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Bathymetry of the Indonesian Sunda margin-relating morphological features of the upper plate slopes to the location and extent of the seismogenic zone

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Abstract. Earthquake history shows that the Sunda subduction zone of the Indonesian margin produces great earthquakes offshore Sumatra, whereas earthquakes of comparable magnitude are lacking offshore Java and the Lesser Sunda islands. Morphological structures in multibeam bathymetric data across the forearc relate with the extent of the seismogenic zone. Its updip limit corresponds to the slope break, most distinct off Java and Lesser Sunda islands, where we find coincident narrow, uniform, continuous outer arc ridges. Their landward termination and a shallow upper plate mantle mark the downdip limit of the seismogenic zone. In contrast the outer arc ridges off Sumatra are wider and partly elevated above sea level forming the forearc islands. The downdip limit of the seismogenic zone coincides with a deeper upper plate mantle. Sunda Strait marks a transition zone between the Sumatra and Java margins. We find the differences along the Sunda margin, especially the wider extent of the seismogenic zone off Sumatra, producing larger earthquakes, to result from the interaction of different age and subduction direction of the oceanic plate. We attribute a major role to the sediment income and continental/oceanic upper plate nature of Sumatra/Java influencing the composition and deformation style along the forearc and subduction fault.

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1 Introduction

The seismogenic zone (SZ) is the unstable regime of the plate interface at a subduction zone, where the largest earthquakes in the world are produced (Scholz, 1998). Its sea- and landward termination are characterized by physical updip and a downdip limit (e.g. Byrne et al., 1988; Hyndman et al., 1997). Moore and Saffer (2001) and Moore, J.C. et al. (2007) relate the updip limit to temperature dependent processes. These take place between 100 °C and 150 °C and cause progressive rheological changes on subducted and accreted sediment. Wang and Hu (2006) classify the seaward part of the forearc into an outer and inner wedge. The outer wedge is actively deforming and builds up the updip velocity strengthening part of the subduction fault, i.e. the seaward portion of the accretionary prism. The inner part is the less deformed part of the forearc, which overlies the velocity weakening part of the subduction fault, i.e. the SZ. Usually, the outer wedge builds a steep surface slope whereas the inner wedge is characterized by a smooth and flat seafloor. The transition from the outer to inner wedge is often marked by a distinct slope break, as observed for example in Nankai, Japan (Park et al., 2002). In the following, we use the term of inner and outer wedge as introduced by Wang and Hu (2006) to describe the transition zone of the updip limit of the SZ.

The downdip termination of the SZ is believed to be mainly governed by temperature related processes at the transition from brittle to ductile deformation, with temperatures at the plate boundary from 350 °C to 450 °C, at ∼40 km depth if the 350 °C isotherm is located at greater depths, or at the interception of the downgoing plate with the overriding

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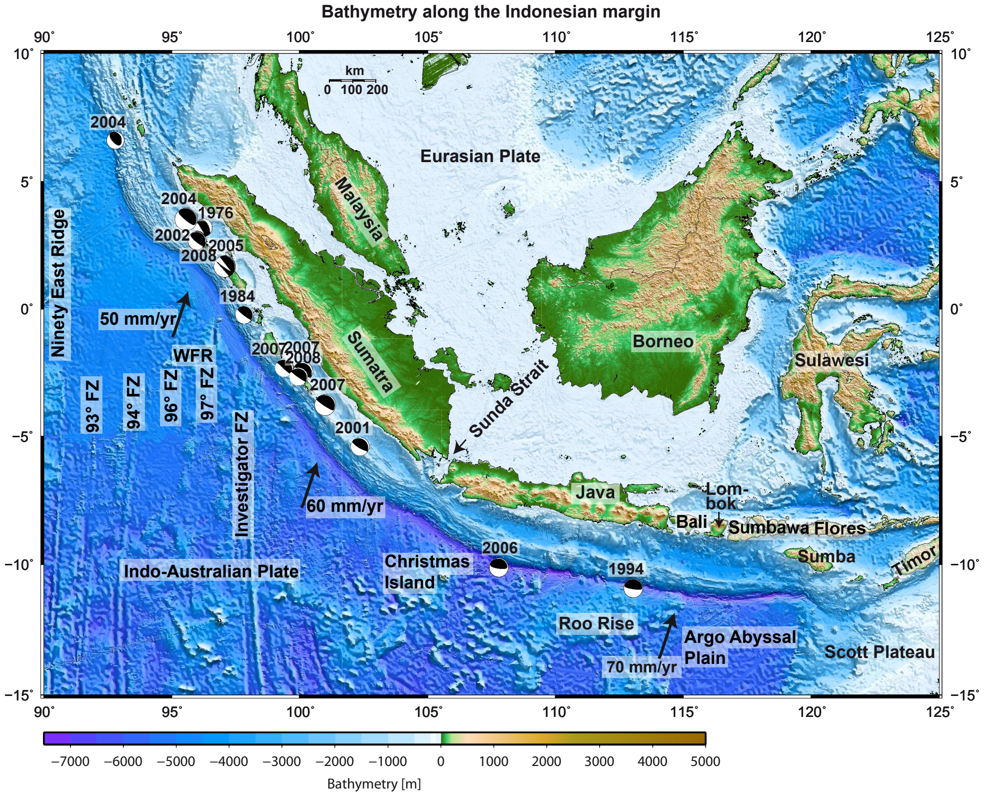

Fig. 1. Bathymetry of the Indonesian margin underlain by satellite altimetry (Smith and Sandwell, 1997). See text for details on data information. Major tectonic features on the incoming plate are annotated, off Sumatra mainly N-S trending fracture zones, off Java elevated plateaus and seamounts. Plate motion direction and velocity (indicated by annotated black arrows; after Simons et al., 2007) vary along the entire margin relative to the upper plate. Centroid Moment Tensors (CMT) of recent (starting from 1976) $M_\mathrm{w} \geq 7$ subduction fault related earthquakes are shown across the Sunda arc (size of "beach balls" correlates with earthquake magnitude, from http://www.globalcmt.org). Further details are discussed in text. WFR – Wharton fossil ridge.

mantle at even colder subduction zones (e.g. Hyndman et al., 1997; Oleskevich et al., 1999). Downward of the downdip limit, the proposed aseismicity and thus stable sliding of the thrust may also occur from contact with the forearc mantle due to the presence of serpentinite, talc, or other hydrated minerals (Hyndman et al., 1997). The temperature ranges imply that the changes from slip to stick behaviour at the updip limit and from unstable to stable sliding at the downdip limit of the SZ are not sharp boundaries but transition zones.

