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Using Earthquake Source Durations along the Sumatra–Andaman Subduction System to Examine Fault-Zone Variations

by Susan L. Bilek

Abstract The 26 December 2004 great Sumatran–Andaman earthquake in the Indian Ocean caused extensive damage and loss of life from intense shaking and the resulting tsunami. Several studies of this earthquake suggest that portions of the fault ruptured at variable speeds, with both fast and slow rupture velocities observed along the 1200 km long rupture length. Variations in rupture velocity during the earthquake may indicate along-strike variations in megathrust frictional conditions that may influence other earthquakes along the zone. Previous work on global subduction zone systems suggests depth-dependent frictional conditions arising from heterogeneous conditions along the fault. In many of the circum-Pacific subduction zones, shallow earthquakes along the subduction megathrust have longer scaled source durations than deeper earthquakes, possibly resulting from variations in frictional conditions with depth. This study focuses on thrust mechanism earthquakes on the Sumatra–Andaman megathrust, examining aftershocks with $M_w > 6.0$ of the 2004 earthquake, as well as earthquakes that occurred in the region between 1992 and 2004. Source duration, depth, and slip distribution are determined for this set of earthquakes to explore the possibility of both along-strike and depth-dependent variations in source parameters and frictional conditions. There is evidence of depth-dependent source parameters for these events, with longer scaled durations for the shallower earthquakes, consistent with previous global studies. No temporal change is apparent in this relationship, as source parameters for previous large earthquakes are similar to those after the earthquake. Along-strike patterns suggest long-duration character for several earthquakes in the southern portion of the rupture zone but no strong evidence of slow character in the northern portion of the rupture zone. It appears unlikely that any long-term variations in the fault-zone character influenced possible slow rupture of the 2004 earthquake.

Introduction

The M_w 9.2 2004 Sumatra–Andaman earthquake and tsunami (Fig. 1) dealt a devastating blow to communities around the Indian Ocean. Peak displacements of ~15–20 m near the northern tip of Sumatra and continued large displacements along the rest of the subduction megathrust led to the massive transoceanic tsunami (Bilham, 2005) that caused the majority of the more than 270,000 fatalities associated with this event. The earthquake shaking itself was widespread, as intensities ranged from VIII to IX along Indonesia to II to III in India and Sri Lanka (Martin, 2005). Tsunami runup heights were measured at ~25 m near the Banda Aceh region of Sumatra (Borrero, 2005), 6 m in Thailand (Titov *et al.*, 2005), and 3–12 m along the coast of Sri Lanka (Liu *et al.*, 2005).

Details surrounding the earthquake rupture itself vary; however, there are several common features. These include rupture of ~1500 km along the Sumatra megathrust, with rapid slip concentrated in the southernmost 500 km (Ammon *et al.*, 2005; Lay *et al.*, 2005; Banerjee *et al.*, 2007; Chlieh *et al.*, 2007; Rhie *et al.*, 2007). One study suggests the possibility of slow slip in the first 50–60 sec of rupture in the southern region near the epicenter (Ammon *et al.*, 2005). Slip continued to the north toward 14° N based on various seismic and geodetic datasets, including waveform inversion, normal modes, aftershock locations, Global Positioning System (GPS), and coral uplift (Ammon *et al.*, 2005; Banerjee *et al.*, 2005; de Groot-Hedlin, 2005; Ishii *et al.*, 2005; Kruger and Ohrnberger, 2005; Ni *et al.*, 2005; Park *et al.*, 2005; Stein and Okal, 2005; Tsai *et al.*, 2005; Vigny *et al.*, 2005). There is debate, however, over whether this northern rupture propagated with a slower rupture velocity than did the southern portion. Several studies have required low rupture velocities in this region, with periods greater than 600 sec (Ammon *et al.*, 2005; Banerjee *et al.*, 2005;

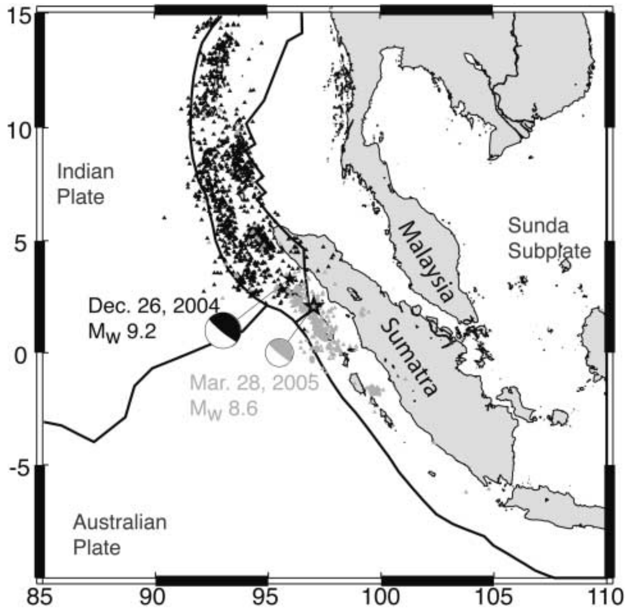

Figure 1. Regional setting of the 2004 and 2005 great subduction zone earthquakes in the Sumatra–Andaman region. Plate boundaries from Bird (2003). Stars indicate epicentral locations of the 2004 (black) and 2005 (gray) mainshocks from the NEIC PDE catalog along with the Harvard CMT focal mechanism for each event. Black triangles show aftershocks of the 2004 event between 26 December 2004 and 26 January 2005. Gray triangles show aftershocks of the 2005 event between 28 March and 28 April 2005.

