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Sunda-Java trench kinematics, slab window formation and overriding plate deformation since the Cretaceous

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Abstract

The kinematics and time-dependence of back-arc extension or compression is one of the most poorly understood aspects of plate tectonics, and has nearly exclusively been studied from snapshots of present-day observations. Here we combine absolute and relative plate motions with reconstructions of now subducted ocean floor to analyse subduction kinematics and upper plate strain from geological observations since 80 Ma along the 3200 km long Sunda-Java trench, one of the largest subduction systems on Earth. Combining plate motions and slab geometries enables us to reconstruct a time-dependent slab window beneath Sundaland, formed through Wharton spreading ridge subduction. We find that upper plate advance and retreat is the main influence on upper plate strain, but subduction of large bathymetric ridges, and slab-window effects, also play a significant, and at times dominant, role. Compression in the Sundaland back-arc region can be linked to advance of the upper plate. Extension of the Sundaland back-arc region correlates with two patterns of upper plate motion, (a) retreat of the upper plate, and (b) advance of the upper plate combined with more rapid advance of the Sundaland margin due to hinge rollback. Subduction of large bathymetric ridges causes compression in the upper plate, especially Wharton Ridge subduction underneath Sumatra over the period 15–0 Ma. Our reconstructions unravel the evolving geometry of a slab window underlying the Java–South Sumatra region, and we propose that decreased mantle wedge viscosities associated with this slab-window exacerbated Palaeogene extension in the Java Sea region via active rifting, and enabled Sumatran continental extension to continue at 50–35 Ma when upper plate advance would otherwise have led to compression.

Keywords: Sundaland; subduction; kinematics; slab window

1. Introduction

Numerous models have been proposed to account for the time-dependence of extension and back-arc basin formation in a subduction setting, including: (1) the extrusion model, where back-arc formation is related to lateral absolute upper plate motion [1–3] (2) the sea-anchor model, where back-arc formation is related to the force generated by the down-going slab resisting lateral motion [2], (3) magmatic models, where back-arc formation is related to mantle flow in the wedge overlying the slab [4–6], and (4) the slab pull model, where back-arc formation is related to subduction hinge rollback caused by negative buoyancy of the subducting slab [7–9]. The "sea-anchor" model and the "extrusion"

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model are the more likely models for back-arc formation according to analysis of recent mantle flow data from the Mariana subduction system [10]. Strain in the "back-arc" region of an upper plate in a subduction setting can range from strongly compressional to seafloor spreading. In order to examine relationships between various plate kinematics parameters and a range of upper plate strain regimes, we focus on the Sunda-Java subduction zone through the Cenozoic. Excluding Andaman Sea back-arc spreading from ~13 Ma to the present [11], the Sundaland margin has experienced compression, non-rift related subsidence, or crustal extension during the Cenozoic [12].

In both the "sea-anchor" model and the "extrusion" model a major parameter that influences upper plate strain is upper plate motion. Upper plate motions have long been associated with upper plate strain [1], with extensional back-arcs correlating with retreating upper plates, and compressional back-arcs correlating with advancing upper plates e.g. [2,13–15]. We have compared reconstructed absolute and trench-normal upper plate motions with strain regimes known to occur in the Sundaland margin to 60 Ma.

Recently, Lallemand and Heuret [13] observed a correlation between present-day shallow slab dip angles (0–125 km) and upper plate strain, with compressive and extensional regimes correlating to low and high shallow slab dips, respectively. Sdrolias and Müller [14] found that a combination of factors, including shallow slab dip (0–100 km), influences the initiation of back-arc spreading and that once initiated, back-arc spreading continues regardless of upper plate motion. Sdrolias and Müller [14], also observed a correlation between age of present-day, non-perturbed subducting lithosphere and shallow slab dip angle (0–100 km), where older subducting lithosphere correlates with steeper shallow slab dip angles and vice versa. We have utilised this relationship to reconstruct shallow slab dips for the Sunda-Java trench back to 80 Ma, using palaeo-age grids. We then compare the reconstructed shallow slab dips with mapped strain regimes through time along the Sundaland margin.

Complicating kinematics at the Sunda-Java trench has been the subduction of the active Wharton Ridge from ca. 70 Ma [16], to 43 Ma [17], and the remainder of the then extinct Wharton Ridge representing a bathymetric ridge from 43 Ma to the present. During subduction of an active ridge, a slab window may form under the upper plate [18,19]. A slab window develops when down-going plates continue diverging but trailing plate edges cease to grow and may even become hot and begin to melt [19]. The slab window widens as this process continues. Slab windows occurring beneath the west coast of North America (e.g. [20–24]), Central America (e.g. [25]) and South America (e.g. [26,27]) have been well studied compared to the Indonesian subduction zone. The palaeo-positions of slab window are normally estimated using geological data from the overriding plate, such as changes in volcanism and tectonic events such as regional uplift. For the Sunda-Java trench we have used time-dependent plate motion vectors combined with reconstructed palaeo-age grids to compute the size and position of the slab window beneath the southern Sundaland margin.

2. Methods

In our study, we split the Sundaland margin into three regions; the Andaman Sea, Sumatra, and Java (see Fig. 1). For each region, we identified and summarized different periods of upper plate strain from Morley [28], Bishop [29], Hall [30], Letouzey et al. [12], Eguchi et al. [31], and Curray et al. [11] (see Fig. 3) and categorised each period based on the method of Jarrard [15].

We calculated shallow slab dip angles at each point along the Sundaland trench for 5 million year time stages from the present to 80 Ma, utilising the relationship $y = 0.1961x + 12.232$, where x is age of subducting lithosphere at the trench, and y is the shallow slab dip angle [14]. We obtained the age of the down-going lithosphere at the trench from revised versions of oceanic palaeo-age grids from Heine et al. [16]. From the calculated shallow slab dip angles, average shallow slab dip angles were computed for each region at all time stages. Averaging the slab dip angles minimizes any distortions in slab dip angle due to proximity to the edge of the subducting plate, which can be around 10° steeper close to slab edges [13].

For each stage we calculated absolute plate motion vectors for four plates; the Sundaland plate (80–0 Ma), the Sumatra-Java plate (or Sundaland margin) (80–0 Ma), the Indian plate (80–45 Ma), and the Australian plate (80–0 Ma) (see Fig. 1). Vectors were calculated at points every 500 km along the Sundaland trench, which was digitised for the present day then fixed to the Sumatra-Java plate for rotation back through time. Our plate reconstructions used the Heine et al. [16] and Gaina and Müller [32] plate kinematic models in a moving hotspot reference frame from O'Neill et al. [33]. Absolute plate motion vectors were used to calculate trench-normal vectors for each plate, which are useful for examining the overall compressional/extensional forces acting on the continental margin.