A correlation of the seafloor morphology with the location of the SZ has been found along different subduction environments, e.g. off Chile (Lange et al., 2007; Haberland et al., 2006) and for the segments of the Sumatra-Andaman (2004) and Nias (2005) great earthquakes, Indonesia (Tilmann et al., 2010). The large risk of recurrence and unequal distribution of major and great earthquakes at the Indonesian archipelago (Fig. 1) make it necessary to study/map the SZ along the entire length of the subduction system.

In this paper we use bathymetric data to relate large scale morphological structures with the location and extent of the SZ along the entire Sunda margin (Figs. 2, 3). The large scale morphological structures are the expression of the upper plate response to the coupling at the plate interface between the subducting oceanic plate and the forearc. We constrain the location of the SZ with the forearc structure found in previous studies. These previous investigations mainly based on seismic and seismological data analysis. Thermal modelling and locations of earthquakes verify the updip limit of the SZ, whereas the downdip termination of the SZ is constrained by seismic wide-angle and seismological analyses. We investigate the upper plate morphology with respect to the localized occurrence (spatial distribution) of major (M_w7.0–7.9) and great ($M_\mathrm{w} \geq 8$) earthquakes produced along the subduction fault (Fig. 1).

1.1 Tectonic setting

There are striking differences in the appearance of forearc structures along the Indonesian margin, e.g. several ridges and islands build up a wide outer arc high off Sumatra, whereas off Java the outer arc high is narrow and completely below sea level (Fig. 1). Key properties of the

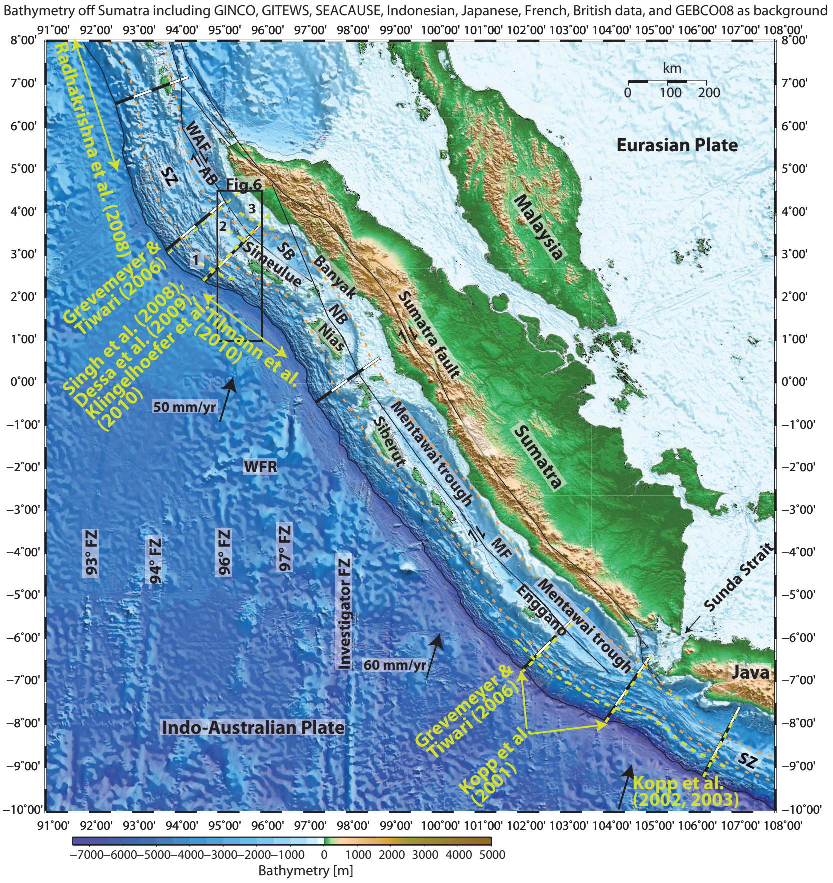

Fig. 2. Bathymetry off Sumatra (multibeam bathymetry, where available underlain by satellite derived bathymetry; Smith and Sandwell, 1997). Tectonic setting is after Newcomb and McCann, 1987. Fracture zones (after Kopp et al., 2008) on the incoming plate as well as subduction direction and velocity (after Simons et al., 2007) are indicated by annotated black arrows on Indo-Australian plate. Major Mentawai islands as well as major faults are annotated along the forearc. Dashed lines sub-parallel to the trench mark the updip and downdip limit of the SZ. The seaward trench-parallel dashed line marking the updip limit of the SZ coincides with the slope break. Profiles and regions are marked and annotated, where additional investigations were available to constrain or refute their limits of the SZ. 200 km scales perpendicular to the trench help constrain distance from the deformation front. Deviations of the limits of the SZ from Grevemeyer and Tiwari (2006) by more than 10 km are marked by dashed lines and discussed further in the text. AB – Aceh basin; MF – Mentawai fault; NB – Nias basin; SB – Simeulue basin; SZ – seismogenic zone; WAF – West Andaman fault; WFR – Wharton fossil ridge.

incoming oceanic plate, such as the age and fabric of the lithosphere, and the setting, origin and structure of the upper plate influence the coupling of the plates along the subduction fault as well as the upper plate response of the subduction system. These properties govern the shape of the forearc.

1.2 The incoming plate and trench

The age of the incoming oceanic Indo-Australian lithosphere is 40 Ma old in northern Sumatra (Mueller et al., 1997), where the Wharton fossil ridge subducts beneath Nias island (Fig. 2). The age of the lithosphere increases to the East and is 160 Ma old where the seafloor of the Argo abyssal plain subducts beneath Sumba island (Mueller et al., 1997). The Indo-Australian plate subducts obliquely underneath Sumatra. The subduction direction is almost normal off Java and further to the East. The convergence rate increases from Northwest (40–50 mm/yr off Sumatra) to Southeast (∼70 mm/yr off Java and Bali) (Simons et al., 2007).