Lay *et al.*, 2005; Stein and Okal, 2005; Tsai *et al.*, 2005; Singh *et al.*, 2006). Other studies, again using various seismic and geodetic datasets, have found that slow slip and low rupture velocities in the northern region are not necessary to explain the data (Ishii *et al.*, 2005; Tsai *et al.*, 2005; Vigny *et al.*, 2005; Banerjee *et al.*, 2007; Chlieh *et al.*, 2007).

These rupture characteristics invoke questions about the possible origins for slow rupture velocities along the northern segment. Previous efforts to examine the role of depth-dependent frictional conditions on a global scale suggest that earthquake rupture behavior varies as a function of depth in most shallow subduction zones. Bilek and Lay (2000, 2002) present variations in earthquake source durations as a function of depth for over 300 earthquakes in 14 circum-Pacific subduction zones. Their findings include a general trend of decreasing moment-normalized duration with increasing depth along the megathrust (Fig. 2). This trend of decreasing duration with depth can be explained by two end-member possibilities. Because the rupture duration is linked to the shear modulus through the rupture velocity, variable shear modulus within the fault volume can explain the depth-dependent durations. Thus the longer duration earthquakes may be indicative of slower rupture velocities due to rupture propagation through low-rigidity materials in the shallow fault zone. Alternatively, the duration variations could be linked to variations in fault area and thus stress drop. In either case, it appears that the earthquake rupture behavior in many subduction zones varies as a function of depth.

This depth variation, and in particular the linkage to variable shear modulus, has important connections with unusual tsunami earthquakes such as the 1992 Nicaragua earthquake. These earthquakes are notable for their anomalously long durations and large tsunami produced even though the earthquakes themselves were not particularly large magnitude earthquakes (Kanamori, 1972; Satake and Tanioka, 1999). Various efforts to model the tsunami produced by the handful of these earthquakes tend to require shallow rupture through materials with low shear modulus in order to match observations at tide gauge stations. Values used for the tsunami earthquake models are comparable to the low shear modulus values estimated by the global earthquake datasets (Bilek and Lay, 1999).

The 2004 Sumatra–Andaman earthquake does not clearly fall into the class of tsunami earthquakes in that a large tsunami is expected for an earthquake of this size. Seno and Hirata (2007) suggest the 2004 earthquake is a hybrid event based on longer source durations determined from tsunami data. They claim increased amounts of slip in near-trench regions based on inversion of sea-surface height data was effective in generating the tsunami. If true, then conditions at the shallow end of the fault will be important for slow slip, and depth-dependent source durations would be expected in this region. In addition, the suggestions of highly variable rupture velocities along the full rupture extent suggest possible variations in frictional conditions along the fault. Because slow rupture velocities during the 2004 earthquake are not required in every study, it would be valuable to determine parameters for other regional earthquakes to investigate the possibility of fault conditions causing slow earthquake behavior along the Sumatra–Andaman region. The goal of the present study is to examine aftershocks and earlier seismicity to test whether any portion of the Sumatra–Andaman subduction zone consistently produces slow, long duration earthquakes that might be indicative of variable conditions along the fault.

Data

As the focus of this study is an examination of possible variations linked to the megathrust zone, the dataset includes shallow earthquakes that likely occurred along the contact with the subducting plate. Criteria for selecting earthquakes include the location, mechanism, and data quality, consistent with the criteria used in previous studies (Bilek and Lay, 1999, 2000). Earthquakes with an underthrusting mechanism located near the subduction zone trench are included if the moment magnitude (M_w) was greater than 6.0. Using this magnitude cutoff ensured the best signal-to-noise ratio on seismograms for each event. Focal mechanism information is derived from the Harvard Centroid Moment Tensor (CMT) catalog. A selected earthquake had a strike within 20°–30° of the local strike of the trench, a dip of $<35°$, and a rake

