre-Torriceli terranes, the westward portion of Solomon Plate (SOL, Fig. 13b), is consumed at a north-dipping subduction zone, with arc-continent collision propagating eastward from 6 to 3 Ma based on another peak in collision-related exhumation (Baldwin et al., 2012; Crowhurst et al., 1996). The Banda Embayment develops through slab-rollback to consume the Jurassic crust from 9 Ma (Hall, 2012; Hinschberger et al., 2005), leading to the present-day configuration of plate boundaries accommodating continued convergence between Eurasia, Australia and the Pacific.

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3.7 The evolution of northern Sundaland and the opening of the South China Sea

The origin of the Borneo core, namely Southwest Borneo is disputed, with some studies proposing a South China autochthonous origin (Ben-Avraham and Uyeda, 1973), while more recent studies argue for an Early Cretaceous origin of the Borneo core from northern Gondwana (Hall, 2012; Metcalfe, 2011) to dock with Sundaland in the Late Cretaceous along the Billiton Depression (Figs. 2 and 5). However, neither Metcalfe (2011) or Hall (2012) present any paleomagnetic evidence to support a Southern Hemisphere origin of the Borneo core in the Early Cretaceous. Instead, the continuity of the Fukien–Reinan volcanic belt and the Danau Formation along the South China margin (Fig. 7) and inside the Borneo core has been invoked to represent a continuous Andean-style Proto Pacific subduction zone in the Mesozoic (Charvet et al., 1994; Honza and Fujioka, 2004), and the tectonic affinity of Borneo with South China (Ben-Avraham and Uyeda, 1973). Paleomagnetic analysis of Schwaner zone plutonic rocks by Haile et al. (1977) indicates that Borneo was largely fixed to the Malay Peninsula at near-equatorial latitudes as part of Sundaland with a counterclockwise rotation of 50° since the mid Cretaceous. The mostly-granitic rocks analyzed had age ranges from the Middle Jurassic to the Late Cretaceous, with the Schwaner granitoids largely yielding ages ranging between 116 and 76 Ma (Haile et al., 1977), based on whole-rock K–Ar methods. Similar ages ranging between 112 and 77 Ma have been reported from islands in the vicinity of the Natuna paleo-subduction zone (Bignell, 1972; Haile and Bignell, 1971; Haile et al., 1977; Kirk, 1968), indicating continuity of the magmatic arc along Borneo and into the Indochinese continental margin. A Jurassic pole, corrected for structural tilt, from Tiong Cihan sediments, within the synthesis of Fuller et al. (1991), with an inclination of 2.4° indicates a paleo-latitude of $\sim 0.43°$ (N/S) following van Hilten (1962) and suggests a near-equatorial position of the southwest Borneo core rather than high southern latitude position on the Gondwana margin.

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The Late Cretaceous is a time of considerable change along the east Asian margin, with the cessation of magmatism and the onset of extension along southeast China by ~ 90 Ma (Li, 2000). This event has previously been linked to the intersection of Izanagi-Pacific mid-oceanic ridge with the east Asian subduction zone (Ben-Avraham, 1978), leading to a hiatus in subduction due to the buoyancy of young crust on the eastern flank of the mid-oceanic ridge. However, the model of Seton et al. (2012) prefers the intersection of this ridge with the east Asian trench in the Eocene, between 55 and 50 Ma, to account for the plate reorganization in the Pacific. Therefore, the Late Cretaceous onset of extension along the east Asian margin is likely a result of Izanagi plate slab-rollback (Li et al., 2012) rather than ridge intersection with the margin.

The South China Sea plays an important role in recording the evolution of Sundaland, and is well studied due to its hydrocarbon potential. A number of NNE–NE trending basins adjacent to the South China margin (Fig. 17a) record at least two major phases of rifting (Fig. 18) – with an early rift phase during the Late Cretaceous–Early Eocene followed by another phase from the Middle Eocene to Early Oligocene (Ren et al., 2002; Hayes and Nissen, 2005). The earliest phase has been linked to the opening of the Proto South China Sea in either a back-arc setting (Honza and Fujioka, 2004; Li, 2000; Zhou et al., 2008) or slab-pull induced microcontinent detachment from subduction along northern Borneo (Deschamps and Lallemand, 2002; Doust and Sumner, 2007). The Late Cretaceous east Asian margin records a significant shift from convergent to extensional setting with cessation of volcanism at the continental Andean-style margin by ~ 90 Ma (Jahn et al., 1976), marking the switch from Andean-style subduction to resemble the modern western Pacific setting (Li, 2000; Li et al., 2012). Northern and central Mindoro in the Philippine Archipelago records metamorphism that is older than Late Cretaceous based on the ages of units overlying the metamorphic basement (Sarewitz and Karig, 1986; Yumul et al., 2009), and as old as Late Paleozoic based on Sr compositions found in marble samples (Knittel and Daniels, 1987). The Zambales Ophiolite on westernmost Luzon, comprised of arc and back-arc assemblages, indicates Eocene ages (based on the sediments overlying the ophiolitic basement) and

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quartz-rich schists that are not found elsewhere on Luzon, suggesting an exotic origin with a metamorphosed continental protolith originating from the South China margin and affinities with continental rocks from Mindanao, Panay and Palawan (Hawkins and Evans, 1983). The Amnay Ophiolite on Mindoro has an emplacement age of 59 Ma from K–Ar dating of hornblende separates (Faure et al., 1989) while the nearby correlatable Sibuyan Ophiolite shows back-arc affinities (Dimalanta et al., 2006; Yumul et al., 2009), suggesting that they likely formed in a Paleocene back-arc setting and adjacent to Paleozoic basement, likely on the South China continental margin. The Semitau continental fragment in Borneo, located between the Boyan and Lupar sutures, may be a candidate for a continental fragment originating on the South China continental margin (Metcalfe, 1996) that is detached by back-arc rifting with continued rollback transferring it to northern Borneo to open the Proto South China Sea in the latest Cretaceous, analogous to the mechanism proposed for the Apennines–Tyrrhenian system in the Mediterranean (Doglioni, 1991; Rehault et al., 1987). For the successor of the Proto South China Sea, the models of Doust and Sumner (2007) and Tongkul (1994) imply south-dipping subduction along northern Borneo by the Eocene that triggers rifting and renewed micro-continent detachment from the South China margin to open the South China Sea. Alternatively, the model of Schlüter et al. (1996) invokes back-arc rifting and extension of the Dangerous Grounds, Reed Bank, Palawan and West Mindoro continental blocks that rifted from mainland China in the Late Cretaceous–Eocene.

We implement the opening of the Proto South China Sea from ∼ 65 Ma (Figs. 13b and 17b), with back-arc rifting along South China to separate the Semitau Block from the mainland and account for the incipient opening of the Beibu Gulf (Beibuwan Basin, Fig. 17b) in the Maastrichtian (∼ 72.1 to 66 Ma) (Clift and Lin, 2001). The back-arc scenario is consistent with the onset of an extensional east Asian margin in the Late Cretaceous (Li, 2000) and the back-arc affinity of ophiolites emplaced at ∼ 59 Ma found on Mindoro (Yumul et al., 2009). The onset of tectonic subsidence on the east Asian basins from ∼ 65 Ma (Lin et al., 2003; Yang et al., 2004) is used as a proxy for the onset of back-arc rifting (Fig. 18). We propose that Mindoro and Palawan were rifted from

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mainland South China in the latest Cretaceous, with seafloor spreading being established in the back-arc by 59 Ma to emplace the Sibuyan and Amnay ophiolites, which were later obducted and accreted to Luzon (Fig. 15). We model the detachment of the Semitau Block from the South China margin at this time through back-arc rifting, based on the biological affinities between Triassic and Jurassic fossil assemblages on Semitau with the South China (Fig. 7). This scenario is consistent with the interpretation of Metcalfe (1999) that the Semitau Block shows Cathaysian biological affinities and detached from South China or Indochina in the Cretaceous or Cenozoic. Thus the Boyan Suture is likely Eocene in age, related to the Sarawak Orogeny on Borneo and the accretion of Semitau, while the Lupar Line is related to the south-dipping subduction and closure of the Proto South China Sea accompanied with the northward-younging Rajang Accretionary Complex on Sarawak (Hutchison, 1996). The collision and incipient subduction of Dangerous Grounds–Reed Bank microcontinents and suturing occurred at ∼ 16 Ma to close the Proto South China Sea and result in the cessation of seafloor spreading in the South China Sea (Briais et al., 1993), based on collisional unconformity and regional deformation (Hutchison, 2004). We interpret that a slab at depths shallower than ∼ 1000 km beneath the South China Sea represents the south-dipping subduction of the Proto South China Sea (PSCS, Fig. 11e–g). Our scenario requires that the Dangerous Grounds, and associated Reed Bank and northern Palawan, continental blocks to collide with Borneo in the Miocene rather than the Cretaceous age proposed by Hall (2012). A younger age for this event is supported by seismic studies of these continental fragments (Schlüter et al., 1996), derived from South China during the opening of the South China Sea, and previously-proposed kinematic models of the region (Clift et al., 2008; Sarewitz and Karig, 1986; Soeria-Atmadja et al., 1999; Tongkul, 1994).

Sundaland played an important role in the extrusion tectonics of SE Asia resulting from the northward impingement of Eurasia by India (Tapponnier et al., 1982). The stability of Sundaland during post-collisional times has been investigated using paleomagnetic evidence suggesting distributed block rotations (Hall et al., 2008; Fuller et al.,

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1999) along a complex network of strike-slip and oblique faults in the region. Much of the extrusion was accommodated along large shear zones and strike-slip zones including the Red River Fault (Hall, 2002; Lee and Lawver, 1995; Leloup et al., 1995), bounding Indochina to the north, and to the southwest along the Sagaing, Three Pagodas, Ranong and associated fault zones that partition the lateral extrusion of Indochina (Morley, 2007; Fyhn et al., 2010b). The dominant NW–SE trending Red River–Ailao Shan shear zone, as the boundary between Indochina and South China, has accommodated anywhere between 200 km (Hall, 2002) and in excess of 500 km (Lee and Lawver, 1995; Tapponnier et al., 1982, 1990) of left-lateral strike slip motion with an onset in extrusion tectonics as early as 35 Ma (Leloup et al., 2001, 2007). The motion along the shear zone reversed during the latest Early Miocene (Morley, 2007), with a smaller dextral offset of ~ 25 km since 19 Ma (Replumaz et al., 2001). Much of the extrusion of Indochina was partitioned and absorbed along smaller NE–SW trending strike slip faults in western Indochina, in particular in Myanmar, Thailand and Laos (Hall, 2002). The magnitude of motion along these faults have been estimated from river offsets, deformed geological units (striations) and other morphological markers of slip, ranging from 10 km of motion along the Mae Chan Fault to 50 km along the Nanting Fault in the Cenozoic (Lacassin et al., 1998; Morley, 2007). Internal deformation of Indochina played an important role along with the wholesale lithospheric-scale expulsion of the Indochina block in absorbing the forces propagated from the India–Eurasia collision zone (Hall, 2002; Hall et al., 2008; Leloup et al., 2001; Tapponnier et al., 1982). Another far-field effect of the collision and the rollback of the Indian subducting slab is the opening of the Gulf of Thailand (Fig. 17), accommodated largely along the Ranong, Three Pagodas and Khlong Marui fault zones that tectonically isolated the Malay Peninsula from mainland Indochina (Watkinson et al., 2008). The eastward extrusion of Indochina (Leloup et al., 2001, 2007; Tapponnier et al., 1990), has been linked to the opening of the South China Sea from 32 Ma at the expense of the Proto South China Sea (Briais et al., 1993). The opening of South China Sea was complex, and included a number of abandoned incipient rifts from ~ 37 Ma, initiation of seafloor spreading

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by 32 Ma and a sequence of southward ridge jumps (Fig. 17b). Coinciding with the end of sinistral motion along the Red River Fault at ~ 17 Ma (Leloup et al., 1995), spreading in the South China Sea ceased (Briais et al., 1993), likely due to the docking of the Dangerous Grounds–Reed Bank continental fragment on northern Sundaland (Hutchison, 2004; Hutchison et al., 2000). The cessation of subduction culminated in the obduction of ophiolites on Palawan by 17 Ma (Lee and Lawver, 1994). Recent work by Cullen et al. (2012) indicates a strong counterclockwise rotation of Borneo between 30 and 10 Ma, who acknowledge that an earlier counterclockwise rotation was likely overprinted by a ~ 35 Ma remagnetisation event.

