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Another potential source of destructive earthquakes and tsunami offshore of Sumatra

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[1] We link geodetic data from the Sumatran GPS Array (SuGAr) and earthquake focal mechanisms to show that a 900-km long backthrust, arising from the Sunda megathrust offshore of Sumatra, has recently become active following the series of great megathrust earthquakes of this past decade. Shallow failure of the Mentawai backthrust explains coseismic displacements during moderate-earthquake clusters in 2005 and 2009. These two clusters represent the first activity on the backthrust in more than 30 years. Existing paleogeodetic evidence of vertical deformation in past centuries is too sparse to characterize earlier major activity, but leaves open the possibility of historic great backthrust earthquakes. Our geodetic evidence for rupture of the Mentawai backthrust during the two recent earthquake clusters suggests that this large fault may well pose an additional seismic and tsunami hazard to the coastal communities of central Sumatra. **Citation:** Wiseman, K., P. Banerjee, K. Sieh, R. Bürgmann, and D. H. Natawidjaja (2011), Another potential source of destructive earthquakes and tsunami offshore of Sumatra, *Geophys. Res. Lett.*, *38*, L10311, doi:10.1029/2011GL047226.

1. Introduction

[2] Since 2004, three great earthquakes have focused considerable attention on the Sumatran section of the Sunda megathrust [e.g., *Chlieh et al.*, 2007; *Briggs et al.*, 2006; *Konca et al.*, 2007; *Konca et al.*, 2008]. Another long fault, the Mentawai fault, runs parallel to the Sunda megathrust from about 1° to 7°S (Figure 1, inset), and for decades it's sense of motion was misinterpreted as strike-slip [e.g., *Diament et al.*, 1992; *Sieh and Natawidjaja*, 2000]. Very recent high-resolution seismic reflection and bathymetric data have shown that it is principally a trenchward-dipping reverse fault system [*Singh et al.*, 2010]. *Singh et al.* [2010] highlight several steeply-dipping recent seismic events that may be located on the Mentawai backthrust. We analyze SuGAr geodetic data and earthquake focal mechanisms to confirm that the backthrust is indeed active and has produced two M_w 6.7 earthquakes. We also discuss sparse, existing paleogeodetic data that bear on whether it has generated very large earthquakes and tsunamis within the past several millennia.

2. Cluster Seismic Activity

[3] Recent, detectable seismic activity on the Mentawai fault started with the 2005 earthquake sequence, which originated just east of the strait that separates Siberut and Sipora islands (Figure 1). The seismic activity started gradually within a week of the great 2005 Nias-Simeulue earthquake. The largest (M_w 6.7) earthquake occurred on the 10th of April and was followed within the next seven hours by M_w 6.5 and 6.1 events. Between the 2nd and 17th of April the cluster included twenty-eight M 5+ earthquakes, whose cumulative seismic moment equals a M_w 6.9 earthquake. The arrival of a tsunami up to a meter high on the southeastern coast of Siberut (firsthand accounts in the auxiliary material) implies a nearby shallow source for the M_w 6.7 earthquake.[1]

[4] Global centroid moment tensor (GCMT) focal mechanism solutions and centroid locations (www.globalcmt.org) of the 2005 cluster are consistent with slip on the Mentawai backthrust (Table S1). The dips of all trench-parallel nodal planes between the 7th and 17th of April are >40. These steep dips and the shallow (12 to 29-km) centroid depth range, signify that these earthquakes were likely not produced by slip on the megathrust (Figure 1, cross-section). Instead, it appears that the earthquakes originated on a relatively steep NE- or SW-dipping fault within the accretionary prism. The 2005 cluster is the first occurrence of such shallow, steeply dipping earthquakes near this recently mapped portion of the Mentawai backthrust system since the beginning of the GCMT catalog in 1976 (for more information see auxiliary material).

[5] The second cluster began on 16 August 2009 with a M_w 6.7 earthquake just east of Siberut. The 2009 cluster overlaps with but is predominantly northwest of the 2005 cluster. It was a less energetic sequence. Only one M 6+ earthquake and nine M 5+ earthquakes (combined moment magnitude of M_w 6.7) occurred from the 16th to 23rd of August. The focal mechanisms and shallow depths of the 2009 earthquakes (12 to 19-km) are also consistent with slip on the SW-dipping Mentawai backthrust (Figure 1, cross-section).