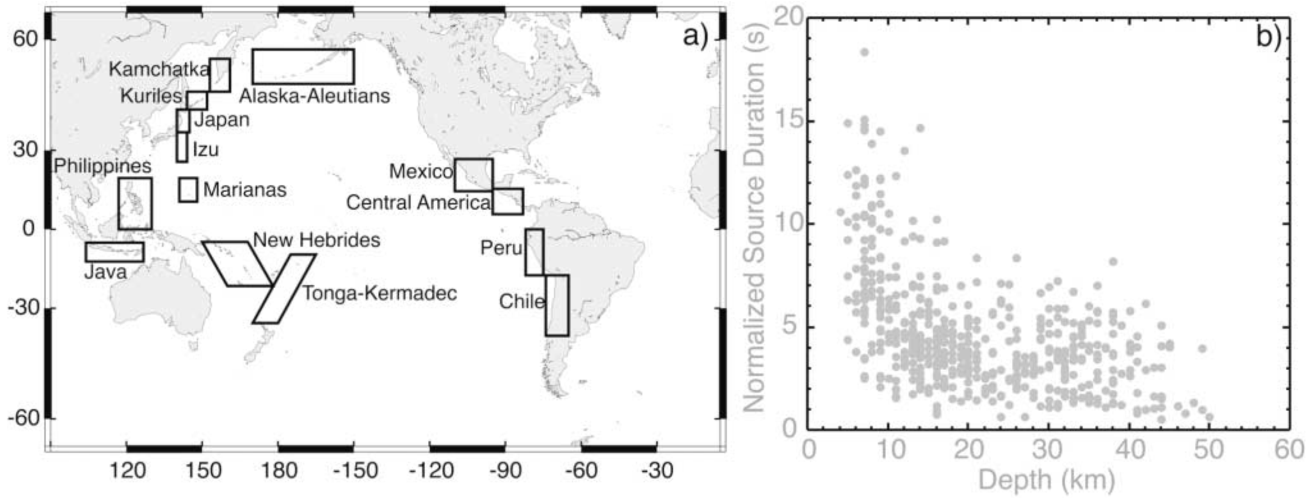

Figure 2. Previous shallow subduction zone studies (Bilek, 2001). (a) Map of regions included in previous studies of shallow subduction zone earthquake parameters, showing the gap in coverage around the Sumatra–Andaman region. (b) Results of global survey, showing decreasing moment-normalized earthquake duration with increasing depth for 345 earthquakes in the 14 subduction zones.

of 90° ± 30°, consistent with an event on the shallowly dipping megathrust plane.

The earthquakes used in this study include aftershocks of the 2004 and 28 March 2005 great earthquakes as well as events that occurred prior to the December 2004 earthquake. Figure 3 shows the National Earthquake Information Center Preliminary Determination of Epicenter (NEIC PDE) locations of 24 earthquakes that occurred between 27 December 2004 and February 2006 (Table 1), as well as 19 earthquakes that occurred between 1992 and December 2004 (Table 2). Several other earthquakes were initially examined because they fit the criteria detailed previously but were removed because of low data quality or an inability to determine a low misfit depth and source time function. Earthquakes that occurred on 26 December 2004 are not included because of the interference with signals from the mainshock that made it difficult to identify specific events, determine focal mechanisms, and model successfully. The 28 March 2005 M_w 8.6 earthquake is also not included in these results because an earthquake of this size precludes the point-source-based modeling described subsequently, but several aftershocks are included in the dataset.

Methods

The source parameters of interest in this study include the earthquake depth and the source duration. Duration is measured from the source time function, a representation of the moment release history of the event. In order to determine source time functions, I use all available teleseismic broadband recordings from the IRIS Data Management Center with time windows containing direct P and S arrivals, along with depth phases (pP, sP) that are helpful in accu-

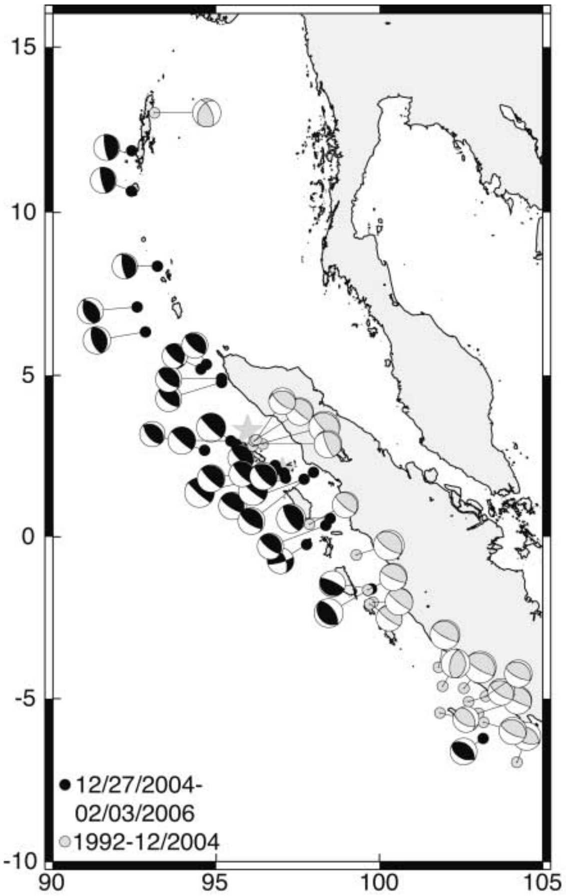

Figure 3. Earthquakes used in this study, including events occurring after the 26 December 2004 earthquake (black) and events that occurred prior to the great earthquakes (gray). Circles show the NEIC PDE locations, and focal mechanisms are taken from the Harvard CMT catalog.