The fabric of the incoming plate differs throughout the entire Sunda margin. Smooth segments subduct beneath the Lesser Sunda islands (the Argo abyssal plain) as well as beneath northern Sumatra (Figs. 2, 3). Prevailing structures imprinted on the incoming plate off Java are seamounts and plateaus (e.g. Roo Rise, Masson et al., 1990). Dominating features are N-S trending fracture zones (FZs; e.g. Kopp et al., 2008) that subduct beneath central Sumatra, the most prominent being the Investigator FZ. These rough morphological structures indent the trench line and cause local uplift of the forearc (as observed by e.g. Kopp et al. (2008) off northern Sumatra). These structures partly rise above the sea

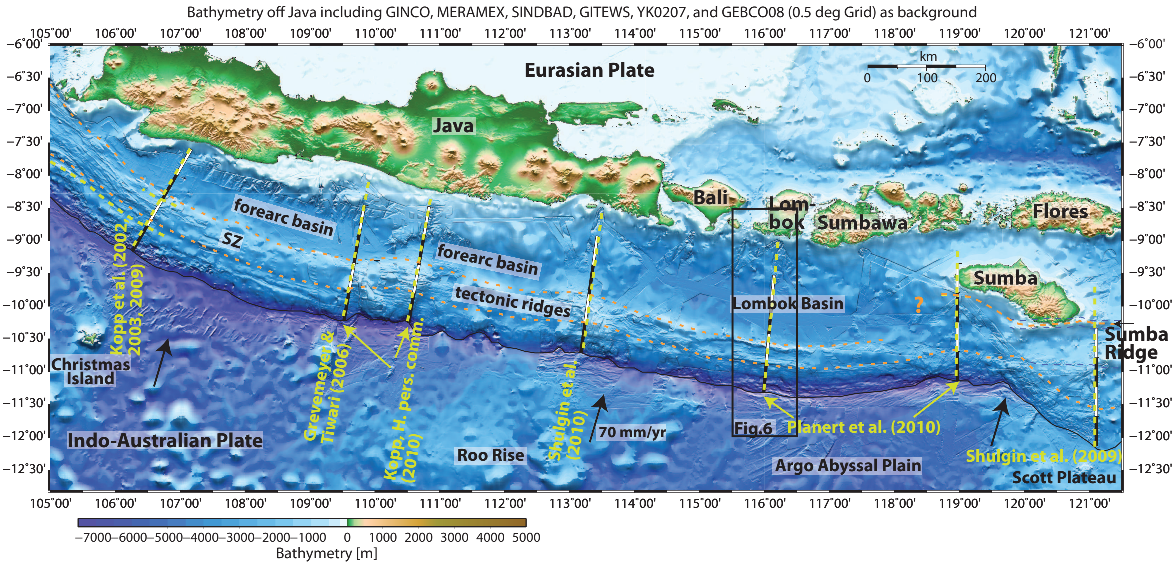

Fig. 3. Bathymetry off Java and the Lesser Sunda islands (multibeam bathymetry (for YK0207 see Soh et al., 2002), where available underlain by satellite derived bathymetry; Smith and Sandwell, 1997). Tectonic setting (after Newcomb and McCann, 1987) on the incoming plate as well as subduction direction and velocity (after Simons et al., 2007) are indicated by annotated black arrows on Indo-Australian plate. Lesser Sunda islands as well as major tectonic features are annotated along the forearc. Dashed lines sub-parallel to the trench mark the updip and downdip limit of the SZ. The seaward trench-parallel dashed line marking the updip limit of the SZ coincides with the slope break. Profiles and regions are marked and annotated, where additional investigations were available to constrain or refute their limits of the SZ. Deviations of the limits of the SZ from Grevemeyer and Tiwari (2006) by more than 10 km are marked by dashed lines and discussed further in the text. 200 km scales perpendicular to the trench help constrain distance from the deformation front. ? marks the transition, where no constraints exist on the depth of the downdip limit of the SZ most likely due to the presence of the Sumba block (Shulgin et al., 2009 and Planert et al., 2010). SZ – seismogenic zone.

level (the forearc islands off Sumatra), as opposed to neighbouring segments where undisturbed oceanic crust enters the trench.

The trench is ∼5 km deep off northern Sumatra increasing to more than ∼6 km off Sunda Strait. The depth of the trench further increases to the East to about 7 km depth off the Lesser Sunda islands. The sediment cover on top of the oceanic plate in the north of Sumatra reaches a thickness of more than 5 km (e.g. Franke et al., 2008; Dessa et al., 2009). The major portion for the sediment income originates from the Himalayas and is transported as far south as the Sunda Strait (Moore et al., 1982). Arc-derived sediments along the entire Sunda margin were deposited in the trench before the outer arc highs developed, but Neogene arc terrane sediments were trapped in the forearc basins and never reached the trench (Moore et al., 1982). Sediment cover on top of the oceanic plate offshore Sumatra decreases to the South to ∼1.5 km off Sunda Strait (Kopp et al., 2001). Further to the East, sediment thickness on top of the Indo-Australian plate decreases to ∼600 m in the Argo Abyssal Plain and seaward of the trench offshore Sumba (Heirtzler et al., 1974; Lueschen et al., 2010). However, basement structures locally crop out in the trench where Roo Rise subducts and further east off Lombok and Sumba islands (Planert et al., 2010).

1.3 The upper plate

The amount of sediment on top of the incoming oceanic plate influences the sediment accumulation at the toe of the upper plate and thus the structure and width of the accretionary prism. Slope failure at the inner trench wall provides an additional source of sediment supply to the trench and plays an important role in building up the accretionary system (Henstock et al., 2006; Brune et al., 2009; Lueschen et al., 2010). Sediments reach a maximum thickness of ∼1.5–2 km in the ∼40 km wide Aceh basin (Seeber et al., 2007). The sediment thickness of the forearc basins varies, sediments locally reach up to 6 km thickness north of Simeulue (e.g. Dessa et al., 2009) decreasing to the south with a thickness of ∼4–5 km (Kopp et al., 2001). Off eastern Java sedimentary sequences are ∼5 km thick in the forearc basin. Reduced sedimentary thickness is observed off Java, where the subduction of thickened oceanic crust of the Roo Rise results in local uplift of the margin (Shulgin et al., 2010). Lombok basin comprises sediments of locally up to more than 4 km thickness (Lueschen et al., 2010; Planert et al., 2010). The outer arc ridges build a barrier, which prevents sediment transport from the landward portions of the forearc onto the outer wedge (Moore et al., 1982). However, the size of the accretionary prism across the south-eastern part of the Indonesian forearc and the Lesser Sunda islands is large in the light of moderate sediment supply (Mueller et al., 2008; Planert et al., 2010). Splay faults cutting through the outer wedge and connecting the seafloor with the subduction fault are observed along several segments off northern Sumatra (Sibuet et al., 2007) as well as off Bali and Lombok islands (Mueller et al., 2008; Lueschen et al., 2010). The surface rupture close or near the surface contributes to a higher potential of tsunami generation during a megathrust rupture (Moore et al., 2007).

The outer wedge borders on pronounced ridge structures. The trenchward termination/slope break of these forearc ridges coincides with the location of and is associated in this study with the updip limit of the SZ (see Figs. 2, 3). Broad, multiple tectonic ridges, partly rising above sea level (e.g. the Mentawai islands) connect wide sedimentary basins off Sumatra, whereas off Java and the Lesser Sunda islands narrow tectonic ridges connect the lower slope with broad sedimentary basins.