We implement the ~ 500 km total displacement along the Red River shear zone following Lee and Lawver (1995), partitioned along splayed faults and internal block deformation south of the Red River Fault (Hall, 2002). The Makassar Strait opens from ~ 50 to 17 Ma (Lee and Lawver, 1994) (Fig. 17b), and Borneo begins to rotate counterclockwise relative to Sundaland from ~ 50 to 10 Ma due to oroclinal bending (Hutchison, 2010). Our preferred model invokes collision of the Semitau continental fragment to northern Borneo in the mid-Eocene to induce the ~ 37 Ma Sarawak Orogeny (Hutchison, 2010) and a potential metamorphic-induced remagnetisation event on Borneo at ~ 35 Ma (Cullen et al., 2012). Northern Palawan accretes to South Palawan, leading to an ophiolite obduction episode and final closure of the Proto South China Sea with the arrival of the Dangerous Grounds and Reed Bank continental blocks by 17 Ma (Hutchison, 1996; Hutchison et al., 2000). These continental fragments choke the subduction zone, resulting in cessation of seafloor spreading in the South China Sea, the obduction of ophiolites on Palawan and Mindoro and the onset of the Sabah Orogeny in Borneo by 15 Ma (Fig. 14).

The dominant tectonic regime was age-coded for present-day basin geometries in the vicinity of Sundaland following the synthesis of Doust and Sumner (2007) (Fig. 17) along with volcanics on Borneo from Soeria-Atmadja et al. (1999) in order to link their evolution to the regional tectonic setting through time. Our model suggests that the Sarawak, Ketungau and Melawi basins were in the vicinity of the Semitau Block on the

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South China margin, with depositional styles indicative of an arc or back-arc setting (Doust and Sumner, 2007) resulting from the subduction of Izanagi oceanic crust from ∼ 65 Ma. The Pearl River Mouth Basin experienced extension from ∼ 63 Ma, while extension in the Beibuwan Basin (Beibu Gulf) and the proto Southwest Palawan basins initiated by 59 Ma related to the opening of the Proto South China Sea. Compression dominated the Ketungau and Melawi basins between ∼ 58 and 50 Ma, followed by a quiescent period in a fore-arc setting until 39 Ma. Compression from ∼ 39 Ma in the Melawi Basin is interpreted as the onset of collision of the Semitau Block, and the initiation of south-dipping subduction of Proto South China Sea crust. This is consistent with contemporaneous widespread volcanism along northern Borneo. More basins experienced extension on the South China margin from ∼ 45 Ma associated with the embryonic rifting of the South China Sea leading to progressive detachment of the Dangerous Grounds–Reed Bank continental block. Extension also propagates to basins associated with the Red River Fault from ∼ 32 Ma, including the Hue, Qui Nohn and East Vietnam basins, coinciding with the onset of seafloor spreading in the South China Sea at the expense of its predecessor, resulting with compressional regimes in the Luconia, Sarawak, Baram, Sabah, Ketungau and Melawi basins. Widespread extension along the Java–Sunda and Sumatra back-arc and the Gulf of Thailand basins is well established by ∼ 34 Ma, suggesting a period of slab-rollback of Indian Ocean crust. Most of these basins experience quiescence by ∼ 22 Ma, followed by a period of basin inversion from ∼ 13 Ma. Basins north and west of the Makassar Straits undergo compression from ∼ 18 Ma, indicating the arrival of the Sula Spur and initial contact with the northern Australian continental blocks. These compressional regimes continue to present day due to the continued convergence and collision of the Indian and Australian plates.

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4 Discussion

4.1 Comparison to other published models

There has been a renewed effort to produce more detailed post-Cretaceous tectonic reconstructions of Southeast Asia, including those of Metcalfe (2011), Hall (2012) and Morley (2012). Our model draws upon such work and many others, cited within. Although there is general agreement that continental fragments detached from northern Gondwana in the latest Jurassic–Early Cretaceous, the pre-rift configuration and destination onto the southern Asian margin varies across the models. We have chosen an approach to invoke the simplest geodynamic scenario required to transfer these blocks onto the Asian active margin. Hall (2012) and Metcalfe (2011) argue southwest Borneo (SWB) was a Cretaceous Gondwana-derived allochthon. We treat southwest Borneo as the core of the block that developed on Paleozoic metasediments as an eastward extension of east Sumatra and Malaya, with the Schwaner Mountains I-type plutons developing from generally westward-dipping subduction of Izanagi oceanic crust in the Cretaceous (Hutchison, 1996; Parkinson et al., 1998). We propose that southeast Borneo, East Java and West Sulawesi block formed a continental sliver that detached in the latest Jurassic–Early Cretaceous from northern New Guinea (Veevers, 1991; Veevers et al., 1991; Audley-Charles et al., 1988). We acknowledge that West Sulawesi and East Java may have origins on the NW Australian shelf, but prefer that the southwest Borneo core does not originate from this region in the Late Jurassic or Early Cretaceous. In order to account for the mechanism to also close the Woyla back-arc along West Burma and Sumatra in the Late Cretaceous, we suggest the possible collision of Gondwana-derived micro-continents sourced from the Argo segment on the NW Australian shelf.

Hall (2012) and Metcalfe (2011) invoke the Billiton Depression on the Sunda Shelf as a paleo- transform boundary, originally proposed by Ben-Avraham (1978), along which the southwest Borneo docked with Sundaland in the Cretaceous. No evidence of flower structures representing the Billiton Depression as a transform boundary in seismic studies have been published, and we suggest that the mid Cretaceous suture on Sundaland instead passes through Luk-Ulo on Java and the Meratus Mountains on Borneo, following Smyth et al. (2007) and Parkinson et al. (1998), whose continuation across the Java Sea is highlighted in gravity anomalies and gravity gradients (Fig. 6). However, it is important to note that we agree that the Borneo core is likely Gondwana-derived, but we believe it rifted from Gondwana much earlier (i.e. Triassic times) rather than the latest Jurassic–earliest Cretaceous rifting event. In the region of the Billiton Depression, we prefer the interpretations that the curved lineaments in the Sunda Shelf and Java Sea support the oroclinal bending model proposed by Hutchison (2010), and suggests that the western core of Borneo was an eastward extension of the Cretaceous Natuna subduction zone. The Cretaceous age subduction-related volcanic chain is presently-found in an east-west orientation within the Borneo core. However, when taking into account a counter-clockwise rotation (CCW) that exceeds 50° since the Cretaceous (Hartono, 1985), then the volcanic chain would better correspond to a generally north-south striking subduction zone, with westward dipping proto-Pacific slabs along eastern mainland Asia. The paleomagnetic-derived rotations of Borneo from the study of Fuller et al. (1999) are consistent with such an orientation of Borneo, suggesting up to 90° CCW rotation since ~ 80 Ma, of which up to 50° CCW rotation occurred since ~ 30 Ma. The lithospheric structure observed in potential field data (Fig. 6) also supports the notion of a pole of rotation very close to western Borneo, resulting in curved structures and oroclinal bending in the Java Sea and the Sunda platform (Hutchison, 2010). As little data exists to constrain the timing of Java Sea rifting, we assume that it was contemporaneous to Makassar Strait opening between 50 and 17 Ma (Lee and Lawver, 1994), consistent with the age of syn-rift sediments (Doust and Sumner, 2007). The lack of continuous transform faults bounding Borneo to accommodate relative rotation to Sundaland require some other mechanism to account for independent rotation of Borneo. The model of Hutchison (2010) invokes oroclinal bending of Sundaland, to accommodate the counterclockwise rotation of Borneo, and is supported by the presence of arcuate lineaments in the tectonic

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fabric of the Java Sea observed in gravity anomalies (Figs. 5, 6 and 8). In addition the Cretaceous-age Natuna subduction zone and associated volcanic arc, accommodating westward dipping subduction of proto-Pacific crust, is presently curved and can be restored by undoing the Cenozoic CCW rotation of Borneo. Although paleomagnetic data from Fuller et al. (1999) suggests up to $\sim 50^{\circ}$ CCW rotation of Borneo between ~ 25 and 10 Ma, we assume that the curved tectonic fabric in the Java Sea was the result of a smaller $\sim 30^{\circ}$ CCW rotation of Borneo between ~ 50 and 10 Ma. The remaining 20° of CCW rotation derived from Borneo may be due to the wholesale rotation of the remaining Sunda Block terranes with Borneo, including the Malaysian Peninsula where similar CCW rotation trends are observed (Fuller et al., 1999; Hall et al., 2008) and accommodated along major regional strike-slip faults and shear zones including the Red River and Three Pagodas fault zones. We postulate that the oroclinal bending of Sundaland may be related to the changing stress regimes along the Java–Sunda trench to the south and the Proto South China Sea subduction to the north, and the coupling between the subducting and overriding plates in periods of slab rollback.

The paleobiological data from northwest Borneo, north of the Schwaner Mountains and the Borneo core, suggests tectonic affinity with the South China block (Fig. 7). Since the accretion of the North Palawan block closed the Proto South China Sea in the Miocene as proposed by Hutchison et al. (2000) and demonstrated by the seafloor spreading model of Briais et al. (1993), then the accretion of the Semitau block to Borneo may be a result of an earlier accretion event as we have implemented. Such a scenario is supported by multiple and temporally discrete ophiolite belts in northern Borneo (Hutchison, 1975, 1996). The generalized volcano-stratigraphic column for West Borneo by Williams et al. (1988) indicates that the granitoid and dacite intrusives in northwest Borneo are distinct from the semi-contemporaneous andesitic volcanics and fluvial and marginal marine sediments in the Schwaner Mountains in the latest Cretaceous. The lack of similar stratigraphic units between northwest Borneo (Kalimantan) and the nearby Schwaner Mountains led the authors to conclude that the regions were

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tectonically distinct. We suggest that the granitoid and dacite intrusives in northwest Borneo may be related to the Semitau volcanic arc.

The model proposed by Hall (2011) suggests that northwest Borneo and southwest Borneo core are derived from the collision of a Pacific-derived Dangerous Grounds block, the "Banda Block" and "Argoland" by the mid Cretaceous. This leads to an eastward jump in the location of subduction and a reversal to eastward-directed subduction polarity, to initiate intra-oceanic subduction in the proto Pacific. However, Dangerous Grounds is typically not assumed to be a continuation of the Luconia–Balingian continental fragment that likely docked to northern Borneo sometime in the Eocene (Fyhn et al., 2010a; Hutchison, 1996). We interpret that the Luconia–Balingian continental fragment is part of the Semitau block docking to Borneo in the Eocene, and that the Dangerous Grounds–Reed Bank continental fragment was a separate block that collided to northern Borneo much later, likely in the Miocene (Hutchison, 1996; Hutchison et al., 2000; Lee and Lawver, 1994). In addition, a scenario with an eastward jump in subduction is incompatible with continuous westward directed subduction of the Izanagi Plate in the Cretaceous along eastern mainland Asia (Seton et al., 2012). The detrital zircon provenance and geochemical study by Li et al. (2012) suggests that during this time the east Asian margin was likely dominated by Andean-style subduction from ~ 190 to 90 Ma, followed by slab rollback and associated continental extension from ~ 65 Ma to produce a margin analogous to the present-day West Pacific. We prefer an Izanagi slab rollback induced rifting of east Asian continental crust from ~ 65 Ma, contemporaneous with the onset of basin formation and tectonic subsidence on the South China margin (Lin et al., 2003; Yang et al., 2004) (Fig. 18), and the progression to seafloor spreading in a back-arc spreading documented by the emplacement of supra-subduction zone ophiolites on the Mindoro block.