We reconstructed the position of the slab window beneath Sundaland, using the method of Thorkelson

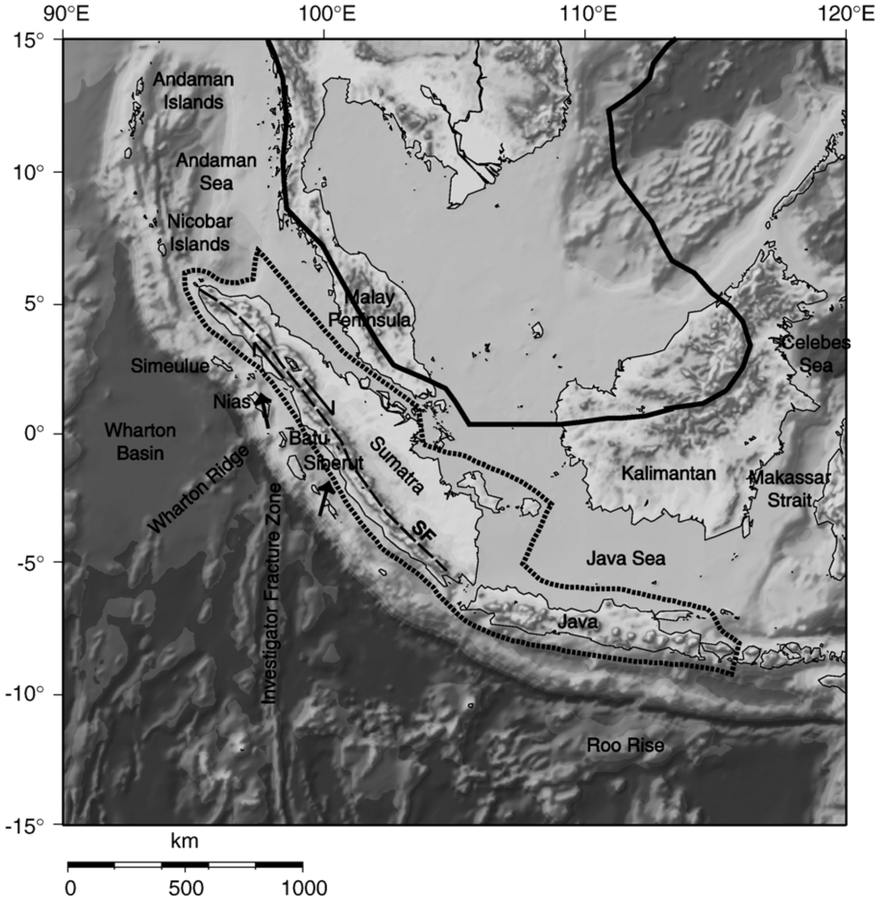


Fig. 1. Topographic and bathymetric map of SE Asia, SF — Sumatra Fault, boundaries of the Sundaland margin (dashed) and the Sundaland core (solid), small arrows depict motion of Sumatran fore-arc northwest and southeast of Batu Island from Prawirodirdjo et al. [48].

[18] which calculates the slab-window position using ridge-transform geometry and convergence vectors. Our absolute plate motion vectors were used to calculate convergence vectors, which were used in conjunction with the reconstructed location of the Wharton Ridge through time from the palaeo-age grids to establish the shape and size of the slab window. Vectors used to calculate the shape of the slab window are presented in velocity–space diagrams in Fig. 2 for time slices where there was an active triple junction at the Sundaland margin. Generally, the geometry of a slab window is affected by relative plate motions, pre-subduction ridge-transform fault geometry, subduction angles, thermal erosion, deformation caused by spherical shell stress and lateral and down-dip changes in the angle of slab dip [18]. In our approach, we have assumed, a horizontal subducted slab, no thermal erosion of the diverging plate edges, and no deformation from spherical shell stress. Due to these assumptions we have calculated a minimum slab window, as adding the effects of a dipping slab and thermal erosion of plate edges would likely lead to a larger extent for the slab window. We have also limited the lateral extent of the slab window to 1000 km perpendicular to the trench because at this point the slab can be assumed to have reached the 660 km mantle discontinuity and the slab window would no longer have a discernable affect on the overriding plate.

3. Plate kinematics and overriding plate deformation

3.1. Plate motions

Fig. 2 illustrates that from 80 Ma to the cessation of Wharton Ridge spreading (~ 43 Ma [17]), the Australian Plate moved at a much slower rate than the Indian Plate (Fig. 2(i–vii)). Initial plate and margin geometry and kinematics of the India–Eurasia collision remains controversial [34], but it is generally accepted that an India–Eurasia related collision slowed northward Indian Plate motion from 60–55 Ma (e.g. [34–36]). Fig. 2(i–viii) shows the Indian Plate moving rapidly from 80 Ma until absolute plate motions dropped from an average of 120 mm/yr at 60–65 Ma to 81 mm/yr by 45–50 and 26 mm/yr by 40–45 Ma. Indian plate motion increases from the low at 40–45 Ma to an average of 69 mm/yr at 30–35 Ma decreasing to 63 mm/yr at 15–20 Ma.

An advancing upper plate is expected to cause compression in the upper plate margin. Our reconstructions show two different types of advancing upper plate motion. The first type, where both the upper margin and upper core advance at the same rate, we call 'uniform upper plate motion'. Uniform upper plate motion occurs for Java from 15 Ma to the present (Fig. 3(viii–x)), which corresponds with compression that is known to have affected Java from ~15 Ma to the present day. This type of upper plate advance also occurs at all points along the Sunda-Java trench from 80 Ma to ~60 Ma, so it is possible that the entire Sunda-Java margin was affected by compression during the period 80–60 Ma. However, the presence of an underlying slab window due to the subduction of the then active Wharton Ridge from 70 Ma may have had an effect on the southeastern portion of the margin.

The second, where reconstructions show the upper margin advancing more rapidly than the upper core, we call 'differential upper plate motion'. Differential upper plate motion occurs for the Andaman Sea at 30–15 Ma (Fig. 3 (i–iii), Sumatra, strongly at 30–15 Ma (Fig. 3(iv–vii)), southern Sumatra, weakly at 50–30 Ma (Fig. 3(vi–vii)), and Java at 45–15 Ma (Fig. 3(viii–x)). The upper margin is known to have experienced extension during all of these periods, which is expected to occur on the upper plate as the margin draws away from the core. Subduction hinge rollback, where the retreating hinge draws the margin away from the core, is the most likely explanation for this pattern of upper plate behaviour. Subduction hinge-roll has previously been suggested as the major mechanism causing Malay–Thai basin extension at 30–15 Ma [28]. Non-rift related subsidence, observed in Java and Sumatra from 15–20 Ma can be explained as the period of change over from extension to compression.

