Seismicity Associated with the Sumatra–Andaman Islands Earthquake of 26 December 2004

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Abstract  The U.S. Geological Survey/National Earthquake Information Center (USGS/NEIC) had computed origins for 5000 earthquakes in the Sumatra–Andaman Islands region in the first 36 weeks after the Sumatra–Andaman Islands mainshock of 26 December 2004. The cataloging of earthquakes of $m_b$ (USGS) 5.1 and larger is essentially complete for the time period except for the first half-day following the 26 December mainshock, a period of about two hours following the Nias earthquake of 28 March 2005, and occasionally during the Andaman Sea swarm of 26–30 January 2005. Moderate and larger ($m_b \geq 5.5$) aftershocks are absent from most of the deep interplate thrust faults of the segments of the Sumatra–Andaman Islands subduction zone on which the 26 December mainshock occurred, which probably reflects nearly complete release of elastic strain on the seismogenic interplate-thrust during the mainshock. An exceptional thrust-fault source offshore of Banda Aceh may represent a segment of the interplate thrust that was bypassed during the mainshock. The 26 December mainshock triggered a high level of aftershock activity near the axis of the Sunda trench and the leading edge of the overthrust Burma plate. Much near-trench activity is intraplate activity within the subducting plate, but some shallow-focus, near-trench, reverse-fault earthquakes may represent an unusual seismogenic release of interplate compressional stress near the tip of the overriding plate. The interplate-thrust Nias earthquake of 28 March 2005, in contrast to the 26 December aftershock sequence, was followed by many interplate-thrust aftershocks along the length of its inferred rupture zone.

Introduction

Hypocenters, magnitudes, and focal mechanisms routinely determined by the U.S. Geological Survey/National Earthquake Information Center (USGS/NEIC) have played an important role in shaping geophysical understanding of the great Sumatra–Andaman Islands earthquake of 26 December 2004 and its associated seismicity. In this article, we elaborate on strengths and limitations of the USGS/NEIC data that should be appreciated by other users of the data. We concentrate our effort on USGS/NEIC detection and calculation of hypocenters, on the USGS body-wave moment-tensors produced by the methodology of Sipkin (1982), and on the seismic energies and apparent-stress values calculated with the methodology of Choy and Boatwright (1995).

In addition to summarizing the characteristics of the routine USGS/NEIC data, we will reconsider these data in light of a consensus that has emerged on the broadscale characteristics of the Sumatra–Andaman Islands sequence. Articles published soon after the great Sumatra–Andaman Islands earthquake of 26 December 2004 have established that the earthquake occurred as predominantly thrust faulting on a shallowly dipping, multisegment plate boundary (Banerjee et al., 2005; Bilham et al., 2005; Lay et al., 2005; Tsai et al., 2005). In the plate nomenclature of Figure 1, the 26 December earthquake ($M_w 9.1$) (Park et al., 2005) involved primarily the underthrusting of the Ninety East–Sumatra orogen (India and Australia plates) beneath the Burma plate. Coseismic rupture occurred from Simeulue north through the Andaman Islands, over a distance of about 1200 km and over a time of about 500 sec (deGroot-Hedlin, 2005; Gilbert et al., 2005; Ishii et al., 2005; Krüger and Ohrnberger, 2005; Tolstoy and Bohnenstiehl, 2005). In addition to intense aftershock activity on, or in the close neighborhood of, the interplate-thrust separating the India/Australia plate from the Burma plate, the mainshock triggered intense aftershock activity on the ridge/transform boundary just east of the Nicobar Islands that separates the Burma plate from the Sunda plate (Figs. 1 and 2). A second great thrust-fault earthquake (Harvard CMT magnitude [Mw (HRV)] 8.6) occurred on 28 March 2005, on the segment of the Sumatra subduction zone immediately to the south of the 26 December 2004 rupture.
Still farther to the south, the segment of the Sumatra subduction zone that ruptured in the great earthquake of 1833 has remained largely quiescent in the year following the 26 December 2004 earthquake and remains a region of high concern for a future great underthrust earthquake (Newcomb and McCann, 1987; Zachariasen et al., 1999). From the framework of the foregoing general characteristics of the Sumatra–Andaman Islands earthquakes, we explore implications of USGS/NEIC computed locations and source parameters for more complete understanding of the mainshock rupture process and the seismotectonics of the Sumatra–Andaman Islands subduction zone.
Preliminary Determination of Epicenters (PDE)

Hypocenters and Magnitudes

The initial origin (hypocenter and magnitude) for a large non-U.S. earthquake detected at the USGS/NEIC is usually determined automatically from computer-detected phase arrivals and amplitudes. The automatically determined origin is reviewed by an analyst, who will commonly change some of the automatically determined data, add new data, and recompute the origin. The subsequent “first reviewed solution” is the first origin that is posted on USGS websites. The preferred origin of the earthquake will, however, change with time as new data are interpreted at the USGS/NEIC or received from cooperating networks: the USGS/NEIC receives arrival-time data and origin estimates from many regional
seismographic networks and from the Reviewed Event Bulletin of the International Data Centre of the United Nations Comprehensive Nuclear-Test-Ban Treaty Organization. The first reviewed solution and subsequent early refinements to the epicenter are collectively known as the Quick Epicenter Determination (QED) for the earthquake. Iterations on the USGS/NEIC origin cease about six weeks after the earthquake’s occurrence with the electronic publication of the Preliminary Determination of Epicenters (PDE) catalog for the week of the earthquake. The QED and PDE origins may be accessed electronically at sites given in the Data Sources section of this article. As noted in that section, some of the data sources provide assessments of the reliability of the earthquake epicenter and hypocenter and an indication of the type of data or assumptions used to constrain focal depth.

