



A slab in depth: Three-dimensional geometry and evolution of the Indo-Australian plate

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[1] Geoscientists use plate tectonics to explain many aspects of both continental evolution and evolution of the planet as a whole. The subduction of material at convergent plate boundaries forms a fundamental component to the theory of plate tectonics. Plates, continents, subduction zones, and spreading centers all exhibit motion and geometric evolution, so to try and resolve the past geometries of the planet, geologists have utilized plate tectonic reconstructions. Here we present a three-dimensional image of the subducted Indo-Australian plate below southeast Asia and show that the geometry of the subducted slab at depth is intimately related to the geometric evolution of SE Asia over the past 50 Ma, including the collision of India with the Asian continent. We show how the once semicontinuous subducting Indo-Australian plate has been segmented during collision between India, Australia, and the subduction margin to the north. Thus we have found that the geometry of the subducted plate should form a key component to the interpretation of the evolution of Earth's surface, as complexities and evolution of the subducted plate are manifest in the evolution of the overriding plate.

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1. Introduction

[2] Since the formulation of the idea that the planet was characterized by individual tectonic plates by Alfred Wegner in 1958, geologists have realized that the array of physiochemical mechanisms associated with plate tectonics is fundamental to the Earth's orogenic history. Consequently, plate tectonics remain the foundation of geosciences. In this paper we present the first detailed regional-scale three-dimensional (3-D) interpretation of the sub-

ducted Indo-Australian plate below India and SE Asia (Figure 1). We also discuss some of the implications that the derived plate geometry has on the evolution of the Indo-Australian plate margin over the past 50 Ma.

[3] Subduction zones form a fundamental component of our concept of plate tectonics. They typically occur at convergent plate boundaries, where oceanic crust and lithosphere dips into the mantle below an overriding plate, for example, the Aleutian Islands, Japan, the western margin of South