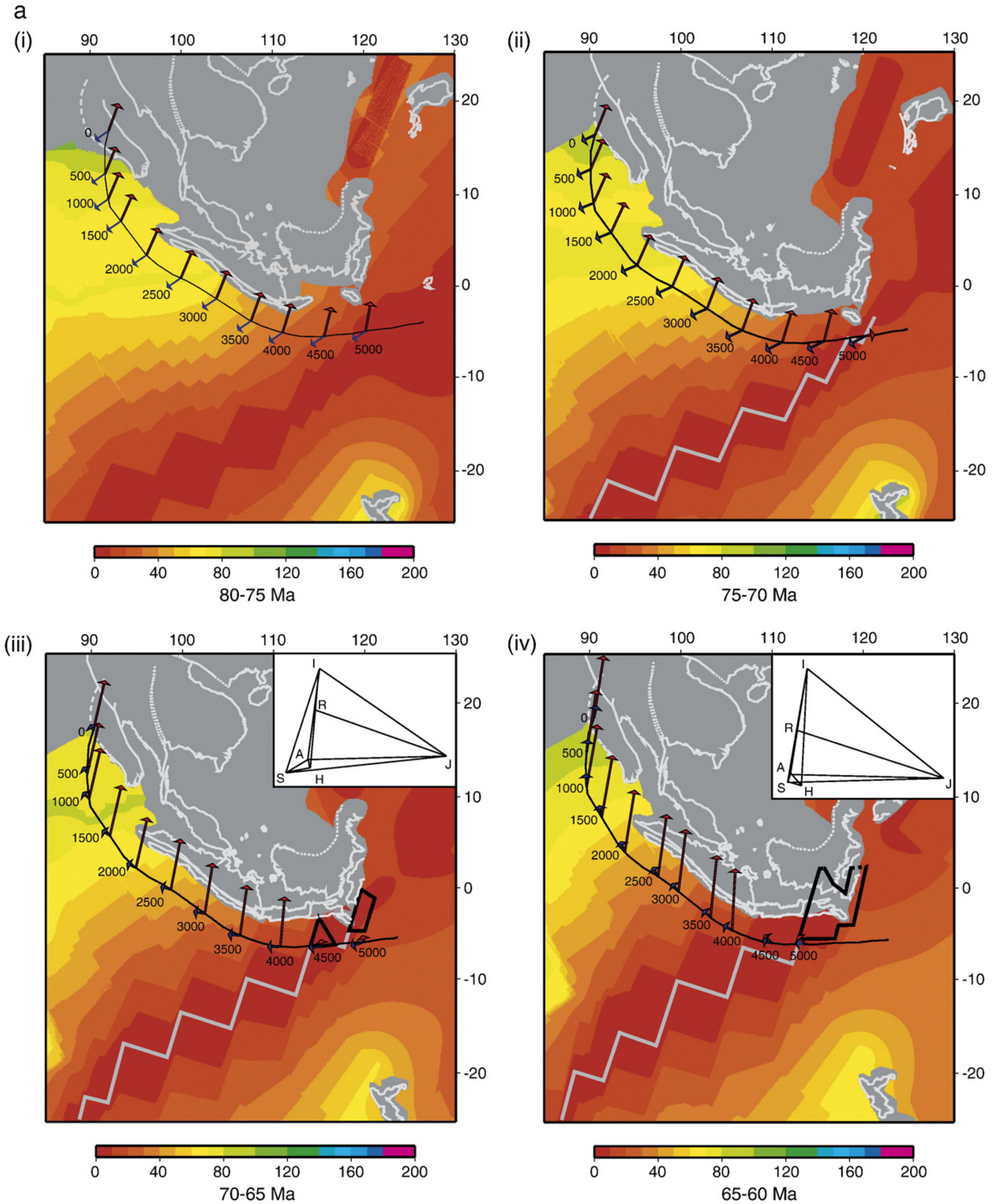
The increase in rate of advance of the Sundaland core at 30–20 Ma at almost all reconstructed locations shown in Fig. 2 is likely to be a product of extrusion caused by India–Eurasia collision. Southeasterly extrusion of Sundaland from 40 Ma caused by the India–Eurasia collision are supported by mantle tomography images showing a change in present-day slab structure at 700 and 1100 km depth [37,38]. 'Hard' collision between India and Eurasia is thought to have caused the slowdown in northward Indian motion at 30–20 Ma [39–41]. Morley [28] shows that more southerly blocks of Southeast Asia were "squeezed out faster than their more northerly neighbours". This pattern fits increased rates of upper plate advance observed at ~50 Ma and 30–20 Ma (Fig. 3), which subside following the initial extrusion related increase.

Our reconstructions (Fig. 3(i–iii)) show retreat of the Andaman Sea upper plate at 15–0 Ma. This correlates with Andaman Sea back-arc spreading that has occurred from ~13 Ma [11]. This correlation has previously been observed by Sdrolias and Müller [14], who also found that once initiated back-arc spreading is not affected by motion of the upper plate and noted that it is believed that spreading in this location is controlled by India–Eurasia related extrusion tectonics.

Figs. 2(v–vi) and 3 show a reversal in Sundaland core motion, from retreating at 55 Ma to advancing by ~47 Ma. This change in motion is a consequence of extrusion tectonics caused by the India collision. Upper plate retreat occurs at all points along the Sunda-Java trench except the northern Andaman Sea at 60–50 Ma (Fig. 3). In the Java region this corresponds with a known period of extension. Retreating upper plates have long been associated with extension in back-arc areas [2,13–15]. To initiate, back-arc spreading requires not only a retreating upper plate but age of down-going lithosphere at the trench >55 Myr, and a shallow slab

Fig. 2. Reconstructed absolute plate motions of the overlying Sundaland plate, and the down-going Indo–Australian plate from 80 Ma to the present. Arrows represent stage (5 Myr) motions of the Sundaland margin (blue arrows), and Indian (Australian) plate (red arrows), and correspond to; (i) 80–75 Ma (ii) 75–70 Ma (iii) 70–65 Ma (iv) 65–60 Ma (v) 60–55 Ma (vi) 55–50 Ma (vii) 50–45 Ma (viii) 45–40 Ma (ix) 40–35 Ma (x) 35–30 Ma (xi) 30–25 Ma (xii) 25–20 Ma (xiii) 20–15 Ma (xiv) 15–10 Ma (xv) 10–5 Ma, and (xvi) 5–0 Ma. Tectonic regimes shown by compressional (black centred 'beachball'), extensional (white centred 'beachball') and subsidence (denoted by 'sub.') symbols (symbols are not oriented, symbolic only) for the Java, south Sumatra and Andaman Sea regions where information was available from the literature [12,29–31]. The location of the mid-ocean ridge and velocity–space diagrams (upper right of each figure) are shown for time slices when there was an active triple junction at the Sundaland Trench, and hence a growing slab window. In the velocity–space diagrams; I — Indian Plate; R — Ridge; S — Sundaland Plate; A — Australian Plate; H — hotspot; J — previous ridge–trench intersection location. The reconstructed positions of the slab window due to the subduction of the Wharton Ridge (active until 43 Ma) are shown by thick black lines, dashed sections where slab window cut off at distance 1000 km from the trench. Thin black line represents our Sunda-Java trench location.

dip >30° [14]. Fig. 2(v–vi) shows that from 60–50 Ma, the age of subducting lithosphere at the trench was <55 Myr at all points on the trench southeast of point 1500, which is insufficient to initiate back-arc spreading at this time. Therefore, we predict that crustal extension affected the southeastern Sundaland back-arc east of point 1500 for the period 60–50 Ma. For the southern Andaman Sea section of the trench (points 1000–1500