In this article, we primarily consider earthquakes that occurred through 2 September 2005, the date of the last PDE origin published at the time we began this study. Within the region bounded by latitudes 10° S and 17° N and longitudes 87° E and 107° E, the USGS/NEIC located 5000 earthquakes. Of these, 1143 were located with a precision such that their 90% confidence ellipses on epicentral coordinates had semiaxes of 10 km or less, and of these highest quality epicenters, 562 were associated with focal depths calculated from depth phases. Figure 2 also contains QED epicenters for the last four months of 2005 that are not included in other figures.

Because many consumers of USGS/NEIC data make use of early QED hypocenters, it is important to comment on the stability of the USGS hypocenters throughout the process of updating from the earliest QED to the final PDE. Figure 3 illustrates that refinement of the QED and PDE solutions in the iterative USGS/NEIC procedure rather commonly resulted in epicentral changes of 10 km or more for earthquakes of the Sumatra–Andaman Islands sequence. The events represented in Figure 3 were very well recorded at teleseismic distances, so Figure 3 probably understates the size of changes that may occur between the first reviewed solution and the final USGS/NEIC origin for small, poorly recorded, shocks.

The formal estimates of precision that accompany QED and PDE hypocenters in some USGS/NEIC catalogs and bulletins (see Data Sources) do not account for the possibility of bias in hypocenter locations that would result from source-station velocities different than those of the AK135 model (Kennett et al., 1995) that is used at the USGS/NEIC to calculate hypocenters. Biases of several tens of kilometers would not be surprising based on experience worldwide. Engdahl et al. (2007) have compared four epicenters recomputed by the method of Engdahl et al. (1998) (hereafter referred to as EHB epicenters) with epicenters for the same earthquakes located by Araki et al. (2006) using data from an ocean-bottom seismograph network that was deployed above the interplate thrust of the 2004 earthquake. The EHB epicenters tend to be southwest of the epicenters of Araki et al. (2006), but by less than 15 km. We think it likely that the PDE epicenters from the same region would experience biases similar to those of the EHB epicenters since the two sets of epicenters are computed with much of the same data, using the same travel-time model. Biases affecting teleseismically determined epicenters from other parts of the Sumatra–Andaman Islands region may, however, differ. Widiwijayanti et al. (1996) report evidence of a 20-km eastward bias in the PDE epicenter of a large earthquake on the southern Sumatran fault in 1994.

Completeness of PDE Registration of Earthquakes in the Sumatra–Andaman Islands Subduction Zone, 1964–Mid-2005

The completeness of PDE registration of earthquakes has improved about 0.5 magnitude units since 1964, with the greatest part of this improvement being associated with the PDE’s incorporation of arrival-time data produced by the United Nations Comprehensive Nuclear-Test-Ban Treaty Organization’s International Monitoring System in 1995. Figure 4 shows the distribution of PDE short-period magnitudes ($m_b$) of Sumatra–Andaman Islands earthquakes as a function of time for three time-periods since 1964.

In Figure 4, we also plot a running mean of computed $m_b$: at the time corresponding to the $i$th earthquake, we plot the value $\text{mean}_{0}^{i}(m_b) = \text{mean}(m_b, m_b^-, m_b^+, \ldots, m_b^+)$, where $m_b^i$ denotes the PDE $m_b$ of the $i$th earthquake. For many geographic regions and time periods, the distribution
Figure 4. Temporal distribution of PDE short-period magnitudes ($m_b$) of Sumatra–Andaman Islands earthquakes: (a) 1964 - 2 September 2005; (b) 16 December 2004–14 May 2005; (c) 26 December 2004–1 January 2005. The 100-point running mean of $m_b$ is plotted at the time of the last earthquake that contributes to the mean, so that the running mean produces a delayed indication of changes in the magnitude–frequency distribution. Earthquakes considered in this figure are those occurring in the region bounded by latitudes 10° S and 17° N and longitudes 87° E and 107° E.
of recorded magnitudes is such that the mean value of $m_b$ is within a few tenths of a magnitude unit of the $m_b$ value above which earthquakes from the region are essentially completely recorded. This empirical result depends on a balancing of the intrinsic increase in the number of earthquakes with decreasing magnitude (described by the $b$-value of the regional Gutenberg–Richter magnitude–frequency relation) with the decrease in earthquake detectability as a function of decreasing magnitude below the threshold of completeness. From an incremental magnitude versus frequency plot for a region (e.g., Fig. 5), one may visually evaluate the extent to which the mean magnitude is likely to approximate the threshold of completeness. Our use of $\text{mean}_{100}(m_b)$ as an indicator of catalog completeness is similar to Wald et al.’s (1998; p. 533) use of the mode of the magnitude distribution as a “quick and dirty indicator of the detection threshold.”

For the Sumatra–Andaman Islands region in 1964–1978, $\text{mean}_{100}(m_b)$ fluctuated between 5.2 and 4.9 (Fig. 4a), with a mean $m_b$ for the whole period (777 earthquakes) of 5.05. A magnitude ($m_b$)–frequency plot for the period 1964–1978 suggests that the threshold of completeness for the entire period is about 5.2 (Fig. 5a). For the Sumatra–Andaman Islands region in 2000–25 December 2004, $\text{mean}_{100}(m_b)$ fluctuated between 4.5 and 4.8 (also Fig. 4a), with a mean $m_b$ for the whole period (1468 earthquakes) of 4.63. The magnitude ($m_b$)–frequency plot for the same time interval suggests that the threshold of completeness is about 4.7 (Fig. 5b).