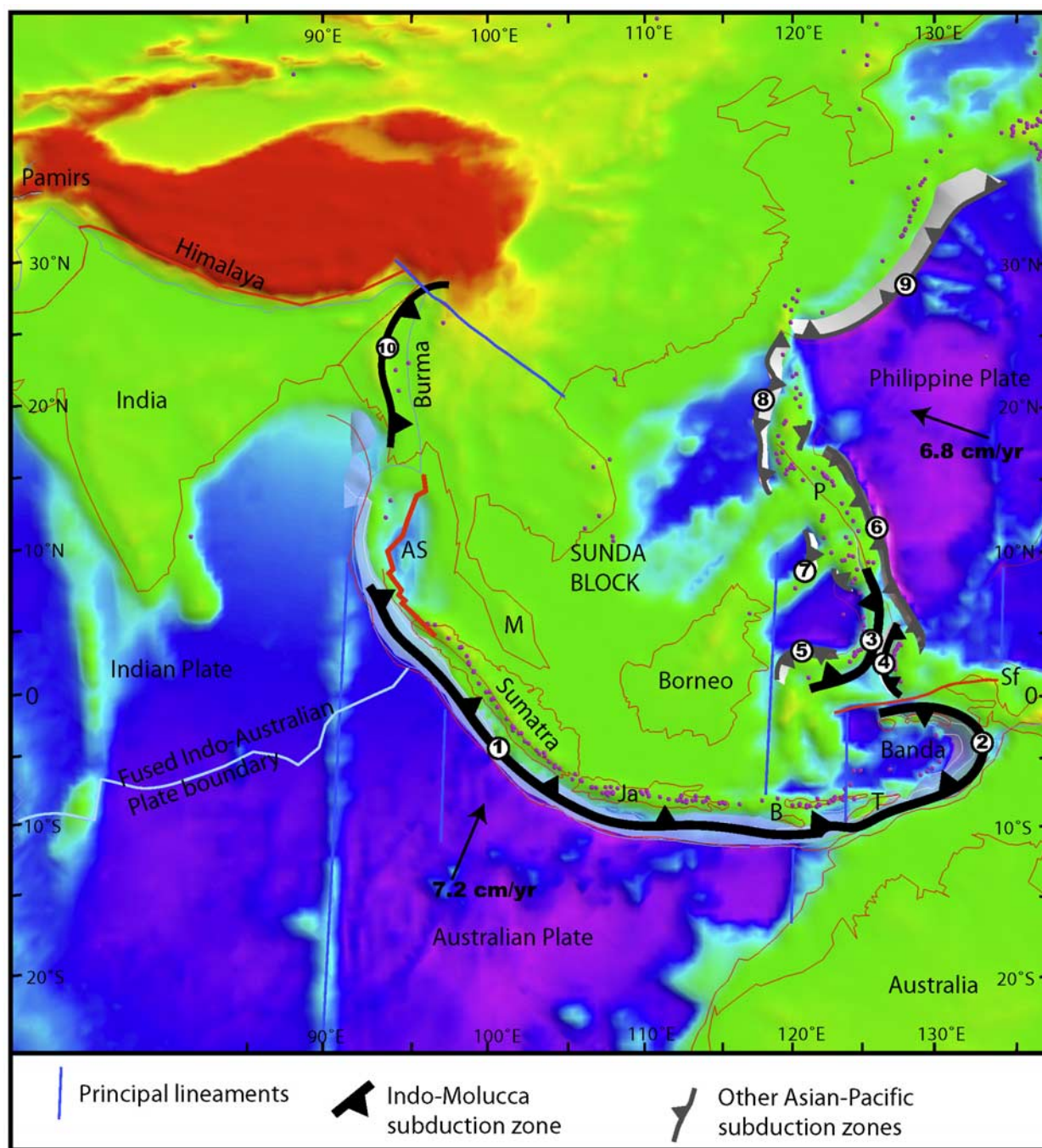


Figure 1. Map showing the topology of India, SE Asia, and Australia and the major subduction zones discussed in the text. The present-day outline of the subduction margin of the northern Indo-Australian plate is shown in black, while minor subduction zones are highlighted in grey. Selected subduction zones are labeled: (1) Sunda Arc, (2) Banda Arc, (3) Molucca Arc, (4) Halamahera Arc, (5) Sulawesi Arc, (6) Philippine Trench, (7) Cagayon Arc, (8) Luzon Arc, (9) Ryuku Trench, (10) Burma Trench. As, Andaman Sea; M, Malaysian Peninsula; P, Philippines; Ja, Java; B, Bali; T, Timor; Sf, Sorong Fault.

America and Scotia. These zones, which dominate the rim of the eastern and western Pacific plates, and have so for millions of yeas, are also some of the most complex geosystems on the planet.

Developing a comprehensive understanding of their geodynamic evolution is key to understanding the evolution and geodynamics of the planet as a whole. Rapid advances in high-performance com-

puter processing and 3-D visualization software have enabled us to begin creating a 3-D interactive digital model of the Earth below its surface by incorporating multiple geoscience-based data resources. The multiplicity of 3-D and 4-D geological and geophysical data sets has also allowed us to create digital models of the internal structure of the planet, which at this stage is focused on subduction zone geometries and dynamics. We then use these interpreted mantle geometries to make inferences and interpretations about the geodynamic evolution of a particular subduction zone or region through time, i.e., when plates and their respective margins had significantly different geometries than they do today.

[4] In this paper we present an interpreted geometry of the subducted Indo-Australian slab. To achieve this we use earthquake hypocenter data from the EHB hypocenter catalogue [Engdahl *et al.*, 1998] as well as comparing results with the USGS NEIC earthquake database for the period between 1990 and 2005. Location errors associated with individual earthquake hypocenters are not included; however, we have applied a constant error for each hypocenter by using a sphere size that is equal to ± 15 km in X, Y and Z.

[5] Within the Sumatra, Banda and Molucca regions, earthquake hypocenters are recorded to maximum depths of up to 650 to 670 km. Accordingly, both earthquake hypocenters and tomography are used to interpret the slab geometry to this depth. In the interpretation presented here, we assume that the earthquake hypocenters that occur below approximately 100 km depth represent inter-slab seismicity, whereas those that occur above 100 km depth may be, at least in part, caused by deformation associated with partial coupling between the subducting and overlying plates or the result of fluid and magma migration within the subvolcanic mantle wedge (e.g., between southern Java and Flores). To define the 3-D geometry of the upper surface (top) of the subducted slab, a triangulated mesh is created using the Gocad (EarthDecisionSuiteTM) software. The initial mesh is a coarse, 360-point (node) surface (Figure 2b) in which each individual nodes can be manipulated and moved until the final mesh surface conforms to the upper limit of the hypocenter clusters (Figures 2a and 2b). The ability to incrementally manipulate the mesh in three dimensions allows complex geometries to be constructed. Regions where there is an abundance of earthquake hypocenters and well-defined tomography are typically interpreted with

a high-resolution (increased mesh nodes) mesh surface. Mesh construction and modification was undertaken using a flat earth model in a Mercator projection before being imported into spherical Virtual Earth models. The interpreted Indo-Australian slab presented here is extracted from the flat earth model but it exhibits minimal distortion due to its position at low latitudes.

[6] Above approximately 660 km depth, the mesh is modified so that it conforms to both the hypocenter data and tomography. Below the maximum depth of hypocenters, P wave tomography is used to determine the slab geometry. Four regional P wave tomographic models were used in the interpretation of the slab surface displayed in Figures 2 and 3: Australia, Indonesia, China and India. The P wave models are from Sri Widiyantoro and presented by *van der Hilst et al.* [1991]. Wave speed variations are relative to ak135 [Kennett *et al.*, 1995]. The models are defined by a total velocity perturbation range of -1.332 to $+1.216$. Fast and slow velocities are illustrated by variations in a color gradient corresponding to blue and red colors, respectively; white is equal to values of 0 (Figures 2b and 2c). Surfaces derived using isovelocities for wave speed perturbations of between $+0.4$ and $+0.9$ were initially used to define regions of relatively fast mantle material which, for the region below Sumatra for example, we interpreted as representing subducted oceanic slab geometries. However, the potential complexity exhibited by mantle structure below SE Asia as inferred from complex plate tectonic reconstructions is interpreted to have contributed to the complexity observed in the tomography data at depths below around 600 km depth.