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4.2 Controversies in tectonic affinities and onset of rifting from northern Gondwana in the latest Jurassic

Most, if not all, of the seafloor documenting the transfer of the Java, east Borneo and West Sulawesi blocks to Sundaland has now been subducted as a result of the long-term northward subduction of the Australian plate. We speculate that the remnant preserved crust of this seafloor spreading system is presently the Molucca Sea Plate (Figs. 1 and 2), as suggested by Wu et al. (2012) who unfolded slabs from positive seismic velocity anomaly contours to determine their paleo-surface extent, which is similar to the study by Richards et al. (2007) in unfolding the Indo–Australian slab and linking it to the tectonic evolution of the region. In the absence of preserved seafloor, we rely on geological evidence for rifting events from the Gondwana margin and the subsequent collisional event on the Asian margin, assuming generally-northward transfer of Tethyan terranes. A critical ambiguity exists in such scenarios, as the pre-rift position of terranes is inherently uncertain due to the lack of preserved conjugate margins (Seton et al., 2012), coupled with uncertain sedimentary correlations and biogeographic affinities (Fortey and Cocks, 1998). Paleo-latitude estimates from paleomagnetic data can have errors of ±10° (e.g. paleo-latitude of Lhasa prior to collision with Greater India, see Zahirovic et al., 2012) and provide no constraints of paleo-longitudes (Torsvik et al., 2008). Recent work using Hafnium (Hf) isotope affinities by Zhu et al. (2011) indicates that the Lhasa terrane (South Tibet) shows strong affinities to coeval detrital zircons from northwest Australia, rather than Greater India, highlighting a robust and meaningful technique to help determine tectonic affinities. However, there are no such studies that can be used to link the pre-rift positions of East Java, east Borneo, Mangkalihat and West Sulawesi to the northwest (NW) Australian shelf (i.e. Argo Abyssal Plain), the New Guinea margin or elsewhere in the Phanerozoic.

The Archean to pre-Cambrian zircon study by Smyth et al. (2007) indicate similarities in relative probability peaks between data from East Java and sediments from the Perth Basin. A more robust conclusion of tectonic affinity would require the additional

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comparison of inherited zircons from New Guinea and other potential source regions. Hall (2012) and Metcalfe (2011) argue that the alluvial diamonds found on Borneo, indicating an Archean age, can be used to infer the origin of Southwest Borneo from the Argo Abyssal Plain on the northwest Australian shelf in the Jurassic. Alluvial diamonds on Kalimantan (Borneo) have an Archean age (~ 3.1 Ga) and are derived from sub-lithospheric continental mantle similar to that of African and Yakutian cratons (Smith et al., 2009). Using Nitrogen-defect aggregation characteristics, Bergman et al. (1988) suggest a potential source for Borneo alluvial diamonds to be the Fitzroy Basin in Australia, Coc Pia in Vietnam, Chelima in India or another local unidentified source due to the lack of nearby lamproites. Taylor et al. (1990) and Smith et al. (2009) acknowledge that diamonds from Borneo may have formed in similar thermal conditions as diamonds from Ellendale (western WA) and Copeton (northeast NSW) in Australia. In addition, Smith et al. (2009) notes that the morphology and "primary etch features of the Kalimantan diamonds are quite different from any lamproite, kimberlite or alluvial diamonds known from the Kimberley Region of Western Australia". Housh and McMahon (2000) identified a continental mantle reservoir source for rocks on New Guinea that has similarities with the reservoirs responsible for the kimberlite and lamproite emplacements in Western Australia, with a likely Proterozoic or Archean age, indicating that the diamonds on Borneo may have formed adjacent to Central and Western New Guinea. As a result, purely relying on alluvial diamonds to place Borneo adjacent to the Argo Abyssal Plain at pre-rift times is inadequate. An Archean age for these diamonds does not help identify the age of rifting from Gondwana, and can only provide a maximum age, while the geographic affinities may link Borneo diamonds to anywhere from Sundaland (Vietnam), India, Western Australia (Ellendale), Eastern Australia (Copeton), Africa, Siberia (Yakutian craton), New Guinea or another location. We argue that the southwest Borneo core was already on the Asian margin by the latest Jurassic and likely did not originate adjacent to the NW Australian shelf due to the contrasting diamond provenances with those in the Kimberley Region. However, it likely originated elsewhere on the Gondwana margin and formed the easternmost portion of the Cim-

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merian terrane that rifted in the early Permian (Metcalfe, 2011). West Sulawesi, East Java, Mangkalihat and easternmost Borneo likely originated from the northern Gondwana margin in the latest Jurassic. Although we place these blocks on the New Guinea margin, we acknowledge that they are equally likely to have originated from the Argo Abyssal Plain and the NW Australian shelf as proposed by Hall (2012) to become candidates for the elusive Argoland terrane (Fig. 12).

Basaltic rocks as old as 158 Ma on Sulawesi (Polvé et al., 1997) may be inconsistent with the initiation of seafloor spreading in the Argo Abyssal Plain of M24 anomaly identification of Robb et al. (2005) (~ 153 Ma using Gradstein et al., 1994, or ~ 155 Ma using Gradstein et al., 2012) or M26 identified by Gibbons et al. (2012) (~ 156 Ma using Gradstein et al., 1994, or ~ 157 using Gradstein et al., 2012). However, the oldest seafloor in the Argo Abyssal Plain from ODP Leg 123, Site 765, yields a K–Ar age of 155 ± 3.4 Ma (Gradstein and Ludden, 1992), suggesting that the mafics on West Sulawesi may in fact represent the earliest seafloor. The bulk-rock K–Ar ages of a basaltic dyke (~ 158 Ma) and that of a diorite intruding a microgabbro (~ 137 Ma) derived from localities on West Sulawesi by Polvé et al. (1997) have been used in this study to infer the onset of seafloor spreading and separation of West Sulawesi and associated blocks from Gondwana in the latest Jurassic. However, this assumes that the basaltic dyke and microgabbro are associated with seafloor spreading, especially since the pillow basalts found on West Sulawesi indicate an Eocene age and younger (Polvé et al., 1997). Polvé et al. (1997) acknowledge that their samples seem to contain two populations of ages, where the latest Jurassic and Early Cretaceous ages consistent with the 137–121 Ma age range described by Bergman et al. (1996) using ^{39}Ar–^{40}Ar on rocks from the same formation. The Luk Ulo–Meratus Suture is also interpreted as containing Jurassic and Early Cretaceous ophiolites and pillow basalts by Metcalfe (2006). The younger post-Eocene population of basalts may be related to ophiolite obduction or deformation as suggested by Polvé et al. (1997) and Yuwono and Maury (1988). The older age range can therefore be attributed to seafloor spreading, and may itself represent a minimum age due to the nature of K–Ar geochronology. The bulk-rock analysis of

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the K-rich basaltic dyke and diorite may have undergone significant ^{40}Ar losses, where up to 60 % of argon may be missing from K-feldspars (orthoclase) in such rocks due to perthitization, deformation, significant exhumation (change in overburden pressure, leading to re-equilibration of orthoclase crystal – resulting in perthitization) or seawater interaction (York and Farquhar, 1972). Since the samples are K-rich, it may indicate a higher proportion of orthoclase which is more likely to leak argon than plagioclase (York and Farquhar, 1972), yielding ages that are much younger. The loss of argon results in minimum ages determined from whole-rock K–Ar geochronology, indicating that the $\sim$ 158 Ma age may be a minimum rather than a maximum age. Such a scenario would require placing West Sulawesi on the New Guinea margin as seafloor spreading initiated earlier and propagated westward in the latest Jurassic (Metcalfe, 2011).

Therefore, when combining the uncertainties in ages of mafic rock fragments and the ambiguities in the alluvial diamond provenance, it can be concluded that the southwest Borneo core likely did not originate on the NW Australian shelf. However, it is entirely possible that East Java and West Sulawesi rifted from this margin in the latest Jurassic, and therefore can be classified as the elusive "Argoland" (Fig. 12). A revised model for the MesoTethys would allow for the transfer of these Argoland fragments to Sundaland, requiring faster spreading rates in the western NeoTethys in order to transfer the Argoland fragments northeastward onto the Southeast Asian margin. Detrital zircon provenance studies that compare the accreted blocks with possible Gondwana margin sources such as Greater India, the NW Australian shelf and New Guinea may help test the end-member scenarios for pre-rift positions of the blocks. Such an approach would also help validate the South China origin for the Semitau block that is presently found in northwest Borneo.

4.3 Future work

In order to better understand the convergence history between the Indo–Australian, Eurasian and Pacific plates, it will be necessary to test plate reconstruction scenarios

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using workflows that link plate kinematics on the surface with computational models of mantle convection (or at least, subduction) whose predictions can be compared to and validated using *P* and *S* wave tomography. In particular, regions with ambiguities in subduction polarities and relative plate motions, such as the Philippine Sea Plate and the northern margin of New Guinea, would benefit from such testing of subduction scenarios, similar to the workflow used in Zahirovic et al. (2012) for testing alternative scenarios of India–Eurasia convergence. For continental regions, developing crustal deformation models resulting from rifting and accretion events would help account for crustal thickening and thinning histories. In particular, testing alternative models of Borneo and Sundaland oroclinal bending using deforming plate models would help test and constrain the evolution of Java Sea basins since the Eocene.

5 Conclusions

We present a new plate motion model that describes the tectonic evolution of northern Gondwana and Southeast Asia since the latest Jurassic, embedded in a global plate reconstruction framework. By providing the digital model, it may become a starting point for an improved understanding of the geodynamic evolution of this complex tectonic domain that links the Tethyan and proto-Pacific realms. We propose rifting of a continental fragment, consisting of West Sulawesi, East Java, and Mangkalihat, from northern Gondwana at ~ 155 Ma. The pre-rift position is uncertain, and likely origins include the Argo Abyssal Plain and the New Guinea margin. The southwest Borneo core likely did not have a latest Jurassic origin from the NW Australian shelf, and the continuation of the Fukien–Reinan massif from east Asian and into Borneo suggests that the southwest Borneo core was already at the Asian margin in the Early Cretaceous. As a result, we prefer an accretion of West Sulawesi, East Java and Mangkalihat to the southwest Borneo core in the Late Cretaceous. We link this accretion event to the contemporaneous closure of back-arc basins along southern Eurasia, notably the Woyla back-arc, along West Burma and Sumatra.

The Late Cretaceous also records a significant change in the character of the margin, from an Andean-style margin to an extensional setting. The onset of rift-related tectonic subsidence from ∼ 65 Ma can be linked to the emplacement of supra-subduction zone ophiolites on Mindoro and the opening of the Proto South China Sea. This back-arc likely detached the Semitau continental fragment from South China and transferred it to northern Borneo in the Eocene due to Izanagi rollback, culminating in the Sarawak Orogeny in the mid- to late-Eocene (∼ 37 Ma following Hutchison, 2010). Subduction polarity reversal began to consume the Proto South China Sea, resulting in the opening of the South China Sea from ∼ 32 Ma which rifted the Dangerous Grounds–Reed Bank continental fragment. The south-dipping subduction at the Palawan Trench ceased at ∼ 17 Ma when these continental fragments choked subduction and resulted in the obduction of the Palawan ophiolites and the Sabah Orogeny on Borneo. Our model attempts to reconcile the latest Jurassic–Early Cretaceous rocks on the Philippine Archipelago with a possible slab-rollback and supra-subduction origin on the eastern periphery of Tethyan seafloor. We account for the formation of the Daito and Oki-Daito Ridges from 85 Ma as subduction-related rollback, and the onset of subduction along the eastern boundary of the Philippine Sea Plate at ∼ 55 Ma, to account for the slab-pull related plate reorganization in the Pacific, as observed in contemporaneous bends in hotspot island chains. We implement a slab rollback model for the origin of the Caroline Plate on the eastern margin of the Philippine Sea Plate, with the Torricelli-Finisterre arc forming on the southern boundary of the Caroline Plate. The Sepik terrane first docks with northern New Guinea by ∼ 27 Ma, with the Torricelli-Finisterre arc colliding with the leading margin from 6 Ma. Our model attempts to reconcile multiple lines of evidence – from surface geology to deep Earth seismic tomographic constraints, and rules of plate tectonics with evolving plate boundaries that are consistent with the relative plate motions. Such models are extendable and open to improvement, and can be tested using numerical models of subduction that can be validated using seismic tomography of the mantle and observations from surface geology.

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Supplementary material related to this article is available online at http://www.solid-earth.net/5/1335/2013/sed-5-1335-2013-supplement.zip.

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Table 1. Summary of the terrane accretions and nomenclature for the Tethyan oceanic domains used in this study following Seton et al. (2012).