Following the mainshock of 26 December 2004, fluctuations in $\text{mean}_{100}(m_b)$ and, correspondingly, the threshold of completeness (Figs. 4b,c) represent three effects. First, in the immediate aftermath of the largest shocks (26 December 2004 and 28 March 2005) and during episodes of particularly intense seismicity (Andaman Sea swarm of late January 2005), earthquakes of a size that would normally have been easily detected and located were lost in the codas of previous shocks. Second, the USGS/NEIC procedure is dependent on input from the United Nations Comprehensive Nuclear-Test-Ban Treaty Organization’s Reviewed Event Bulletin (REB) in order to catalog smaller teleseisms from the Sumatra region. At the times that the USGS/NEIC cataloged the earthquakes represented in Figure 4, the IDC had not published REBs for the periods 28 December 2004–6 January 2005 and 30 January–08 February 2005. The unavailability of REB data raised the threshold of completeness for the PDE for the two 10-day periods. Third, there is evidence of a “little variable factor” (e.g., Freedman, 1966) in the extent to which different USGS/NEIC analysts interpreted data from small teleseismically recorded aftershocks during the early part of the 26 December aftershock sequence. Individual days of the aftershock sequence were typically handled by single USGS/NEIC analysts. In the intensely active early days of the aftershock sequence, analysts were told to concentrate their efforts on aftershocks whose $m_b$ might approach 5 or greater and to pick up significantly smaller aftershocks as time allowed. For the period December 28–January 01 (Fig. 4c)

\[ N = \text{number of earthquakes with magnitude} = m_b \]
\[ \bigcirc \quad N = \text{number of earthquakes with magnitude} \geq m_b \]

Figure 5. Cumulative and incremental magnitude ($m_b$)–frequency plots for (a) 1964–1978; (b) 1 January 2000–25 December 2005; (c) 20 days in 2004 and 2005 for which the REB of the International Data Centre (IDC) was not published in sufficient time for REB data to be included in the USGS/NEIC data stream. We estimate the threshold of completeness ($m_c$), by eye, as the magnitude below which numbers of earthquakes fall-off from a line with $b$-value 1.25 (Frohlich and Davis, 1993) that passes through $N$ for $m_b$ 5.2–5.5. Earthquakes considered in this figure are those occurring in the region bounded by latitudes 10° S and 17° N and longitudes 87° E and 107° E.
Seismicity Associated with the Sumatra–Andaman Islands Earthquake of 26 December 2004

There is a day-to-day variability in the smallest aftershock located, which must reflect how individual analysts handled the process of selecting events to process.

For the Sumatra–Andaman Islands region, the mean $m_b$ for a time window appears to be about 0.1 magnitude unit less than the magnitude corresponding to essentially complete registration of earthquakes (Fig. 5). We think it likely that the USGS/NEIC record of aftershocks to the 26 December earthquake is significantly incomplete at $m_b$ 5.1 for the first half-day after the mainshock. Mean $m_{100}(m_b)$, after reaching a peak of 5.3 after the mainshock, doesn’t subside to a value of 5.0 until 16 hr after the mainshock. Otherwise, Figure 4 would suggest completeness at $m_b$ 5.1 and above at a resolution corresponding to the time window spanned by 100 events. We think that the record of aftershocks is in fact missing shocks of $m_b$ 5.1 in the first two hours following the Nias earthquake of 28 March 2005, but that the effect is attenuated in mean $m_{100}(m_b)$ (Fig. 4b) because the 100-point mean in the immediate aftermath of the March mainshock was taken over a time window of more than 5 hr. A few $m_b$ 5.1 and larger shocks of the Andaman Sea swarm of 26–30 January could be lost in the codas of immediately preceding shocks of the same swarm. For other time periods, the record of aftershock seismicity should be substantially complete for $m_b$ 5.1 and larger. A plot of magnitude versus frequency for the 20 days for which there were no REB suggests that the threshold of completeness for those days was about $m_b$ 5.0 (Fig. 5c), but values of mean $m_{100}(m_b)$ suggest that the threshold may be more like 5.1 for subintervals within the 20 days (Fig. 4c). For time intervals other than those just identified as problematical, the values of mean $m_{100}(m_b)$ suggest a level of completeness of $m_b$ (PDE) of about 4.6 (e.g., Fig. 4b).

USGS Body-Wave Moment Tensors of the Sumatra–Andaman Islands Mainshock/Aftershock Sequence

The USGS/NEIC routinely determines moment tensors of earthquakes larger than about 5.5 using the body-wave moment tensor methodology of Sipkin (1982). The USGS body-wave moment tensors are available electronically through sites that are described in Data Sources. The USGS moment tensors are based on inversion of composite $P$ waveforms consisting of $P$, $pP$, and $sP$, and are independent of the moment tensors produced by Harvard University using the centroid moment tensor methodology (Dziewonski et al., 1980; Global CMT Project, 2006), which are based substantially on later-arriving signals. Moments computed by the two methodologies are on average very similar for earthquakes smaller than about 7.3; the Harvard CMT moments tend to be systematically larger than the USGS moment for larger earthquakes (Sipkin, 1986). We attribute the systematic differences in moments of largest earthquakes to the shorter data time windows used in the body-wave moment tensor method, which result in the USGS procedure sampling less of the long source time functions of the largest earthquakes than the Harvard CMT procedure. Orientations of the moment tensors are generally similar, though some differences exist due to the different types of data used at the USGS/NEIC and at Harvard (Sipkin, 1986). Because most of the teleseismic body-wave data come from ray paths with steep takeoff angles, strikes of steeply dipping planes in the USGS moment tensor solutions tend to be better resolved than strikes of shallowly dipping planes. Focal depths should generally be well resolved by the USGS body-wave moment tensor inversion, with the exception of large events whose source time functions are longer than the time intervals separating the direct $P$ phase and reflected phases.