Table 1

Earthquakes in Dataset (27 December 2004–February 2006)

Date (yy/mm/dd)	Origin Time	Latitude (°)	Longitude (°)	M_w	M_0 (N m)	Depth (km)	Duration (sec)	Normalized Source Duration (sec)
04/12/27	09:39:06	5.35	94.65	6.0	1.25e18	36	2	1.95
04/12/29	01:39:41	8.38	93.16	6.0	1.10e18	7	6	6.10
04/12/31	02:24:00	7.12	92.53	6.0	1.34e18	18	6	5.72
05/01/02	15:35:56	6.36	92.79	6.3	3.43e18	17	11	7.67
05/01/04	09:13:12	10.67	92.36	6.1	1.57e18	23	5	4.52
05/01/09	22:12:56	4.92	95.12	6.0	1.08e18	39	4	4.10
05/01/26	22:00:42	2.70	94.60	5.9	7.73e17	8	8	9.16
05/02/09	13:27:25	4.80	95.12	6.0	1.09e18	44	4.5	4.60
05/02/26	12:56:53	2.89	95.57	6.7	1.31e19	27	11	4.90
05/03/30	16:19:41	2.99	95.41	6.4	4.56e18	7	10	6.34
05/04/03	00:59:21	0.37	98.32	6.0	1.17e18	31	3	3.00
05/04/03	03:10:56	2.02	97.94	6.3	2.97e18	41	5	3.65
05/04/08	05:48:37	−0.22	97.73	6.1	1.64e18	18	9	8.02
05/04/10	10:29:11	−1.64	99.61	6.7	1.33e19	8	12	5.32
05/04/10	17:24:39	−1.59	99.72	6.1	1.54e18	11	9	8.20
05/04/11	06:11:11	2.17	96.76	6.1	1.67e18	26	4	3.54
05/04/16	16:38:03	1.81	97.66	6.4	4.51e18	33	6	3.82
05/04/28	14:07:37	1.91	96.49	6.3	3.46e18	6	11	7.64
05/05/10	01:09:05	−6.23	103.14	6.2	2.59e18	7	6	4.59
05/05/14	05:05:18	0.59	98.46	6.7	1.58e19	35	10	4.19
05/05/19	01:54:52	1.99	97.04	6.9	2.46e19	29	17	6.14
05/06/08	06:28:10	2.17	96.72	6.1	1.49e18	26	5	4.60
05/07/05	01:52:04	1.84	97.09	6.6	1.12e19	10	11	5.17
05/07/30	15:13:20	5.21	94.49	6.0	1.16e18	39	1	1.00
05/11/19	14:10:15	2.23	96.77	6.3	3.83e18	26	6	4.03
06/02/03	20:34:10	11.90	92.37	6.1	1.56e18	20	5	4.52

Table 2

Earthquakes in Dataset (1992–June 2004)

Date (yy/mm/dd)	Origin Time	Latitude (°)	Longitude (°)	M_w	M_0 (N m)	Depth (km)	Duration (sec)	Normalized Source Duration (sec)
92/02/06	01:12:38	−5.72	103.16	6.3	3.98e18	34	7	4.64
92/04/18	09:16:52	−5.45	103.00	6.6	9.16e18	36	11	5.52
93/08/04	11:31:18	−1.63	99.61	6.4	5.05e18	32	6	3.67
93/09/01	14:03:19	2.99	96.12	6.3	3.09e18	10	12	8.66
94/05/11	08:18:15	−2.01	99.77	6.4	5.26e18	16	13	7.85
94/05/11	21:14:33	−2.06	99.67	6.1	1.64e18	28	5	4.45
94/10/31	11:48:13	3.02	96.19	6.1	1.85e18	12	12	10.27
95/11/05	16:29:58	−4.92	103.22	6.3	3.73e18	39	5	3.39
98/04/01	17:56:23	−0.54	99.26	7.0	3.33e19	40	12	3.92
00/06/06	09:58:06	−5.09	102.70	6.2	2.19e18	35	3	2.43
00/06/07	23:45:26	−4.61	101.90	6.7	1.28e19	14	14	6.29
00/09/12	16:27:24	−5.43	101.82	6.0	1.28e18	10	10	9.68
01/01/16	13:25:09	−4.02	101.78	6.8	1.97e19	34	16	6.22
01/02/13	19:28:30	−4.68	102.56	7.3	1.16e20	34	16	3.45
02/06/27	05:50:35	−6.96	104.18	6.5	6.58e18	5	8	4.49
02/09/13	22:28:29	13.04	93.07	6.5	6.35e18	13	12	6.81
02/11/02	01:26:10	2.82	96.08	7.2	9.01e19	34	15	3.52
02/11/02	09:46:46	2.95	96.39	6.3	3.26e18	15	9	6.38
04/05/11	08:28:48	0.41	97.82	6.1	1.54e18	12	11	10.01

