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# Subduction system variability across the segment boundary of the 2004/2005 Sumatra megathrust earthquakes

A. Shulgin [a], H. Kopp [a,*], D. Klaeschen [a], C. Papenberg [a], F. Tilmann [b], E.R. Flueh [a], D. Franke [c], U. Barckhausen [c], A. Krabbenhoeft [a], Y. Djajadihardja [d]

[a] *GEOMAR Helmholtz Centre for Ocean Research Kiel, Wischhofstr. 1-3, 24148 Kiel, Germany*
[b] *German Research Center for Geosciences (GFZ), Telegrafenberg, D-14473 Potsdam, Germany*
[c] *Federal Institute for Geosciences and Natural Resources (BGR), Stilleweg 2, D-30655 Hanover, Germany*
[d] *Agency for the Assessment and Application of Technology (BPPT), Jl.M.H. Thamrin No. 8, Jakarta 10340, Indonesia*

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## ABSTRACT

Subduction zone earthquakes are known to create segmented patches of co-seismic rupture along-strike of a margin. Offshore Sumatra, repeated rupture occurred within segments bounded by permanent barriers, whose origin however is still not fully understood. In this study we image the structural variations across the rupture segment boundary between the Mw 9.1 December 26, 2004 and the Mw 8.6 March 28, 2005 Sumatra earthquakes. A set of collocated reflection and wide-angle seismic profiles are available on both sides of the segment boundary, located offshore Simeulue Island. We present the results of the seismic tomography modeling of wide-angle ocean bottom data, enhanced with MCS data and gravity modeling for the southern 2005 segment of the margin and compare it to the published model for the 2004 northern segment. Our study reveals principal differences in the structure of the subduction system north and south of the segment boundary, attributed to the subduction of 96°E fracture zone. The key differences include a change in the crustal thickness of the oceanic plate, a decrease in the amount of sediment in the trench as well as variations in the morphology and volume of the accretionary prism. These differences suggest that the 96°E fracture zone acts as an efficient barrier in the trench parallel sediment transport, as well as a divider between oceanic crustal blocks of different structure. The variability of seismic behavior is caused by the distinct changes in the morphology of the subduction complex across the boundary related to the difference in the sediment supply.

## 1. Introduction

Since 2004, repeated large and great megathrust earthquakes along the Sumatra subduction zone have ended a ~40 yr period of relative moderate ($Mw < 8.5$) global seismic activity. Studies of the $Mw = 9.1$ Sumatra–Andaman earthquake in 2004 and following events of magnitudes $\geq 8.4$ in 2005 and 2007 confirmed previous observations of segmented rupture areas of earthquakes along subduction zones (Ando, 1975; DeShon et al., 2005; Spence, 1977). Offshore Sumatra, rupture occurs in discrete patches (e.g. Chlieh et al., 2007), bounded by distinct barriers along-strike. Detailed seismological studies reveal variations in the updip limit of the 2004 and 2005 ruptures, respectively (Ammon et al., 2005; Ishii et al., 2005). These observations imply across-strike heterogeneity in physical properties along the megathrust. The controlling physical processes, however, are still not fully understood.

The tectonics around Northern Sumatra are predominantly controlled by the subduction of the oceanic Indo-Australian plate underneath Eurasia. The current convergence rate offshore Northern Sumatra is estimated at 51 mm/yr (Prawirodirdjo and Bock, 2004). The increasing obliquity of the convergence northwards from the Sunda Strait (McCaffrey, 2009; Moore and Curray, 1980) results in the formation and development of a number of arc-parallel strike-slip fault systems (Fig. 1). The most significant are the Sumatra and the West Andaman Fault systems, accommodating arc-parallel strain (Malod and Kemal, 1996; Mosher et al., 2008; Sieh and Natawidjaja, 2000) offshore central-southern Sumatra. For the Mentawai fault system (Berglar et al., 2010; Diament et al., 1992; Kopp et al., 2001; Lelgemann et al., 2000; Malod and Kemal, 1996), recent findings suggest deformation dominated by backthrusting (Singh et al., 2010, 2011).

The "seismic unzipping" of the Sumatra margin since 2004 offers the unique opportunity to investigate the relationship

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[*] Corresponding author. Tel.: +49 431 600 2334; fax: +49 431 600 2922.
*E-mail address:* hkopp@geomar.de (H. Kopp).