Figure 6 shows epicenters of shallow-focus (depth <70 km) earthquakes in the region of the Sumatra–Andaman Islands earthquake, 26 December 2004 to 2 September 2005, for which USGS moment tensors were determined. Focal mechanisms are represented according to their
type of faulting: normal-fault mechanisms are those for which the $T$ axis has a plunge $\leq 45^\circ$ and the $P$ axis has plunge $> 45^\circ$; reverse-fault mechanisms are those for which the $T$ axis has plunge $> 45^\circ$ and the $P$ axis has plunge $\leq 45^\circ$; strike-slip mechanisms are those for which both $T$ and $P$ axes have plunge $\leq 45^\circ$. We have also distinguished reverse-fault mechanisms whose moment tensors (though not necessarily their locations) are consistent with shallow interplate thrust faulting. These interplate-thrust-consistent mechanisms are defined with respect to the four interplate-thrust segments whose orientations are given in Table 1 and that are plotted in map view in Figures 9, 10, and 11. The interplate-thrust-consistent mechanisms are those reverse-fault mechanisms for which the azimuth of the slip vector for motion on the most shallowly dipping plane is directed to the north or east and is within $20^\circ$ of being perpendicular to the strike of the Table 1 segment within which the epicenter lies.

A noteworthy feature of Figure 6 is the scarcity along much of the 26 December rupture zone of moderate and large shocks (those of a size that USGS body-wave moment tensors could be determined for them) whose locations and focal mechanisms are consistent with their being interplate-thrust earthquakes. There are some probable interplate thrust aftershocks at the southern end of the 26 December rupture, and there is an intense, 150-km-long zone of likely interplate-thrust earthquakes offshore of Banda Aceh, which we will call the Offshore Banda Aceh source. Elsewhere along the 26 December rupture, there are only isolated events whose locations and mechanisms are consistent with their occurring on a shallowly east- or northeast-dipping thrust fault. Under the assumption that interplate-thrust aftershock activity would be intense on unruptured sections of the interplate thrust that were adjacent to the mainshock rupture surface (e.g., Aki, 1979; King, 1983), we infer from the paucity of interplate-thrust consistent aftershocks in most of the 26 December aftershock zone that the mainshock ruptured completely through the seismogenic zone along most of its length. Throughgoing rupture of most of the seismogenic zone is also implied by geodetic observations (Chlieh et al., 2007).

Another interesting feature of Figure 6 is the number of moderately large aftershocks near the trench axis, among which are reverse, normal, and strike-slip earthquakes. The diversity of faulting types is inconsistent with the global tendency for near-trench, intraplate aftershocks following great thrust-fault earthquakes to be predominantly extensional events within the oceanic plate underlying the aseismic thin edge of the accretionary wedge on the overriding plate (Christensen and Ruff, 1988). We will discuss these events further in subsequent sections.

### Estimates of Apparent Stress for Large Aftershocks

The USGS/NEIC determines radiated energy $E_S$ and energy magnitude $M_e$ for many earthquakes larger than 5.5 using the methodology of Boatwright and Choy (1986).
Seismicity Associated with the Sumatra–Andaman Islands Earthquake of 26 December 2004

Figure 8. Distribution of apparent stresses for reverse-fault earthquakes of Figure 7, plotted as a function of distance along line AA' of Figure 7. Apparent stresses of the mainshocks of 26 December 2004 and 28 March 2005 and the Siberut earthquake of April 2005 are identified with the year/month/day of those events. Shocks identified as forearc shocks are those with epicenters between 60 km and 220 km from the trench axis. The near-trench reverse-fault shocks of Figure 8 all have epicenters within 60 km of the trench axis.

From the $E_s$, apparent stress $\tau_a$ can be computed as $\tau_a = \mu E_s/M_0$, where $\mu$ is rigidity at the source and $M_0$ is seismic moment. The $E_s$ values are available online at sites listed in Data Sources. For the purpose of estimating apparent stress we use $M_0$ determined by the Harvard CMT methodology (Dziewonski et al., 1980; Global CMT Project, 2006) and $\mu$ that is implied for the earthquake focal depth by the AK135 velocity model (Kennett et al., 1995). The focal depth used in computing $\tau_a$ is that measured from the broadband waveforms (Choy and Dewey, 1988).

Among shallow-focus Sumatra–Andaman Islands aftershocks whose seismic energies and apparent stresses could be determined by the methodology of Boatwright and Choy (1986), the vast majority have apparent stresses less than 1 MPa (Fig. 7). Due to the exceptionally long duration of the body waves ($\sim 500$ sec), the seismic energy and apparent stress of the 26 December 2004 mainshock could not be calculated with the methodology routinely used at the USGS. Choy and Boatwright (2007) develop a methodology specifically for the 26 December mainshock and estimate a radiated energy of $1.4 \times 10^{17}$ J. Assuming $\mu = 3.7 \times 10^{10}$ Pa and using the Harvard $M_0 = 4.0 \times 10^{22}$ N m, this yields an apparent stress of 0.13 MPa for the 26 December mainshock. The highest apparent stresses represented in Figure 7 are associated with strike-slip earthquakes that, we shall argue below, occurred in the oceanic lithosphere of the Ninety East–Sumatra orogen. This is consistent with a global trend for oceanic, strike-slip intraplate earthquakes to have high apparent stress (Choy and McGarr, 2002).

In subsequent sections of this article we will be particularly concerned with the genesis of reverse-fault and thrust-fault earthquakes within the Sumatra–Andaman Islands aftershock sequence. Figure 8 shows the along-arc distribution of apparent stresses for these earthquakes. The forearc shocks of Figure 8 occur at a position within the subduction zone similar to that in which great interplate thrust-fault earthquakes occur worldwide (Byrne et al., 1988; Wells et al., 2003). Most of these shocks are interplate-thrust consistent by the convention of Figure 6, although a few of the forearc reverse-fault shocks have USGS body-wave moment tensor focal mechanisms whose northeast-dipping nodal plates dip more steeply than 45°. The apparent stresses for the forearc reverse faults have a mean of 0.4 MPa and a median of 0.3 MPa, which compare well with the average apparent stress of 0.3 MPa found by Choy and Boatwright (1995) for interplate thrust-fault earthquakes worldwide. The five near-trench reverse-fault earthquakes of Figure 8 occur in a tectonic environment that, worldwide, does not com-
monly produce reverse-fault earthquakes (see Nicobar Islands and Andaman Islands Segments of the 26 December Rupture Zone and the Andaman Sea). They have apparent stresses that are average or below average with respect to the global mean for interplate thrust faults.