Region	Central Tethys (present-day India–Lhasa)	Eastern Tethys (present-day West Burma and Sumatra)	Eastern Tethys (present-day Sundaland)
Eurasia	Qiangtang	Indochina	Indochina
		PaleoTethys	
Cimmerian Blocks (Sundaland core) rifted from northern Gondwanaland	Lhasa	Sibumasu, West Sumatra	Malay Peninsula, Southwest Borneo core
		MesoTethys	
Latest Jurassic rifted blocks from northern Gondwanaland		Argoland? Mawgyi? Sikuleh?	West Sulawesi, Mangkalihat, East Java, easternmost Borneo
	NeoTethys		**Proto Molucca Sea**
Gondwana breakup in Early Cretaceous	India		Sula Spur
		Indian Ocean	

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Table 2. Data and interpretations used for constructing plate motion model.

Region	Feature	Timing	Dating Method	Interpretations based on data and models from:
Australian NW Shelf	Onset of seafloor spreading	155 ± 3.4 Ma	K–Ar of basaltic basement	Gradstein and Ludden (1992)
West Sulawesi, East Java, Mangkalihat and easternmost Borneo	Late Jurassic rifting	Shallow marine sandstones in Bantimala Complex	Late Jurassic ammonites, gastropods and brachiopods in Paremba Sandstone	Sukamoto and Westermann (1992) Wakita (2000)
	Onset of seafloor spreading	∼ 158 Ma	K–Ar of diorite, microgabbro and basaltic dyke	Polvé et al. (1997)
	Collision with intra-oceanic arc	∼ 120 to 105 Ma (Peak at ∼ 115 to 11 Ma)	K–Ar from greenschists, blueschists and eclogites	Parkinson et al. (1998)
	Suturing to southwest Borneo core	Late Cretaceous (∼ 80 Ma)	Stratigraphy, K–Ar and U–Pb of metamorphics, synthesis of previous studies	Wakita (2000) Clements and Hall (2011)
New Guinea	Rifting on northern New Guinea (Sepik)	Late Cretaceous	Stratigraphic interpretations	Hill and Hall (2003) Pigram and Symonds (1991)
	Papuan Ultramafic Belt crystallisation (Emo volcanics?)	Late Cretaceous (Maastrichtian)	Papuan Ophiolite emplacement interpretation from surface geology	Davies and Jaques (1984)
	Emo metamorphics accretion, obduction and onset of north-dipping subduction along Sepik	∼ 35 to 31 Ma	$^{40}Ar/^{39}Ar$	Worthing and Crawford (1996)
	Sepik accretion to New Guinea	27 to 18 Ma	K–Ar thermochronology	Crowhurst et al. (1996)
	Torricelli-Finisterre Arc accretion to northern New Guinea	6 Ma to present	K–Ar thermochronology	Crowhurst et al. (1996)
Sumatra and Sunda active margin	Woyla Group including oceanic plate, arc and carbonate assemblages	Late Jurassic to Early Cretaceous	Litho- and bio- stratigraphy, K–Ar ages of Sikuleh Batholith intruding Woyla Group (97.7 ± 0.7 Ma)	Barber and Crow (2005)
	Pre-Cenozoic subduction-related magmatic arc	264 to 75 Ma (e.g. Sibolga Batholith)	K–Ar, $^{40}Ar/^{39}Ar$	Cobbing (2005) McCourt et al. (1996)
	Cenozoic subduction-related magmatic arc	65 Ma to present	K–Ar	Bellon et al. (2004) McCourt et al. (1996)
	Eocene carbonate platforms	Eocene to Early Oligocene (Pre-rift stage)	Stratigraphy	De Smet and Barber (2005)

Table 2. Continued.

Region	Feature	Timing	Dating Method	Interpretations based on data and models from:
South China Sea	Change from compressional to extensional margin indicated by emplacement of A-type granites	Cretaceous, ~ 90 Ma	$^{40}Ar/^{39}Ar$ of ductile shear zones, U–Pb zircon ages of deformed plutons, Rb–Sr, K–Ar	Li (2000)
	Onset of Proto South China rifting	~ 65 Ma	Onset of tectonic subsidence on South China margin	Lin et al. (2003) Yang et al. (2004)
	Onset of Proto South China Sea seafloor spreading	~ 59 Ma	Supra-subduction zone ophiolites on Mindoro K–Ar dating of hornblende separates	Faure et al. (1989)
	Back-arc formation of Proto South China Sea	Paleocene	Affinity of Sibuyan Ophiolite to Mindoro ophiolites	Dimalanta et al. (2006) Yumul et al. (2009)
	Semitau affinity with South China	Jurassic and Triassic	Paleobiology	Metcalfe (1996) This Study
	Semitau (and Luconia-Balingian continent?) collision with northern Borneo	Eocene	Inversion of regional basins	Fyhn et al. (2010a)
		Eocene (~ 37 Ma)	Sarawak Orogeny related to Sibu Zone uplift	Hutchison (2004)
	Onset of rifting in the South China Sea	Eocene (~ 37 Ma)	Interpretations of seismic sections, stratigraphy and tectonic subsidence	Hutchison (2004) Briais et al. (1993) Lin et al. (2003) Yang et al. (2004)
	Onset of Seafloor Spreading	~ 32 Ma	Magnetic anomaly identifications in the South China Sea	Briais et al. (1993)
	Collision and attempted subduction of Dangerous Grounds–Reed Bank along northern Borneo (originating on South China margin)	~ 17 Ma	Sabah Orogeny	Hutchison (1996) Hutchison et al. (2000)
	Collision of Northern Palawan and obduction of ophiolites	Early Miocene	Interpretations from stratigraphy and surface geology	Yumul Jr et al. (2003)

Table 3. The origin and present-day candidates for micro-continents that collided with the NeoTethyan intra-oceanic arc are controversial and vary substantially across published models. We acknowledge that the easternmost Borneo, Mangkalihat, East Java and West Sulawesi may have originated from either the Argo Abyssal Plain or the New Guinea margin. However, we do not believe that the Southwest Borneo core rifted from northern Gondwana in the latest Jurassic with these blocks.

Terrane	Tectonic Origin	Accretion Age	Accreted to	Reference
West Burma	Argo Abyssal Plain	Triassic	Indochina	Metcalfe (2011), Hall (2012)
	Argo Abyssal Plain	Late Cretaceous	Sibumasu	Metcalfe (1994), Heine et al. (2004)
Mawgyi	Intra-oceanic island arc	Late Cretaceous	West Burma	Mitchell (1993)
	Possibly underlain by Gondwana continental fragments colliding with an intra-oceanic arc			This Study
Sikuleh, Natal, Lolotoi	Intra-oceanic island arc	Late Cretaceous	Sumatra	Barber (2000)
	Continental fragments			Acharyya (1998), Metcalfe (1996)
Southwest Borneo	Argo Abyssal Plain	Late Cretaceous	Sundaland	Metcalfe (2011), Hall (2012)
	Northern Gondwana	Early Permian		This Study
Easternmost Borneo, Mangkalihat, East Java and West Sulawesi	Argo Abyssal Plain	Late Cretaceous	Sundaland	Metcalfe (2011), Hall (2012), This Study
	New Guinea			This Study

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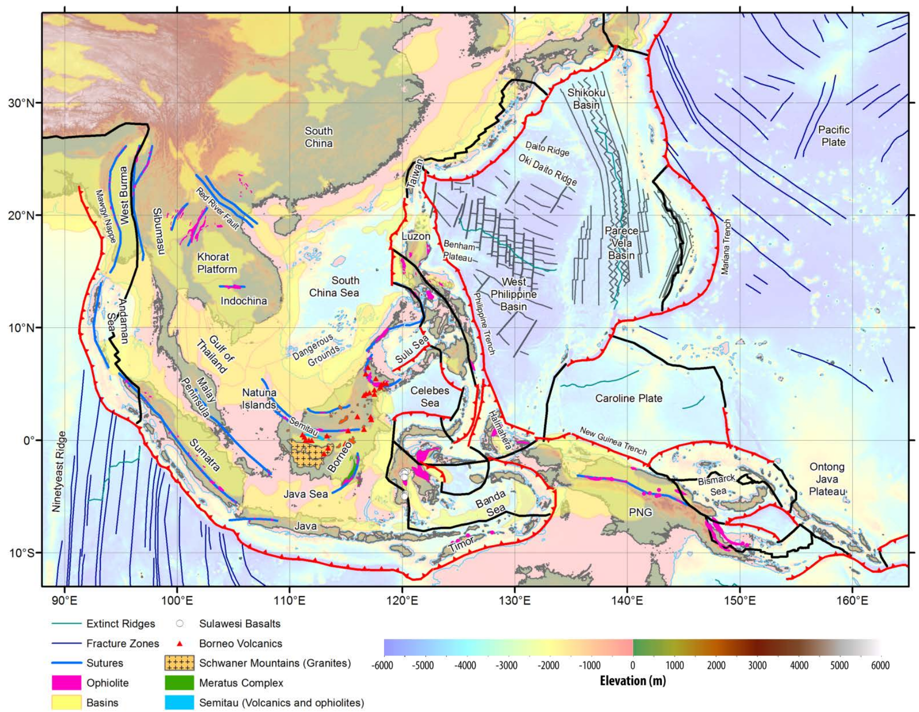

Fig. 1. Regional tectonic setting with plate boundaries (MORs/Transforms – black, Subduction zones – teethed red) from Bird (2003) and ophiolite belts representing sutures modified from Hutchison (1975) and Baldwin et al. (2012). Isochrons for the West Philippine Basin are digitized from Hall et al. (1995), while the isochrons for the Shikoku and Parece Vela Basins are from Sdrolias et al. (2004). West Sulawesi basalts are from Polvé et al. (1997), fracture zones are from Matthews et al. (2011) and basin outlines are from Hearn et al. (2003).

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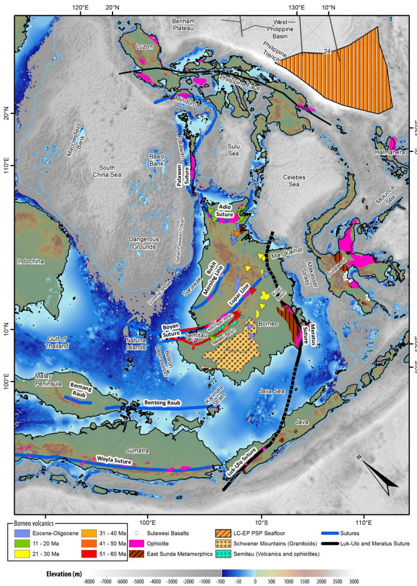

Fig. 2. Sundaland suture distributions with the Cretaceous-age Luk–Ulo and Meratus sutures resulting from the accretion of East Java, easternmost Borneo, Mangkalihat and West Sulawesi. The Billiton Depression has been previously invoked as a Cretaceous suture resulting from the docking of Southwest Borneo with Sundaland. However, little evidence has been presented to indicate that this is a (Cretaceous-age) suture. We prefer that the Luk–Ulo and Meratus sutures (black) represent the Cretaceous suture accommodating the accretion of East Java, easternmost Borneo, Mangkalihat and West Sulawesi. We interpret the Schwaner granitoids to be continuous with the Natuna Arc and the Fukien–Reinan Massif (see Fig. 7) as an Andean-style subduction zone along east Asia in the Cretaceous. The Boyan Suture and Lupar Line bound the Semitau block (red outline) that accreted to northern Borneo in the mid Eocene to result in the Sarawak Orogeny. LC-EP PSP = Late Cretaceous (?) – Early Paleogene Philippine Sea Plate seafloor crust. Eocene to Recent volcanics on Borneo are age-coded from Soeria-Atmadja et al. (1999).