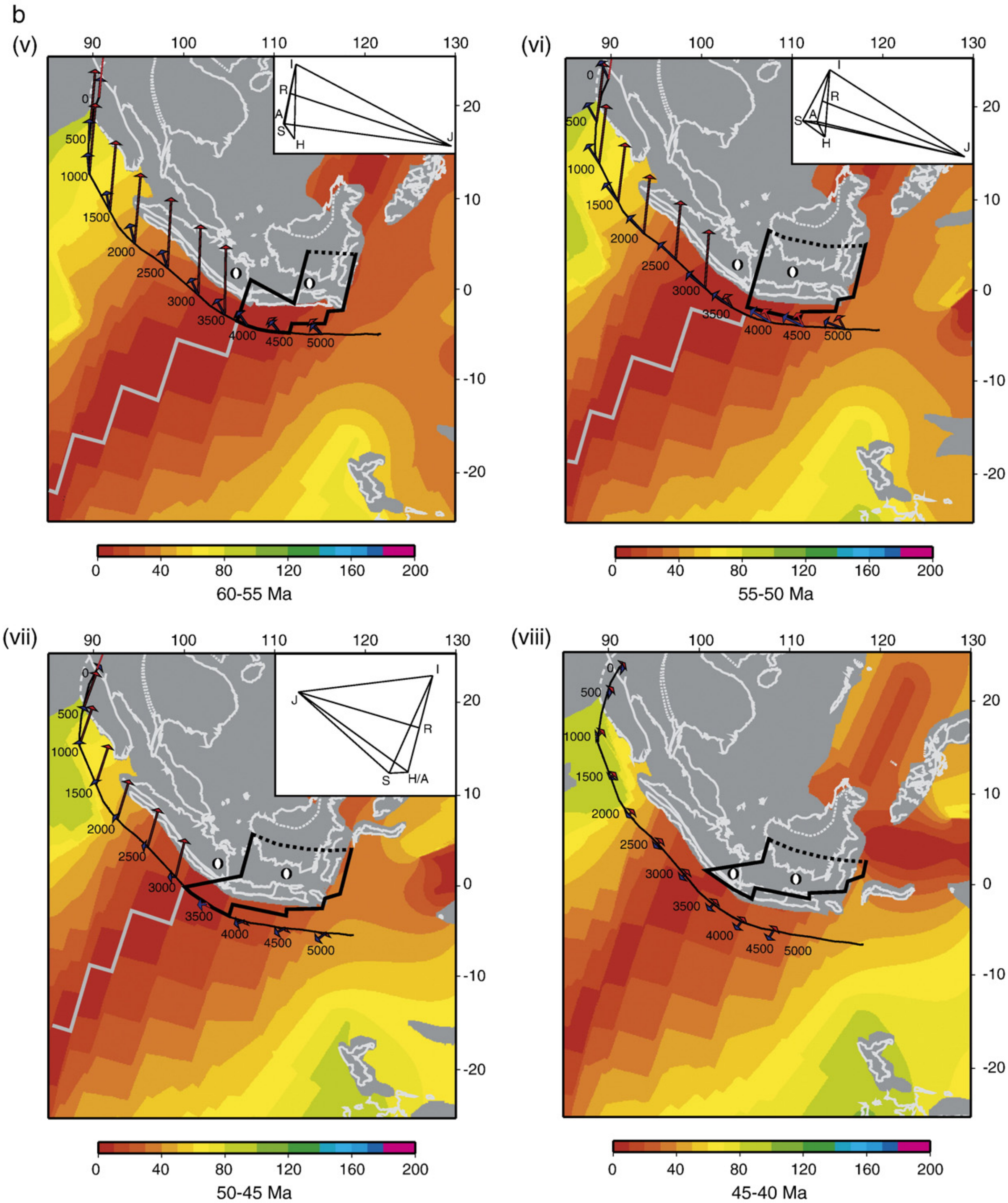


Fig. 2 (*continued*).

Fig. 2(v–vi)) the age of subducting lithosphere at the trench was >55 Myr, and Fig. 3(ii–iii) shows upper plate retreat. However, our reconstructed slab dip for the Andaman Sea for 60–50 Ma is ~22°, suggesting that conditions were not conducive to back-arc spreading initiation in the Andaman region at this time.

Central and northern Sumatran upper plate retreat suggests that the Sumatra back-arc should have

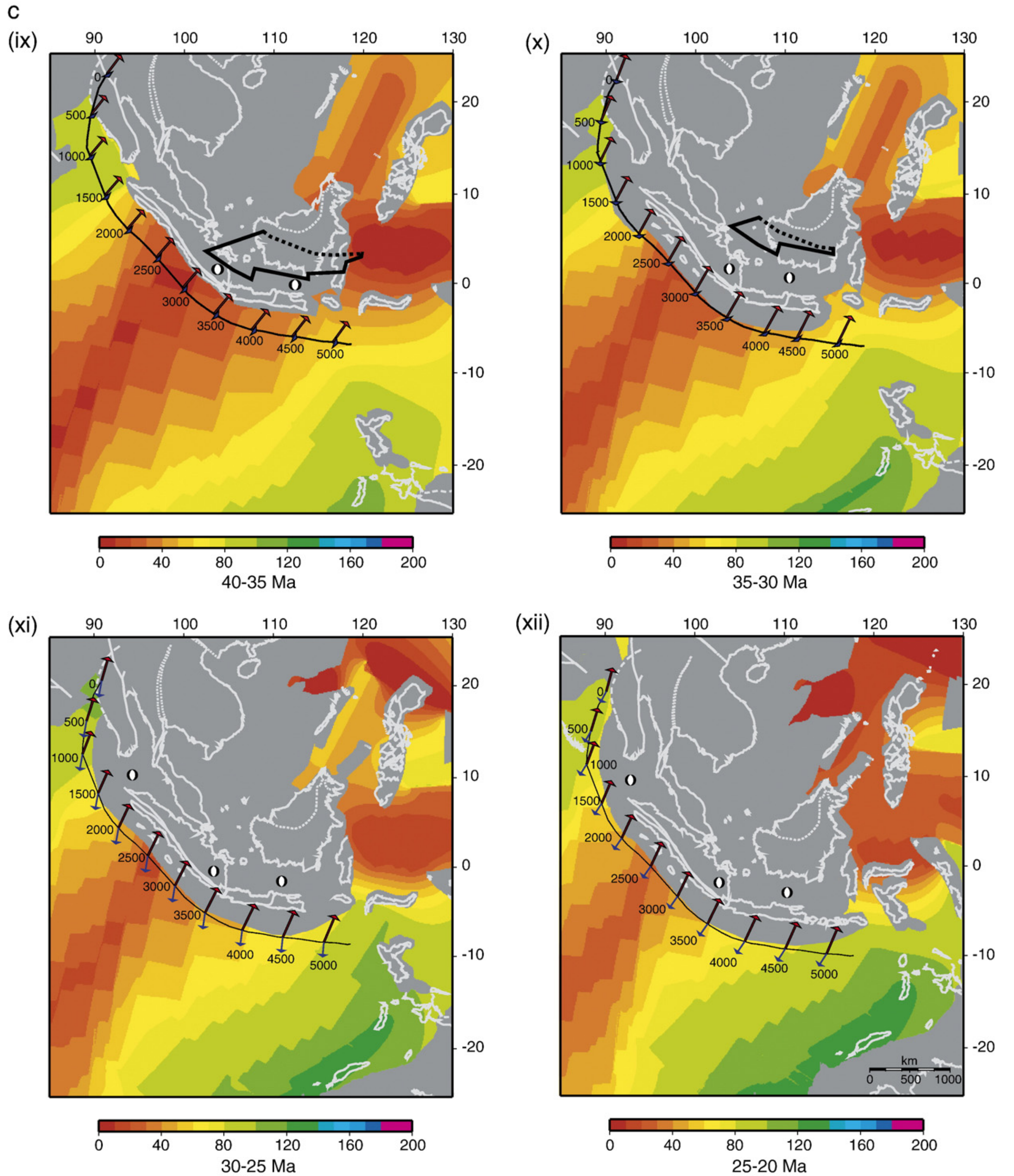


Fig. 2 (*continued*).

experienced extension from 15 Ma to the present (Fig. 3 (iv–vii)). However, compression is known to have affected this area during this period. It is likely that the presence of the subducting Wharton Ridge and Investigator Fracture Zone (IFZ) are responsible for this deviation from the expected upper plate regime.