Seismicity following the 26 December Mainshock

Seismicity in the 9 months following the great 26 December 2004 earthquake occurred densely in an approximately 2000-km-long zone of the shallow Sumatra subduction zone. For purposes of discussion and data presentation, we subdivide the region of most intense activity into four segments (Table 1). The northwest Simeulue (Fig. 9), Nicobar (Fig. 10), and Andaman (Fig. 10) segments were all active in the immediate aftermath of the 26 December mainshock (Fig. 2). The Nias–Siberut segment (Fig. 11) became highly active with the earthquake of 28 March 2005.

Cross sections for all segments are plotted in Figure 12. The projections of the plate interface have dips indicated in Table 1. They are positioned so as to emerge at the deformation front of the Sumatra–Andaman Islands accretionary wedge, as mapped by Pubellier et al. (2003).

Focal depths of most PDE (depth phase) events are based on interpreted $pP$ phases read on short-period waveforms and interpreted with the AK135 velocity model (Kennett et al., 1995). In regions beneath the Sunda Trench near the deformation front, where water depths may be as large as 5 km, the phase $pwP$ may be misinterpreted as $pP$ on short-period records (Choy and Engdahl, 1987; Engdahl et al., 1998), leading to overestimates of focal depth in PDE (depth phase) events by up to 15 km. Because there is a well-recognized mechanism by which the near-trench PDE (depth phase) hypocenters might be biased too deep, we base our subsequent discussion of near-trench seismotectonics primarily on focal depths determined by the body-wave moment tensor methodology.
Seismicity Associated with the Sumatra–Andaman Islands Earthquake of 26 December 2004

S35

Figure 11. Seismicity of the Nias–Siberut segment of the Sumatra–Andaman Islands arc, 26 December 2004–2 September 2005. The cross section in Figure 12d is based on data within the box; the dashed line corresponds to the 0-km point of the cross section. The 1833 rupture zone is as plotted by Zachariasen et al. (1999). The deformation front and faults are as in Figure 6.

Figure 11. Seismicity of the Nias–Siberut segment of the Sumatra–Andaman Islands arc, 26 December 2004–2 September 2005. The cross section in Figure 12d is based on data within the box; the dashed line corresponds to the 0-km point of the cross section. The 1833 rupture zone is as plotted by Zachariasen et al. (1999). The deformation front and faults are as in Figure 6.

In Figure 12, events with body-wave moment-tensor mechanisms are plotted at centroid depths computed by matching observed waveforms to theoretical waveforms, again using the AK135 model. As an independent assessment of the body-wave moment tensor focal depths, we checked them against broadband focal depths (Choy and Dewey, 1988) for a set of 44 Sumatra–Andaman Islands earthquakes for which both USGS/NEIC body-wave moment tensors and USGS/NEIC radiated energies had been determined. The two sets of focal depths agree to within 2 km, in the mean and median, with a standard deviation of 5 km. The generally good agreement of the moment tensor depths with the broadband focal depths notwithstanding, we acknowledge the possibility that some of the moment tensor depths could be biased by unusual conditions such as those found near the trench axis. The USGS/NEIC body-wave moment tensor methodology does not explicitly account for the presence of the near-trench water layer, for example, or for the effect of seafloor topography interacting with the water layer (e.g., Wiens, 1989).

The Northwest Simeulue Segment of the 26 December Rupture Zone

The mainshock of 26 December nucleated in the northwest Simeulue segment (Fig. 9). The USGS body-wave moment tensor procedure yielded a focal depth of 7 km for the mainshock. The finite source dimensions and the extended source time function of the mainshock, source properties that are not accounted for in the USGS procedure, make this focal depth too unreliable to influence tectonic speculation, and we have not plotted the mainshock hypocenter in the cross section. Figure 12c, that corresponds to Figure 9. We have plotted the epicenter of the mainshock at the 0-km depth of the section. If the mainshock nucleated on a plate interface that has an average dip of 12° from the deformation front to the hypocenter, the hypocenter would be at a depth of about 36 km.

Interplate thrust events at the southern end of the 26 December aftershock zone presumably occurred on the unruptured interplate-thrust fault that is adjacent to the south end of the mainshock rupture, where stresses favorable to interplate thrusting were increased rather than decreased by the occurrence of the mainshock. USGS body-wave moment tensor focal depths for most of these earthquakes place them close to a thrust interface that dips 12° northeastward from the trench (Fig. 12c).

The Offshore Banda Aceh source has the characteristics expected of an interplate thrust source. Its distance from the deformation front at the Sunda trench (about 200 km) and the focal depths of its shocks (those determined by the body-wave moment tensor procedure have average depths of about 40 km) are consistent with its lying on an interface that has an average dip of about 10° from the deformation front to the source region, slightly shallower than the 12° dip assumed for the interplate thrust in Figure 12c. Assuming that the Offshore Banda Aceh source does represent northeast-directed underthrusting, body-wave moment tensor focal mechanisms of the source events imply that the plate interface locally dips about 30°, which in turn implies a steepening of the subducted slab with depth. A steepening of the dip of the subducted slab in the vicinity of the Offshore Banda Aceh source is also demonstrated effectively with the hypocenter data and cross-section projections of Engdahl et al. (2007).