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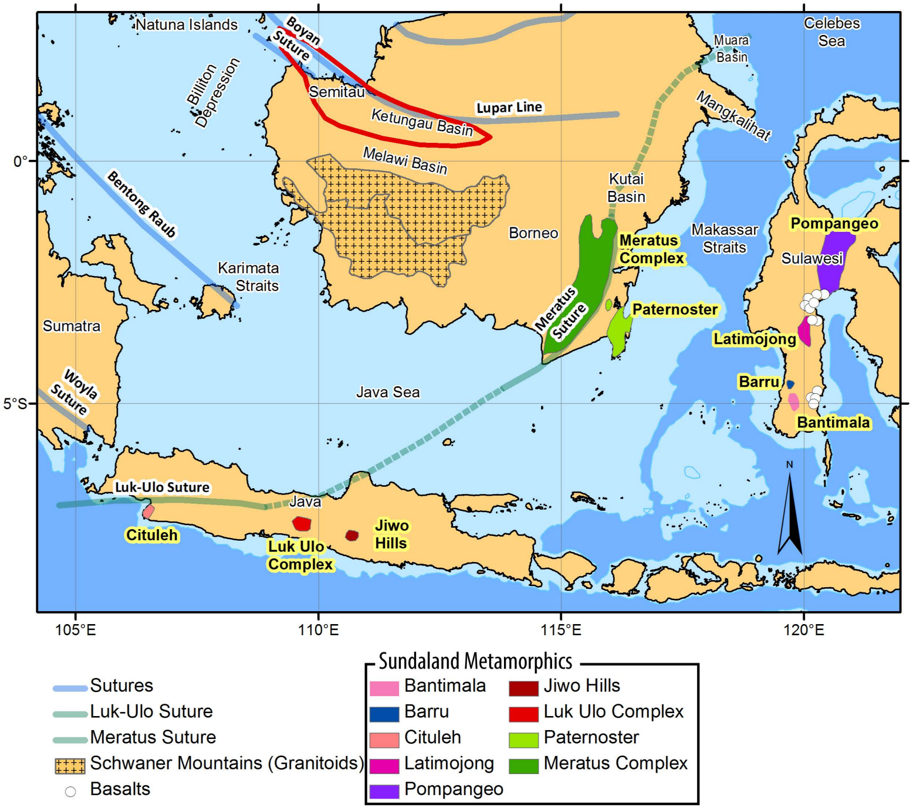

Fig. 3. The accretion history of Sundaland is contained within metamorphic belts (Wakita, 2000) that span east Java and Borneo across the Luk–Ulo and Meratus sutures. These metamorphic belts record the onset of peak metamorphism at ~ 115 Ma (Parkinson et al., 1998), with final suturing to the Sundaland core by ~ 80 Ma (Clements and Hall, 2011; Wakita, 2000).

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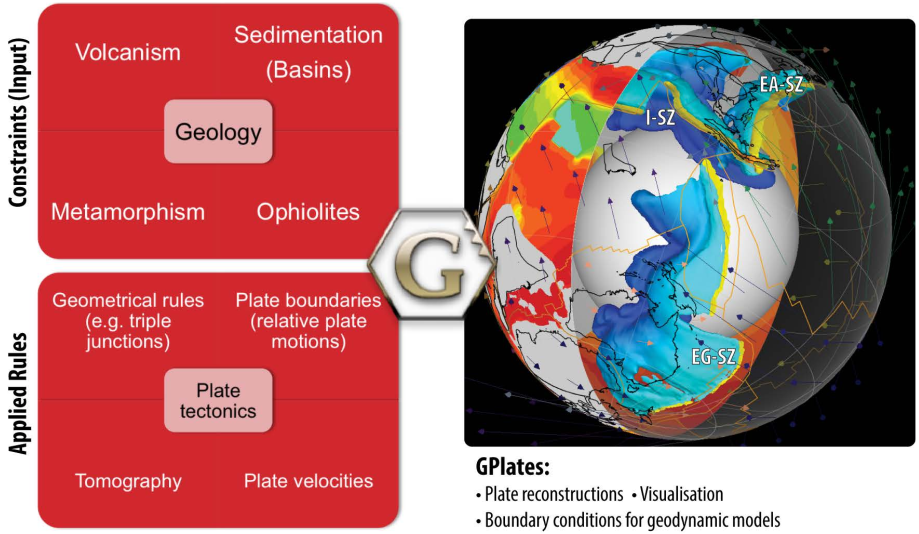

Fig. 4. In the absence of preserved seafloor documenting the Late Jurassic–Early Cretaceous rifting from northern Gondwana, present-day geology was used to infer rifting events, collisions and final suturing. Plate tectonic boundary conditions such as geometrical rules of triple junction closure and relative plate velocity thresholds were applied to generate evolving plate boundaries in open-source plate reconstruction software, *GPlates*. Seismic tomographic depth slices were consulted for the history of the Philippine Sea Plate and northern New Guinea in the Cenozoic due to the subduction-dominated nature of their margins. Such kinematic model can then be linked to numerical simulations of subduction, as illustrated with blue-shaded slabs derived from the Zahirovic et al. (2012) geodynamic models of Tethyan subduction. I-SZ = intra-oceanic Tethyan subduction zone, EA-SZ = East Asian subduction zone, EG-SZ = East Gondwana subduction zone.

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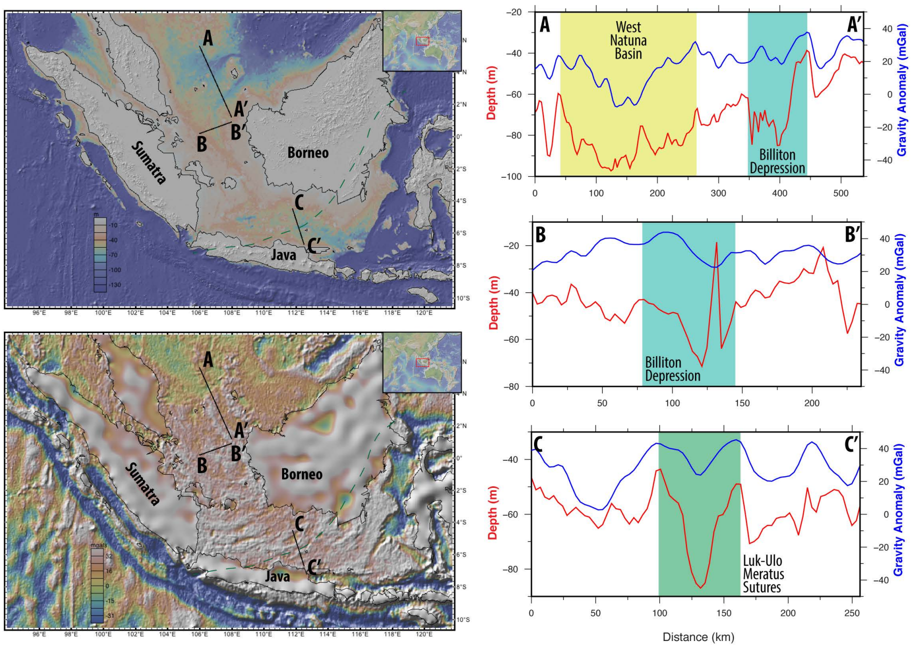

Fig. 5. Global Multi-Resolution Topography from Ryan et al. (2009) (top left) and gravity anomalies from Sandwell and Smith (2009) (bottom left) with profiles through the West Natuna Basin and Billiton Depression (**A** and **B**), compared to the signature of the Luk–Ulo and Meratus sutures in the Java Sea. The Billiton Depression (East Natuna Basin) is narrower than the West Natuna Basin but is not continuous to reach Java in order to be a significant suture zone onto which the Southwest Borneo core is accreted. It also does not cross-cut the older Bentong-Raub suture zone (Figs. 2 and 3).

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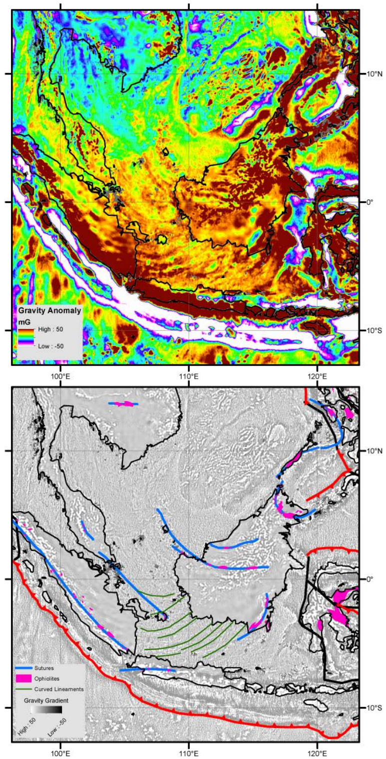

Fig. 6. Gravity anomalies (top) and vertical gravity gradients (bottom) from Sandwell and Smith (2009) highlight the tectonic fabric of Sundaland, with curvatures likely resulting from oroclinal bending as proposed by Hutchison (2010). The Cretaceous Woyla, Luk–Ulo and Meratus sutures, along with the Paleozoic Bentong-Raub suture, retain a strong signature of a lithospheric-scale discontinuity. Conversely, the Billiton Depression is not visible as a lithospheric-scale heterogeneity, and instead is likely to be only a topographic depression related to rifting in the West and East Natuna Basins (see Fig. 5).

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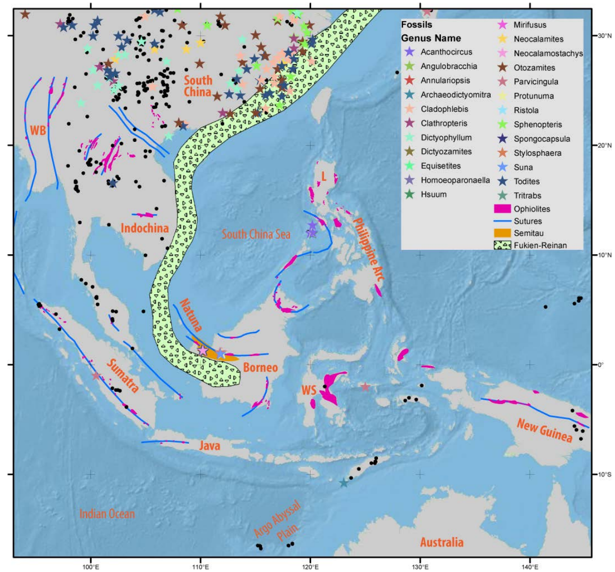

Fig. 7. Triassic and Jurassic fossil occurrences with coloured stars representing 24 fossil genera found on Borneo, within the Semitau continental block (orange), suggesting that the paleobiological affinity between South China and this part of Borneo is significant. Although sampling of Indochina may be lower than of South China, the fossil occurrences do not indicate tectonic affinity between Indochina and Semitau (Borneo) during the Triassic and Jurassic. Paleobiological data from the global Paleobiology Database suggests that the Semitau Block was along the South China mainland during the Triassic and Jurassic. The Natuna Ridge across central present-day Borneo represents the westward-dipping subduction zone that consumed the proto-Pacific, and resulted in the emplacement of the Schwaner Mountain granitoids, Natuna Arc and Fukien–Reinan Massif in the Cretaceous along east Asia (modified from Honza and Fujioka, 2004).

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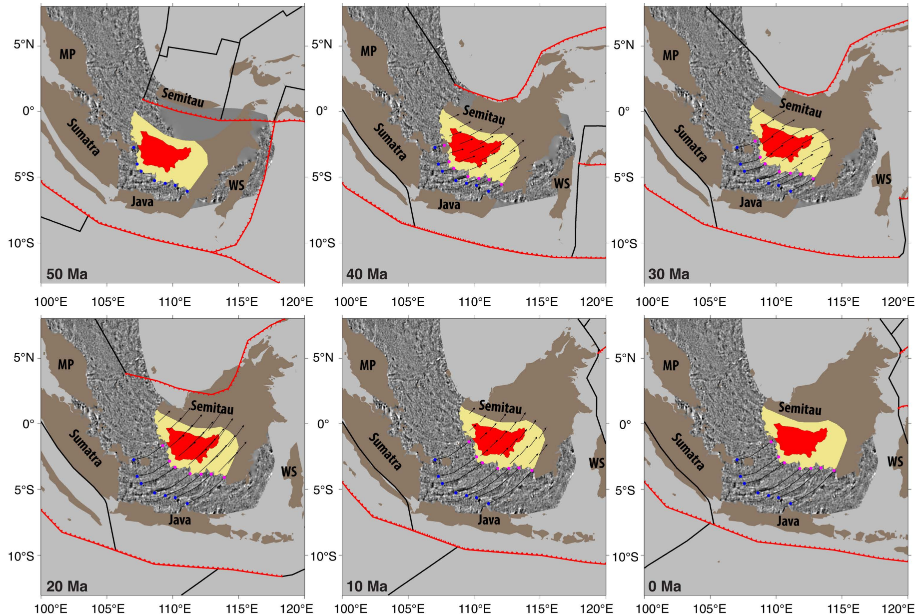

Fig. 8. The curved lineaments on the Sunda Shelf have been proposed by Hutchison (2010) to represent evidence of oroclinal bending of the continental promontory. We digitize these curvatures from the vertical gravity gradient from Sandwell and Smith (2009) and attempt to undo the rotation, following the curvatures and assuming that they can be used to derive an Euler rotation. We partition the counterclockwise rotation of Borneo from 50 to 10 Ma following evidence of rifting in the Java Sea. Plate boundaries are plotted in a Sumatra-fixed reference frame. The Borneo core (yellow) is largely comprised of the Schwaner Mountains and related granitoids (red), which is used to sample the velocity field of Borneo's motion relative to Sundaland. Endpoints along the curvatures are used to constrain the motion, with Sumatra (blue) held fixed and the equivalent reference points near Borneo (magenta) are used as guides for the motion that is interactively generated using *GPlates*. MP = Malay Peninsula, WS = West Sulawesi.