Major forearc basins are present offshore northern Sumatra. The continuity of the forearc basin structure is disrupted around Banyak island and between Nias and Siberut islands and Sumatra, whereas typical forearc basins form the Mentawai trough offshore central and southern Sumatra (Fig. 2). There is no typical forearc basin off Sunda Strait and off eastern Java, where subduction of the Roo Rise results in an uplift of the forearc (Shulgin et al., 2010), but again, a basin is found off the entire Lesser Sunda margin up to the island of Sumba.

Several arc-parallel faults accommodate oblique subduction (Karig et al., 1980). One of these major fault systems is the Mentawai fault zone that runs across the forearc basin between the Mentawai archipelago and Sumatra. The Sumatra fault zone is located along the volcanic arc on Sumatra (Diament et al., 1992).

1.4 Recent investigations along the Indonesian margin

Newcomb and McCann (1987) analyzed historic earthquakes and found great ($M_\mathrm{w} \geq 8$) interplate earthquakes off Sumatra. They noted major ($M_\mathrm{w} 7.0-7.9$) earthquakes to occur off Java and the Lesser Sunda islands, whereas great thrust earthquakes were missing in that region. The main target of later studies was the deep structure of the subduction systems offshore southern Sumatra and the Sunda Strait (Kopp et al., 2001, 2003) and western Java (Kopp et al., 2002, 2006) of the Indonesian island arc.

The interest in and the number of investigations along the Indonesian island arc increased rapidly after the 2004 Sumatra-Andaman megathrust earthquake (e.g. Lay et al, 2005; Ladage et al., 2006; Henstock et al., 2006). Major concern was attributed to the megathrust rupture and processes governing the rupture mechanisms (e.g. Lay et al., 2005). A clear segmentation of the subduction system offshore northern Sumatra is found by analyses of the aftershock distributions (e.g. DeShon et al., 2005; Engdahl et al., 2007) of the great neighbouring 2004 Sumatra-Andaman and 2005 Nias earthquakes as well as analysis of multichannel seismic (MCS) data (Franke et al., 2008). Franke et al. (2008) suggest a major influence of the subducting plate structure to segmentation of the margin.

Several bathymetric studies focus on regional structures, their major interest is on the slope morphology offshore northern Sumatra, e.g. Ladage et al. (2006), Henstock et al. (2006), Graindorge et al. (2008), Kopp et al. (2008). We concentrate our study on the entire Sunda margin pointing out the differences between the Sumatra and the Java margins. Here we show the compilation of the entire bathymetric dataset of the Indonesian island arc (Fig. 1).

2 Data and methods

Several research cruises were planned and conducted in the late 1990s to study the subduction zones of the Indian Ocean mainly with respect to the deep structure of the subduction systems. After the December 2004 Sumatra-Andaman great earthquake and subsequent tsunami, additional shiptime was available. Several cruises within the German Indonesian Tsunami Early Warning System (GITEWS) project (Rudloff et al., 2009) were conducted. The surveys and compiled data provide important background for the establishment of an offshore component of the GITEWS (Boebel et al., 2010; Schöne et al., 2010) and tsunami simulations (Behrens et al., 2010).

Bathymetric data were acquired along the entire Indonesian island arc during these numerous German funded research cruises (e.g. Mueller et al., 2006). Some of these cruises were conducted with the Indonesian research vessels Baruna Jaya (W. Pandoe, personal communication, 2009). Multibeam bathymetric data available were also acquired during Japanese (Soh et al., 2002, 2005), French (Graindorge et al., 2008), and UK cruises (Henstock et al., 2006). All bathymetric data were cleaned, data acquired with different systems were made compatible, and merged with the GEBCO08 (Smith and Sandwell, 1997, http://www.gebco.net) bathymetry grid in areas not covered by multibeam data (Figs. 1–3). Land data are based on 1 km topography derived from the US Geological Survey SRTM30 gridded digital elevation model.

We calculated gradients from bathymetry grids to facilitate the classification of characteristic subduction related structures (Figs. 4, 5). Enlargements of representative areas are shown for Sumatra and Java/Lesser Sunda margins (Figs. 4, 5), where gradients are draped over the bathymetric relief. Figure 6 shows the same characteristic regions where blow ups of the bathymetric charts are underlain by representative cross sections.

Grevemeyer and Tiwari (2006) found that the upper plate geometry governs the size of the SZ along the Indonesian subduction zone: a large SZ concurs with the deep mantle

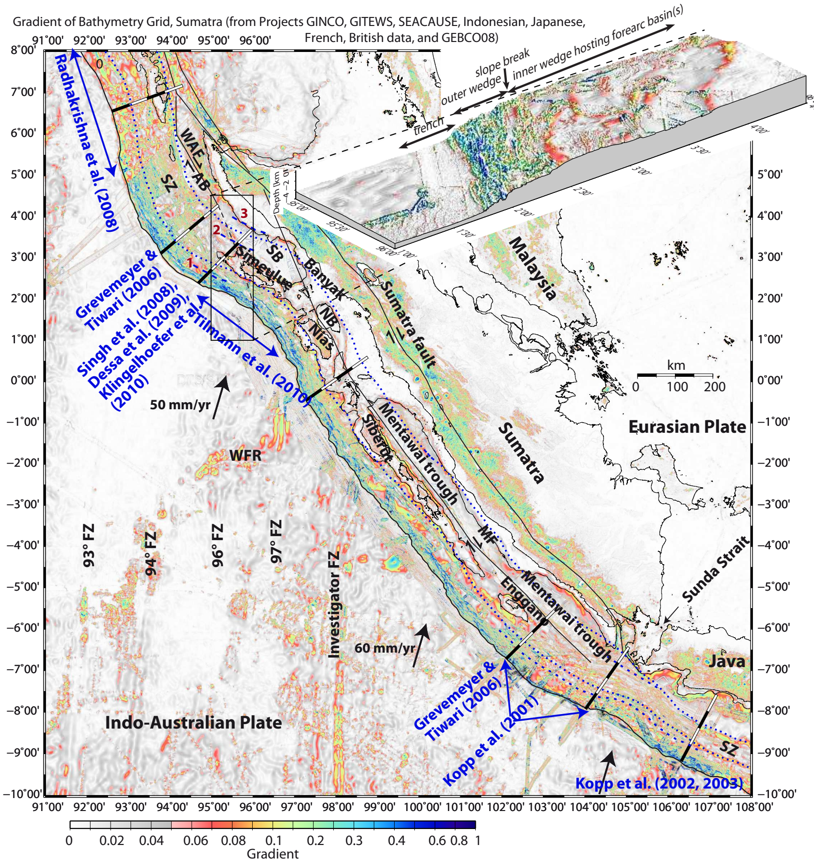

Fig. 4. Gradients of bathymetric data off Sumatra. Annotations and details as described in Fig. 2. Blue dashed lines mark the updip and downdip limits of the SZ, here. Inset shows close-up of representative area off Sumatra (same region as shown in Fig. 6). Gradients are draped on perspective view of bathymetry relief. Trench, outer wedge, slope break and inner wedge are indicated.