3. GPS Measurements

[6] Several continuously operating SuGAr stations recorded surface motions (for more information see the auxiliary

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[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL047226.

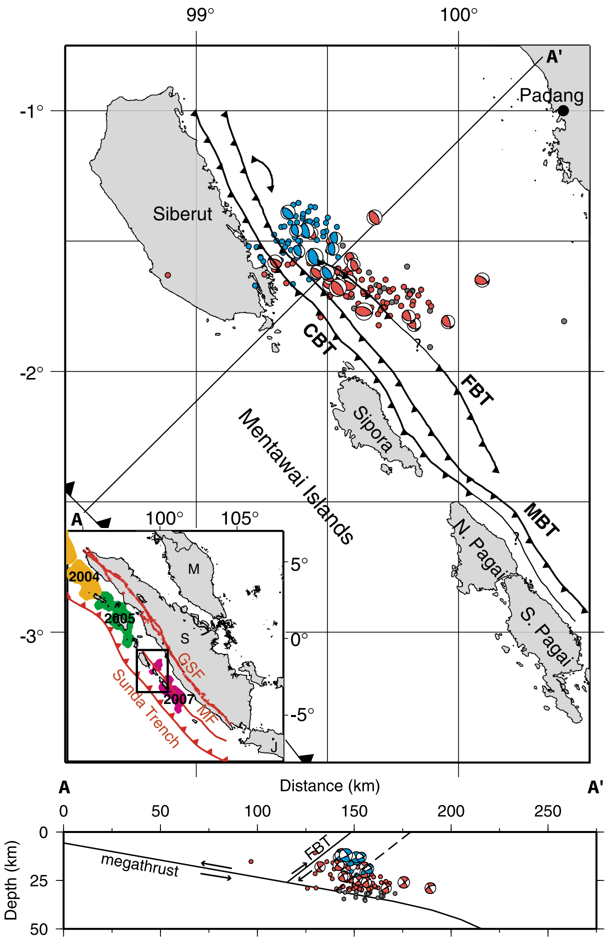

Figure 1. Tectonic setting and cluster activity near the Mentawai Islands. Two recent earthquake clusters near the Mentawai fault, above a section of the Sunda megathrust that has not broken in at least two centuries [*Natawidjaja et al.*, 2006]. Double-difference relocated earthquakes [*Pesicek et al.*, 2010] from the start of the 2005 cluster until one month following its largest earthquake; events above and below 30 km appear as red and dark gray circles, respectively. EHB earthquake locations from the first month following the 2009 M_w 6.7 earthquake are blue (E. R. Engdahl unpublished data, method from *Engdahl et al.* [2007]). Backthrust fault traces are from *Singh et al.* [2010]: frontal backthrust (FBT), main backthrust (MBT), and coastal backthrust (CBT). GCMT focal mechanisms from both clusters are plotted at their centroid locations. (Inset) Recent great earthquake ruptures of the Sunda megathrust [*Chlieh et al.*, 2007; *Briggs et al.*, 2006; *Konca et al.*, 2008]. M, S, and J are Malaysia, Sumatra, and Java. GSF and MF are the Great Sumatran fault and the entire extent of the Mentawai fault. (Cross-section) Relocated earthquakes with reviewed and accepted depths and focal mechanisms from the two recent clusters are projected onto a NE-oriented section with megathrust geometry from *Hayes et al.* [2009]. The frontal backthrust is projected to the plate interface. The dashed fault is fitted to the relocated earthquakes shallower than 30 km depth (see auxiliary material).

material) associated with the 2005 and 2009 clusters (locations on Figures 3a and 3b). The position time series from the three stations that detected the 2005 cluster appear on Figure 2a. The largest recorded offset occurred at NGNG on the 10th of April (day 100), the day of the three M 6+ earthquakes. The northeastward motion and subsidence of NGNG indicates that slip on a NE-dipping fault is not a plausible cause for the cluster. The motions of MSAI and PSKI are small, implying that the source is closer to NGNG.

[7] The position time series for the three GPS sites closest to the 2009 cluster shows that the largest offset appears on the 16th of August (day 228), the day of the M_w 6.7 earthquake (Figure 2b). The horizontal motion at NGNG and TLLU is northeastward, whereas MSAI moves to the southeast. The more northerly motion of NGNG in 2009 demonstrates that the 2009 source is north of the 2005 source. Moreover, subsidence of all of Siberut sites implies a shallow source east of the island.