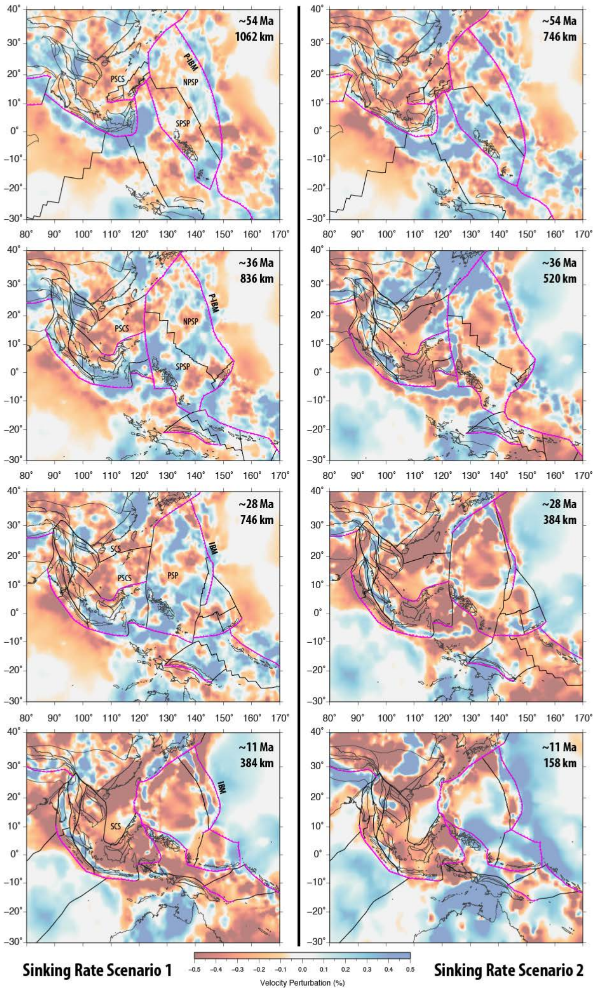

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Fig. 9. Plate reconstructions superimposed on age-coded depth slices of MIT-P (Li et al., 2008) seismic tomography with two end-member sinking rate scenarios. Scenario 1 applies a 3 and 1.2 $cm\,yr^{-1}$ sinking rate of slabs in the upper and lower mantle, respectively, following Zahirovic et al. (2012). Scenario 2 applies a whole-mantle slab sinking rate of 1.4 $cm\,yr^{-1}$ as a low sinking rate end-member. The longitudinal position of the Philippine Sea Plate (PSP) is calibrated to the location of the slab material to coincide with the modelled subduction zone geometries. In addition, convergence along the Australian and Pacific segments was preserved to minimize trench advance, and account for the roll-back of the Pacific slab and coupling to the Izu–Bonin–Mariana (IBM) Arc resulting in the opening of the Shikoku and Parece Vela basins. SCS = South China Sea, PSCS = Proto South China Sea, NPSP = North Philippine Sea Plate, SPSP = South Philippine Sea Plate, (P) IBM = (Proto-) Izu–Bonin–Mariana Arc.

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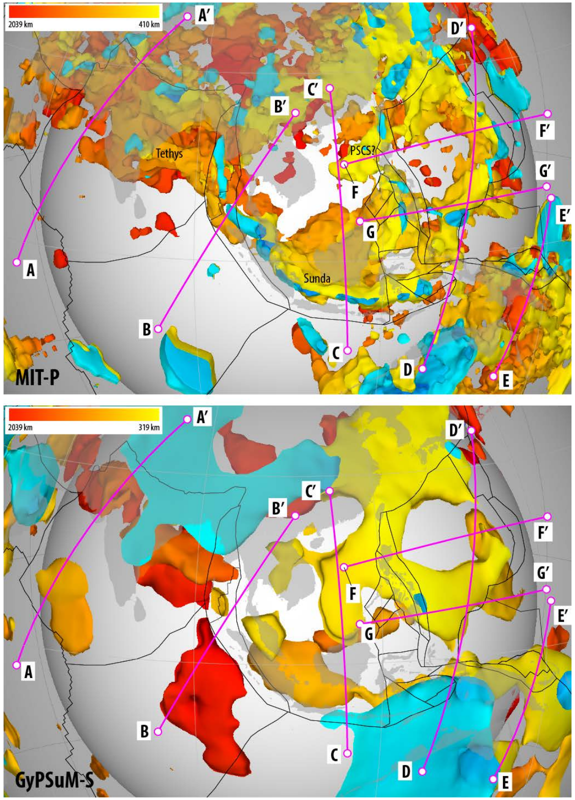

Fig. 10. 3-D visualisation of +0.2 % seismic velocity anomaly iso-surfaces in MIT-P (top) and +0.9 % seismic velocity perturbation in GyPSuM-S (bottom) models. Profiles A to G represent the vertical profiles (see Fig. 11) that capture the convergence and subduction histories of the region since the Cretaceous. Present-day coastlines are translucent grey shades and present-day plate boundaries are translucent black lines. Slab volumes are coloured by their depth, while the light blue colour represents the interior surface of these slabs. PSCS = Proto South China Sea slab.

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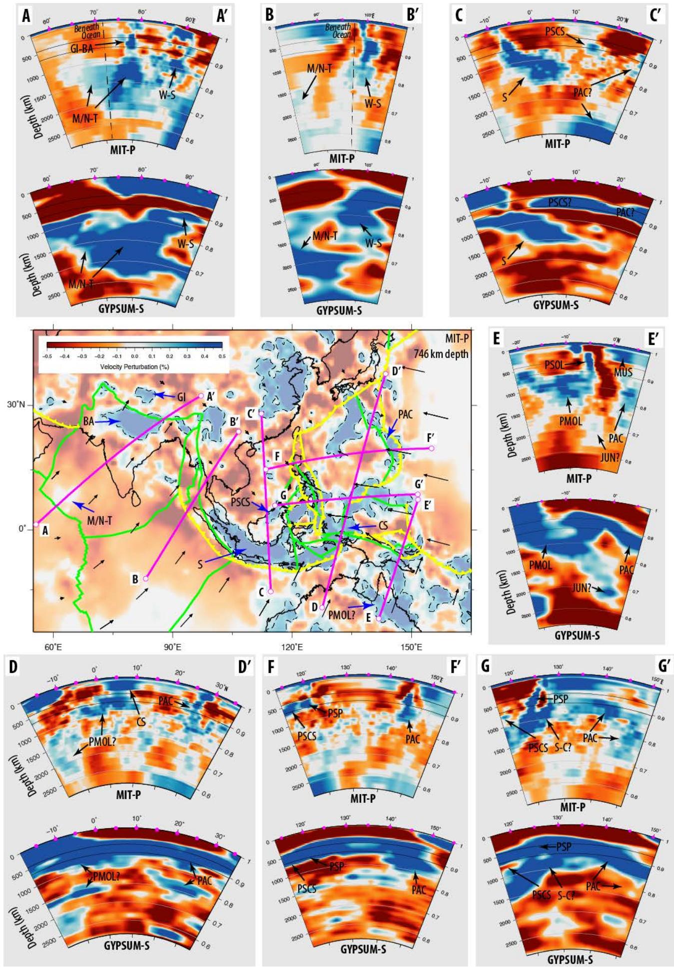

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Fig. 11. Vertical profiles from MIT-P (Li et al., 2008) and GyPSuM-S (Simmons et al., 2009) seismic tomography models, surface locations based on the magenta profiles in Fig. 10. The first-order differences between the *P* and *S* wave models is that the amplitude of the positive seismic velocity anomalies significantly diminishes away from continental coverage (e.g. dashed lines in profiles **A** and **B**). A depth slice at 746 km from MIT-P is provided for reference with super-imposed present-day coastlines and plate boundaries. Interpreted slab sources are labelled: GI-BA = Greater India-NeoTethyan back-arc slab, M/N-T = Meso- and Neo-Tethyan slabs, W-S = Woyla-Sunda slabs, S = Sunda slab, PSCS = Proto South China Sea slab, PAC = Pacific slab, PMOL = Proto Molucca slab, PSOL = Proto Solomon slab, CS = Caroline slab, PSP = Philippine Sea Plate slab, S-C = Sulu-Celebes slabs.

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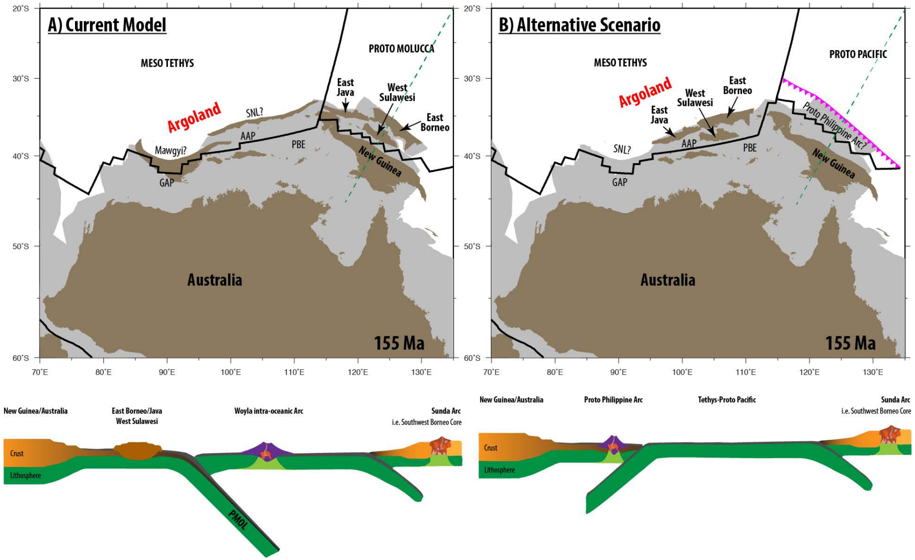

Fig. 12. End-member pre-rift scenario along northern Gondwana during the latest Jurassic (∼ 155 Ma) rift timing with a triple junction detaching the East Java, West Sulawesi, East Borneo and Mangkalihat from New Guinea driven by north-dipping subduction along the Woyla intra-oceanic arc representing the model implemented in this study (left). Alternatively, these blocks may have originated in the Argo Abyssal Plain (AAP) and a back-arc scenario may have existed along New Guinea (right), similar to the Incertus Arc proposed by Hall (2012). However, if this back-arc spreading did not detach continental blocks, then it may be the source for the Proto Philippine Arc. It is beyond the scope of this study to resolve whether the Mawgyi Nappes on West Burma or the Woyla Terranes on Sumatra contain micro-continental blocks, as it remains a continued source of controversy. We prefer the accretion of buoyant micro-continents in this region in order to account for the closure mechanism of the Woyla back-arc in the Late Cretaceous. GAP = Gascoyne Abyssal Plain, PBE = Proto Banda Embayment, SNL = Sikuleh, Natal, Lolotoi and Bengkulu micro-continents. Schematic cross-sections approximately follow dashed green line and are modified from Bouilhol et al. (2013).