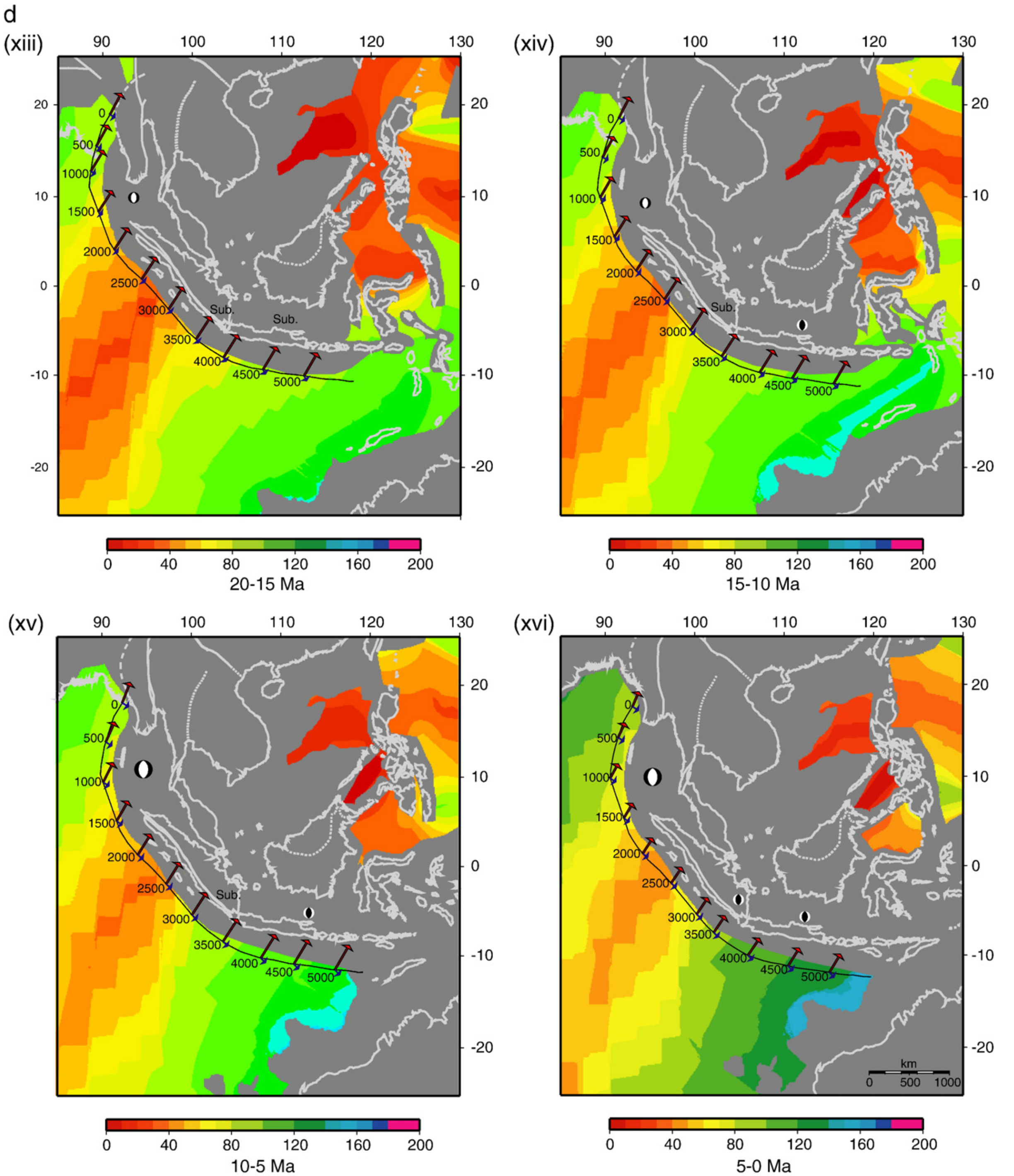


Fig. 2 (*continued*).

3.2. Bathymetric ridge subduction

The Wharton Ridge first subducts beneath eastern Java [16], at 70 Ma, which likely caused the Sundaland margin to rotate clockwise about a rotation pole close to the area at this time. Presently, the Wharton Ridge and Investigator Fracture Zone IFZ subduct beneath northern–central Sumatra (Fig. 1). The subduction of bathymetric features

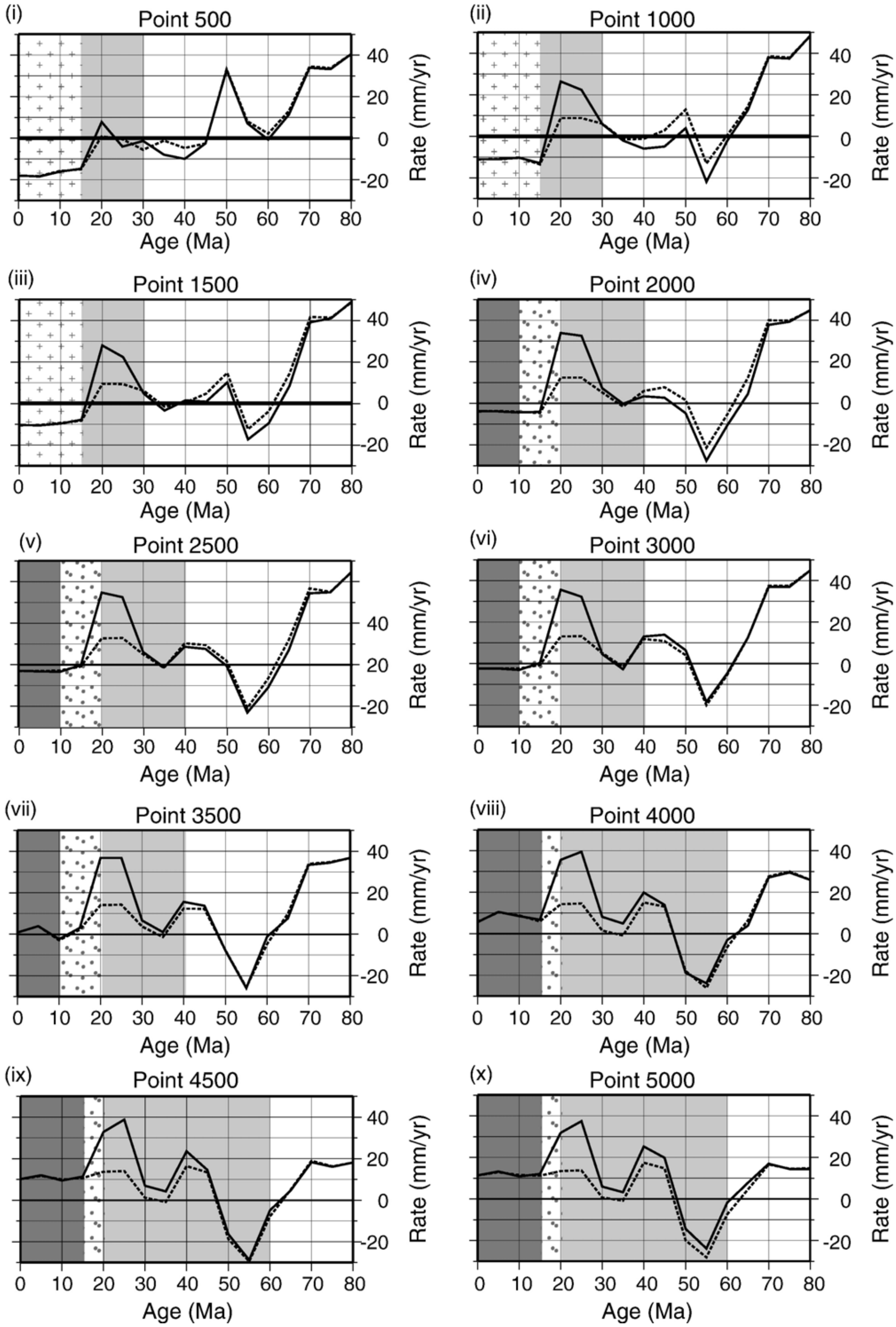


Fig. 3. Trench-normal component of the reconstructed absolute plate velocity plotted for the Sundaland core and margin for the period 0–80 Ma at points every 500 km along the Sunda-Java trench (see Fig. 2). Positive values indicate advance (oceanward motion) and negative values indicate retreat (landward motion) of the upper plates. Background shading represents known tectonic regimes for the Sundaland back-arc summarised from Morley [28], Bishop [29], Hall [30], Letouzey et al. [12], Eguchi et al. [31], and Curray et al. [11], where (1) compression is represented by crosses, (2) subsidence is represented by dots, (3) extension is represented by light shading, and (4) spreading is represented by dark shading.

is widely accepted to cause broadly distributed deformation in the fore-arc [42,43]. Geodetic strain and rotation rates show that the northern Sumatran region currently endures a highly compressive regime [44]. Rates of seismic deformation are at a maximum offshore Sumatra near Nias Island (5.2±0.65 mm/yr) and progressively decrease northward (1.12±0.13 mm/yr) [45]. Due to oblique subduction and extension to the north, Sumatra, and the Sumatran fore-arc, are divided into a series of NW–SE striking slices that move towards the northwest, separated by right-lateral faults [46]. Most displacement on these faults occurs in northwest Sumatra and dissipates towards the southeast [47]. Geodetic observations from GPS data [48] reveal an interesting change in Sumatran fore-arc motion centred around Batu Island (Fig. 1). Southeast of Batu Island, the Sumatra fore-arc moves northeast, roughly parallel with the motion of the Indian plate, while northwest of Batu Island the Sumatran fore-arc moves to the northwest [48]. This change in fore-arc motion has been ascribed to decoupling between the northern fore-arc and mantle wedge due to increased pore pressures in the fore-arc thrust fault due to subduction of thick Nicobar fan sediments [48].

