The 25 October 2010 Mentawai tsunami earthquake ($M_w$ 7.8) and the tsunami hazard presented by shallow megathrust ruptures

T. Lay, 1 C. J. Ammon, 2 H. Kanamori, 3 Y. Yamazaki, 4 K. F. Cheung, 3 and A. R. Hutko 5

Received 20 December 2010; revised 9 February 2011; accepted 15 February 2011; published 22 March 2011.

[1] The 25 October 2010 Mentawai, Indonesia earthquake ($M_w$ 7.8) ruptured the shallow portion of the subduction zone seaward of the Mentawai islands, off-shore of Sumatra, generating 3 to 9 m tsunami run-up along southwestern coasts of the Pagai Islands that took at least 431 lives. Analyses of teleseismic P, SH and Rayleigh waves for finite-fault source rupture characteristics indicate ~90 s rupture duration with a low rupture velocity of ~1.5 km/s on the 10° dipping megathrust, with total slip of 2–4 m over an ~100 km long source region. The seismic moment-scaled energy release is $1.4 \times 10^{26}$, lower than $2.4 \times 10^{26}$ found for the 17 July 2006 Java tsunami earthquake ($M_w$ 7.8). The Mentawai event ruptured up-dip of the slip region of the 12 September 2007 Kepulauan earthquake ($M_w$ 7.9), and together with the 4 January 1907 ($M_w$ 7.6) tsunami earthquake located seaward of Simeulue Island to the northwest along the arc, demonstrates the significant tsunami generation potential for shallow megathrust ruptures in regions up-dip of great underthrusting events in Indonesia and elsewhere. Citation: Lay, T., C. J. Ammon, H. Kanamori, Y. Yamazaki, K. F. Cheung, and A. R. Hutko (2011), The 25 October 2010 Mentawai tsunami earthquake ($M_w$ 7.8) and the tsunami hazard presented by shallow megathrust ruptures, Geophys. Res. Lett., 38, L06302, doi:10.1029/2010GL046552.

1. Introduction

[2] Coseismic slip zones for great underthrusting earthquakes on subduction zone megathrusts often do not extend seaward to the trench, leaving uncertainty regarding whether the up-dip region is a zone of stable sliding that slips aseismically before or after great events [e.g., Hsu et al., 2006] or a still coupled region with potential for future large earthquakes. Large earthquakes that rupture the shallow, near-trench region of megathrusts are relatively rare, but such events can be exceptionally tsunamigenic and are often characterized by low rupture velocity and large slip in relatively low rigidity material [e.g., Polet and Kanamori, 2000; Bilik and Lay, 2002]. When the rupture velocity for a tsunamigenic faulting event is low enough that the seismic waves have unusually weak short-period seismic wave energy relative to the long-period signals levels, the event is called a tsunami earthquake [Kanamori, 1972; Kanamori and Kikuchi, 1993].

[3] A large tsunamigenic earthquake struck the shallow Sumatra subduction zone on 25 October 2010 (3.484°S, 100.114°E, 14:42:22 UTC, $m_b = 6.5$, $M_S = 7.3$; U.S. Geological Survey, Magnitude 7.7 – Kepulauan Mentawai Region, Indonesia, 2010, http://earthquake.usgs.gov/earthquakes/eqinthenews/2010/usa00043nx/#details.). The Global Centroid Moment Tensor solution (GCMT; G. Ekström, Global CMT Web Page, 2010, http://www.globalcmt.org/) for the event indicates a shallow dipping ($7^\circ$) underthrusting mechanism with a best double couple moment $M_w = 6.7 \times 10^{25}$ Nm ($M_w$ 7.8). Our inversion of 40 three-component 0.001–0.005 Hz W-phase ([Kanamori and Rivera, 2008] observations from 28 global broadband network stations has a predominantly double-couple point-source solution 12 km deep with $M_w = 5 \times 10^{20}$ Nm ($M_w$ 7.7) and a nodal plane dipping $10^\circ$ toward the northeast (Figure 1).

[4] The rupture area is seaward of the Pagai islands of the Mentawai group offshore of Sumatra. This stretch of the subduction zone likely failed in the great Sumatran events of 1833 ($M \sim 9$) and 1797 ($M \sim 8.8$), although the up-dip extent of these ruptures is not well constrained [Natawidjaja et al., 2006]. The 2010 event ruptured the megathrust up-dip of the 12 September 2007 Kepulauan earthquake ($M_w$ 7.9), and northwest of the great 12 September 2007 Sumatran earthquake ($M_w$ 8.4) (Figure 1) [Konca et al., 2008]. Finite-source rupture models for the 2007 Kepulauan event do not extend to the trench, although GPS and paleogeodetic data indicate strong coupling (>50%) of the megathrust well seaward of Pagai prior to the 2007 events [Chlieh et al., 2008].