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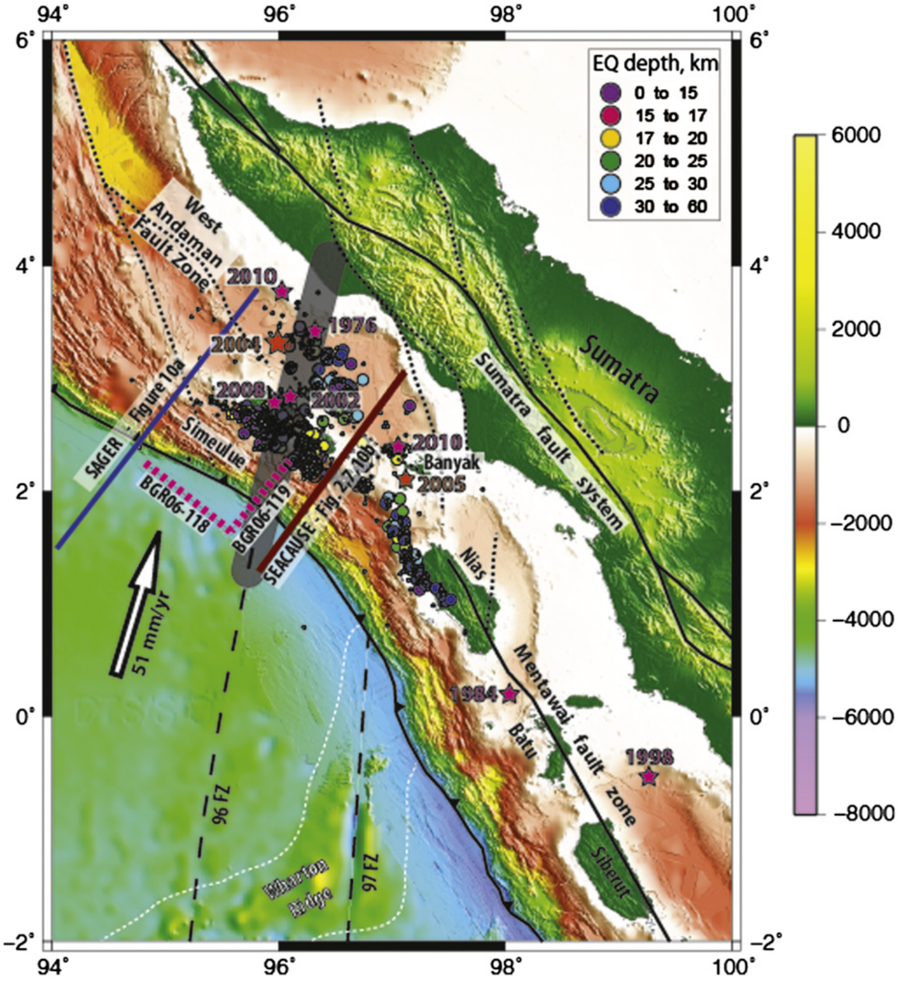

**Fig. 1.** Map of the study area offshore Northern Sumatra. The location of the wide-angle (SeaCause) and the collocated MCS (BGR06-135) profiles described in this study are shown by red line. The arrow shows the plate convergence vector. Major faults are shown by black solid and dashed lines (after Curray, 2005). Hypocenter locations of Mw ≥ 7.0 earthquakes are shown by magenta stars. The local seismicity relocated in a pseudo 3D model (recorded for 3 month in 2006, see text) is shown by depth color-coded circles (rms < 0.1 s, seismicity with poor depth constrains is shown by gray circles; after Tilmann et al., (2010). The proposed segment boundary between the rupture areas of the 2004 and 2005 earthquakes is shown by thick gray line (Franke et al., 2008). Dashed white lines mark the extent of the Wharton Ridge in the vicinity of the trench. Bold black dashed lines are the fracture zones on the oceanic plate identified from the bathymetric and magnetic data. Blue line—seismic profile SAGER shown in Fig. 7 from Klingelhoefer et al. (2010). Dashed magenta lines—MCS profiles described in Franke et al. (2008). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

between interseismic coupling and the mechanical properties of the megathrust including the nature of asperities and barriers to megathrust ruptures. The 2004 earthquake asymmetrically ruptured to the north over a distance of more than 1200 km, while the 2005 event showed a bidirectional rupture. However, there is a clear delineation between these events, located underneath the island of Simeulue (Ammon et al., 2005; Briggs et al., 2006; Gahalaut and Catherine, 2006; Subarya et al., 2006). Franke et al. (2008), based on bathymetry and multichannel seismic (MCS) data, proposed the segment boundary running NE–SW through the island of Simeulue, as discussed earlier by Briggs et al. (2006) (Fig. 1). The observed location of the pivot line (a proxy to the downdip limit of the rupture area) of the pre-2005 earthquake net uplift on Simeulue (Meltzner et al., 2006) spatially correlates with the proposed segment boundary.

A number of possible scenarios were suggested for the formation of segment boundaries: these include tectonic structures in the overriding plate (Collot et al., 2004; Ryan and Scholl, 1993), mechanical discontinuities in the subducting plate (Aki, 1979; Spence, 1977) and topographic relief on the oceanic plate such as seamounts, ridges or fracture zones (Bilek et al., 2003; Bilek, 2010. Offshore Sumatra, the oceanic plate is characterized by prominent tectonic features observed in the bathymetry and magnetic data (Sclater and Fisher, 1974): north–south trending fracture zones enter the trench around 96°E and 97°E (Deplus et al., 1998). In addition, the Wharton Ridge, representing the southwest–northeast trending segments of a fossil spreading axis, is approaching the trench offshore Nias (Fig. 1). For northern Sumatra, Subarya et al. (2006) suggested that the segment boundary between the 2004–2005 patches is linked to the subduction of the 96°E fracture zone on the oceanic plate, based on the coseismic slip modeling results. This fracture zone was identified from magnetic studies (Sclater and Fisher, 1974), as well as from the bathymetry data seaward of the trench; in the vicinity of the trench no anomalous relief is observed, due to increase of sediment fill. In an MCS profile presented by Franke et al. (2008) (their Fig. 5) the fracture zone is manifested by an area of low/absent reflectivity from the top of the oceanic crust, as well as in the thinning of the sedimentary cover. It was also shown that this is a pre-existing feature and not subduction-related, based on the sediment onlap above the zone of shallow basement (Dean et al., 2010).