4. Deformation Modeling

[8] We model both clusters using the principal component analysis-based inversion method (PCAIM) developed by *Kositsky and Avouac* [2010]. This method uses the Green's functions for a dislocation in an elastic homogeneous half-space [*Okada*, 1985]. Clusters of seismicity can be associated with slow slip, which may produce more deformation than is expected by summing the magnitude of all of the events in the cluster. PCAIM allows epoch-by-epoch inversion and enables us to model the time series for the most active period of the clusters. Thus, we can ascertain if the slip was restricted mainly to the days of the M_w 6.7 earthquakes or if there was considerable slow slip.

[9] For simplicity we assume that slip on the frontal backthrust fault (FBT), the mapped backthrust trace closest to the earthquake clusters, caused all observed motion. The horizontal spread of the earthquakes and the offset between the relocated earthquake hypocenters, consisting of teleseismic double-difference relocations for the 2005 cluster [*Pesicek et al.*, 2010] and EHB relocations for the 2009 cluster (E. R. Engdahl unpublished data, using methods from *Engdahl et al.* [2007]), and the FBT in the Figure 1 cross-section may be due to errors in the reported earthquake locations. For the region southwest of the island of Simeulue, *Tilmann et al.* [2010] found that CMT centroids have a southwestward bias and EHB locations have a northeastward bias relative to the aftershock locations determined using a temporary seismic array. The teleseismically determined earthquake locations in the Mentawai backthrust region may also suffer from systematic location bias due to strong local velocity heterogeneities. Alternatively, the earthquake locations east of the FBT may indicate rupture of an unmapped, outward-propagating, blind thrust fault. We explore modeling slip on such a backthrust (dashed fault in Figure 1, cross-section) in the auxiliary material.

[10] We invert for distributed slip on a two-segment fault grid, consisting of 5-km square slip patches, to seek the optimal location of peak coseismic slip. The two-segment fault model changes strike at a prominent bend in the FBT (Figure 3 and Table S2) and extends from the surface to ~25 km, the depth of the underlying megathrust. The dip and rake values are based on the backthrust focal mechanisms.

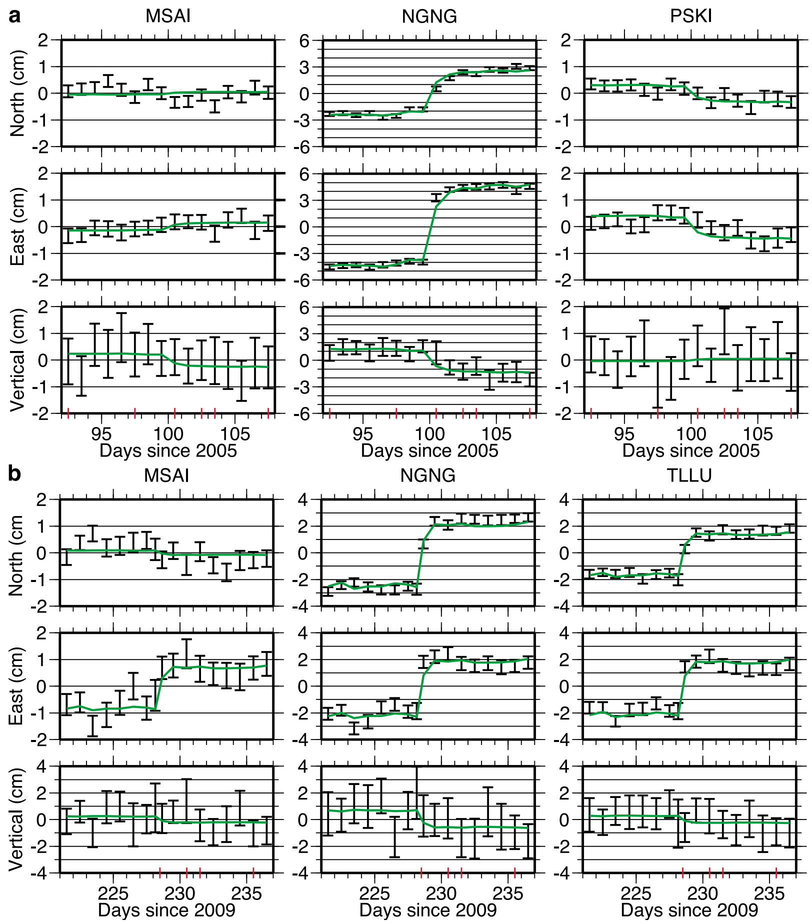

Figure 2. Cluster GPS time series. Horizontal and vertical position time series with one-sigma uncertainty bars for the most energetic periods of the clusters. Superimposed are the predictions from the two-segment model (green curves). (a) The 2005 Cluster. (b) The 2009 Cluster. The red vertical bars signify days with earthquakes large enough to have a GCMT solution.