The strength of the Offshore Banda Aceh source suggests that, in contrast to most of the Sumatra–Andaman Islands interplate thrust north of the 26 December epicenter, strain on the interplate thrust offshore of Banda Aceh increased rather than decreased as a result of the 26 December mainshock. The mainshock rupture of 26 December may have passed to the west of the region of the Offshore Banda Aceh source, leaving the interplate thrust offshore of Banda Aceh unbroken but in close proximity to a segment of the thrust that experienced very large displacements. This explanation is consistent with model III of Ammon et al. (2005), which has low displacement at the site of the Off-
Figure 12. Sections of aftershock seismicity across the Sumatra–Andaman Arc. (a) Andaman Islands (Fig. 10); (b) Nicobar Islands (Fig. 10); (c) northwest Simeulue (Fig. 9); (d) Nias and Siberut (Fig. 11). Hypocenters are plotted from within the boxes shown in Figures 9–11. Hypocenter symbols are as in Figures 9–11, but PDE hypocenters are plotted only when constrained by depth phases. OBA source, Offshore Banda Aceh source. Inclined planes have dips of segments in Table 1, and their updip depths correspond to the local trench depths. The earthquakes of 26 January, 28 March, and 10 April all occurred in 2005 and are discussed in the text.
Seismicity Associated with the Sumatra–Andaman Islands Earthquake of 26 December 2004

shore Banda Aceh source and a zone of very high displacement just updip of the source (Fig. 9). We note that the Offshore Banda Aceh source lies downdip of a change in the trend of the Sumatra trench and beneath a change in trend of faults in the overlying forearc (Fig. 9) and speculate that a distortion of the plate interface at depth, corresponding to the change of trends of the surface features, may have created a barrier to mainshock rupture propagation along the deep plate interface. The Offshore Banda Aceh subset of the forearc shocks has a large range of apparent stresses (Fig. 8). Following the reasoning of Choy and Kirby (2004), this may imply that the Offshore Banda Aceh source is producing both events occurring on relatively low-strength preexisting faults and events occurring as the result of breakage of new or immature faults.

Aftershock activity in the northwest Simeulue segment is high near the updip edges of the zones of maximum displacement in model III of Ammon et al. (2005) (Fig. 9). The focal depths of most near-trench shocks in the northwest Simeulue segment, including most of the depths determined from the body-wave inversion method, would place them well below an inclined thrust that dips at about 12° from the deformation front at the tip of the accretionary wedge to the epicentral region of the 26 December mainshock (Fig. 12c). A notable exception is the aftershock of 26 January 2005 (discussed in the next section).

Nicobar Islands and Andaman Islands Segments of the 26 December Rupture Zone and the Andaman Sea

The Nicobar Islands segment also experienced substantial near-trench activity that was concentrated near the updip edge of the zone of maximum thrust faulting (model III, Ammon et al., 2005) in the 26 December mainshock (Fig. 10). Normal-fault, strike-slip, and reverse-fault mechanisms are present among aftershock focal mechanisms. The occurrence of aftershocks with normal-fault mechanisms trenchward of the source of a great underthrust earthquake is consistent with a pattern observed worldwide: near-trench intraplate earthquakes in subducting slabs are ultimately due to plate-bending extensional stresses and they are facilitated by the reduction of compressional strain associated with the downdip occurrence of the thrust-fault earthquake (e.g., Stauder, 1968; Chapple and Forsyth, 1979; Christensen and Ruff, 1988). The near-trench strike-slip aftershocks probably occurred in the subducting Ninety East–Sumatra orogen of the India/Australia plates. Strike-slip earthquakes occur elsewhere in the Ninety East–Sumatra orogen (Stein and Okal, 1978; Bergman and Solomon, 1985), and coupling of intraplate strike-slip and interplate-thrust faulting in the Sumatra subduction zone near 5° S (Fig. 2) is documented by Abercrombie et al. (2003).

The near-trench reverse-fault earthquakes have faulting mechanisms that are unusual worldwide for near-trench environments that are associated with shallowly dipping interface-thrust zones. Table 2 lists hypocenters of near-trench aftershocks for which reverse-fault mechanisms were determined by the USGS body-wave moment tensor methodology; the focal mechanisms are represented in Figure 13. The near-trench regions of most subduction zones are not characterized by reverse-fault earthquakes. Shallowly dipping plate interfaces just landward of trench axes are commonly aseismic, even in major aftershock sequences (Byrne et al., 1988). In subduction zones that do have near-trench reverse-fault earthquakes, these earthquakes typically occur below the neutral plane of the bending subducting lithosphere and below the earthquakes induced by extensional stress in the bent plate (Chapple and Forsyth, 1979). Body-wave moment tensor focal depths of most reverse-fault earthquakes in the northwest Simeulue segment (Fig. 9) are deep enough that these shocks might be attributable to compressive stresses below the neutral plane of a bending slab (Fig. 12c), but most of the near-trench reverse-fault aftershocks in the Nicobar and Andaman Islands segments of the Sumatra–Andaman aftershock zone (Fig. 10) have shallower body-wave moment tensor focal depths than most of the normal-fault earthquakes and they occur very near the interface between the subducting plate and the overriding plate (Fig. 12a,b). We also view the average or slightly below average apparent stresses of the near-trench reverse-fault earthquakes (Fig. 8) as being more suggestive of rupture of relatively weak near-surface lithosphere than they are suggestive of rupture of competent oceanic lithosphere below the neutral plane of a bent plate.