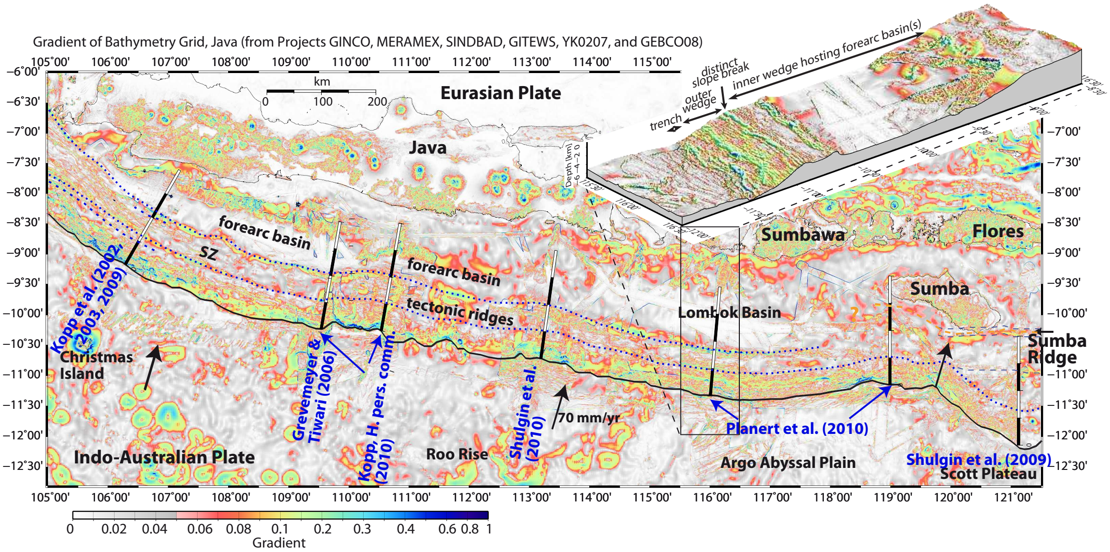

Fig. 5. Gradients of bathymetric data off Java and the Lesser Sunda islands. Annotations and details as described in Fig. 3. Blue dashed lines mark the updip and downdip limits of the SZ, here. Inset shows close-up of representative area off Lombok island (same region as shown in Fig. 6). Gradients are draped on perspective view of bathymetry relief. Trench, outer wedge, slope break and inner wedge are indicated.

wedge off Sumatra and a negative trench-parallel Bouguer gravity anomaly (TPGA) whereas a small SZ coincides with a positive TPGA off Java and a shallow hydrated mantle wedge.

We checked if the features seen in gravity anomalies can be identified in the bathymetric data. Therefore we picked the position of the slope break landward of the outer wedge indicated by the dashed seaward trench-parallel lines in Figs. 2–5. These lines coincide with Grevemeyer and Tiwaris (2006) approximation for the updip limit of the SZ based on the 100° isotherm from thermal modelling (their base points are indicated in the maps, Figs. 2–5).

Another striking structure is a major ridge further landward stretching across the Java and Sunda Lesser islands margin (landward trench-parallel dashed line, Figs. 3, 5). This ridge structure coincides with Grevemeyer and Tiwaris (2006) approximation for the downdip limit of the SZ based on the intersection of the subducting slab with the upper plate mantle.

We tried to find this coherence of bathymetry with the SZ, which is striking for the Java and Sunda Lesser islands margin, for the Sumatra margin. There we find it difficult to identify the slope break in some regions, e.g. in the northernmost part of the map presented in Figs. 2 and 4. Whereas the slope break can be easily identified in other regions of the Sumatra margin, e.g. seawards off Siberut island and south to Enggano island (Figs. 2, 4). Again, the slope break coincides with Grevemeyer and Tiwaris (2006) approximation for the updip limit of the SZ. There is no such clear bathymetric structure as for the Java margin that can be associated with the downdip limit off Sumatra, at once. Therefore, for the Sumatra margin we took the limits of Grevemeyer and Tiwaris (2006) as initial approximation for the downdip limit, verified them with results from regional studies (e.g. Radhakrishna et al., 2008) (dashed landward trench-parallel line, Figs. 2, 4) and then compared these with distinct bathymetric structures.

We verified the updip and downdip limits of the SZ identified in the bathymetry and gradients of the seafloor with other studies for the entire Sunda margin. Mainly seismic and seismological constraints are taken into account to refine the extent of the SZ. Large deviations from other studies compared with our approximation of the SZ are marked by dashed lines (Figs. 2–5) and explained further below. All relevant studies and verifications are discussed in detail in the following.

3 Results

From the identification of the slope break in the bathymetric and gradient charts we obtain the updip limit of the SZ at ∼50 km from the deformation front for northern Sumatra. Off Simeulue and further South, the updip limit of the SZ is shifted landward to ∼70 km from the deformation front (dashed seaward trench-parallel line, Figs. 2, 4). Off Java and the Lesser Sunda margins the updip limit of the SZ lies at ∼60 km from the deformation front (dashed seaward trench-parallel line, Figs. 3, 5).

The downdip limit of the SZ off Sumatra lies at ∼180 km from the deformation front north of Simeulue island and at ∼190 km south of it (dashed landward trench-parallel line, Figs. 2, 4). From the bathymetric and gradient map we can associate the distinct landward ridge with the downdip limit of the SZ at a distance of ∼110 km off Java and the Lesser Sunda margin (dashed landward trench-parallel line, Figs. 3, 5).

Additional regional studies listed in the following verify these values.

