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Complex slab subduction beneath northern Sumatra

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[1] New data provided by the 2004–2005 Sumatra-Andaman great earthquake sequences allow us to image with improved detail the *P*-wave velocity structure beneath Sumatra and adjacent regions. Below northern Sumatra, we find that the slab is folded at depth, exhibiting geometry similar to that of the volcanic arc and the trench at the surface. We speculate that this fold plays a major role in the segmentation of the Sumatra megathrust, and may impede rupture propagation in the region. North of Sumatra, significant slab material in the mantle transition zone is imaged for the first time, and we infer the presence of a major tear between the upper mantle and transition zone there. **Citation:** Pesicek, J. D., C. H. Thurber, S. Widiyantoro, E. R. Engdahl, and H. R. DeShon (2008), Complex slab subduction beneath northern Sumatra, *Geophys. Res. Lett.*, *35*, L20303, doi:10.1029/2008GL035262.

1. Introduction

[2] The boundary between the Andaman and Sunda subduction zones is marked by a distinct bend in the trench offshore northern Sumatra. This area also hosts subduction of the Investigator Fracture Zone (IFZ) and the Wharton Fossil Ridge (WFR), and is the locus of the southeast termination point of the diffuse deformational boundary between the Indian and Australian plates. It is also the boundary between the rupture areas of the 2004 M_w 9.2 and 2005 M_w 8.7 megathrust earthquakes (Figure 1). Consequently, there is great interest in characterizing the nature of the incoming and downgoing plate in order to determine how the plate geometry may be affecting subduction and seismogenesis. In this study, we perform a tomographic inversion of teleseismic data using a nested regional-global approach [*Widiyantoro and van der Hilst*, 1996] in order to determine the *P*-wave velocity structure of the Indonesia region. We focus on the Burma (Myanmar), Andaman, and Sumatra subduction zones (Figure 1), where new data provided by the 2004–2005 megathrust sequences (Figure S1) [*Engdahl et al.*, 2007] provide a substantial increase in ray coverage (Figure S2).[1] This increase in data allows us to use smaller model cell sizes and results in significant improvements in slab amplitude recovery. In our new model, the fast subducting slab is well imaged in the upper mantle throughout the region, with significant variations in dip along strike. We interpret folding of the subducting slab beneath northern Sumatra and speculate on its relation to shallow structure and seismogenesis. In addition, we present evidence for a significant tear in the upper mantle slab below Burma. Finally, we show that, in the lower mantle, the ancient Neo-Tethys slab is a distinct and prominent feature.

2. Data and Methodology

[3] We inverted global teleseismic arrival time data for events that are well constrained by the Engdahl, van der Hilst, and Buland (EHB) criteria for single event relocation [*Engdahl et al.*, 1998]. Our dataset includes global earthquakes for the time period 1964–2006 and earthquakes in the Sumatra region from 1918–2006 [*Engdahl et al.*, 2007]. This includes 1,664,212 first arriving *P* phases and 38,801 depth phases (26,877 *pP* and 11,924 *pwP*), which increase upper mantle sampling. We employed the nested regional-global tomographic method of *Widiyantoro and van der Hilst* [1996, 1997]. The model space was parameterized into 0.5° cells regionally with cell thickness increasing with depth, from 35 km at the surface to 110 km at the base of the regional model at 1500 km depth. While previous studies have focused on the southern and eastern subduction zones of Indonesia, we focus on the northwestern subduction zones and we have extended the northern boundary of the regional model to 25°N (compared to 15°N used by *Widiyantoro and van der Hilst* [1996, 1997]) to fully encompass the Andaman and Burma subduction zones. The finer regional model cells are surrounded by 5° global cells that also vary in thickness to 2889 km depth, with an average thickness of $\sim$180 km. We performed a single iteration, computing initial arrival time residuals relative to the ak135 global model [*Kennett et al.*, 1995]. We excluded arrivals with a residual greater than 3 standard deviations, which for our data is $\sim$6 sec. The inverse solution was obtained via the conjugate gradient least squares algorithm LSQR [*Paige and Saunders*, 1982]. We conducted checkerboard resolution tests (Figures S3 and S4) and synthetic slab tests (Figures S5 and S6) and we compared our model to other previously published Indonesian tomography images for which rigorous resolution tests have been conducted [*Hafkenscheid et al.*, 2001; *Replumaz et al.*, 2004; *Widiyantoro and van der Hilst*, 1996, 1997]. We observe all of the main large-scale mantle features of these studies along the Burma, Andaman, and Sumatra subduction zones, and our comparisons indicate similar recovery of features throughout the Indonesia region, with generally enhanced amplitude. Thus, we are confident that