[7] The interpreted position of the slab surface using P wave tomography was created by manually moving mesh nodes so that the surface fell on or close to the point where the gradient between fast and slow wave speeds was greatest (Figures 2b, 2c, and 3). Regions within the tomographic model that are characterized by a distinctive “thinning” of the fast-wave speed anomaly and where there is reduced or no hypocenter data recorded (e.g., Figure 3) can be interpreted as regions where subducted slab might be missing or significantly thinned and may be interpreted as highlighting the location of gaps or tears in the subducting slab. We have not included alternate interpretations showing relatively small horizontal or subhorizontal slab tears in this model at this time. Nevertheless, on the basis of our analysis and interpretation of both the tomography

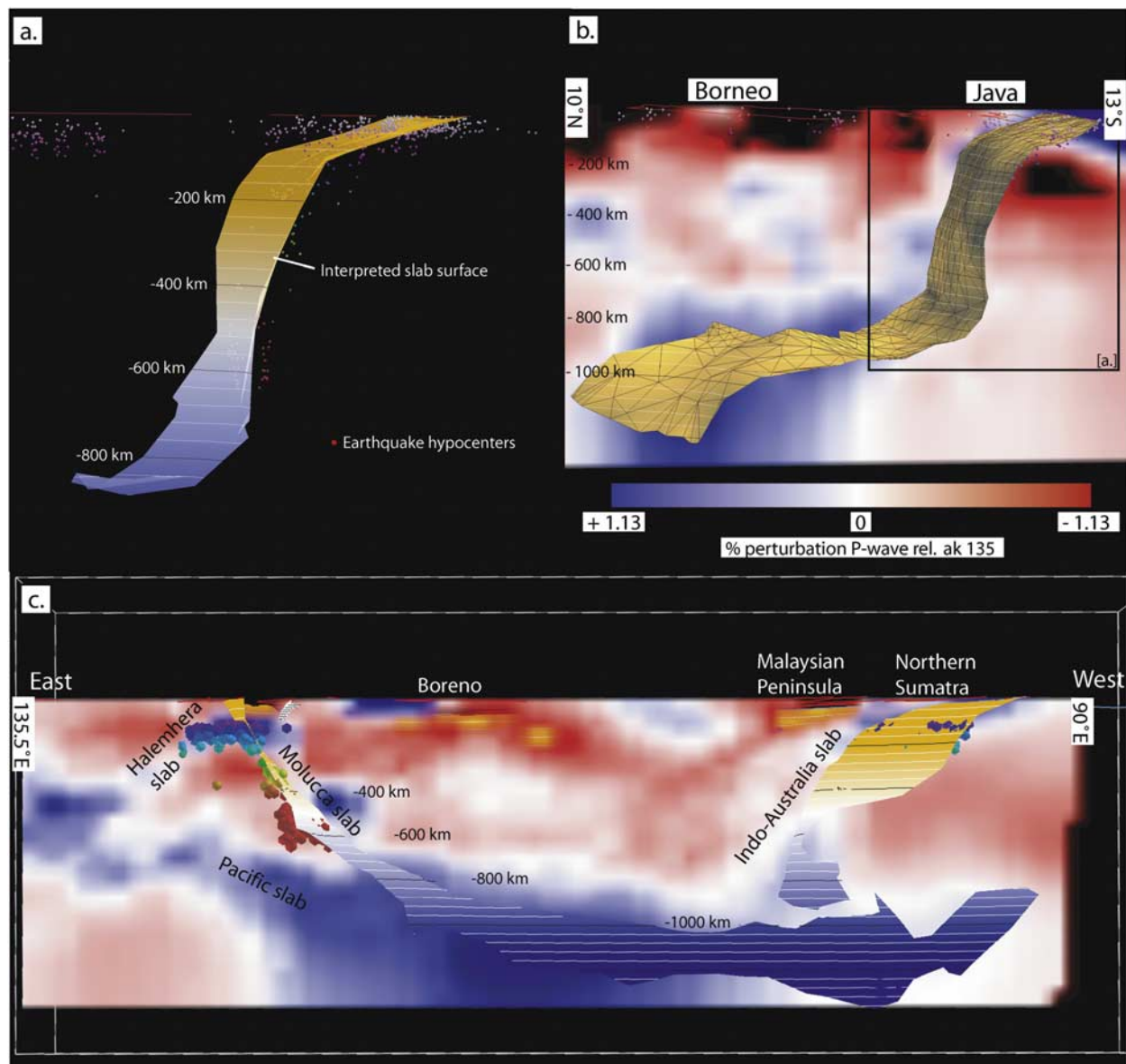


Figure 2. Vertical sections through two regions of the interpreted Indo-Australian slab showing the correlation between the interpreted shape and position of the mesh surface with respect to the two principal data sets used to constrain its geometry, namely, earthquake hypocenters and tomography. Figure 2a shows the upper 800 km of an interpreted section of the slab section illustrated in Figure 2b. The surface is constructed so that it conforms to the outer limit of the earthquake hypocenters as well as being constrained by the location of the fast anomaly highlighted in the tomography. Triangulated mesh surface together with tomography and earthquake hypocenters is shown in Figure 2b. Figure 2c is an east-west oriented section through the west-dipping Molucca Slab and the north-dipping Indo-Australia slab below Sumatra. The geometry of the slab below 600 km depth is shown relative to the location of the high wave speed anomaly.

and hypocenter information, we would suggest that both horizontal and vertical tears in the slab are not only possible but probable; however, higher-resolution models are required to resolve this issue.