The Wharton Ridge subducts beneath Nias Island where seismic deformation is highest and the IFZ subducts directly beneath Batu Island where the Sumatran fore-arc begins to move in a northwest direction. Thus, subduction of the Wharton Ridge and IFZ is another mechanism causing the high seismic deformation rates, change in fore-arc motion, and concentration of strike-slip motion that occurs in northern Sumatra. Fig. 3(iv–vii) shows that rate of Sumatran upper plate retreat at 15–0 Ma is not rapid (0–5 mm/yr), so it is likely that extension experienced by the Sumatra back-arc from this mechanism is relatively small. It is possible that present-day compression from subduction of the Wharton Ridge and Investigator Fracture Zone dominates over extension resulting from the retreating upper plate. It is likely that this domination of compressive strain related to bathymetric ridge subduction has dominated over upper plate motion related extension since 15 Ma.

Subduction of the Wharton Ridge initiated at ~70 Ma ([16], (see Fig. 2(ii)) and has migrated ~2400 km (30 km/Ma) along the Sunda-Java trench to its present-day location. During the period 50–15 Ma, the upper plate adjacent to the location of Wharton Ridge subduction is both observed and predicted (using upper plate motions) to have experienced extension. Plate motions were generally stronger at this time compared with those affecting Sumatra over the past 15 Myr and so dominated over the compressional effects of the subducting Wharton Ridge.

The Roo Rise (Fig. 1) is presently being subducting adjacent to Java. Subduction of this major bathymetric feature is currently causing deforming the Javanese fore-arc [49]. Roo Rise subduction is likely to be contributing to Javanese compression in addition to compression caused by upper plate advance since ~15 Ma. Onset of Roo Rise subduction is unknown so the period over which it has influenced Javanese upper plate strain is unknown.

3.3. Slab window

A slab window may form between the diverging plates of a subducting active mid-ocean ridge. Due to the hotter mantle wedge temperatures expected in conjunction with a slab window, the viscosity may be decreased in the mantle wedge and a low viscosity mantle wedge can lead to horizontal extension in normal subduction zones [18,24,50,51]. Our reconstructions show that a slab window was underlying southern/central Sumatra at 45–35 Ma (Fig. 2). Our reconstructions show a minimum slab-window extent as the effects of slab dip and thermal erosion of plate edges are excluded, both of which result in increasing the lateral extent of the slab window. Fig. 2(v–vii) shows the western edge of the slab window in a stationary position at the southern tip of Sumatra from 60–45 Ma. It is likely that thermal erosion of the Indian plate edge over this 15 million year period would have progressively shifted the slab-window edge across southern Sumatra earlier than 45–40 Ma shown in Fig. 2(vii–viii). Plate motion reconstructions from 50 Ma (Fig. 3) show an advancing upper plate in Sumatra suggesting that a compressive regime should have existed, however extension is observed from geological evidence. The underlying slab window may have enabled extension to continue from ~50 Ma until the onset of subduction hinge rollback at 35 Ma.

An underlying slab window can also lead to cessation of arc volcanism [18], while the progression of a slab edge across a region can change chemical signatures, increase volume and extend the range of volcanism [18]. Plutonism occurred in Indonesia from 60 Ma but was restricted to Sumatra (and further inland from the trench) and ceased at around 50 Ma [30,52]. In general, this Palaeogene volcanic activity was much more prominent in south and central Sumatra than northern Sumatra [30] and it has previously been noted that this pattern of volcanism may be related to subduction of the Wharton Ridge [16]. It is possible that this underlying slab window was responsible for the burst of volcanic activity in south and central Sumatra from 60 to 50 Ma as thermal erosion caused progression of the Indian plate edge across southern Sumatra. Cessation of volcanism at ~50 Ma suggests that the slab window was established beneath southern Sumatra causing volcanic activity to halt. Subduction related plutonism, focussed along the Sumatran Fault Zone from the Mid-Miocene [52], re-established in Sumatra at around 30 Ma, when that the slab window was no longer positioned beneath this region.

The slab window underlies Java at 70–40 Ma (Fig. 2 (iii–viii)). At 60–45 Ma extension occurred across southern Kalimantan and the Java Sea, as well as some spreading in the Makassar Straits [12,53,54]. Extension caused by the presence of the underlying slab window may have exacerbated Javanese back-arc extension, already induced by a retreating upper plate, enabling spreading to occur in the Makassar Strait. It is also possible that the underlying slab window was responsible for inhibited Javanese volcanism prior to ~42 Ma [55].

3.4. Shallow slab dip angle

Fig. 4 shows our reconstructed shallow slab dips (SSD) plotted against upper plate strain obtained from the literature for the Indonesian margin. Computed SSD in the 'slightly extensional' category, that fall outside the present-day relationship of Lallemand and Heuret [13], represent subduction of young (<23 Ma) lithosphere. Mid-ocean ridge subduction was excluded from the studies of Lallemand and Heuret [13] and Sdrolias and Müller [14]. Fig. 4 shows that, if these values are excluded, our reconstructed regional SSD fall within the pattern observed for the present day by Lallemand and Heuret [13].

Observed SSD (0–125 km) for the Andaman, Sumatra and Java regions are 24.6°, 23.9°, and 22.7°, respectively [56], while our calculated SSD are 29°, 25.5°, and 36°, respectively. The deviation between observed and calculated clearly shows that the age of subducting lithosphere alone cannot be used to reconstruct shallow slab dips, and that further parameters need to be incorporated into the calculations, such as horizontal and vertical mantle flow, and down-going plate motions. Therefore, due to errors in the estimation of SSD from the age of subducting lithosphere, as well as the broad nature of the relationship between upper plate strain and SSD it is not possible to use the age of subducting lithosphere to predict palaeo-upper plate strain regimes.

4. Conclusions

Upper plate strain expected for Sundaland back-arc regions from reconstructed trench-normal plate motions of the Sundaland core and margin correlate well with known upper plate strain regimes. The three types of upper plate motion to affect the Sundaland margin since 80 Ma are:

(1) A consistently advancing upper plate corresponds to compression in the overriding back-arc, caused by the collision between the down-going Indian plate and the advancing Sundaland plate,
(2) An advancing upper plate, where the Sundaland margin advances more rapidly than the Sundaland core, correlates with extension in the upper plate e.g. southern Andaman Sea, Sumatra and Java at 30–15 Ma, 35–15, and 45–15 Ma, respectively. The only mechanism for the margin to advance faster than the core is pulling by subduction hinge rollback,
(3) Uniform upper plate retreat correlates with extension in the upper plate in two cases, Javanese crustal extension 60–50 Ma, and spreading in the Andaman Sea 15–0 Ma.