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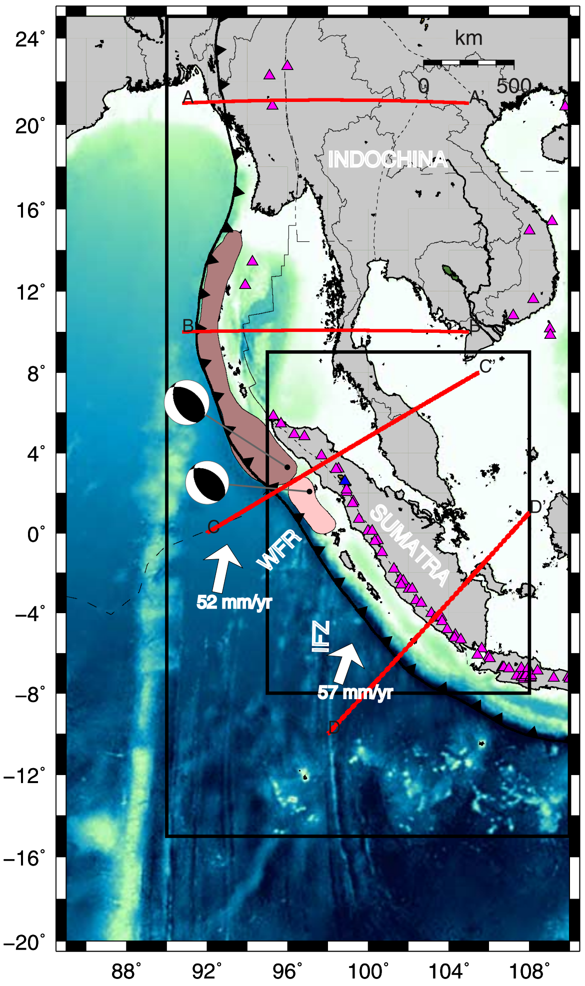

Figure 1. Map of the Burma, Andaman, and Sumatra subduction zones showing the positions of the cross-sections in Figure 2. Also shown are the Harvard Centroid Moment Tensor solutions, epicenters, rupture areas [*Ammon et al.*, 2005] of the 2004 and 2005 megathrust earthquakes and the locations of the Investigator Fracture Zone (IFZ) and Wharton Fossil Ridge (WFR). Volcanoes are shown as magenta triangles (Toba Caldera is blue). ETOPO5 bathymetry, tectonic boundaries [*Coffin et al.*, 1998], and convergence vectors [*Sieh and Natawidjaja*, 2000] are also shown. The west and south edges of our regional model are shown and correspond to the limits of the layers in Figure 3. The inset box shows the area represented in Figures 4 and S6.

the features we discuss below are at least as well recovered and resolved as previous models and are superior in the Sumatra region, due to increased data coverage.

3. Discussion

[4] We image a strong slab signature of fast *P*-wave anomalies along the Burma, Andaman, and Sumatra arcs at upper mantle depths (Figures 2 and 3). The dip of the imaged slab varies from moderately dipping below Burma and northern Sumatra (25–50°) to more steeply dipping (60–90°) below the Andaman Islands and southern Sumatra (Figure 2). This variation in slab dip roughly correlates with the age of the incoming seafloor (steeper dips correlate with older subducting slabs) and agrees with the dip inferred by previous studies [*Kennett and Cummins*, 2005; *Shapiro et al.*, 2008] and with well-constrained