[8] To better constrain our interpretations, plate tectonic reconstructions of Hall [1996], Hall and

Spakman [2002], Heine *et al.* [2004], Stampfli and Borel [2002], Scotese *et al.* [1988], and Replumaz *et al.* [2004] were used to evaluate the plate tectonic history of SE Asia including plate position and the location and longevity of subduction zones. The reconstructions show that SE Asia is characterized by a complex plate tectonic history including

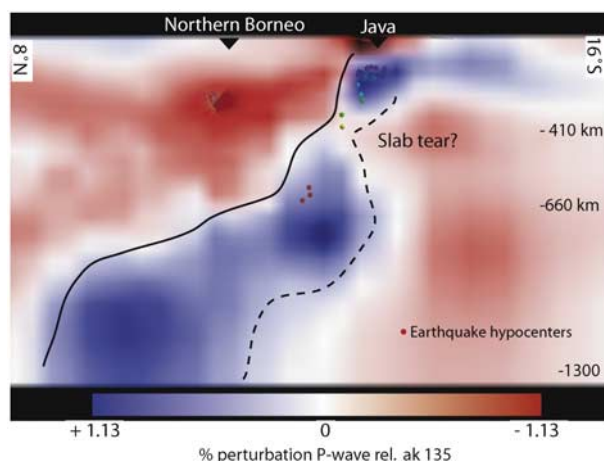


Figure 3. A north-south oriented vertical cross section through the P wave tomography model below Java and Northern Borneo. This cross section highlights the variability in the thickness of the fast wave speed anomaly with depth, but similar variability exists along the strike length of the plate boundary. Earthquake hypocenters extend to 660 km depth. The interpreted upper and lower surface of the slab is shown. The well-defined narrowing of the fast wave speed anomaly at 410 km depth may indicate thinning or tearing of the slab there.

multiple short- and long-lived subduction zones. Additionally, 3-D analysis of the tomographic data shows that the mantle structure below SE Asia is extremely complex and, although we have interpreted several segments of slab from the tomography, in this paper we have focused on presenting the interpreted 3-D geometry of the Molucca Sea slab and the Indo-Australian slab.

[9] The present-day limit of the northwestern Indo-Australian plate extends from the Banda Arc in the east and continuing to the west along the southern margin of Java and Sumatra. The northern limit of the subduction margin terminates at the plate suture

between India and Eurasia in central Burma (Figure 1). Over ~50 Ma ago, prior to the closure of the Tethys Ocean and collision between continental India and Asia, this subduction zone had a vastly different morphology and extent than it does today. The Molucca subduction zone and the associated Molucca Sea slab (Figure 1) lies to the north of Banda and is included as part of the Australian plate as discussed below.

[10] The present-day geomorphology of the Molucca Sea Trench is defined by an approximately 1100 km wide, laterally discontinuous arcuate subduction zone where the oceanic crust of the Molucca Sea is interpreted to be subducting to the west below the Celebes Basin (Sea) and Northern Sulawesi. A well-defined Wadati-Benioff zone highlights the west-dipping Molucca Sea slab to depths of around 300 km [McCaffrey *et al.*, 1980] and in our model to 550 km depth. A west-dipping high-wave speed anomaly is evident in the P wave tomography that parallels the hypocenter data (Figure 2); however, unlike the limited depth of the hypocenters, the anomaly extends to over 1300 km deep. The interpreted slab geometry is presented in Figures 2a and 2b. Between the surface and 600 km depth we have interpreted the lithospheric slab as a relatively simple, curvi-planar sheet (Figure 2). Below 600 km depth, however, the angle of the interpreted slab changes from steep to relatively shallow attitudes (Figure 2). Below 800 km depth, the high-velocity domain that defined the 1100 km wide subducted Molucca Sea Slab continues to the west where it links with the fast wave speed anomaly that defines the base (>800 km) of the Indo-Australian plate discussed below. Accordingly, this interpretation implies that, at depth, the Molucca Sea and Indo-Australian slabs form part of the same continuous section of subducted plate that were separated/torn during the evolution of the subduction zone.

Figure 4. Interpreted geometry of the Indo-Australian slab below India and southeast Asia. Figure 4a is a view looking from above at the same region of SE Asia illustrated in Figure 1 but with the topology of the crust removed. Some crustal regions are shown as transparent green for geographic reference. The interpreted geometry of the subducted Indo-Australian slab is shown as a contoured and colored surface or sheet, which projects from the surface (i.e., trench) to 1300 km depth in the mantle. The color gradient applied to the slab shows orange and blue colors corresponding with shallow and deep slab material, respectively. The principal features of the interpreted slab are (1) the presence of a subvertical tear separating the Banda Arc (2) from the Molucca Sea slab (3). The two slab segments connect at depth (>800 km), suggesting that, in the past, the now separate slabs formed part of the same continuous subducting plate. The location of the northern Indo-Australian subduction margin, prior to collision between India and Asia, is evident as an anomaly interpreted as slab material located between 800 and 1300 km depth below India. Figure 4b is an oblique view of the same interpreted slab surface presented in Figure 4a. The image is taken looking to the southeast across India toward NW Australia so that the shape of the vertical tear separating the Banda Slab from the Molucca Sea Slab can be seen. Also evident is the subhorizontal tear separating the upper part of the Indo-Australian Slab from the older, remnant slab below India.