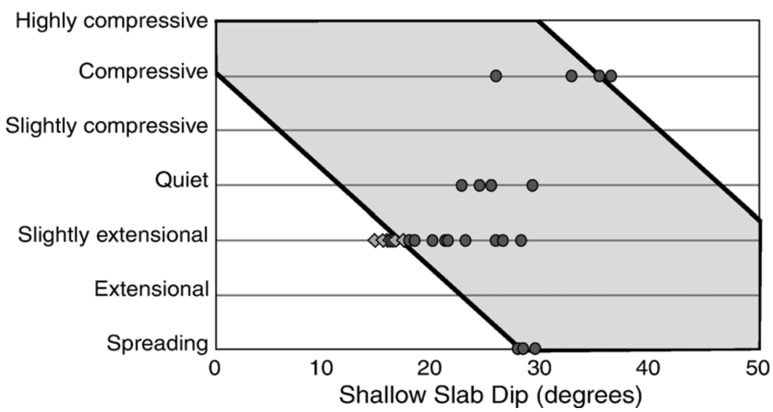


Fig. 4. This figure shows our shallow slab dip angles plotted against back-arc tectonic regime [11,12,28–31]. The black lines indicate the envelope of the present-day relationship for worldwide subduction zones from Lallemand et al. [13]. Light grey diamonds represent shallow slab dips for which the age of subducting lithosphere is <23 Ma. Dark grey circles are all other data points.

Periods where predicted upper plate strain from upper plate motions does not match observed upper plate strain can be explained by forces arising from the slab window and subduction of large bathymetric ridges. In present-day Java, compression is enhanced by subduction of the Roo Rise, while in Sumatra, 15–0 Ma, compression from Wharton Ridge and IFZ subduction overrides induced extension forces from upper plate retreat. The underlying slab window, formed through subduction of the Wharton Ridge, may have exacerbated extension in the Java Sea and south Kalimantan region and possible seafloor spreading in the Makassar Strait at ~60–45 Ma. The slab window may also have enabled extension to continue in Sumatra from ~50 Ma until the onset of subduction hinge rollback at 35 Ma when a uniformly advancing upper plate could have otherwise led to a compressive regime. The progression of the slab window across Java and southern Sumatra also appears to have some correlation with Indonesian volcanic activity with the presence of the underlying slab window corresponding with an absence of Javanese volcanism until ~42 Ma [55], and the progressing edge of the slab window corresponding with an episode of volcanism from 60–50 Ma in southern Sumatra.

The relationship between our reconstructed shallow slab dips and known Sundaland upper plate strain regimes falls within the envelope of observed slab dips for the present day. However, due to the errors associated with calculating shallow slab dips from age of subducting lithosphere, and the broad nature of the relationship between present-day dips and upper plate strain, our reconstructed shallow slab dips are not useful for predicting palaeo-upper plate strain regimes.

References

[1] C.G. Chase, Extension behind island arcs and motions relative to hot spots, J. Geophys. Res. 83 (1978) 5380–5387.

[2] C.H. Scholz, J. Campos, On the mechanism of seismic decoupling and back arc spreading at subduction zones, J. Geophys. Res. 100 (1995) 22,103–22,122.

[3] E. Mandovani, D. Albarello, D. Babbucci, C. Tamburelli, M. Viti, Genetic mechanism of back-arc opening: insights from the Mediterranean deformation pattern, in: E. Boschi, E. Ekstrom, A. Morelli (Eds.), Problems in Geophysics for the New Millennium, Editrice Compositori, Bologna, 2000, pp. 611–643.

[4] M.V. Rodkin, A.G. Rodnikov, Origin and structure of back-arc basins: new data and model discussion, Phys. Earth Planet. Inter. 93 (1996) 123–131.

[5] D.E. Karig, Origin and development of marginal basins in the western pacific, J. Geophys. Res. 76 (1971) 2542.

[6] N.H. Sleep, M.N. Toksoz, Evolution of marginal seas, Nature 233 (1971) 548–550.

[7] W.M. Elsasser, Seafloor spreading as thermal convection, J. Geophys. Res. 76 (1971) 1101–1112.

[8] P. Molnar, T. Atwater, Interarc spreading and Cordilleran tectonics as alternatives related to the age of subducted oceanic lithosphere, Earth Planet. Sci. Lett. 41 (1978) 330–340.

[9] J.F. Dewey, Episodicity, sequence, and style at convergent plate boundaries, in: D.W. Strangway (Ed.), The Continental Crust and Its Mineral Deposits Special Paper, vol. 20, The Geological Association of Canada, Toronto, 1980, pp. 553–573.

[10] T. Volti, A. Gorbatov, H. Shiobara, H. Sugioka, K. Mochizuki, Y. Kaneda, Shear-wave splitting in the Mariana trough—a relation between back-arc spreading and mantle flow? Earth Planet. Sci. Lett. 244 (2006) 566–575.

[11] J.R. Curray, D.G. Moore, L.A. Lawver, F.J. Emmel, R.W. Raitt, M. Henry, R. Kieckhefer, Tectonics of the Andaman Sea and Burma, Geological and Geophysical Investigations Of Continental Margins, vol. 29, AAPG Memoir, 1978, pp. 189–198.

[12] J. Letouzey, P. Werner, A. Marty, Fault reactivation and structural inversion. Backarc and intraplate compressive deformations. Example of the eastern Sunda shelf (Indonesia), Tectonophysics 183 (1990) 341–362.

[13] S. Lallemand, A. Heuret, On the relationships between slab dip, back-arc stress, upper plate absolute motion, and crustal nature in subduction zones, Geochem., Geophys., Geosyst. 6 (2005), doi:10.1029/2005GC000917.

[14] M. Sdrolias, R.D. Müller, The controls on back-arc basin formation, Geochem., Geophys., Geosyst. 7 (2006) Q04016, doi:10.1029/02005GC001090.

[15] R.D. Jarrard, Relations among subduction parameters, Rev. Geophys. 24 (1986) 217–284.

[16] C. Heine, R.D. Müller, C. Gaina, Reconstructing the lost Eastern Tethys Ocean Basin: constraints for the convergence history of the SE Asian margin and marine gateways, in: P. Clift, D. Hayes, W. Kuhnt, P. Wang (Eds.), Continent-Ocean Interactions in Southeast Asia, Geophys. Monogr. Ser., vol. 1149, American Geophysical Union, Washington, 2004.

[17] K.S. Krishna, D. Gopala Rao, M.V. Ramana, V. Subrahmanyam, K. Sarma, A.I. Pilipenko, V.S. Shcherbakov, I.V. Radhakrishna Murthy, Tectonic model for the evolution of oceanic crust in the northeastern Indian Ocean from the Late Cretaceous to the early Tertiary, J. Geophys. Res. 100 (1995) 20011–20024.

[18] D.J. Thorkelson, Subduction of diverging plates and the principles of slab window formation, Tectonophysics 255 (1996) 47–63.

[19] W.R. Dickinson, W.S. Snyder, Geometry of subducted slabs related to San Andreas transform, J. Geol. 87 (1979) 609–627.

[20] T. Atwater, J. Severinghaus, Relative plate motions in Northeast Pacific, 85 Ma to present, as recorded by magnetic lineation patterns, in: Anonymous (Ed.), 28th International Geological Congress. International Geological Congress, Abstracts—Congres Geologique Internationale, Resumes, vol. 28; 1, International Geological Congress, 1989, pp. 60–61, [location varies], International.

[21] R.G. Bohannon, T. Parsons, Tectonic implications of post-30 Ma Pacific and north American relative plate motions, Geol. Soc. Amer. Bull. 107 (1995) 937–959.

[22] D.J. Thorkelson, R.P. Taylor, Cordilleran slab windows, Geology 17 (1989) 833–836.

[23] J.K. Madsen, D.J. Thorkelson, R.M. Friedman, D.D. Marshall, Cenozoic to recent plate configurations in the pacific basin: ridge subduction and slab window magmatism in western North America, Geosphere 2 (2006) 11–34.