3.1 Off Sumatra from North to South

Seismicity and gravity anomalies reveal the downdip limit of the SZ in terms of upper plate mantle intersecting the oceanic subducting slab at a distance of ∼160–170 km from the trench axis and at a depth of ∼35 to 40 km for the Andaman region from 5° to 9° N (Radhakrishna, et al., 2008). Several studies were conducted in the area north of Simeulue island at 3° N to 4° N using MCS and wide-angle seismic studies (Singh et al., 2008; Dessa et al., 2009; Klingelhoefer et al., 2010) as well as gravity and thermal modelling (Klingelhoefer et al., 2010). All of them obtain similar depths for the updip limit of the SZ in that region. Their seaward termination of the megathrust ranges from ∼20–30 km distance from the deformation front (dashed line #1, Figs. 2, 4). The range for the downdip limit is larger: The highly debated Singh et al. (2008) with ∼170 km distance from the trench at ∼30 km depth though is close to the estimate by Grevemeyer and Tiwari (2006). Above the downdip limit of the SZ Singh et al. (2008) observe backthrusts in the upper part of the margin in their MCS dataset. Dessa et al. (2009) obtain ∼200 km at ∼35 km depth and Klingelhoefer et al. (2010) reveal a downdip limit of the SZ at 210 km and ∼40 km depth taking the 350 °C isotherm (dashed line #3, Figs. 2, 4) or ∼250 km from the trench and at a depth of ∼60 km taking the 450 °C isotherm. All of these studies reveal an unusually shallow upper plate Moho depth of ∼25 km at a distance of ∼140 km (dashed line #2, Figs. 2, 4) from the deformation front implying that the 2004 Sumatra-Andaman great earthquake nucleated within the upper plate mantle at a distance of 190 km from the trench at 36 km depth.

Tilmann et al. (2010) correlate the updip limit of the SZ in the 2004 Sumatra-Andaman great earthquake with the 500 m depth contour seaward of Simeulue island by analyzing aftershock distribution from a local seismological network (Figs. 2, 4). At the neighboring segment off Nias (from aftershock distribution of the 2005 Nias earthquake), this updip termination of the SZ is shifted landward by ∼25 km.

Further studies are based on combined MCS with wide-angle seismic data off southern Sumatra and the Sunda Strait

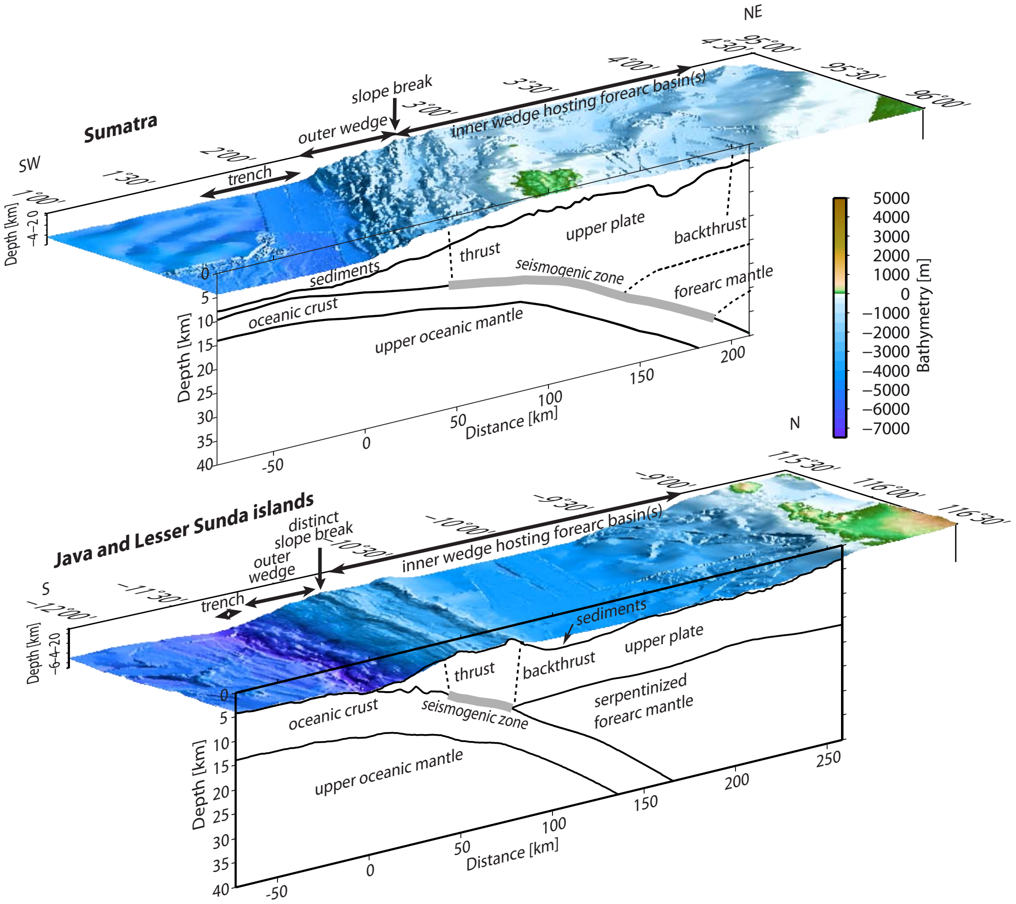

Fig. 6. Sketches of typical trench-perpendicular cross sections implemented in sections of bathymetrical charts for Sumatra (top) and Java and the Lesser Sunda islands (bottom) to highlight differences in subduction setting affecting the earthquake hazard across the Indonesian margin. Cross sections are modified after wide-angle refraction models from Dessa et al. (2009) for Sumatra and after Planert et al. (2010) for Java and the Lesser Sunda islands. SZ are thick solid grey lines along the subduction fault, terms characterizing the forearc are after Wang and Hu (2006). Thrust and backthrust connecting the SZ with the seafloor are indicated by dashed lines. Off Sumatra the backthrust is indicated only to a depth, where Singh et al. (2006) also observe the backthrust. Off Sumatra the upper plate mantle is indicated by two dashed lines, one interpretation off Simeulue (after Singh, et al., 2006; Dessa et al., 2009), where the SZ reaches down into the mantle at 140 km from the trench and the deeper mantle intersecting the subduction fault at the downdip limit of the SZ. Note that cross sections were originally located in the middle of these bathymetric maps.

(Kopp et al., 2001; Kopp and Kukowski 2003). Kopp and Kukowski (2003) model a dynamic backstop, its seaward termination may also be interpreted as transition from outer to inner wedge marking the updip limit of the SZ (Wang and Hu, 2006). The position of the dynamic backstop is ∼35 km from the deformation front at a depth of ∼10 km, the one off Sunda Strait at a distance of ∼40 km from the trench at ∼11 km depth (dashed line, Figs. 2, 4). The upper plate mantle off southern Sumatra south of Enggano island is beyond the model limits of the wide-angle data (deeper than 30 km at subducting slab interface and further than ∼250 km distance from the trench axis; Kopp et al., 2001). The downdip limit for the Sunda Strait transect is constrained by gravity modelling with a distance of 140 km from the deformation front at a depth of 25 km (Kopp et al., 2001).