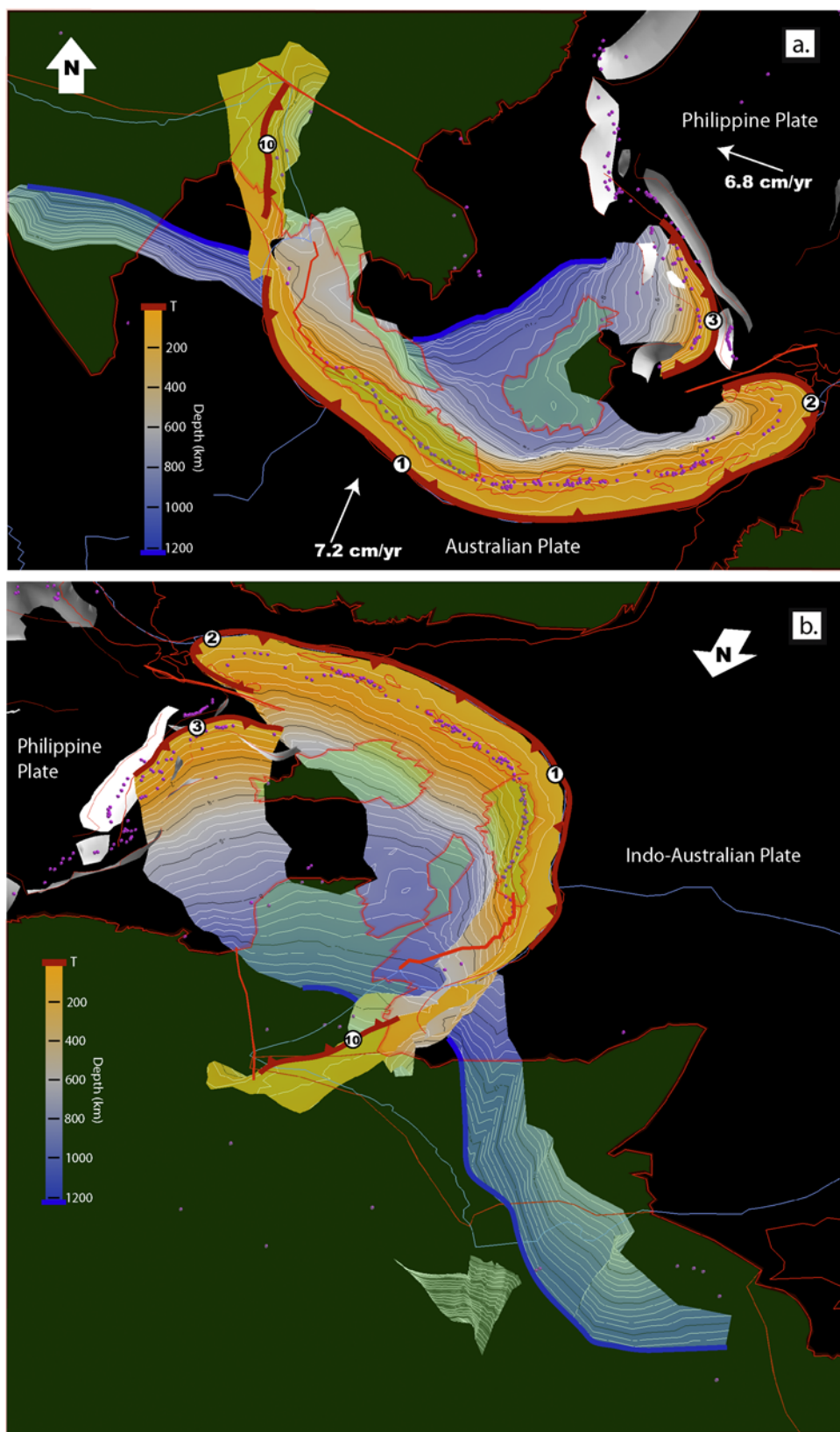


Figure 4

The interpreted 3-D geometry of the slab illustrated in Figures 2a and 2b shows the formation of a subvertical tear between the western edge of the Molucca Sea slab and the northeastern edge of the Banda Arc. The base of the tear between the two slab segments is located at around 800 km depth (Figures 2 and 4).

[11] Like the Molucca slab, the distinctive, concave shape of the Banda Arc is mimicked by the geography of the trench and island arc at the surface. Our interpretations of the tomography and hypocenter data show that the subducted section of the Indo-Australian plate is a west-dipping sheet that is also concave to the west (Figures 2 and 4). The northern terminus of the present-day Banda subduction zone abuts the E-W oriented Sorong Fault and at depth is marked by a lack of a Wadati-Benioff zone. A cessation in volcanism in the overriding plate also occurs where the subducted plate ends. With increasing depth (>400 km), the distinctive concave shape of the slab is progressively lost and a planar, northwest-dipping sheet-like morphology is revealed (Figures 2 and 4). Between 800 km and 1000 km depth, the slab exhibits a distinctive shallow NW-dipping morphology. Such subhorizontal anomalies (transient shallow/flat slab) are more commonly imaged at, or slightly above the 660 km discontinuity [Wortel and Spakman, 2000; Lallemand *et al.*, 2001; Widiyantoro *et al.*, 1999] where subducted lithosphere is interpreted to reside at density contrast defined by the ringwoodite to perovskite and magnesio-wüstite phase transition [e.g., Lebedev *et al.*, 2002; Shearer and Flanagan, 1999; Bina *et al.*, 2001; Ito and Takahashi, 1989]. The reasons for the uncharacteristic change in morphology of the subducted Indo-Australian slab at 800–1000 km depth are less certain; however, we would suggest that it is indicative of the change in subduction zone dynamics (i.e., increased rates of hinge rollback) at the time the slab was nearer to the Earth's surface. The evolution of this subduction system in SE Asia is discussed below. Below this shallow-dipping section, the slab exhibits a relatively consistent, north-dipping geometry, an almost east-to-west oriented trend and is continuous with the base of the aforementioned Molucca slab (Figures 2 and 4). The contrasting geometry of the semiplanar Molucca Sea slab and the arcuate Banda slab suggests that, after initial development of the subvertical tear of the once laterally continuous Indo-Australian plate, the two slabs have evolved independently with the Banda arc attaining a higher degree of curvature relative to the adjacent Molucca Sea slab.