rately determining depth. The multistation deconvolution method (Ruff and Kanamori, 1983; Ruff and Miller, 1994) as used in previous work (Bilek and Lay, 2000) is used here to determine the source time function. The deconvolution method is based on computing synthetic Green's functions for each event using the best double couple of the Harvard CMT solution and a model of a water layer over a uniform half-space with *P*-wave velocity of 6.0 km/sec. Seismograms are deconvolved by Greens functions generated for a range of 15–30 source depths, obtaining a source time function for each trial depth. The depth at which the deconvolution minimizes the misfit between the data and synthetic seismograms is the best solution for each earthquake.

Processing results are shown for the 16 January 2001 M_w 6.9 earthquake (Fig. 4). Eleven stations are used for this deconvolution, including 2 *SH* waveforms (Fig. 4a). Using a well-distributed set of seismograms reduces the trade-offs between depth and source time function shape. Twenty-two depths are used as possible source depths in the range between 10 and 40 km, bracketing the range of depths provided by the NEIC and Harvard catalogs. The misfit between data and synthetics is smallest at a depth of 34 km (Fig. 4b). The source time function determined for the depth of 34 km indicates a duration of 16 sec for the majority of moment release, with some additional low-amplitude oscillations later in the time function, most likely results of inaccuracies in the Green's function. For each earthquake, error bars are assigned to depth and duration estimates based on the range of depths with low misfit and the ease of determining the termination of primary moment release. A detailed discussion of various error sources in the determination of these parameters is provided in Bilek *et al.* (2004).

Because rupture duration is typically proportional to the cube root of seismic moment (Kanamori and Anderson, 1975; Houston *et al.*, 1998) the raw durations are corrected to remove this effect. Each duration estimate is divided by the cube root of the Harvard CMT seismic moment estimate, normalized by $M_0 = 1.16 \times 10^{18}$ N m, the seismic moment of an M_w 6.0 earthquake. Harvard CMT catalog moments are used for scaling rather than the moments determined in this processing because the Harvard CMT catalog moments tend to be more stable due to the use of large numbers of long-period data. This moment normalization removes the effect of increasing duration with increasing seismic moment, allowing for the comparison of scaled duration with other parameters.

Results

Normalized source durations for the Sumatra earthquakes appear to have a depth dependence similar to that observed for the global subduction zone earthquake dataset (Fig. 5). Earthquakes with the shallowest depths between 5 and 15 km have a mean moment-normalized duration of 7.2 sec, whereas deeper earthquakes have a mean duration of ~4 sec. In addition, the aftershock behavior is identical to the depth-dependent behavior of earthquakes occurring in the region before the great 2004 event. This suggests that no significant changes occurred along the fault as a result of the 2004–2005 great earthquakes that might impact these source