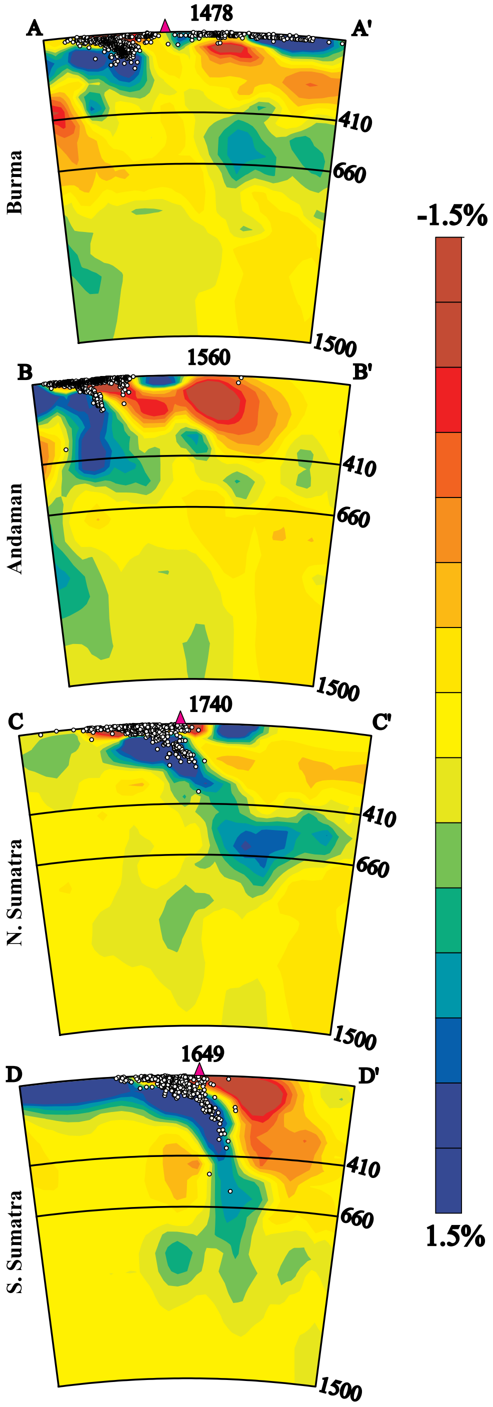

Figure 2. Cross-sections through the model (positions shown in Figure 1) showing the contrasting dips of the slab in different regions. Perturbations relative to ak135 [*Kennett et al.*, 1995] are shown from −1.5% to 1.5%. Earthquake relocations [*Engdahl et al.*, 2007] (circles) and volcano positions (triangles) are also shown. For each region, cross-section lengths are listed in km at the top.

