Active deformation across the Sumatran forearc over the December 2004 M_w 9.2 rupture

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ABSTRACT

A 220-km-long, single-channel seismic reflection profile crosses the northern Sumatra margin and presumed rupture zone of the December 2004 M., 9.2 tsunamigenic earthquake and images active deformation across the forearc. At the largest wavelength (tens of kilometers), the forearc surface is defined by a steep, 55-km-wide outer slope, a 110-km-wide upper slope forming a broad depression between two forearc highs, and a 25-km-wide steep inner slope between the landward high and forearc basin. Superimposed on these prism-wide variations are anticlinal ridges spaced ~13 km apart; the inner and outer slopes are characterized by landward and seaward fold vergence, respectively. Between anticlines, growth strata deposited in slope basins are folded at ~2–3 km wavelengths. These small folds deform the seafloor and increase in amplitude with depth, verging toward anticlinal hinges. We suggest that long-wavelength variations are consistent with variations in strength across the forearc. The ~13 km anticline spacing implies deformation of a slope apron that deforms independently of a stronger wedge interior. Growth strata geometries indicate ongoing deformation within individual basins. Our model for prism architecture suggests that the wedge interior advances during great earthquakes like the 2004 $M_{w}9.2$ event, peeling up shallower and less competent trench fill, deforming the toe and the upper slope of the forearc, and producing seabottom uplift responsible for the tsunami.

Keywords: forearc, Sumatra, growth sedimentation, wedge, tsunami.

INTRODUCTION

Plate boundary segments undergoing large moment release during subduction earthquakes are associated with overlying forearc basins and negative, trench-parallel, free-air gravity anomalies (Wells et al., 2003; Song and Simons, 2003). Such patterns suggest that processes controlling asperity positions along megathrusts may be manifested in long-term behavior of the forearc and in evolution of forearc structure (Fuller et al., 2006). Along accretionary margins, where large subduction earthquakes occur (e.g., the Aleutians), perhaps 70% of forearc deformation occurs within several million years after accretion near the toe, with an exponential decrease in total shortening rate landward (von Huene and Klaeschen, 1999). The Kodiak Formation, or the exposed inner high of the Aleutian forearc, records large ductile strains (>50% shortening from 73 to 60 Ma), but little to no ductile strain during subsequent subduction when accretion was farther outboard (Fisher and Byrne, 1992). Such observations suggest that the inner forearc is stable and strong, acting as a backstop for younger, actively deforming wedge sediments in the outer forearc (Wang and Hu, 2006).

Structural history and distribution of deformation in the forearc are important for under-

standing patterns of interplate coupling, ground motion, and tsunamigenic potential. To evaluate structures across the Sumatran forearc in the area of greatest moment release associated with the December 26, 2004, M_w9.2 earthquake (Lay et al., 2005), seismic reflection profiles imaged a series of slope basins that overlie the region of initial large moment release, as defined by inversion of teleseismic data (Ammon et al., 2005; Chlieh et al., 2007). We use a single, cross-prism profile from the Sumatra Earthquake and Tsunami Offshore Survey (SEATOS), Line 1, to characterize shallow accretionary structures across >200 km of the forearc (Fig. 1). These observations suggest that convergence-related deformation occurs predominantly in young accreted sediments, decoupled from older, deformed terrain, which acts as a backstop.

BACKGROUND

The December 2004 M_w 9.2 earthquake initiated offshore north-central Sumatra and propagated ~1200 km to the north-northwest, with maximum slip offshore northern Sumatra of >10 m (Ammon et al., 2005) (Fig. 1). At the southern edge of the 2004 rupture, Eocene oceanic crust subducts along with 2–3 km of Nicobar Fan strata, overlain by a trench sediment wedge ~500 m thick (Karig et al., 1979). Offshore central Sumatra (Karig et al., 1980; Moore et al., 1980; Moore and Curray, 1980) and farther southeast (Schlüter et al., 2002), structure along the deformation front is typically a seaward-vergent, fault-related fold. In contrast, offshore northern Sumatra, frontal structures are both arcward and seaward vergent, and vergence switches in discrete segments along strike (Moore et al., 1980; Henstock et al., 2006). In this region, trench-slope basins that are arcward of the frontal thrust record the Neogene distribution of forearc shortening.