[12] The interpreted 3-D geometry of the Indo-Australian slab below central and southern Sumatra appears relatively simple dipping steeply to over 1000 km below the island chain (Figures 2 and 4), which is consistent with the cross-section interpretations of *Replumaz et al.* [2004]. At 800 km depth below the Andaman Sea, the slab exhibits a shallow dip, which is not apparent some 1000 km south below southern Sumatra. A subhorizontal, laterally extensive “gap” in the fast velocity anomaly at around 500–600 km depth below Sumatra is interpreted as a subhorizontal tear; however, we have not included this in our interpretation. Nevertheless, a notable feature is that the relative slow anomaly extends laterally for less than 500 km suggesting that the “tear” is only locally developed in the section of slab below central Sumatra.

[13] To the north of Sumatra the geometry of the slab changes dramatically. The Indo-Australian plate no longer forms a single continuous sheet to 1300 km depth, as is evident further south. Here, no earthquake hypocenters are recorded below 250 km, whereas further south, hypocenters are recorded as deep as 600 km. In addition, the relatively fast wave speed anomaly defining the slab appears to also terminate at 500 km depth. On the basis of this evidence, we would suggest that the subducted slab to the north of Sumatra terminates at approximately 500 km depth below the Malay Peninsula (Figures 2 and 4).

[14] Approximately 400 km below the base of this section of slab, and some 800 km below northern Sumatra, occurs a distinctly linear fast wave speed anomaly in the P wave tomography data set. The anomaly is continuous between 800 km depth and the base of the tomography model at 1300 km depth. This anomaly is continuous with the base of the interpreted Indo-Australian slab imaged further south and the basal section of the Molucca Sea Slab (Figures 2 and 4). Thus the anomaly, and the interpreted lithospheric slab that it represents, continues as a relatively linear zone between 800 km and 1200 km depth from below northern Sumatra toward the northeast and below central India (Figures 2 and 4). The anomaly was interpreted by *Replumaz et al.* [2004] as defining the location of the subduction margin prior to collision between India and Asia. We would also suggest that the slab is the relict Neo-Tethyn oceanic crust that, prior to circa 55 Ma [Stampfli and Borel, 2002; Sengor and Natal'in, 1996; Dercourt *et al.*, 1993; van der Voo *et al.*, 1999] underwent north-directed subduction. The 3-D images presented in Figures 2 and 4 show

that the Neo-Tethyn slab as continuous with the base of the Indo-Australian plate below southern Sumatra. Further, the anomaly and (slab) is also continuous with the base of the Molucca Slab to the east. This implies that, prior to the collision between India and Asia, the region was characterized by a single continuous, NE trending subduction zone, which included the Molucca slab to the north.

[15] North of Sumatra and to the north and east of the Andaman Sea, the upper section of the Indo-Australian slab continues toward northern Burma. Earthquake hypocenter data as well as a well-defined domain characterized by fast P wave velocities exists below Burma, which is interpreted as a section of lithospheric slab there. We would suggest that the slab must be the northern termination of the Indo-Australia plate. At the surface, the subduction margin is arcuate, concave to the east. Here, the overriding Asian continental crust is characterized by west-directed extension that forms the Arakan Yoma. The plate exhibits a relatively shallow angle of subduction to around 120 km depth where it steepens and continues to a depth of approximately 300 km. In the interpretation that we have presented here, we have not included the interpreted slab geometry of this slab below this 300 km depth, but preliminary interpretations suggest that the slab may continue as an east-dipping sheet (slab) below southern Asia.

[16] Between latitudes 14°N and 17°N, corresponding with the Northern Andaman Sea, no hypocenters are recorded. This seismogenic quiet domain separates the well-defined sections of subducted slab to the north and south, as described above. A lack of arc-related volcanism characterizes the overriding plate in this zone. Finally, the section does not exhibit a high-wave speed perturbation in the P wave tomography despite the age of the crust at the subduction zone being of similar age to the north and south where the same tomography model exhibits a well-defined anomaly. We would suggest that the region of plate convergence to the northwest of the Andaman Sea (i.e., below 14°N and 17°N latitude) represents a region that contains no actively subducting. This lack of slab may be accounted for if we consider the formation of a tear between the northern Burmese section of slab and the Sumatran section to the south.

2. Discussion

[17] Reconstructions of the Neo-Tethyn Arc prior to the collision between India and Eurasia show the primary subduction zone trending NW where it is

continuous with the southern margin of Pakistan [e.g., *Replumaz et al.*, 2004; *Sengor and Natal'in*, 1996] (see Figure 5a). The subduction margin between the Paleo-Banda Sea and southeastern Pakistan had an estimated length of around 8000 km, but its present-day length, i.e., after collision between India and Asia is over 12,000 km. Mechanisms must be considered that can accommodate ~50% of extension of the orogenic margin between circa 50 Ma and present.