[11] Figure 3a displays the 2005 cumulative slip model. The main locus of slip is centered at 9 km depth and is consistent with the epicentral location of the 2005 earthquakes, but is ~10 km shallower than the average centroid depth for the 2005 cluster. Figure 3b shows the 2009 cumulative slip model. The 2009 high-slip region is distinctly northwest of the 2005 patch. Maximum modeled slip in 2009 extends from the surface to about ~8 km, shallower

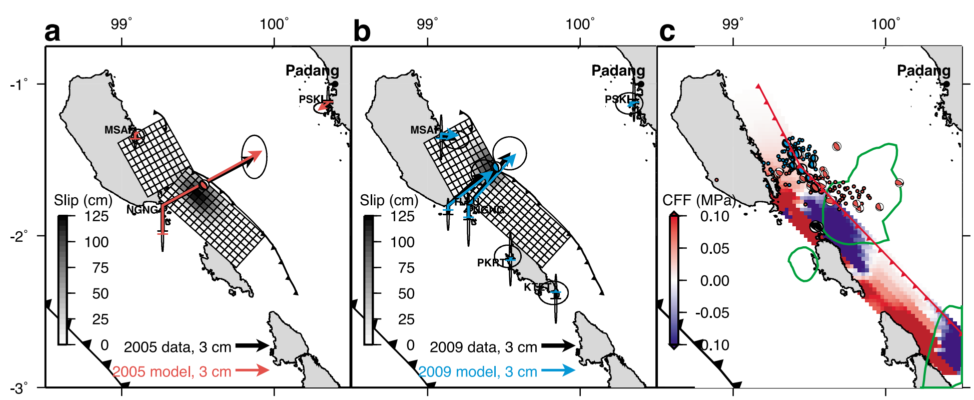

Figure 3. Deformation observations and slip models. Average displacements for the 2005 and 2009 sequences (black arrows tipped with 95% confidence ellipses) and cumulative motions predicted by the two-segment slip model (colored arrows) for (a) the 2005 cluster and (b) the 2009 cluster. Gray shading within the grids shows surface projection of the fault slip. (c) CFF change on the backthrust resulting from the 2007 M_w 7.9 earthquake. The green lines are 1 m slip contours for the 2007 earthquake [*Konca et al.*, 2008]. The 2005 cluster is red, the 2007 triggered events are black, and the 2009 cluster is blue.

than the modeled 2005 rupture and consistent with the shallower centroid depths for the 2009 earthquakes. The similarity between the geodetically derived cumulative magnitudes, M_w 6.9 in 2005 and M_w 6.7 in 2009, and those derived from summing the seismic moments (also M_w 6.9 and 6.7) implies that nearly all the detectable deformation occurred during the recorded earthquakes.

5. Megathrust-Backthrust Stress Interaction

[12] To understand whether this recent resurgence of activity on the Mentawai backthrust could have been triggered by the past decade's series of megathrust earthquakes, we explore the stressing relation between the Sunda megathrust and the Mentawai backthrust. It is especially important to understand how the Sunda megathrust affects the backthrust system because it lies over the Siberut segment, the largest remaining portion of the megathrust without a modern great rupture. In general, megathrust ruptures relieve shear stress on the overlying section of the backthrust while increasing the shear stress on sections further along strike. Moreover, megathrust ruptures unclamp the shallow portion of the backthrust and further lock the deeper portion of the backthrust.

[13] Static Coulomb failure stress (CFF) change values (for more information see auxiliary material) at the 2005 cluster location resulting from the 2005 Nias earthquake are positive, but are likely too small to explain the renewed activity. Thus, the short time interval between the two events suggests a dynamic stressing process triggered the cluster activity.