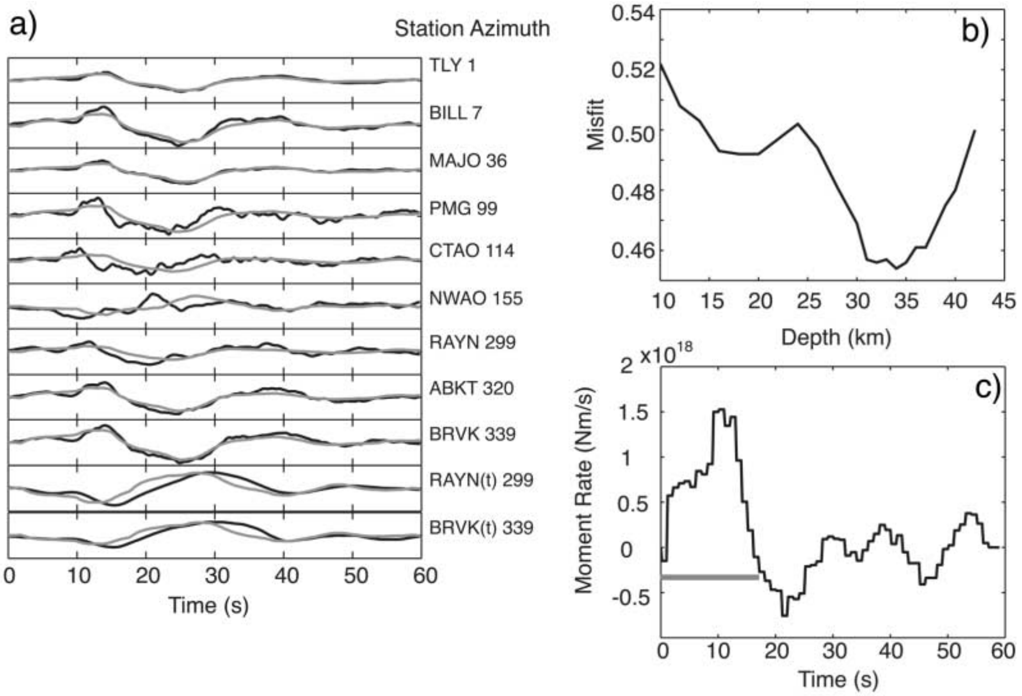

Figure 4. Example of data processing for the 16 January 2001 earthquake. (a) Seismograms (black) and synthetics (gray) produced for a depth of 34 km. Station names and azimuths are listed for each station. Bottom two seismograms show *SH* waves on the transverse component, and the rest of the data are vertical component *P* waves. (b) Depths used in the deconvolution, plotted with the misfit between the data and synthetics at each depth. Lowest misfit occurred at 34 km; thus, it is the optimal depth for the earthquake. (c) Source time function for this event at 34-km depth. Duration is measured as the time of the majority of the moment release, in this case 16 sec (gray bar).

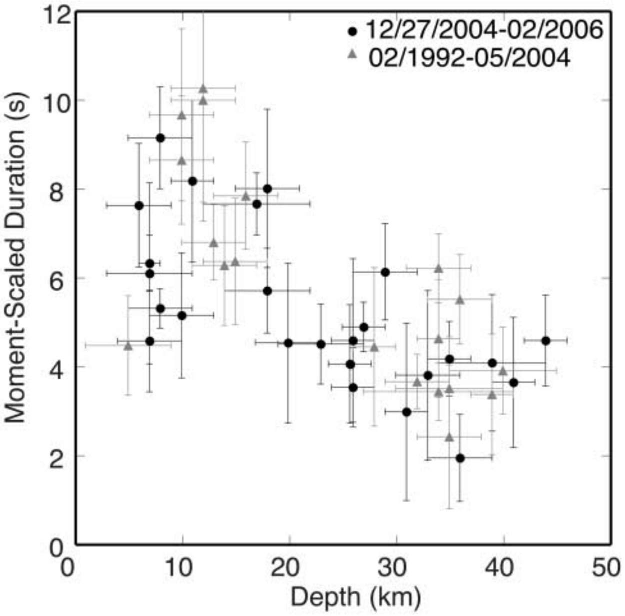

Figure 5. Moment-normalized source duration as a function of depth. Aftershocks of the 2004 and 2005 earthquakes (black) are plotted with previous seismicity (gray). Error bars in depth indicate range of low-misfit depths; errors in duration represent the range of duration values in this depth range as well as difficulty in choosing the termination of the main moment release pulse. There is a clear trend of decreasing duration with increasing depth for both sets of earthquakes, similar to the trend observed for the global dataset (Fig. 2b).

parameters and has implications for temporal stability of features or conditions of the megathrust zone that can impact earthquake rupture behavior.

Previous efforts based on global datasets attempt to explain these depth-dependent durations in terms of end-member models of rupture velocity (and shear modulus) variations or fault area (and stress drop) variations. In both end-member models, the durations determined here can be used to estimate shear modulus or stress drops variations, finding a clear increase in either shear modulus or stress drop with depth, similar to that found in the global studies. The following discussion is based on using these duration variations as possible indications of variable rupture velocity and shear modulus. Independent estimates of rupture velocity and/or fault area based on this dataset are the subject of ongoing efforts and beyond the current scope of the article.

Discussion

Variations in duration observed with this dataset can be used to indicate variable rupture velocity and shear modulus within the fault. These links can be made through direct mapping of the duration to rupture velocity through division of an estimate of fault dimension by the rupture velocity, assuming a constant fault dimension. The rupture velocities can be linked empirically with shear-wave velocities, and through this connection, normalized durations can be used to estimate shear modulus.

Rather than making assumptions of fault areas, here I simply examine possible along-strike variations in the duration as proxies for variable rupture velocities and compare with possible rupture velocity variations suggested for the 2004 event (Fig. 6). The northernmost segment of rupture in the Andaman Islands has been suggested as a possible location of slow slip (Ammon *et al.*, 2005; Banerjee *et al.*, 2005; Lay *et al.*, 2005; Stein and Okal, 2005), with the epicentral area also a possible region of slow slip in the first 50 sec of rupture (Ammon *et al.*, 2005). The along-strike comparison of durations suggests long-duration earthquakes are common in the epicentral region; however, the few datapoints in the northern Andaman segment are not indicative of very slow rupture durations. The hypothesis I set out to test was that conditions (such as low shear modulus materials) were present in the northern Andaman segment that lead to low velocity rupture and long durations for smaller magnitude events in that segment. Based on the lack of long-duration events found in that region, I suggest that there is no anomalous condition in this northern region that could lead to slow rupture velocities in the 2004 or other earthquakes in the Andaman segment. Clearly additional datapoints are desired to make this a stronger case; however, few large earthquakes have occurred in that segment.