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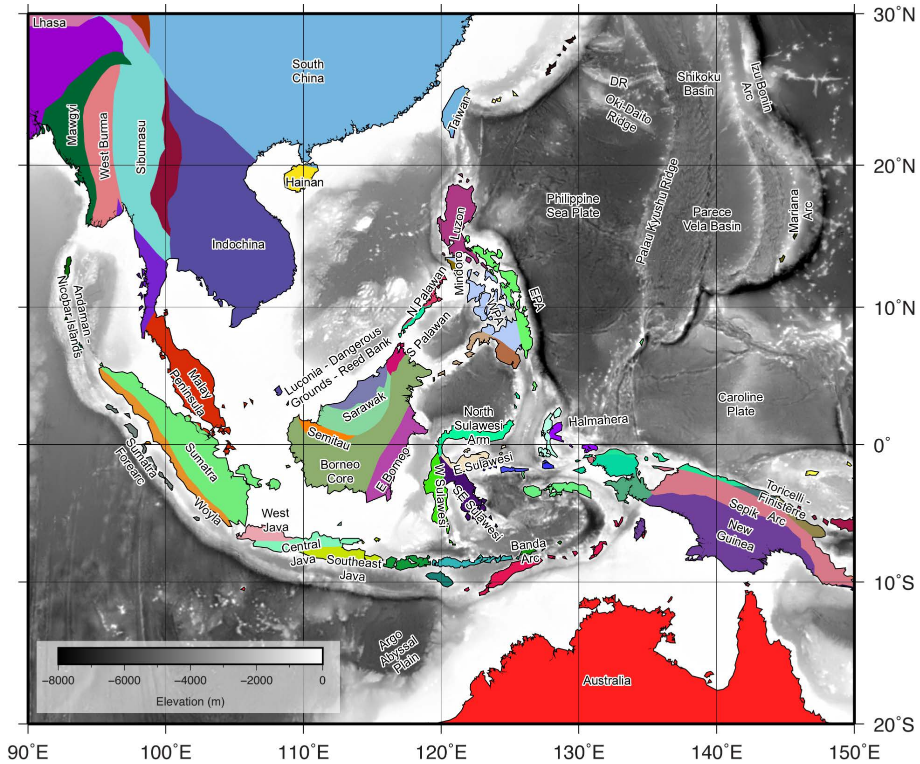

Fig. 13a. Present-day distribution of blocks and tectonic features (including oceanic basins, arcs and ridges) related to the long-term convergence of the Eurasian, Indo–Australian and Pacific plates. Plate reconstructions in Fig. 13b use this colour scheme for reference. Grey shading is ETOPO-1 bathymetry (Amante et al., 2009). DR = Daito Ridge, WPA = West Philippine Arc, EPA = East Philippine Arc.

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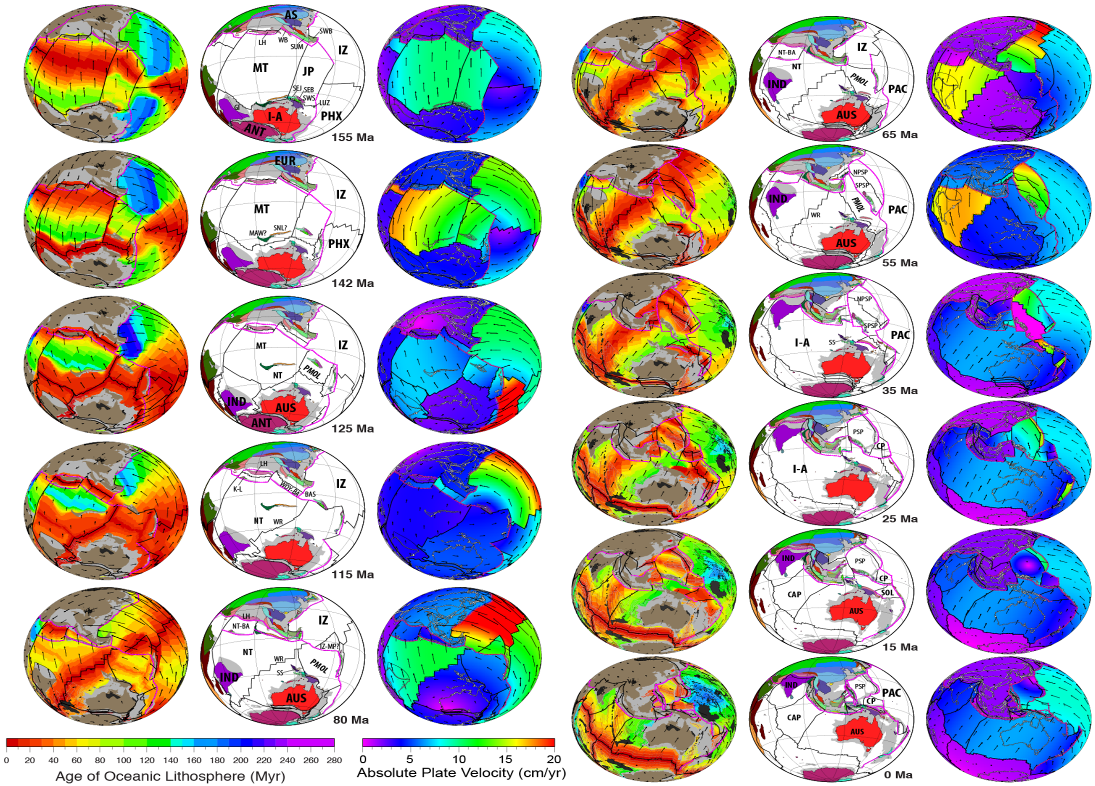

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Fig. 13b. Plate reconstructions with coloured blocks (middle), seafloor ages (left) and plate velocities (right). Northern Gondwana experiences a rifting event in the latest Jurassic (∼ 155 Ma), and we implement the detachment of Argoland continental fragments, easternmost Borneo, East Java, Mangkalihat and West Sulawesi at this time. The embryonic portions of the Philippine Arc are likely related to the easternmost portion of Tethyan seafloor spreading with supra-subduction affinities of latest Jurassic–Early Cretaceous volcanics. The intra-oceanic subduction system in the central NeoTethys, accommodating India–Eurasia convergence, also becomes established in the Early Cretaceous. Gondwana-derived continental fragments begin to collide with the intra-oceanic subduction system in the mid Cretaceous, and suture to Sundaland by ∼ 80 Ma and to West Burma/Sumatra by ∼ 70 Ma. A pre-existing transform on the eastern margin of the Philippine Sea Plate converts to a west-dipping subduction zone consuming Pacific crust by ∼ 55 Ma, and may be associated with the regional plate re-organisations and bends observed in Pacific hotspot island chains at ∼ 50 Ma. Continued convergence of Indo-Australia with Eurasia results in the contact of the Sula Spur with the Java–Sunda trench by ∼ 25 Ma. The Sepik composite terrane docks to New Guinea by 27 Ma, followed by accretion of the Prince Alexander–Finisterre–Torricelli arc from 6 Ma. Subduction Zones = magenta teethed lines, Transforms/MORs = black lines, Continental extent = grey, Large Igneous Provinces (LIPs) = dark grey. AS = Asian Plate, EUR = Eurasian Plate, MT = MesoTethys, NT = NeoTethys, JP = Junction Plate, PMOL = Proto Molucca Plate, IZ = Izanagi Plate, PHX = Phoenix Plate, I-A = Indo–Australian Plate, ANT = Antarctic Plate, AUS = Australian Plate, IND = Indian Plate, GI = Greater India, LH = Lhasa, WB = West Burma, SUM = Sumatra, SWB = Southwest Borneo, SEJ = Southeast Java, SEB = Southeast Borneo, SWS = Southwest Sulawesi, LUZ = Luzon, N-S/PSP = North/South Philippine Sea Plate, SS = Sula Spur, WR = Wharton Ridge, NT-BA = NeoTethyan Back-arc, K-L = Kohistan–Ladakh, WOY-BA = Woyla Back-arc, BAS = Barito Sea, MAW = Mawgyi microcontinent, CAP = Capricorn Plate, SNL = Sikuleh, Natal, Lolotoi and Bengkulu micro-continents, IZ-MP? = Izanagi Microplate?, CP = Caroline Plate, SOL = Solomon Sea Plate. (Orthographic projection with centre co-ordinate 15° S, 110° E)

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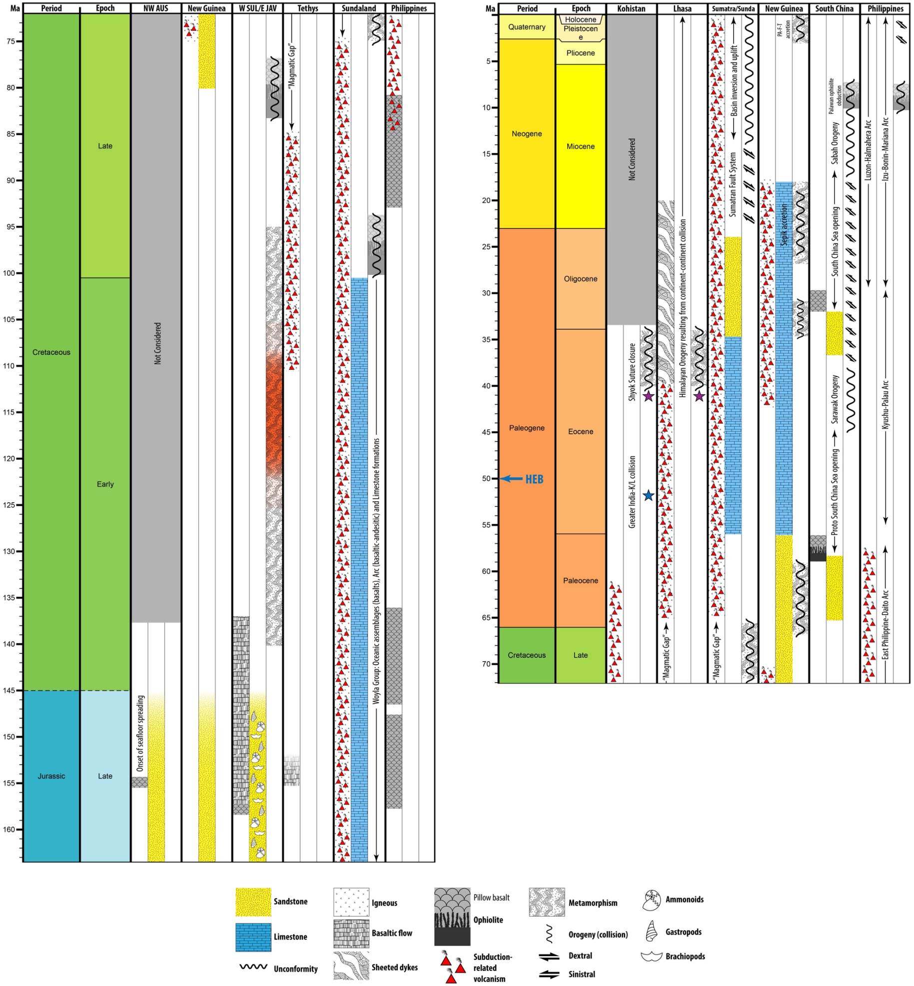

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Fig. 14. Summary of first-order tectonic events related to the latest Jurassic Gondwana rifting and the evolution of the Tethys and Sunda region since the Cretaceous. For each region major volcanic (left column), sedimentary (middle column) and metamorphic (right column) events are documented. HEB = Hawaiian-Emperor Bend time based on (Sharp and Clague, 2006), K/L = Kohistan–Ladakh, PA-F-T = Prince Alexander–Finisterre–Torricelli.