[24] V.B. Sisson, A.R. Poole, N.R. Harris, H.C. Burner, T.L. Pavlis, P. Copeland, R.A. Donelick, W.C. McLelland, Geochemical and

geochronologic constraints for genesis of a tonalite–trondhjemite suite and associated mafic intrusive rocks in the eastern Chugach Mountains, Alaska; a record of ridge-transform subduction, Spec. Pap. — Geol. Soc. Am. 371 (2003) 293–326.
[25] S.T. Johnston, D.J. Thorkelson, Cocos–Nazca slab window beneath Central America, Earth Planet. Sci. Lett. 146 (1997) 465–474.
[26] V. Ramos, Seismic ridge subduction and topography: foreland deformation in the Patagonian Andes, Tectonophysics 399 (2005) 73–86.
[27] C. Guivel, Y. Lagabrielle, J. Bourgois, H. Martin, N. Arnaud, S. Fourcade, J. Cotten, R. Maury, Very shallow melting of oceanic crust during spreading ridge subduction: origin of near-trench Quaternary volcanism at the Chile Triple Junction, J. Geophys. Res. 108 (2003), doi:10.1029/2002JB002119.
[28] C.K. Morley, Combined escape tectonics and subduction roll-back arc extension: a model for the evolution of Tertiary rift basins in Thailand, Malaysia and Laos, J. Geol. Soc. (Lond.) 158 (2001) 461–474.
[29] M.G. Bishop, South Sumatra Basin Province, Indonesia: the Lahat/Talang Akar–Cenozoic total petroleum system, Open-File Report 99–50 S, U. S. Department of the Interior U.S. Geological Survey, 2000.
[30] R. Hall, Cenozoic geological and plate tectonic evolution of Southeast Asia and the SW Pacific: computer-based reconstructions, models and animations, J. Asian Earth Sci. 20 (2002) 353–431.
[31] T. Eguchi, S. Uyeda, T. Maki, Seismotectonics and tectonic history of the Andaman Sea, Tectonophysics 57 (1979) 35–51.
[32] C. Gaina, R.D. Müller, Cenozoic tectonic and depth/age evolution of the Indonesian gateway and associated back-arc basins, Earth-Sci. Rev.(submitted for publication).
[33] C. O'Neill, R.D. Müller, B. Steinberger, On the uncertainties in hotspot reconstructions, and the significance of moving hotspot reference frames, Geochem., Geophys., Geosyst. 6 (2005) 002005, doi:10.1029/2004GC000784.
[34] A.V. Abrajevitch, J.R. Ali, J.C. Aitchison, A.M. Badengzhu, Davis, J. Liu, S.V. Ziabrev, Neotethys and the India–Asia collision: insights from a palaeomagnetic study of the Dazhuqu ophiolite, southern Tibet, Earth Planet. Sci. Lett. 233 (2005) 87–102.
[35] T.-Y. Lee, L.A. Lawver, Cenozoic plate reconstruction of Southeast Asia, Tectonophysics 251 (1995) 85–138.
[36] G.D. Acton, Apparent polar wander of India since the Cretaceous with implications for regional tectonics and true polar wander, in: T. Radhakrishna, J.D.A. Piper (Eds.), Indian Subcontinent and Gondwana: A Palaeomagnetic and Rock Magnetic Perspective 44, Mem. Geol. Soc. India, 1999, pp. 129–175.
[37] S. Widiyantoro, R. van der Hilst, Structure and evolution of lithospheric slab beneath the Sunda Arc, Indonesia, Science 271 (1996) 1566–1570.
[38] A. Replumaz, H. Karason, R.D.v.d. Hilst, J. Besse, P. Tapponnier, 4-D evolution of SE Asia's mantle from geological reconstructions and seismic tomography, Earth Planet. Sci. Lett. 221 (2004) 103–115.
[39] R.G. Gordon, C. Demets, J.Y. Royer, Evidence for long-term diffuse deformation of the lithosphere of the equatorial Indian Ocean, Nature 395 (1998) 370–374.
[40] P. Patriat, J. Achache, India–Eurasia collision chronology has implications for crustal shortening and driving mechanisms of plates, Nature 311 (1984) 615–621.
[41] P. Patriat, J. Segoufin, Reconstruction of the Central Indian Ocean, Tectonophysics 155 (1988) 211–234.
[42] T.W. Gardner, D. Verdonck, N. Pinter, R.L. Slingerland, K.P. Furlong, T.F. Bullard, S.G. Wells, Quaternary uplift astride the aseismic Cocos Ridge, pacific coast of Costa Rica, Geol. Soc. Amer. Bull. 104 (1992) 219–232.
[43] W.-Y. Chung, H. Kanamori, A mechanical model for plate deformation associated with aseismic ridge subduction in the New Hebrides arc, Tectonophysics 50 (1978) 29–40.
[44] G.W. Michel, Y. Yue Qui, Z. Sheng Yuan, C. Reigber, M. Becker, E. Reinhart, W. Simons, B. Ambrosius, C. Vigny, N. Chamot-Rooke, X. Le Pichon, P. Morgan, S. Matheussen, Crustal motion and block behaviour in SE-Asia from GPS measurements, Earth Planet. Sci. Lett. 187 (2001) 239–244.
[45] M.R. Krishna, T.D. Sanu, Shallow seismicity, stress distribution and crustal deformation pattern in the Andaman–West Sunda arc and Andaman Sea, northeastern Indian Ocean, J. Seismol. 6 (2002) 25–41.
[46] M. Diament, H. Harjono, K. Karta, C. Deplus, D. Dahrin, M.T. Zen, M. Gerard, O. Lassal, A. Martin, J. Malod, The Mentawai fault zone off Sumatra: a new key for the geodynamics of Western Indonesia, Geology 20 (1992) 259–262.
[47] R. McCaffrey, Slip partitioning at convergent plate boundaries of SE Asia, in: R. Hall, D. Blundell (Eds.), Geological Society Special Publication, Tectonic Evolution of Southeast Asia, vol. 106, 1996, pp. 3–18.
[48] L. Prawirodirdjo, Y. Bock, R. McCaffrey, J.F. Genrich, E. Calais, C. Stevens, S.S.O. Puntodewo, C. Subarya, J. Rais, P. Zwick, Fauzi, geodetic observations of interseismic strain segmentation at the Sumatra zone, Geophys. Res. Lett. 24 (1997) 2601–2604.
[49] H. Kopp, E.R. Flueh, C.J. Petersen, W. Weinrebe, A. Wittwer, Meramex Scientists, The java margin revisited: evidence for subduction erosion off java, Earth Planet. Sci. Lett. 242 (1-2) (2006) 130–142.
[50] M.I. Billen, M. Gurnis, A low viscosity wedge in subduction zones, Earth Planet. Sci. Lett. 193 (2001) 227–236.
[51] D.J. Thorkelson, K. Breitsprecher, Partial melting of slab window margins: genesis of adakitic and non-adakitic magmas, Lithos 79 (2005) 25–41.
[52] W.J. McCourt, M.J. Crow, E.J. Cobbing, T. Amin, Mesozoic and Cenozoic plutonic evolution of SE Asia: evidence from Sumatra, Indonesia, in: R. Hall, D. Blundell (Eds.), Tectonic Evolution of Southeast Asia, Geol. Soc. Spec. Publ., vol. 106, Geological Society of London, 1996, pp. 321–335.
[53] R. Hall, Reconstructing Cenozoic SE Asia, in: R. Hall, D.J. Blundell (Eds.), Tectonic Evolution Of Southeast Asia, Geological Society Special Publications, The Geological Society London, London, 1996, pp. 153–184.
[54] M. Fuller, J.R. Ali, S.J. Moss, G.M. Frost, B. Richter, A. Mahfi, Paleomagnetism of Borneo, J. Asian Earth Sci. 17 (1999) 3–24.
[55] H. Smyth, R. Hall, J. Hamilton, P. Kinny, East Java: Cenozoic basins, volcanoes and ancient basement, Indonesian Petroleum Association Thirtieth Annual Convention and Exhibition, 2005.
[56] C. Cruciani, E. Carminati, C. Doglioni, Slab dip vs. lithospheric age: no direct function, Earth Planet. Sci. Lett. 238 (2005) 298–310.