Earthquakes in the southern region near the epicenter show a wide range of durations, including very long durations for earthquakes in the shallow portion of the subduction zone. These long duration events provide support for the model proposed by Seno and Hirata (2007) for slow slip at the shallow portion of the fault. In addition, the longest duration events occurred at approximately 3° N, in the epicentral region that may have experienced some slow slip early in the rupture (Ammon *et al.*, 2005).

Some of the wide range in duration is related to the wide range of depth in the southern region (Fig. 7). This range of depths is similar to the range observed in aftershocks recorded by a temporary ocean bottom seismometer (OBS) network in the epicentral region (Araki *et al.*, 2006).

In addition, there are shallow events with relatively short durations. These may reflect significant heterogeneity in the fault zone. A fault-zone model of heterogeneous frictional or strength conditions both down dip and along strike can cause this range in earthquake behaviors (Bilek and Lay, 2002). Variable strength or frictional conditions can arise from subducting variable thicknesses of sediment, horst and graben features, and other topography, as well as influences from hydrologic conditions. There is a thick sediment blanket entering the trench region (Moore *et al.*, 1980; Hilde, 1983) that may have an effect on the rupture velocities.

Other subduction zone parameters change along strike within the 2004 rupture zone as well. The slab-dip angle, age, and obliquity of subduction increase in the northern segment (Lay *et al.*, 2005). However, a physical connection

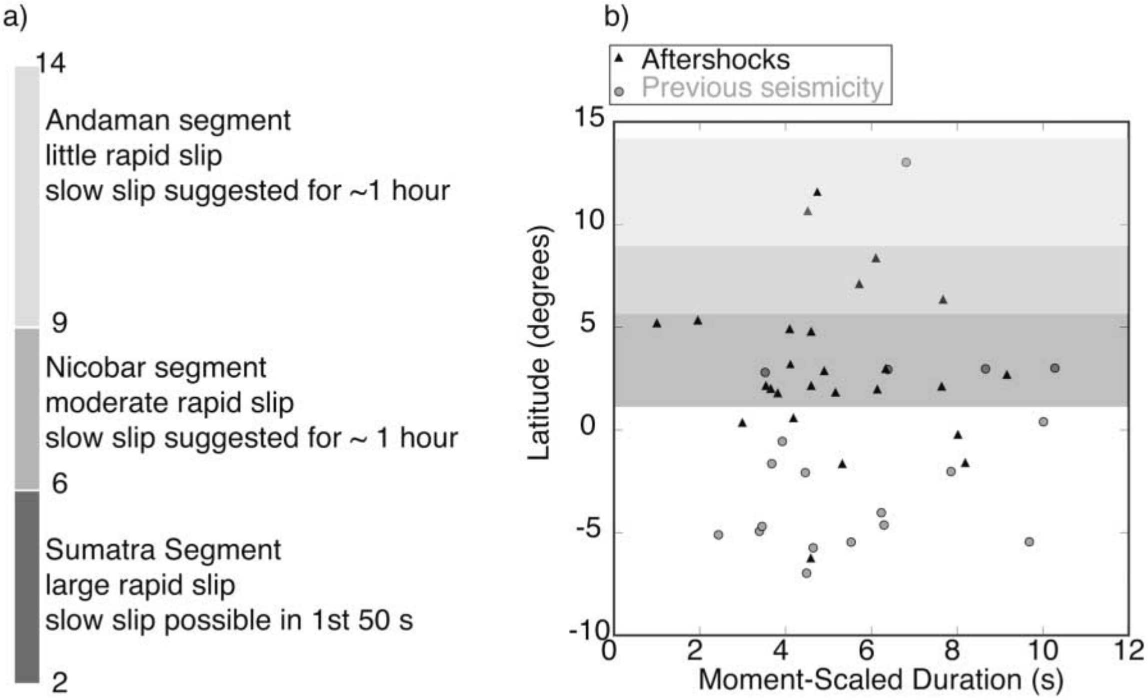

Figure 6. Source parameter comparison with rupture behavior of the 2004 Sumatra earthquake. (a) Schematic showing the along-strike variations in rupture velocities during the 2004 earthquake as described by Ammon *et al.* (2005). Slow slip is suggested in the northern Andaman segment as well as possibly near the epicenter in the southern rupture segment. (b) Along-strike variations in moment-normalized duration. Latitude of each event from the NEIC PDE catalog. Both aftershocks (black) and previous seismicity (gray) are plotted. There is a wide range of durations, including the longest durations, in the southern rupture segment of the 2004 event (dark gray), whereas the few datapoints in the northern segment (light gray) do not suggest anomalously long durations.