METHODS

In May 2005, a high-resolution, singlechannel seismic (SCS) survey was conducted across the northern Sumatran forearc. SEATOS surveying was guided by the HMS Scott swath bathymetry survey, conducted earlier in 2005 (Fig. 1; Henstock et al., 2006). The seismic source was a 2-gun array of generator-injector air guns totaling 420 in3. Reflections were received by hydrophones in a 61-m-long Teledyne streamer towed at ~4 m depth. Processing included bandpass filtering, gain recovery, and FK-migration. Here we interpret Line 1, a 220-km-long profile from the northwestern tip of Sumatra to undeformed Sunda Trench sediment on the incoming India-Australia plate (Figs. 1 and 2).

RESULTS

The forearc exhibits three component morphologies: (1) a steep (8° or more), southwestfacing outer slope, (2) a broad upper slope defining a topographic low between inner and outer highs, and (3) a steep northeast-facing slope into the forearc basin bordering the volcanic arc. The resultant sinusoidal bathymetry contrasts the general view of a convex-up accretionary wedge exhibiting homoclinal slope toward a trench (Zhao et al., 1986). Off northern Sumatra, the highest point in the forearc is ~55 km arcward of the deformation front, at the seaward edge of the upper slope (Fig. 2). From this high landward, the top of the prism defines a broad bathymetric depression between two forearc highs (Fig. 2). First, the prism surface drops to the



Figure 1. Seismo-tectonic setting of northern Sumatran accretionary margin. Focal mechanism shows epicenter of 26 December 2004, M_w 9.2 earthquake. Tectonics modified from U.S. Geological Survey poster of the M9.0 Sumatra–Andaman Islands earthquake of 26 December 2004 (U.S. Geological Survey, 2004). Aftershock data from U.S. Geological Survey (2006) and relief data from National Geophysical Data Center (2006). Yellow rectangles represent surface projections of rupture segmentation, estimated via displacement measurements of global positioning system stations and inverse methods (Chlieh et al., 2007). Inset: Digital elevation model of northern Sumatra forearc based on HMS *Scott* swath multibeam data (Henstock et al., 2006).

northeast, toward the arc, for ~75 km (Fig. 2). Farther landward, the prism then rises gently for ~40 km to the second forearc high (Fig. 2). Finally, the prism drops again, this time along a steep northeast-facing slope into the largest of the slope basins (Fig. 2).

Superimposed on forearc-wide bathymetric variations is a repeated, shorter-wavelength variability related to structural highs and intervening slope basins. Highs are spaced at ~13 km intervals, and 14 such culminations occur across

~200 km of forearc (Fig. 2). Sediments within individual slope basins are in turn deformed, at ~2–3 km wavelengths, including locally the sea-floor (Fig. 3).

Outer Slope

At the seaward end of Line 1, we interpret flatlying reflections as sediments filling the Sunda Trench to thicknesses of 2 km or more (Fig. 2). Near the deformation front, two small, symmetric, upright folds produce ridges on a 5-km-wide culmination. Farther northeast, sediments tilt along a synclinal axis to form a dip slope, $\sim 12^{\circ}$, that rises from the trench floor to the top of the first of 14 ~13-km-wavelength culminations between the trench and the forearc basin (1 in Fig. 2). A ridge midway up this slope (Fig. 3A) is a small landward-vergent fold that may be parasitic to the larger anticline. Still higher, the outer slope is scarred by what we interpret as a landslide that truncates seaward-dipping strata on the southwest side of the same anticline (1 in Fig. 2). On the landward limb, an 8-km-wide compound basin contains three small ridges, each defined by smaller, fault-bounded anticlines that verge seaward (Fig. 3A). Sediments within this compound basin appear increasingly deformed downsection, suggesting growth sedimentation. The seafloor rises >2 km in a series of steps to the highest point in the forearc (4 in Fig. 2), ~55 km landward of the deformation front.