[5] The 2010 Mentawai event struck at 9:42 PM local time, producing ground shaking on Pagai less intense than for the 2007 Kepulauan event, and although tsunami warnings were broadcast on local television many of the isolated coastal areas were unprepared for the large tsunami waves that swept onto Pagai’s southwestern coast, with peak run-ups ranging from 2.5 to 9 m (K. Satake, personal communication, 2010). The official loss of life reported by the Indonesian National Disaster Management Agency is currently 431, with 88 missing.

2. Rupture Process of 25 October 2010 Event

[6] We develop finite-source models for the rupture process of the Mentawai earthquake using teleseismic recordings of P, SH, and short-arc Rayleigh wave (R1) recordings from global seismic network stations. Inversion for finite-fault models requires many assumptions and constraints on the solution. We adopt a $10^\circ$ dip for the fault plane based on the W-phase solution, a strike of 324° based on the local
trend of the trench, and the rupture velocity, $V_r$, is constrained using R1 source time functions (STF) in finite-fault inversions [Ammon et al., 2006a, 2006b] and back-projection of seismic network recordings of P-waves [Ishii et al., 2005; Xu et al., 2009].

[7] Broadband P wave recordings from the F-Net in Japan were used in the back-projection imaging to bound the overall rupture finiteness. The back-projections suggest that the source region radiated short-period energy for about 90 s, with slow propagation toward the northwest over a distance of about 100 km with $V_r \sim 1.0-1.5$ km/s (Figure 2 and Animation S1 of the auxiliary material), with slip concentrated seaward and beneath the Pagai Islands.  

[8] Finite-fault inversions of teleseismic P, SH, and R1 STFs assuming fixed $V_r$ values ranging from 1.0 to 2.5 km/s indicate a slight preference for $V_r = 1.5$ km/s (Figure S1), and the corresponding slip distribution covers a 100 km long region of 2–3.5 m slip located seaward of Pagai (Figure 1, left). For this model the source velocity structure was a half-space with P wave velocity of 5.0 km/s, S wave velocity of 2.9 km/s, and density of 2300 kg/m$^3$, with each subfault having a half-cosine source time function with duration of 8, 12, 16, 20 or 24 s. The seismic moment for this inversion is $M_s = 6.2 \times 10^{20}$ Nm ($M_w = 7.8$) and about 83% of the weighted data signal was fit (Figure S2). The subfault details are shown in Figure S3.  

[9] Linear inversion of 55 broadband P and SH waves using $V_r = 1.5$ km/s and a layered velocity structure (Table S1) appropriate for the low velocities found in the shallow wedge region [Collings et al., 2010] gave a similar single patch of seismic moment release, with the slip being enhanced in the region near the toe of the sedimentary wedge (Figure 1, right). The inversion used 16 s long subfault source functions comprised of 7 overlapping 2-s rise-time triangles. The teleseismic body wave data set alone has very limited resolution of source finiteness; inversions with different rupture velocities all fit the data waveforms at about the 83% level (e.g., Figure S4). The subfault details are shown in Figure S5. The inversion including R1 STFs indicates about 50 km more northwestern expansion of the source than the body wave solution, while the more compact body wave slip distribution is shifted slightly up-dip. The models differ in data and parameterization, with smoother features in the slip distribution being better resolved when R1 is included, but rougher features better resolved when just body waves are used. The body waves have somewhat better depth-resolution, while the inversion with long-periods better constrains seismic moment and along-strike directivity. Both solutions place the large slip region up-dip of the primary slip zone for the 2007 Kepulauan event and on the northwestern margin of the 2007 great Sumatran event rupture zone (Figure 1). The two slip models in Figure 1 indicate the overall uncertainty in the teleseismic solutions, and are similar to models produced by other research groups [Newman et al., 2011; e.g., Y. Yamanaka, 2010, http://www.seis.nagoya-u.ac.jp/sanchu/Seismo_Note/2010/NGY31.html]. It may be viable to improve constraints on the slip distribution when GPS data on Pagai are eventually analyzed. Aftershocks fringe the strong slip regions, with a concentration up-dip of the hypocenter (Figure S6 and Animation S2). Animations S3 and S4 depict the rupture expansion for both models.  

[10] The spectrum of the source time function from the P and SH inversion (Figure 3, inset) was combined with azimuthally-averaged P wave spectra to characterize the overall source spectrum (Figure 3), which is significantly depleted in short-period amplitudes relative to expectations for a reference $\omega^2$-squared source spectrum, consistent with other tsunami earthquakes (Figure S7). The P wave ground velocities were used to compute the seismic energy release over the duration indicated by the source time function, 

---

1Auxiliary materials are available in the HTML. doi:10.1029/2010GL046552.
giving a radiated seismic energy estimate [Venkataraman and Kanamori, 2004], of $E_R = 9.2 \times 10^{14}$ J. Using the GCMT seismic moment, the moment-scaled energy ratio $E_R/M_o$ is $1.4 \times 10^{-6}$ (Figure S8). Similarly computed scaled-energy values for the 2 June 1994 ($M_w$ 7.8) and 17 July 2006 ($M_w$ 7.8) Java tsunami earthquakes were found to be $0.37 \times 10^{-6}$ and $3.5 \times 10^{-6}$, respectively. The large discrepancy between $m_b$ and $M_w$, low moment-scaled energy value, and compact source area and low rupture velocity of the Mentawai event establish that it shares common characteristics with other tsunami earthquakes [Polet and Kanamori, 2000; Bilek and Lay, 2002].