between these subduction zone parameters and slow slip is unclear. Efforts using the global dataset to identify specific subduction zone parameters, such as age and slab dip, that could explain along-strike or interregion variations have yet to be successful (Bilek, 2001). In addition, there have been comparisons between the 2004 rupture segments and changes in the morphology of the subducting slab as noted by tomographic studies. Kennett and Cummins (2005) suggest links between the northern regions of rupture and distinctive reductions in bulk modulus of the slab at 75–100 km as estimated by ratio of shear to bulk sound speeds. They suggest these changes in slab physical properties at depth may act as barriers to high-frequency rupture propagation; however, it is unclear how important these variations may be at the shallower depths of the rupture.

There is also a wide range of durations observed for earthquakes to the south of the 2004 rupture zone, extending into the region of the 28 March 2005 earthquake (Fig. 6). The long durations in this region occurred in the shallow portion of the subduction zone. There is no suggestion of slow slip during the 2005 event, and several slip distributions for the 2005 earthquake suggest that slip occurred deeper on the fault than for the 2004 earthquake (Ammon *et al.*, 2005; Walker *et al.*, 2005), and deeper than most of these longer duration smaller magnitude events. The depth of slip and the likely interaction with low-rigidity materials in the fault zone will have an impact on the earthquake behavior, as seen in global subduction zone studies.

Conclusions

Based on analysis of earthquake source parameters of duration and depth, there appears to be a clear depth dependence for moment-normalized durations of earthquakes occurring in the Sumatra–Andaman subduction zone. This depth dependence is similar to behavior observed in other shallow subduction zones around the circum-Pacific and may be indicative of shear modulus or stress drop variations with depth in this region. Parameters for earthquakes that occurred prior to the 2004 great earthquake behave identically to parameters for aftershocks of that event, suggesting that the 2004 event did not affect any subduction zone conditions that may impact earthquake rupture. Along-strike variations in rupture velocity suggested for the 2004 earthquake do not clearly correlate with along-strike variations in the moment-normalized durations, except perhaps in the epicentral region between 2° and 6° N latitude. This suggests that there were no specific fault-zone conditions that led to slow slip in the Andaman segment.

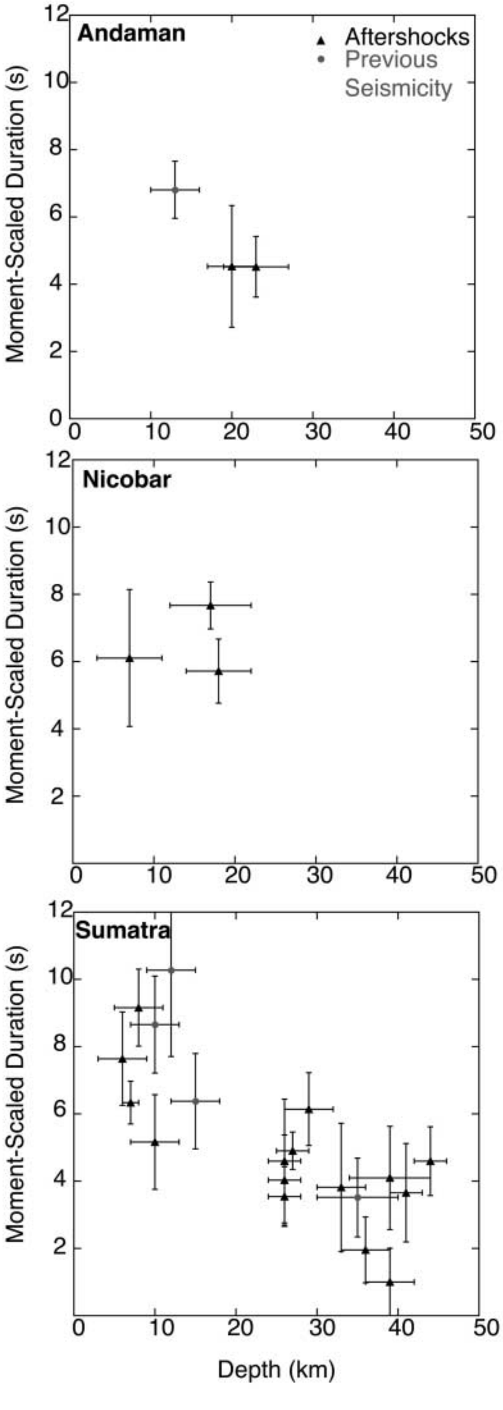

Figure 7. Moment-scaled duration as a function of depth for the three rupture segments. The southern Sumatra segment has the widest range of durations and depths. The longest durations of the entire region are found at shallow depth in the Sumatra segment. The northern Andaman segment includes earthquakes in the shallow half of the entire dataset, but durations of these events are not anomalously long.

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