The close spatial association of near-trench reverse-fault aftershocks with the deformation front at the toe of the accretionary wedge (Fig. 13) suggests that the aftershocks are a seismogenic response to interplate compressional stress near the tip of the overriding plate. The hypocenter of the earthquake of 26 January 2005, 22:00 coordinated universal time (UTC), is quite close to the inferred position of the interplate thrust (Fig. 12c, 13), and the shock’s focal mechanism is consistent with an interplate-thrust origin (Fig. 13). Bilek (2006) determines a long source duration for this earthquake, which is also consistent with a shallow-focus, interplate-thrust mechanism. Focal mechanisms of most of the shallow-focus reverse-fault near-trench events of the Nicobar Islands segment, however, are not consistent with slip on a shallowly arcward-dipping interplate thrust (Fig. 13). In light of possible epicenter biases of several tens of kilometers (see PDE Hypocenters and Magnitudes), and considering uncertainty in the configuration of the interplate decollement, we think it is possible that some of the focal mechanisms with steeply arcward-dipping nodal planes represent slip on splay faults that branch upward from the interplate thrust several tens of kilometers landward of the deformation front. This origin for the near-trench reverse-fault aftershocks would not conflict with the hypothesis (e.g., Seno and Hirata, 2007) that the large-displacement 26 December coseismic rupture extended to the deformation front in the latitudes of the near-trench reverse-fault aftershocks. Alternatively, large horizontal compressional stress near the
Table 2

<table>
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<th>Longitude</th>
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The focal mechanisms of these shocks are plotted in Figure 13. Depths are those determined with the body-wave moment tensor methodology.

Figure 13. USGS/NEIC body-wave moment tensor mechanisms and focal depths for regions near the toe of the northwest Sumatra and Nicobar segments of the Sumatra arc. Table 2 lists the earthquakes for which mechanisms and depths are plotted. The deformation front of the Sumatra–Andaman Islands accretionary wedge is as mapped by Pubellier et al. (2003).
and mechanisms consistent with thrust faulting on the plate interface occurred along the length of the inferred rupture zone at distances of more than 40 km from the deformation front at the toe of the overriding plate (Figs. 11, 12d). The region within 40 km of the deformation front was largely quiescent; the lack of aftershock activity accords with the hypothesis that strain release at the toe of the overriding plate is usually accommodated by aseismic slip (Byrne et al., 1988).

The Siberut earthquake of 10 April 2005, $M_w$ (HRV) 6.7, occurred within the inferred rupture zone of the great 1833 Sumatra earthquake (Fig. 11) (Newcomb and McCann, 1987; Rivera et al., 2002) near the projected position of a plane dipping inland from the steep inner wall of the trench at an angle of 12° (Fig. 12d). The focal mechanism of the 10 April earthquake implies reverse faulting, but the northeast-dipping plane has a dip of about 60°, which is not consistent with slip on a gently dipping interplate thrust. The apparent stress of the 10 April earthquake is also somewhat high with respect to interplate-thrust earthquakes worldwide (Fig. 8). Taken together, the location, focal mechanism and apparent-stress observations suggest that the 10 April earthquake was either an intraplate earthquake occurring close to, but not on, the plate interface or a splay fault rooted on the plate-interface decollement.

Under the hypothesis that great faults tend to nucleate near locations marked by previous clusters of seismicity within generally quiescent seismic gaps (Kanamori, 1977), the 10 April earthquake and its aftershocks are of scientific interest as possibly marking the nucleation point of a future repetition of the 1833 Sumatra earthquake. The 26 December 2004 Sumatra mainshock is, in fact, an example of a great earthquake that nucleated within a previously active segment of a subduction zone and propagated to sections of the subduction zone interface that had been quiescent prior to the mainshock (Fig. 2); (Deshon et al., 2005). The practical implications of the occurrence of the 10 April earthquake are not clear. The source region of the 1833 Sumatra earthquake is already recognized as the potential site of a great underthrust earthquake in upcoming decades (Newcomb and McCann, 1987; Zachariasen et al., 1999), and the occurrence of the 10 April earthquake does not provide a clear indication of when a future great underthrust earthquake might occur. The shallow subduction zone southeast of Siberut had experienced seismicity in the decades prior to the 10 April 2005 earthquake, including many shocks having focal mechanisms consistent with interplate thrusting (see figure 1 of Rivera et al. [2002]). The 10 April shock therefore does not represent the emergence of seismicity in a segment of the 1833 rupture zone that had been quiescent prior to the earthquake of 26 December 2004.

Discussion

In the Data Sources section of this article we provide Internet addresses for accessing seismological data of the U.S. Geological Survey’s National Earthquake Information Center. Our conclusions on the data themselves are as follows:

The USGS/NEIC has computed hypocenters and magnitudes for a huge number of earthquakes of the Sumatra–Andaman Islands sequence that began with the magnitude [$M_w$ (HRV)] 9.0 earthquake of 26 December 2004. The number of events (5000) processed for this sequence alone through 2 September 2005 is about equal to the total number of earthquakes published annually in the PDE in the early 1970s.

Among USGS/NEIC data that are available electronically over the Internet, there are parameters associated with individual seismic events that permit selection of subsets of hypocenters that are most likely to be reliably located. For this study, we have based a number of conclusions on the subset of hypocenters whose 90% epicenter ellipses have semiaxes of 10 km or less in length and whose focal depths were constrained by use of depth phases. These events constitute about 11% of all hypocenters located by the USGS/NEIC.

The routine USGS/NEIC hypocenters and confidence intervals don’t account for some widely recognized sources of hypocentral error, such as biases due to lateral variations in seismic-wave velocity or misinterpretation of the $PwP$ phase as a $pP$ phase. The 11% of hypocenters that we consider most likely to be well located may still be affected by these sources of hypocentral error.