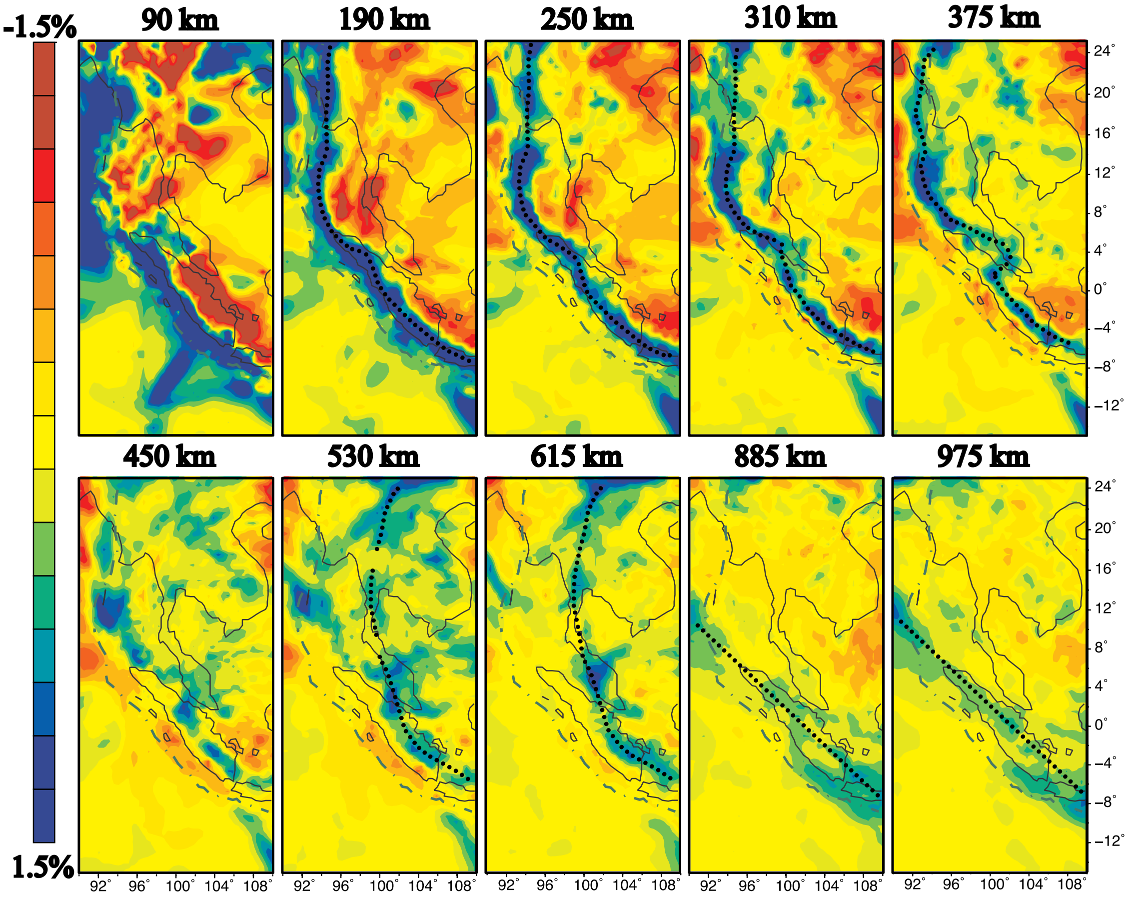

Figure 3. Selected model depth layers with the same scale as Figure 2. A fold in the upper mantle slab is evident from 190–530 km. In general, three slab trends are inferred from the model results and shown as dotted black lines: (1) the shallow trend mimicking current subduction plate boundaries, (2) the concave east shape of transition zone material, and (3) the NW-SE trend of the lower mantle remnant Neo-Tethys slab.

teleseismic event relocations [*Engdahl et al.*, 2007]. The latter correlate well with the upper edge of the subducting slab (Figures 2 and S7).

[5] Below northern Sumatra, there is a distinct change in the strike of the slab (Figure 3) that mimics the trend of the trench and the shape of the volcanic arc observed at the surface (Figure 1). At depth, however, the slab does not appear to be as gently curved. Rather, the slab segments northwest and southeast of the center of the bend are relatively planar and meet to form a relatively sharp fold (Figures 4 and S8). The shape of this fold and its position agree well with fast anomalies seen in previous tomographic studies [*Hafkenscheid et al.*, 2001; *Replumaz et al.*, 2004] at similar depths. In addition, *Fauzi et al.* [1996] also infer a deflection in the location of the slab in their study of seismicity below Toba Caldera. They used local earthquake relocations to deduce the slab location from depths of 75–175 km.

[6] Given the correlation of this fold with the location of the bend in the trench and the volcanic arc and its inferred presence as shallow as 75 km depth [*Fauzi et al.*, 1996], we infer that this fold is a primary and continuous feature of the subducting slab from the surface into the mantle transition zone. Although we cannot yet resolve this fold at crustal depths, projection of the inferred fold axis to the surface places it in the area of maximum curvature of the trench (Figure S8). We expect that future higher resolution studies will delineate this fold at shallower levels.

[7] The proximity of this slab fold to the locations of the 2004 and 2005 megathrust earthquakes (Figure 4) suggests that the fold may influence rupture propagation. *Briggs et al.* [2006] identify a saddle-shaped region on Simeulue Island that experienced minimal uplift from the 2004 and 2005 megathrust events. They suggest that this region may serve as an impediment to rupture propagation. The saddle could be the surface expression of the fold axis and the structural cause for rupture termination hypothesized by *Briggs et al.* [2006]. Alternatively, the axis of this fold might be expressed on the megathrust as the tear inferred by *Briggs et al.* [2006] south of Simeule Island, between the Banyak Islands and Nias Island. *Shapiro et al.* [2008] show that the oceanic lithosphere subducting here is hotter and thinner than lithosphere subducting to the north and south. The megathrust below these islands likely hosts the subducted continuation of the WFR and/or the IFZ. A thinned and folded subducting slab could develop a tear that would influence rupture propagation along the megathrust.

[8] If this fold is indeed continuous from the surface to at least 530 km depth as we contend, then this implies that the initiation of the bend in the subduction zone must have

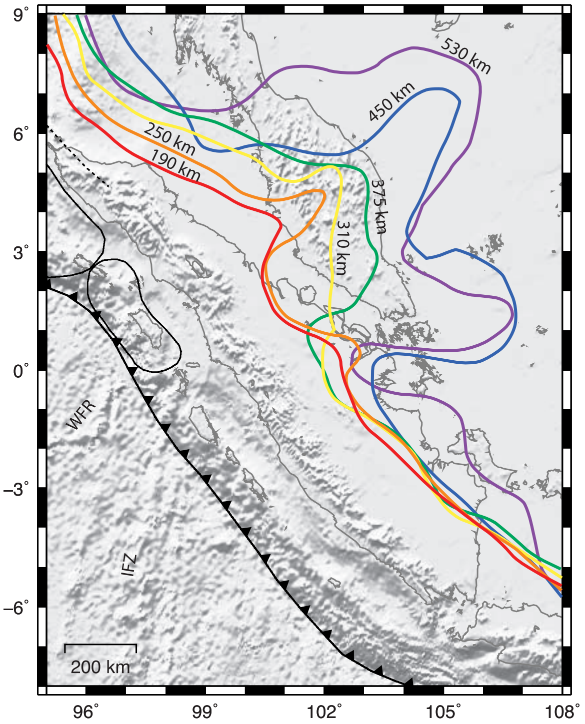

Figure 4. Map showing smoothed tracings of the +0.5% velocity perturbation contours at model layer depths from 190–530 km. Bending of the contours illustrates folding of the subducting slab at these depths (see also Figure S6).