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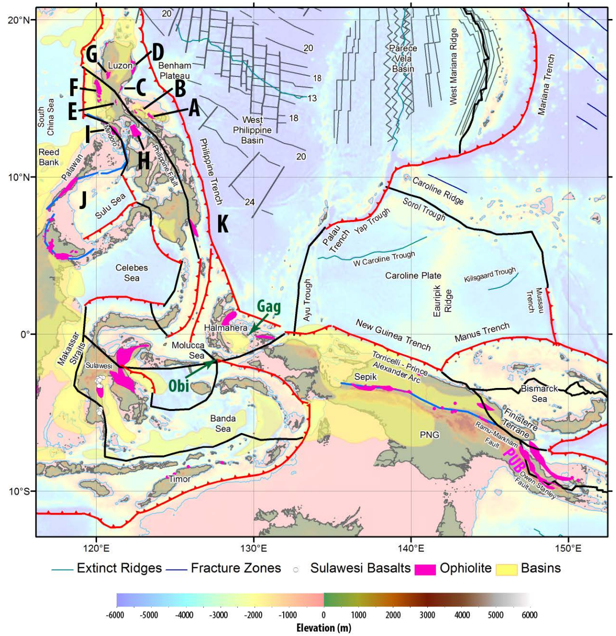

Fig. 15. Regional tectonic setting of the Philippine Sea Plate, Papua New Guinea and the Caroline Plate, following symbology of Fig. 1. The crystallization ages of ophiolites were used to infer oceanic crust age, while the metamorphic age was used to infer collision and obduction. A = Lagonoy Ophiolite, B = Calaguas Ophiolite, C = Dibut Bay Ophiolite, D = Casiguran Ophiolite, E = Montalban Ophiolite, F = Zambales-Angat Ophiolite, G = Itogon Ophiolite, H = Marinduque Basin/Sibuyan Ophiolite, I = Mindoro/Amnay Ophiolites, J = Palawan Ophiolite, K = Pujada Ophiolite, PUB = Papuan Ultramafic Belt.

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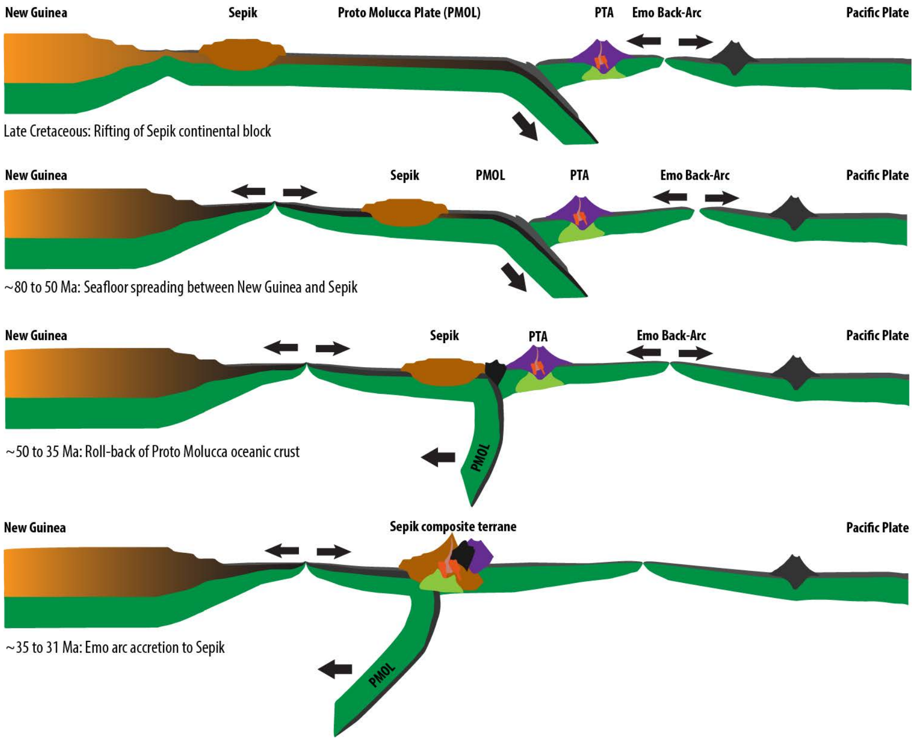

Fig. 16. Schematic cross-section of Sepik tectonic evolution depicting a Late Cretaceous rifting scenario of the Sepik continental fragment and eventual collision and accretion of the Emo Volcanics that formed in a back-arc setting, likely on the periphery of the Pacific Plate resulting from roll-back of the Proto Molucca slab (PMOL). The Emo volcanic arc accretes to Sepik, leading to continued north-dipping subduction of Cretaceous-age seafloor, terminating at 27 Ma when the Sepik composite terrane is accreted onto northern New Guinea. PTA = Proto Torricelli Arc. Cross-section largely follows the profile (dashed green) in Fig. 12.

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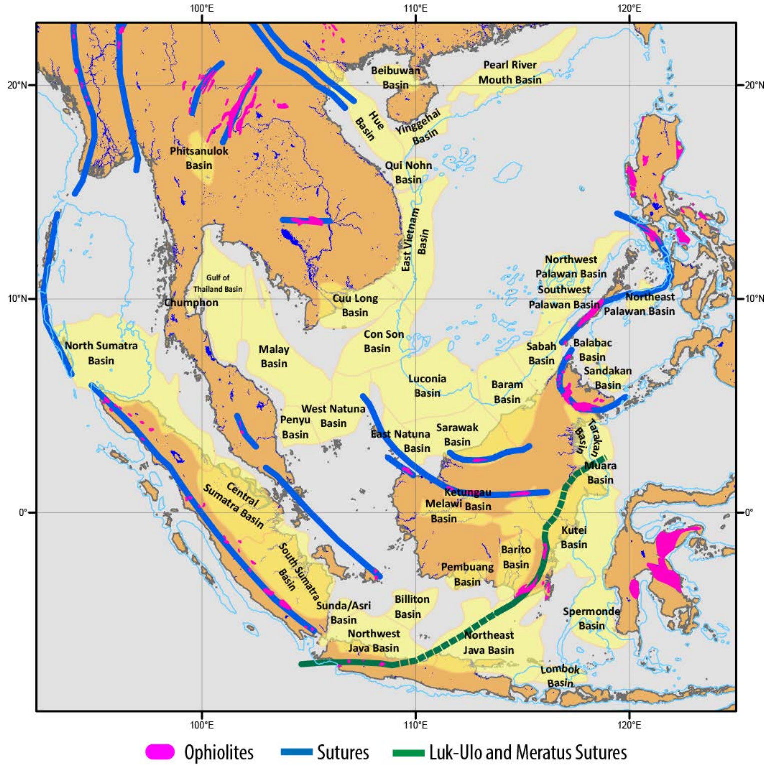

Fig. 17a. Basins (shaded yellow) in Southeast Asia record significant tectonic events, which can be used to help refine timing of extensional and collisional events in plate motion models. The dominant tectonic regime was age-coded to each basin through time following Doust and Sumner (2007).

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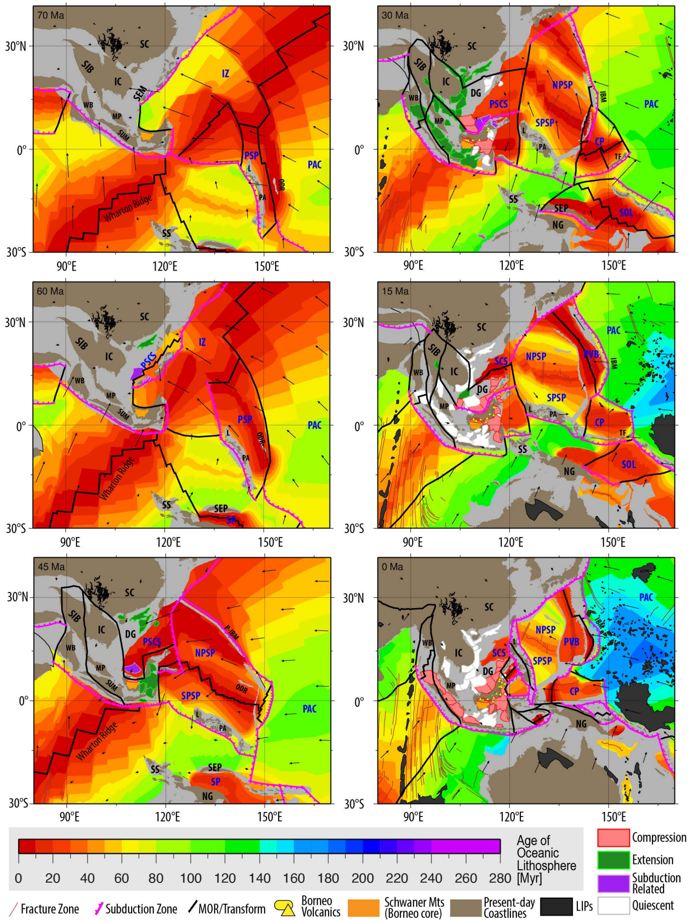

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Fig. 17b. Regional reconstructions with seafloor age, continental extents (light grey), reconstructed present-day coastlines, LIPs, plate boundaries, velocities, age-coded basins and Borneo volcanics from Soeria-Atmadja et al. (1999). The Proto Izu–Bonin–Mariana (P-IBM) west-dipping subduction initiates by 55 Ma following a conversion of a transform to a convergent plate boundary to consume Pacific (PAC) crust. The Proto South China Sea (PSCS) opens as a back-arc basin from 65 Ma, with seafloor spreading initiating by 59 Ma that detaches the Semitau (SEM) and South Palawan blocks from mainland South China (SC). These blocks collide in the mid-Eocene with northern Borneo, resulting in the Sarawak Orogeny and cessation of north-west dipping subduction of Izanagi (IZ) crust in this region. Subduction re-initiates at a south-dipping convergent margin along northern Borneo by ~ 40 Ma to result in slab pull driving the rifting and opening of the South China Sea (SCS) from 37 Ma, with seafloor spreading initiating by 32 Ma and detaching the Luconia–Dangerous Grounds–North Palawan blocks (DG) from South China. Continued subduction transfers these blocks to northern Borneo and South Palawan, resulting in suturing, ophiolite obduction and the Sabah Orogeny by ~ 15 Ma. Basins were age-coded from Doust and Sumner (2007) and colour-coded by their dominant tectonic regime, and indicate extension occurred the Makassar Straits between ~ 55 and 35 Ma, while the Java Sea basins largely experience extension between 35 and 25 Ma, followed by a period of quiescence and tectonic inversion (compression) from ~ 15 Ma. The convergence of the Australian–Pacific–Sunda plates at present-day has resulted in largely compressional regimes parallel to the Java–Sunda and Palawan trenches, along with the basin inversion experienced in the Makassar Straits resulting from the collision of the Sula Spur (SS) with Sundaland. SIB = Sibumasu, IC = Indochina, MP = Malay Peninsula, SS = Sula Spur, SP = Sepik Plate, SEP = Sepik composite terrane, NG = New Guinea, ODR = Oki-Daito Ridge, PVB = Parece-Vela Basin. All other label descriptions are found in Fig. 13b. (Mercator projection with 125° E standard parallel)

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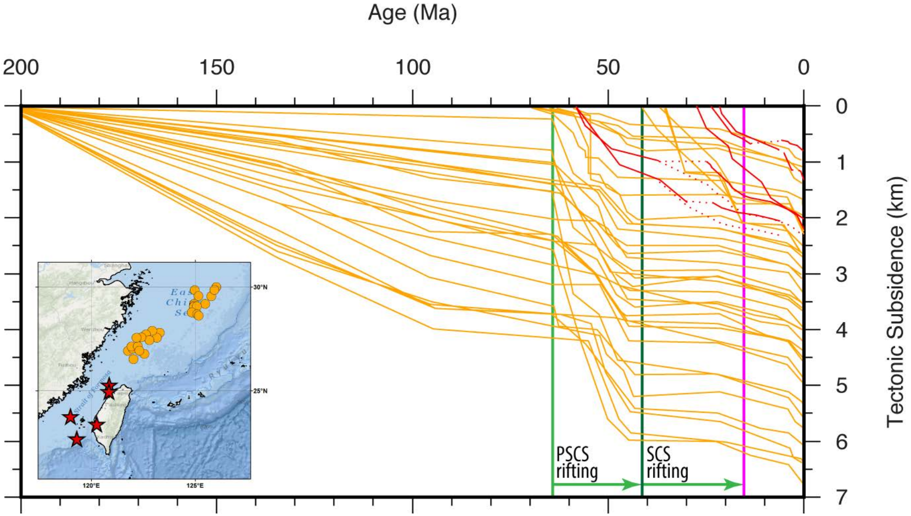

Fig. 18. Tectonic subsidence records from basins adjacent to Taiwan and east China indicate an acceleration of tectonic subsidence from ∼ 65 Ma that we interpret to be the opening of the Proto South China Sea (PSCS) as a back-arc basin, followed by another episode of subsidence in the mid Eocene (∼ 42 Ma) resulting from South China Sea (SCS) rifting. Figure modified from Lin et al. (2003) (red) and Yang et al. (2004) (orange).

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