3.2 Off Java from West to East

Kopp et al. (2002) reveal a shallow upper plate mantle in a depth of ∼22 km in the western part of Java (106/107° E) at a distance of about 100 km from the trench from wide-angle seismic studies (landward dashed line, Figs. 3, 5). For the same profile, a low velocity décollement is visible in MCS data to a distance of 50–55 km from the trench (Kopp et al., 2009), which correlates with the distance for the updip limit of the SZ from thermal modelling (Grevemeyer and Tiwari, 2006). However, the seaward termination of the dynamic backstop (Kopp and Kukowski, 2003) is at ∼45 km distance from the trench at ∼13 km depth (seaward dashed line, Figs. 3, 5). The same distance from the trench and depth of the forearc mantle are retrieved from wide-angle refraction analyses within the MERAMEX project at 110° E and 111° E (H. Kopp, personal communication, 2010). Further to the East, the intersection of the upper plate mantle with the subducting slab occurs at a depth of ∼18 km (Shulgin et al., 2010) at 113° E where Roo Rise subducts beneath eastern Java. An even shallower forearc mantle at 16 km depth is observed by Planert et al. (2010), who show a narrowing (∼90 km from the trench) of the downdip limit for the SZ (assuming the downdip limit coincides with the onset of the upper plate mantle) at 116° E where normal oceanic crust subducts beneath the Lombok section of the Sunda arc. At 119° E the resolution of the profile becomes poor, contentiously fixing upper plate mantle at ∼140 km distance from the trench. Planert et al. (2010) attribute the deep upper plate mantle at this part of the subduction zone to the presence of the Sumba block at the Sunda-Banda arc transition zone. Also Shulgin et al. (2009) show a very large distance (200 km from the Timor trench; dashed line, Figs. 3, 5) of the downdip limit for the SZ beneath the Sumba Ridge at the Sunda-Banda arc transition zone (121° E) These latter values have to be regarded with caution, because their resolution of these parts of the profiles are very poor (the location and dip of the subducting slab is not well-constrained).

4 Discussion: differences of bathymetric expressions comparing the Sumatra and Java (including the Lesser Sunda islands) margins

The extent of the SZ across Sumatra and Java/Lesser Sunda margin is uniform if each is regarded individually. However, these two margins clearly differ from each other and the differences are discussed below.

4.1 The outer wedge

Along most of the Indonesian margin a steep lower slope is associated with the outer wedge or seaward part of the accretionary prism, which shows imbricate thrust faults that correlate with small scale changes in the seafloor gradient (Figs. 4, 5). Several of these thrusts are present off Sumatra, whereas only some are observed off Java (lower slopes, insets of Figs. 4, 5). We attribute this difference to the smaller amount of sediment income and thus less accumulation across the outer wedge off Java compared to the huge amounts of sediment income off northern Sumatra. Two larger scale structures are present on the outer wedge off Sumatra, south of Siberut island, and we interpret these as ridges formed by subducted elevated features on the incoming plate as implicated by the slight trench retreat and the onset of subduction of elevated structures on the incoming plate at 99°–100° E. Off central Java (111°–112° E) similar large scale structures are found on the outer wedge, however, the difference to smaller scale neighbouring structures across the lower slope may arise from different data resolution (GEBCO dataset only at 111°–112° E). Although clear proof from subseafloor imaging is missing here, we do not exclude buried elevated features due to the trench retreat at the toe of the wedge.

4.2 The slope break

A distinct slope break as observed by Park et al. (2002) in Nankai distributes along almost the entire Indonesian forearc (Figs. 4, 5). It is the transition of the outer to the inner wedge and coincides with the updip limit of the SZ obtained by the numerous studies described above (seaward trench-parallel line in Figs. 2–5). Along Java and the Lesser Sunda islands (Lueschen et al., 2010) as well as off Sumatra (e.g. Sibuet et al., 2007) splay faults connect the subduction fault with the seafloor along the slope break. Rosenau and Oncken (2009) found long-term permanent deformation at the updip and downdip limits on the SZ by analog modelling of great ($M_{\mathrm{w}} \geq 8$) earthquakes. They termed the faults occurring at the updip limit of the SZ protothrust (a pair of seaward and landward dipping thrusts). We infer that the distinct slope break is the surface expression of the sharp transition of changes of the physical properties of the upper plate material (the compressive, deforming outer wedge to stronger, less deforming inner wedge), as well as the accompanying change of plate coupling along the subduction fault from stable sliding to the locked SZ as explained by the Coulomb wedge model (Wang and Hu, 2006).

There are two locations in our investigation area, where the slope break is unincisive, where no distinctive difference in the gradient can be associated with the updip limit of the SZ: the portion of northern Sumatra northwards of the northernmost profile from Grevemeyer and Tiwari (2006) and the region off Sunda Strait (Fig. 4). Note the gradient change coincides, however, with the downdip limit of the SZ in these two exceptional areas.

The distinctness of the slope break may depend on the sharpness of the updip limit of the SZ (Wang and Hu, 2006). We apply this to our geological setting where the transition from outer to inner wedge off Sumatra is less sharp than off Java and the Lesser Sunda islands (insets of Figs. 4, 5 and Fig. 6). We speculate that the dominating, controlling factor shaping the outer wedge and slope break is the sediment income. This would lead us to the assumption that the outer wedge off Sumatra differs from the inner wedge only by the degree of consolidation/alteration of the material forming the dynamic backstop (as defined by Kopp and Kukowski, 2003). This is in conjunction with the largest sediment accumulation in the northernmost part of our investigation corresponding to the indistinct slope break. This does not apply to the area off Sunda Strait where we attribute the indistinct slope break to the transition of change of geological setting (i.e. differing subduction direction, fabric/texture of the incoming oceanic plate, sediment income, nature of the upper plate is continental/oceanic) between Sumatra and Java. Comparing with different regions, the margin of Alaska (von

Huene and Klaeschen, 1999), for example, does not show a distinct slope break, which Wang and Hu (2006) postulate to be the result of a less sharp contrast in deformation style from outer to inner wedge.

4.3 The inner wedge

Adjacent to the slope break the seaward part of the inner wedge is composed of outer arc high tectonic ridges subparallel to the trench. Offshore Java and the Lesser Sunda islands two pronounced ridges build up the outer arc high in some parts of the margin hosting piggy-back basins (e.g. off Bali/Lombok, Mueller et al., 2008; Lueschen et al., 2010) neighbouring landward broad forearc basins. The uniform ridge structure is slightly elevated and shifted landwards where Roo Rise subducts. This outer arc high ridge structure is narrow, ∼40 km in extent off Lombok and broadens to ∼50 km in extent with its westward continuation. The location of the seaward ridge of the outer arc high coincides with the updip and the landward ridge coincides with the downdip termination of the SZ off Java and the Lesser Sunda islands (trench-parallel dashed lines, Figs. 3, 5). Planert et al. (2010) show a strong lateral seismic velocity difference above the intersection of the upper plate mantle with the subducting slab (downdip of SZ). Such a lateral seismic velocity contrast is observed less distinctively on all other profiles further west off Java (Shulgin et al., 2010; Kopp et al., 2002). A clear fault is not visible in coincident MCS data (Lueschen et al., 2010) but one can speculate that there is a thrust (unresolved in existing MCS data) connecting the subduction fault with the seafloor at the downdip limit if the SZ described as protobackthrust by Rosenau and Oncken (2009) from analogue modelling.