Upper Slope

We define the upper slope as an ~115-kmwide region (Fig. 2) that characterizes a bathymetric depression between the two highest points in the forearc. Eight anticlinal ridges (5-12 in Fig. 2) and seven intervening basins punctuate this depression. The basin closest to the outer forearc high appears starved of recent sediments (~75 km thick, Fig. 2); all of the other structural lows contain up to 0.5 s (~0.5 km) of fill (Figs. 3B, 3C). These basins show evidence for increasing deformation with depth; sedimentary layers thin or onlap growing anticlines (Fig. 3). Folding at ~2-3 km wavelengths suggests continued shortening throughout the seismically observable history of slope sedimentation across the prism (Fig. 2). In all but two of these basins, intrabasin folding involves the seafloor. Smallscale folds are generally symmetric within individual basins, but show vergence consistent with flexural shear on the flanks of larger anticlines (Fig. 3C).

Inner Forearc and Forearc Basin

The inner forearc high is ~180 km from the deformation front (Fig. 2). Landward of this high, the prism drops ~1.3 km to two anticlinal highs en route to the base of the inner forearc basin slope (Fig. 2). These folds verge seaward, toward the inner forearc high (Fig. 3D). At the base of the slope, a thick sedimentary package is observed along strike of the Aceh Basin to the southeast. Stratified sedimentary basin fill is ~1.5 s (~1.5 km) thick, overlying a seismically chaotic package. Deeper fill along the seaward edge of the basin appears deformed into folds, where it abuts the more highly deformed forearc wedge (Fig. 3D). In contrast, the upper stratified fill thins and onlaps the landward side of the basin, above a seaward-dipping reflector resembling an angular unconformity bounding the southwest side of the Sumatran volcanic arc (Figs. 1 and 3D).



Figure 2. Single channel seismic reflection profile, Line 1, of SEATOS expedition (Sumatra Earthquake and Tsunami Offshore Survey; see Fig. 1 inset for location). Anticlinal ridges are numbered (1–14) from Sunda Trench to Aceh (forearc) Basin. A–D are basin structures (see Fig. 3).

DISCUSSION

Line 1 shows that Sunda forearc structure and bathymetry vary at three distinct wavelengths: (1) tens of kilometers, defined by the steep outer slope (Figs. 2 and 3A), gentle upper slope (Figs. 2 and 3B, 3C), and steep inner forearc (Figs. 2 and 3D), (2) ~13 km, the wavelength of 14 structural culminations characterizing the prism surface (Fig. 2), and (3) ~2–3 km, the wavelength of folds within individual slope basins (Figs. 3A–3D).

The long-wavelength variations (Fig. 2) have important implications for bulk wedge properties, when viewed in the context of critical wedge mechanics (Davis et al., 1983). In any such system, the wedge taper (defined as surface slope, α + basal décollement dip, β) is a stable configuration that reflects the strength of the wedge interior and shear stress along the basal décollement. The observed 8°-12° outer slope (Fig. 3A), combined with an estimate of 5° for the basal décollement dip (Kieckhefer et al., 1981), is consistent with a wider taper than most accretionary wedges (Davis et al., 1983; Wang and Hu, 2006). We suggest that this implies either deformation of weak trench sediments in the wedge interior or a higher shear stress along the basal décollement at the updip end of this plate boundary. Increased basal friction beneath the outer wedge is predicted to occur during great earthquakes (Wang and Hu, 2006).

The slope break at the outer forearc high (Fig. 2) suggests either an increase in wedge strength landward or a drop in shear stress across this part of the décollement (e.g., Zhao et al., 1986). However, such variations in wedge and décollement properties are not enough to explain the observed gentle arcward slope that occurs for ~60 km (Fig. 2) to the center of the observed upper slope topographic depression. The position where the wedge goes from positive α to negative α , the outer forearc high, could correspond with increasing arcward dip on the basal décollement (e.g., Fuller et al., 2006).