[18] To accommodate the increase in length of the eastern part of the subduction margin between northern Burma and northeastern Molucca, we would suggest that the once continuous slab, as imaged in the tomography below 800 km depth, formed a tear in the slab near the western margin of the subduction zone. The tear separated the slab into the Banda and Molucca sections. The timing of formation and the location of the tear can be reconciled with plate tectonic reconstructions (Figure 4). The position of the initial tear and the timing of its formation is consistent with the collision between the western Papua New Guinea and the proto-Sorong Fault with the northern Australian arc at approximately 25 Ma (Figure 5b), but following collision, the Banda and the Molucca Arcs evolved independently (Figures 5c–5e).

[19] The change in morphology of the slab at 800 km depth below the Banda Arc, i.e., switch from moderately dipping to shallow dipping, can be also explained in a reconstruction framework. To pinpoint the timing of the initiation of the subvertical tear that now separates the two slab sections, which also coincides with the location of the shallow section of slab, we have compared the rate of subduction with the depth at which the tear occurs on the subducted slab. To estimate the total length of subducted slab of subduction and therefore the age of the slab at depth we have estimated that approximately 1500 km of crust was produced at the Australia-Antarctic rift during 50 Ma of northward motion of Australia. Accordingly, approximately 1500 km of crust must have been consumed (subducted) at the northern Australian plate boundary between 50 Ma and present. The tear in the slab initiates at just below 800 km depth. Here the slab must be around 25 Ma old. This age corresponds with the reconstructions, which show the time of impact between the NE continental fragments on the Australian plate with the subduction zone near Banda to be at circa 25 Ma (Figure 5b).

[20] Immediately above the nick point of the tear (800 km depth), the Indo-Australian section of the

slab exhibits a shallow angle of subduction as described above. Following tearing at circa 25 Ma, it is envisaged that the Banda section of the subduction zone experienced increased rates of rollback, facil-

itated by toroidal flow of the mantle around the newly developed plate edges. Rapid hinge retreat resulted in shallow-slab subduction angles [Stegman *et al.*, 2006; Christensen, 1996]. Rapid rollback of the eastern part of the Indo-Australian plate can explain the development of flatter slab after tearing at 25 Ma. The characteristic curvature exhibited by the Banda Arc initiates at a depth of approximately 400 km. On the basis of the calculated age of the slab with depth, this would imply initial formation of the arcuate geometry at around 12–15 Ma ago.

[21] The major subhorizontal tear between the Indo-Australian slab below Sumatra and the lower, NW-trending Neo-Tethyn slab is centered at around 800 km depth, suggesting it also initiated at around 25 Ma; however, the maximum depth of the interpreted break between the upper and lower plate segments lies at around 1000 km depth, so the tear may have initiated as early as 32–33 Ma ago if slightly slower rates of northward plate motion after 55–60 Ma are employed [e.g., Dewey *et al.*, 1989].

[22] The base of our tomographic model data lies at a depth around 1340 km; however, due to variation in the angle in the dip of the slab, the interpreted down-dip length of subducted slab below central Java and Borneo is approximately 1600 km. Some 1500 km of crust (Australian oceanic plate) has been generated at the oceanic ridge between Ant-