Off Sumatra (from Enggano to Siberut island) the outer arc high is also made of two tectonic ridges with about the same extent as the ridges off Java, but contrary to the margin off Java and the Lesser Sunda islands the SZ extends further landward. Scholz (1998) finds frictional properties of the plate interface responsible for the buildup of ridges above the SZ. In this tectonic setting the change of subduction direction is likely to cause a change in friction along the subduction fault. Thus the SZ widens and its downdip limitation extends further landward. It is likely that frictional properties, i.e. stronger coupling along the plate interface of the SZ off Sumatra are responsible for the uplift of the outer high ridges above sea level and formation of the Mentawai islands. However, it is striking that the forearc is further uplifted in those areas, where the N-S trending FZs from the oceanic plate subduct under the Eurasian plate. The most distinct plateau forms the continuation of the shelf between Nias and Siberut islands and lies in the assumed continuation of the most distinct FZ, the Investigator FZ. The plateau hosting Banyak island corresponds to the continuation of the 97° FZ.

We speculate that the depth of the mantle wedge below the forearc region is determined to a large degree by the differing origins and composition of the upper plate, namely continental in nature for Sumatra and oceanic for Java and the Lesser Sunda margin. We infer that the change in fabric of the oceanic crust as well as the subduction direction and the competent rock making up the dynamic backstop of the forearc interact and contribute to the frictional coupling of the subduction fault being stronger off Sumatra than off Java and the Lesser Sunda islands. Thus the mantle wedge of the upper plate is deeper and the downdip limit of the SZ as well as the wider extent of the SZ off Sumatra in contrast with the shallow upper plate mantle and narrow SZ off Java and the Lesser Sunda islands.

Off Sunda Strait no distinct outer arc high is present and several small scale ridges similar to the structure of the outer wedge maybe in response to the change of subduction direction. Also the upper plate mantle wedge was modelled at 140 km distance from the trench from wide-angle seismic data (Kopp et al., 2001). This forms the transition between the deep upper plate mantle combined with the complex wide outer arc high ridge structure above the SZ off Sumatra contrary to the shallow upper plate mantle combined with the narrow SZ off Java.

The location of the updip limit of the SZ (landward trench-parallel line, Figs. 2, 4) does not correlate as well with prominent morphological features as the one off Java and the Lesser Sunda islands. There is a correlation of the landward termination of the SZ with a change in slope gradient (and pattern) in the northernmost part of Sumatra (northwards of the northernmost Grevemeyer and Tiwari (2006) profile) as well as off Sunda Strait. However, the downdip limit of the SZ does not correlate with the coastline (as observed in different regional settings, e.g. Chile) nor with major fault systems like the Mentawai fault despite a small portion of the West-Andaman fault at 6°–7° N (Figs. 2, 4).

A backthrust found by Singh et al. (2008) in MCS data corresponds to a slight lateral seismic velocity increase modelled by Dessa et al. (2009) on a coincident wide-angle seismic line. The backthrust in the MCS data of Singh et al. (2008) connects the subduction fault with the seafloor at the downdip limit of the SZ. We propose such a protobackthrust, as described by Rosenau and Oncken (2009) from analogue modelling, for the Java and Lesser Sunda margin (Fig. 6) at the lateral seismic velocity increase.

5 Conclusions

The method to identify the extent of the seismogenic zone (SZ) from seafloor morphology proves valid for the updip limit of the SZ across the entire Sunda margin. Within this study the extent of the SZ was identified from bathymetric and gradient charts off Java and the Lesser Sunda islands. However, additional investigations are needed to constrain the downdip limit of the SZ off Sumatra.

The SZ is uniformly wide for the Sumatra margin. The extent of the SZ narrows off Sunda Strait, which is the transition between the Sumatra margin and the uniformly narrow extent of the SZ of the Java/Lesser Sunda margin. The differences across the Sumatra and Java/Lesser Sunda margins with respect to the location and width of the SZ affecting the upper plate morphology are as follows:

1. The appearance and extent of the outer wedge differs.

   The outer wedge is uniformly ∼50 km wide off Java and the Lesser Sunda islands. The extent of the outer wedge varies off Sumatra being mostly ∼70 km wide in some areas narrowing to 50 km width. The gradients of the outer wedge are smaller off Java and the Lesser Sunda islands compared with the steeper lower slope off Sumatra. The slope of the outer wedge off Java and the Lesser Sunda islands is cut by one/two steeper ridges (∼5 km extent), whereas the outer wedge off Sumatra is made up of several of these steep ridges (∼5 km extent).

2. The slope break corresponds to the updip limit of the SZ along the subduction fault.

   The updip limit of the SZ is associated with the seawardmost part of the outer arc high forming the rather distinct slope break off Java and the Lesser Sunda islands, whereas it is indistinctive off large parts of Sumatra.

3. The inner wedge shows differences along the Indonesian margin.

   Uniform trench-parallel ridge structures lie off Java and Lesser Sunda islands, whereas non-uniform trench-parallel outer arc high structures consisting of several broad tectonic ridges off Sumatra shape the seaward part of the inner wedge.

We find a combination of parameters responsible for the above structures and the shape of the forearc. These are: the structure of the incoming plate, its convergence rate and direction, the amount of sediment income, and the nature of the upper plate (continental/oceanic in Sumatra/Java and Lesser Sunda islands). Likewise, these factors influence the coupling at the plate interface.

The non-uniform ridge structure along the entire Sumatra margin developed probably due to the constant accretion of the wedge and the gradually seaward growth and thus consolidation of the sediments (former outer wedge accretionary prism) in the seaward part of the inner wedge. The consolidation across the Sumatran forearc is therefore likely more gradual than the sharp transition from outer to inner wedge and above the downdip limit of the SZ across the Java/Lesser Sunda forearc.

Off Sumatra the SZ is up to more than twice as wide as off Java and the Sunda islands, enlarging the unstable regime off Sumatra compared to the setting in Java and thus the risk of sudden stress release in a great earthquake.

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