The consistent ~13 km spacing between active structural ridges across the top of the prism (Fig. 2) is consistent with dominant wavelength theory and buckling of a near-surface mechanical layer (e.g., Fletcher, 1974). We suspect that the observed shortening is restricted to near-surface rocks, likely com-



Figure 3. Highlights of slope basins and forearc basin structures across Sumatra accretionary prism: (A) frontal toe region, (B) basins on upper slope, (C) slope basins within larger depression (showing landward and seaward vergent 2–3 km wavelength folding), and (D) example of sedimentary fill of forearc basin. See Figure 2 for locations of profile segments along Line 1.

posed of deformed slope sediments. Moreover, the spacing is consistent with a mechanical layer thickness of only kilometers, not the full thickness of the wedge. The vergence of ~13-kmwavelength folding reverses across the two forearc highs in the long-wavelength bathymetry (Figs. 3A, 3D), suggesting flexural flow. The observed deformation probably occurs within a passive roof (e.g., Banks and Warburton, 1986) that is delaminated from a strong wedge not seismically imaged. The sharp break in slope seaward of the outer forearc high (~65 km, Fig. 2) could represent the updip limit of this stronger wedge.

Slope basin strata along Line 1 are increasingly deformed with depth, much like slope basin deposits exposed on Nias Island to the south (Moore and Karig, 1980; Fig. 3D). Vergence of these structures changes across the forearc (Fig. 3C), and is consistent with flexural shear toward anticlinal culminations (Fig. 2). Shortening of individual basins has created some low-amplitude structural highs (Fig. 3B); slope basin sediment fill then onlaps, thins, and is incorporated into upward-growing anticlines. This pattern suggests that there was once a more extensive slope apron that is now folded to form these highs (Fig. 2). Along the southwest edge of the largest basin, sediments are being incorporated into an adjacent forearc ridge along a steep, northeast-facing deformation front (Fig. 3D). SEATOS seafloor samples from structural highs consist of calcareous and clastic sediments, indicating that much of the material now exposed at the seafloor may originally have been derived from Sumatra. Continuing forearc deformation has isolated deposition into progressively smaller basins (Figs. 2 and 3). Sediment dispersal from Sumatra possibly crossed the whole forearc until the late Neogene, when subduction of thick Nicobar Fan strata built up the forearc sufficiently to block sediment pathways from the arc (e.g., Moore et al., 1982).

Our observations of ongoing folding at different prism positions (Fig. 2) indicate that nearsurface shortening is active across the ~200 km expanse of the forearc. Deformation appears restricted to an upper slope apron that we suspect deforms independently of a stronger wedge interior. A similar process occurs along the Cascadia subduction zone (Adam et al., 2004) and many mountain fronts like the Canadian Rockies, Pyrenees, and Brooks Range that border thick, incoming foreland basin sequences (Vann et al., 1986). Such a model requires that the roof exhibit arcward or landward vergence along the deformation front. Multibeam bathymetry (Henstock et al., 2006), a 1970s multi-channel seismic survey (Moore et al., 1980), and SEATOS SCS data collected elsewhere (Fig. 2) make it clear that the deformation front, though segmented along strike, is landward vergent southeast of Line 1. Landward vergence has been attributed to low shear stress and high fluid pressures on the décollement (e.g., Mackay, 1995), but such low shear stress would lead to a narrow taper, and our seismic observations suggest a wide taper near the deformation front (Fig. 2). Landward-vergent frontal structures (Henstock et al., 2006) and the presence of a syncline rather than a seawardvergent thrust at the deformation front suggest that shallow sediments are weakly coupled with the seaward-vergent plate boundary system.

CONCLUSIONS

Seismic observations of active folding within basins at different prism positions indicate that near-surface shortening is actively occurring across the entire northern Sumatra forearc, from the deformation front to the Aceh Basin. Deformation may be restricted to an upper slope apron that buckles at a wavelength of ~13 km, independent of a stronger wedge interior. We conclude that in this forearc, great earthquakes initiate the following sequence: (1) advance of the strong inner wedge, (2) movement of the outer forearc high seaward, deformation at the prism toe, and peeling up of weaker, shallower trench fill, and (3) shortening and uplift of the upper slope. This combination of processes can enhance uplift across a substantial portion of the forearc and therefore could have important implications for tsunamigenesis of the December 26, 2004 event.

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