Since the 1960s and early 1970s there has been a reduction of about half an $m_b$ magnitude unit in the threshold of completeness for the registration of routine seismicity in the Sumatra–Andaman Islands region, from $m_b$(USGS) about 5.2 to $m_b$(USGS) about 4.6. Within the 2004–2005 Sumatra–Andaman Islands aftershock sequence, however, there were fluctuations in the level of completeness due to the loss of events in the coda of large earthquakes, due to USGS/NEIC dependence on the REB of the United Nations Comprehensive Nuclear-Test-Ban Treaty Organization for data on small Sumatra-region teleseisims, and due to a variability in the performance of different USGS/NEIC analysts. Outside of periods of about half a day following the 26 December 2004 mainshock, a period of about 2 hr following the 28 March 2005 earthquake, and possibly short periods during the Andaman Sea swarm of 26–30 January 2005, the cataloging of aftershock activity should be complete down to $m_b$(USGS) 5.1. Excluding periods of most intense activity and excluding a 20-day period for which data were not available from the REB, the threshold of completeness should be about $m_b$(USGS) 4.6.

USGS body-wave moment tensor solutions of Sumatra–Andaman Islands earthquakes allow identification of different modes of strain release within the sequence and provide estimates of focal depth for larger aftershocks that are based on waveform modeling.

Apparent stress estimates for the Sumatra–Andaman Islands are consistent with trends seen in global studies. High-
Figure 14. Occurrence of earthquakes in the central 26 December aftershock zone, before and after the Andaman Sea swarm of 26–30 January 2005. Deformation front and faults are from Pubellier et al. (2003).

1. The absence of interplate-thrust events along most of the downdip edge of the 26 December 2004 mainshock rupture implies that the rupture extended completely through the downdip part of the seismogenic interplate thrust of the Sumatra–Andaman Islands subduction zone for most of the length of the mainshock.
2. An exceptional, 150-km-long zone of intense interplate-thrust activity offshore of Banda Aceh may represent a segment of the deep, seismogenic, interplate thrust that was bypassed by the mainshock fault rupture.
3. Intense aftershock activity occurred near the Sunda trench and the deformation front updp of the inferred mainshock rupture. Near-trench normal-fault and strike-slip earthquakes probably represent intraplate seismicity within the Ninety East–Sumatra orogen of the India and Australia plates, and some of the deeper near-trench reverse-fault earthquakes may also correspond to release of stresses generated by plate bending. A group of shallow-focus, near-trench, reverse-fault earthquakes represents a type of seismic activity that is not common in subduction zones and may correspond to an unusual seismogenic response to interplate convergence near the tip of the overriding plate.
4. The extraordinary Andaman Sea swarm of 26–30 January 2005 occurred on a section of the transform fault/spreading center system of the Burma plate–Sunda plate boundary. At a regional scale, it constituted a burst of activity within a section of the plate boundary that was already producing aftershocks and that would continue to produce aftershocks following the swarm.
5. The intense interplate-thrust aftershock activity following the 28 March 2005 earthquake contrasts with the lack of such activity along much of the deep 26 December rupture and suggests that the rupture zone of the 28 March 2005 earthquake, as large as it was, either did not break completely through the seismogenic zone or was rapidly restressed from neighboring, currently stressed segments of the interplate thrust.
6. The Siberut earthquake of 10 April and its aftershocks are of unusual interest because they occurred in the middle of the rupture zone of the great Sumatra earthquake.
of 1833. The location and focal mechanism of the 10 April mainshock imply that it occurred close to, but not on, the shallowly dipping interplate thrust. Although much of the 1833 rupture zone has been quiescent in recent decades, the region of the 10 April shock had experienced appreciable earthquake activity in the decades before 26 December 2004.

Data Sources

The first reviewed solution and subsequent QED origins within seven days of the earthquake are posted at http://earthquake.usgs.gov/eqcenter/recenteqsww/Quakes/quakes_all.php (last accessed May 2006).

The QED and final PDE origins after seven days following the earthquake are available at http://neic.usgs.gov/neis/epic/ (last accessed May 2006). The compressed file format is the most data-rich output format: in addition to providing hypocenter and several magnitude types, this format also provides a qualitative assessment of the reliability of the earthquake epicenter and an indication of the type of data or assumptions used to constrain focal depth.

90% confidence ellipses on epicenter coordinates, used to select PDE epicenters and hypocenters that are plotted in Figures 9–12 and Figure 14, were calculated from 90% confidence ellipsoids on hypocentral coordinates that are contained in machine-readable Earthquake Data Reports that are available at ftp://hazards.cr.usgs.gov/weekly/ (contains events occurring within the immediately preceding year; last accessed May 2006) and ftp://hazards.cr.usgs.gov/edr/mchedr/ (contains events occurring from 1990 up to the time covered by the previously cited web site; confidence ellipsoids are available for events occurring since late 1996; last accessed May 2006). We project the 90% confidence ellipsoids on hypocentral coordinates to 90% confidence ellipses on epicenter coordinates using software written by Ray Buland (personal comm., 1995) that is available from author J. W. Dewey upon request.

The USGS body-wave moment tensor solutions and calculations of radiated energy associated with QED events are listed on file “qdevents.txt” that is available at ftp://hazards.cr.usgs.gov/weekly/ (last accessed May 2006). For the first 7 days after an earthquake these data are also available by going to http://earthquake.usgs.gov/eqcenter/recenteqsww/Quakes/quakes.all.php (last accessed May 2006) and following links to a specific earthquake and then to the Scientific and Technical page for that earthquake.

The USGS body-wave moment tensor solutions and calculations of radiated energy associated with PDE origins occurring from 6 weeks to one year from the current date (approximately) are available at ftp://hazards.cr.usgs.gov/weekly/manuscript/ (last accessed May 2006) and the same parameters for PDE origins occurring from 1994 to one year from the current date are available at ftp://hazards.cr.usgs.gov/pde/manuscript/ (last accessed May 2006). A searchable database of USGS body-wave moment tensors from 1980 and radiated energy estimates from November 1986 is updated about a year after the occurrence of an earthquake and is available at http://neic.usgs.gov/neis/sopar/ (last accessed May 2006). Broadband focal depths associated with the radiated energy estimates are available from author G. L. Choy upon request.

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References