[14] The closer 2007 megathrust earthquakes stressed the section of the Mentawai fault between Siberut and Sipora more than the 2005 Nias earthquake. The largest 2007 aftershock, a M_w 7.9 event, produced the greatest stress changes in the cluster region out of all the recent megathrust earthquakes. It increased CFF on the deeper portion of the backthrust northwest of Sipora, and indeed steeply dipping M_w 6.5 and M_w 5.0 thrust ruptures occurred there three hours and 3 days following the megathrust earthquake (Figure 3c). In addition, the 2007 aftershock created a significant stress shadow over the 2005 cluster region and mildly enhanced stress within the future 2009 cluster region. Thus we suggest that the 2007 aftershock triggered two 2007 backthrust earthquakes and encouraged the cluster activity to migrate further northwest in 2009.

6. Discussion and Conclusions

[15] We have shown that at least a portion of the Mentawai backthrust, above the Sunda megathrust is active. It produced two adjacent clusters of shallow, moderate earthquakes in 2005 and 2009, with the 2005 M_w 6.7 earthquake producing a moderate tsunami. These relatively small events raise several important scientific questions that also have humanitarian implications.

[16] Is the Mentawai backthrust active along its entire 900-km length? If so, does it commonly rupture in short sections, as in 2005 and 2009, or is it capable of producing much larger earthquakes? Does it sometimes slip concurrently with the megathrust, analogous to a ~200-km-long backthrust that is now suspected to have failed simultaneously with the Sunda megathrust in 2004, north of Simeulue [*Chauhan et al.*, 2009; *Plafker et al.*, 2006; *Singh et al.*, 2011]. All these questions point to one big question: Is the Mentawai backthrust another plausible source for very large, destructive earthquakes and tsunami along the coast of Sumatra?

[17] Currently, the only evidence bearing on these questions is sparse paleogeodetic data from the coral reefs of the Mentawai Islands. Although the islands subsided very slightly during the shallow 2005 and 2009 ruptures, our elastic dislocation modeling shows that large Mentawai backthrust events, with concurrent slip along deeper parts of the backthrust, would produce uplift of the islands. Moreover, such ruptures should produce southwestward tilt of the islands, toward the Indian Ocean, in contrast to northeastward tilt during great megathrust events (see representative models in auxiliary materials). Most of the sudden uplift events recorded by island corals over the past 700 years exhibit landward tilt and are thus consistent with slip on the Sunda megathrust [*Sieh et al.*, 2008]. Only one large uplift event, about 1685, has ambiguous enough indication of tilt to allow the hypothesis that it resulted from slip on the backthrust. Our elastic dislocation modeling (for more information see auxiliary material) shows that ~2.3 m of slip on the main backthrust (MBT) extending from northern Siberut to North Pagai could fit the 1685 uplift pattern within the 10 cm uncertainties and would equal a M_w 7.9 event. Additional sampling of the fossil corals on the islands would provide a clearer picture of the uplift pattern for this 1685, and earlier uplift events, and better elucidate whether the deformation was caused by slip on the megathrust, the backthrust system, or a combination of the two.

[18] The past few years of global seismicity have reminded us that large ruptures on faults can occur very infrequently. The damaging Wenchuan earthquake of 2008 has an approximately 3000 year recurrence interval and the unexpected 2011 Tohoku event has a recurrence interval >1000 years. One out of place coral microatoll sitting in the intertidal zone on the northern tip of South Pagai suggests that very large backthrust events may have recurrence intervals of several thousands of years. Mid-Holocene microatolls, ranging in age from about 4,500 to 6,000 years exist within the current intertidal zone at many locations around the Mentawai Islands [*Natawidjaja et al.*, 2006; *Zachariasen*, 1998] and one would not expect to find older microatolls in the intertidal zone because sea level did not reach the current level until about 6,000 years ago. We speculate that the one microatoll sitting in the intertidal zone, which grew about 8,100 years ago [*Zachariasen*, 1998], was uplifted ~6 meters before ~6,500 BP to account for the change in sea level. This is scant evidence of a rare faulting event that ruptures the entire length of the MBT. With an average 15 m of slip, the backthrust may be capable of producing M_w 8.5+ events.

[19] The resurgence of earthquake activity on the Mentawai backthrust that we have documented here, including two M_w 6.7 earthquakes, suggests that more work is needed to fully characterize the fault's rupture history and magnitude potential. An active backthrust also implies that we need to modify existing models of interplate strain accumulation to account for the buildup of upper plate strain in the forearc region. In addition, tsunami simulations for a range of backthrust earthquake magnitudes are needed to ascertain whether the hazard is locally limited between the

east coast of the Mentawai Islands and the densely populated west coast of Sumatra, or if an ocean-wide scenario is possible.

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