3. Tsunami of 25 October 2010 Event

[11] The tsunami generated by the Mentawai event was recorded by DART buoy 56001, which is located far from the coastline and in deep water (13.961°S 110.004°E; Figure S9). We computed the surface elevation at DART 56001 using the non-linear dispersive wave model NEOWAVE [Yamazaki et al., 2009, 2011] for the two finite-source models in Figure 1. NEOWAVE is a staggered finite difference model, which includes a vertical momentum equation and a non-hydrostatic pressure term in the nonlinear shallow-water equations to describe tsunami generation from seafloor deformation and propagation of weakly dispersive tsunami waves. The fault parameters at each subfault allow computation of the seafloor deformation (Figures S10 and S11) using the planar fault model of Okada [1985]. Superposition of the deformation from the subfaults with consideration of their rupture initiation time and rise time reconstructs the time history of seafloor vertical displacement and velocity for the input to NEOWAVE. We use the British Oceanographic Data Centre General Bathymetric Chart of the Oceans (GEBCO), re-sampled on a 1-arcmin grid (=1800-m resolution) for the computations.

[12] The observed and computed tsunami waveforms and spectra at DART 56001 for the two finite source models are shown in Figure 4. The source model obtained when the R1
STFs are included predicts the primary tsunami amplitude well, but has a slight phase lag resulting from lower predictions of waves shorter than 22 min. The tsunami calculation for the body wave model slightly underestimates the first wave’s amplitude due to smaller amplitude predicted for the 30-min and 73-min wave components, but shows very good agreement with the overall phase. The first wave is directly from the source, while the subsequent waves are a combination of waves from the source, reflection from islands, and leakage of trapping waves over the shelf. High-resolution bathymetry is required to reproduce the reflected and leaked trapped waves at DART 56001. Considering the grid resolution, the general agreement indicates that the shallow seismic slip models are compatible with the far-field tsunami excitation.

4. Discussion

[13] The 25 October 2010 Mentawai earthquake qualifies as a tsunami earthquake, and shares attributes with the M ~ 7.6 1907 Sumatra earthquake [Kanamori et al., 2010] that likely ruptured off-shore of Simeulue, Nias and Batu Islands (Figure S9). Both are tsunamigenic events that ruptured updip regions of strongly coupled megathrust zones that have deeper great interplate events. The 1994 and 2006 Java [Ammon et al., 2006b; Abercrombie et al., 2001] tsunami earthquakes have similar seismic radiation characteristics to the Mentawai event, but the Java events ruptured updip of weakly coupled megathrust zones that appear not to fail in great interplate events. The low levels of short-period seismic wave radiation for these events, and the resulting weak local ground shaking can undermine public response to the possibility of imminent tsunami arrival. Technical methods for very rapid (<15 min) local event detection and moment characterization appear to be essential for developing any effective tsunami warning capability for tsunami earthquakes, and this must include effective societal implementation and public education.

[14] The seaward position of the Mentawai islands enabled geodetic inversion for locked portions of the shallow megathrust, and the Mentawai earthquake occurred in a region identified as having been partially to fully locked. For most regions the resolution of geodetic inversions for offshore locking of the megathrust is very limited, and when a great event like the 27 February 2010 Chile (Mw 8.8) earthquake does not rupture all the way to the trench it is unclear whether there remains potential for shallow tsunami
earthquakes to occur. The most promising approach to this problem is to improve imaging of coseismic and post-seismic slip for great events along with geodetic inversion for megathrust locked regions in the interseismic interval [e.g., Moreno et al., 2010]. Indonesia is evidently exposed to hazard from conventional great megathrust events as well as up-dip tsunami earthquakes in both strongly and weakly coupled portions of the subduction zone. It is reasonable to expect that similar hazard of shallow megathrust tsunami earthquakes exists in other subduction zones in both regions where great underthrusting events occur as well as in weakly coupled environments.

Acknowledgments. This work made use of GMT and SAC software. The IRIS DMS and the F-Net data centers were used to access the data. We thank Kenji Satake for information about the tsunami run-up observations on Mentawai. E. Geist and two anonymous reviewers provided very helpful comments on the manuscript. This work was supported by NSF grant EAR0635570 and USGS Award Number 05HQGR0174. The Editor thanks Eric Geist and two anonymous reviewers for their assistance in evaluating this paper.

References