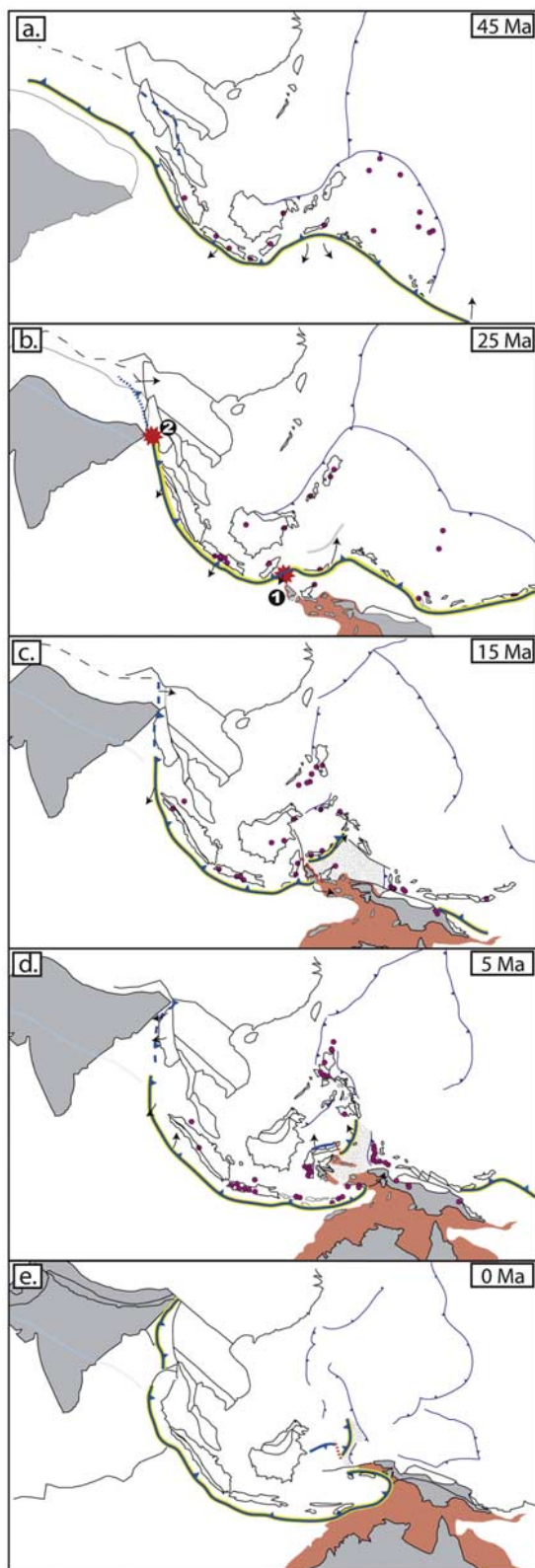


Figure 5. Schematic reconstructions focused on the geometric evolution of the northern Indo-Australian plate subduction margin (red and yellow line) between 45 Ma and present. Reconstructions are modified from those presented by Hall [1996]. In Figure 5a the NW-trending subduction margin is shown immediately prior to collision between greater continental India and the subduction zone. Black arrows show the direction of the future migration of the subduction zone. By circa 35 Ma, India collided with the subduction zone to the north. At 25 Ma (Figure 5b) the continued northward motion of India resulted in the continent overriding the subducted plate, causing subhorizontal tearing between the upper and lower sections of plate. At the same time, fragments of continental Australia (western Papua New Guinea as marked in Figure 5b as point 1) collided with the central part of the semicontinuous subduction margin, thereby triggering tearing of the subduction zone at that point. Figures 5c and 5d show the continued northward motion of India and subsequent formation and evolution of the east-dipping Burma Arc as well as the segmentation and independent evolution of the proto-Molucca Sea Slab and proto-Banda Arc to the north of continental Australia. Figure 5e shows the present-day geometry of the subduction zone. Purple circles represent active volcanism for the different times shown.

arctica and Australia (SE Indian Ridge) since 50 Ma ago. The north-directed motion of the Australian plate and concomitant subduction along its northern margin in part, controls the production of new oceanic crust at the ridge. Accordingly, approximately 1500 km of crust must have been subducted since 50 Ma. Motion exhibited by the subduction margin and ocean ridge are relatively minor and are not considered for this simple calculation. Nevertheless, the base of the interpreted slab must be over 50 Ma old and potentially up to 70 Ma old. No gap in the tomography exists that might be expected if subduction had ceased for a period of time and, furthermore, the anomaly continues unbroken to 1340 km depth (Figures 2 and 3) and in models presented by *Replumaz et al.* [2004] the anomaly extend to over 1500 km depth. The relatively voluminous region of the mantle characterized by faster than average wave speeds between 1000 and 1300 km depth (Figure 3) may indicate that accumulation of slab material may have occurred at this depth and that subduction of oceanic crust and lithosphere may have been ongoing for over 100 Ma.

[23] To further accommodate the increased length of the subduction margin, a near subvertical tear developed between the Indo-Burma subduction zone and the subduction along northern Sumatra below the southern Burma platelet. The subducted slab beneath Burma (the northern Burma platelet) is interpreted to have initially formed as the N-dipping subducted Indian plate during closure of the Neo-Tethys and prior to the collision between the Indian continent and the NW-trending Tethyn subduction front. During collision between India and Asia, the Indian continental landmass overrode the Tethyn subduction zone (Figures 5b–5e). The upper section of the eastern Tethyn-Indo-Australian slab was detached (torn) from the underlying subducted slab along a horizontal tear essentially cutting the once continuous slab into its upper and lower sections. The upper section of the slab underwent clockwise rotation about a point near northern Sumatra (close to the intersection between the fused Indo-Australian plate boundary and the Sunda Trench) and to the east toward the Asian continental landmass (Figures 5c–5e). The detached lower section of subducted Indo-Australian plate (Neo-Tethyn Slab) remained close to the position and orientation of the Tethyn subduction zone prior to it being overridden by the Indian continent.

[24] The N-S directed extension between the slab segments is manifest and accommodated by extension at the surface as spreading along the Andaman

Sea rift at a half rate of approximately 2 cm a^{-1} [*Curry et al.*, 1979; *Raju*, 2005]. We envisage the Andaman Sea to have developed in response to two factors: (1) the west-directed rollback and retreat of the Indo-Burma Slab and (2) the south- and southwest-directed rollback of the Indo-Australian plate from below Sunda. The latter motion is also driven in part by the counterclockwise torsion associated with the north and NE-directed advance of the Australian plate and the south-directed resistive torque imposed by collision between India and the Asian plate [e.g., *Sandiford et al.*, 2004].

[25] The lack of seismicity and volcanism in the region to the NNW of the Andaman Sea is due to the formation of a complex, but near-vertical tear in the Indo-Australian plate that has formed in response to the overall N-S directed extension on the plate there. The north-directed motion of India, the tordoidal “flow” of crustal material around the eastern Indian syntaxis (see models by *Shen et al.* [2001] and *Tapponnier et al.*, 1982) and the west- and southwest-directed rollback of the Sumatra section of the Indo-Australian plate [*Sandiford et al.*, 2005] caused N-S directed extension of the Indo-Australian plate at depth while extension at the surface is manifest as N-S directed extension and plate spreading in the Andaman Sea since ~ 18 Ma ago. The location of this detachment is also coincident with the point of subduction of the eastern 90°E ridge, which may also act as a pinning point separating the Indo-Burma Subduction system to the north from the Sunda and Indonesian Subduction systems to the south.

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