developed earlier than previously thought. *Richards et al.* [2007] estimate that the slab below Sumatra at 800 km depth began subducting at ~25 Ma. Assuming a constant rate of subduction, this implies that the folded slab now at 530 km depth began subducting at ~17 Ma. Recent studies of the tectonic evolution of SE Asia [*Replumaz et al.*, 2004; *Richards et al.*, 2007] do not show significant bending of the trench until ~5 Ma, and thus cannot account for this feature. If the lithospheric fold controls the bend in the trench, then bending must have begun prior to 5 Ma.

[9] The origin of this fold and the bend in the trench may be tied to the evolution of the Wharton spreading ridge, which first began subducting beneath Java at 70 Ma [*Whittaker et al.*, 2007]. The lithospheric fold we observe in the upper mantle below Sumatra is likely the result of oblique subduction of the WFR, extinct since ~45 Ma [*Deplus et al.*, 1998]. This would require the fold and the trench bend to have migrated northwest with respect to the overriding plate, following the migration of the WFR [*Whittaker et al.*, 2007]. Alternatively, the fold may be a static feature of the plate boundary, independent of any structure on the downgoing plate. However, this seems unlikely, given the obliquity of subduction. We suspect that the fold is a result of deformation of the Indo-Australian plate along the thinned and weakened axis of the WFR. The structural complexities resulting from this scenario would certainly affect rupture propagation on the megathrust.

[10] The upper mantle slab north of Sumatra, along the Andaman segment, appears to dip much more steeply, nearly 90° (Figure 2b), in good agreement with previous tomographic studies [*Kennett and Cummins*, 2005; *Shapiro et al.*, 2008]. This has been associated with slab roll back and extension in the Andaman Sea [*Kennett and Cummins*, 2005; *Richards et al.*, 2007] since at least 11 Ma [*Khan and Chakraborty*, 2005]. North of the Andaman segment, below Burma, the slab dips more moderately, about 30° (Figure 2a). Our results show that significant amounts of slab material exist in the transition zone below Indochina that was not imaged in previous studies (Figures 2a and 3). The lack of continuity between upper mantle and transition zone anomalies (Figures 2a and S9) below the Burma and Andaman arcs suggests that there may be a slab tear between these segments and the adjacent northern Sumatra segment. Despite vertical smearing in our results at these depths (as indicated by Figures S3–S6), a clear contrast in the trend of the slab in the transition zone (530 and 615 km layers in Figure 3) as compared to shallower depths suggests that the tear occurs in the slab above the transition zone. The cause and timing of this tear with respect to the tectonic development of the region is unclear. However, it most likely initiated somewhere along the Burma segment, where slab separation is largest, and then propagated laterally southward toward the fold below northern Sumatra.

[11] In the lower mantle below central and southern Sumatra, we see significant subhorizontal high velocity anomalies that generally appear contiguous with the upper mantle slab. These anomalies dip in the opposite direction (toward the southwest) to that of the slab in the upper mantle (Figures 2c and 2d). The depth, contrasting dip, and NW trend of the lower mantle features (Figure 3) suggest that they are all remnants of the ancient Neo-Tethyan oceanic lithosphere, subducted during the Cretaceous, that previous tomographic studies have observed and interpreted [e.g., *van der Hilst et al.*, 1997; *Van der Voo et al.*, 1999]. *Widiyantoro and van der Hilst* [1996] show distinctly separate anomalies below southern Sumatra and propose a slab tear in this region. In contrast, our higher-resolution results show that the slab extends through the transition zone, well into the lower mantle below southern Sumatra, and is not clearly distinguishable from the deeper, broader lower mantle anomalies. Thus, the location of the tear separating the upper mantle slab from the lower mantle remnant Neo-Tethys slab is most likely farther north below northern Sumatra.

4. Summary

[12] Our new model reveals that the slab subducting below western Indochina and Sumatra exhibits a complex geometry that has developed as the region has evolved tectonically. The most dramatic feature from our results is the fold in the slab below northern Sumatra, which may be acting as a barrier to rupture along the megathrust. The upper mantle slab below Burma appears separated from its deeper extension, implying that a tear exists there. Future plate reconstructions must account for both the folding and tearing of the slab evident in our results. Important outstanding issues include the cause and timing of folding, and the details of its potential influence on stress accumulation and rupture initiation and propagation.

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