Teleseismic Relocation and Assessment of Seismicity (1918–2005) in the Region of the 2004 $M_w$ 9.0 Sumatra–Andaman and 2005 $M_w$ 8.6 Nias Island Great Earthquakes

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Abstract The $M_w$ 9.0 2004 Sumatra–Andaman Islands and $M_w$ 8.6 Nias Island great earthquake sequences have generated over 5000 catalog-reported earthquakes along $\sim$1700 km of the Sumatra–Andaman and western Sunda regions. Studies of prior regional seismicity have been limited to global catalog locations that often have poorly constrained epicenters and depths. Approximately 3650 teleseismically well-recorded earthquakes occurring in this region during the period 1918–2005 are relocated with special attention to focal depth. Reduced uncertainties of epicenters and depths in the region (on the order of 15 and 10 km, respectively) foster interpretation of focal mechanism data and provide additional details about the subducting Indian and Australian plates. The revised earthquake dataset reveals a sharp delineation between aftershocks of the 2004 and 2005 earthquakes near Simeulue Island and a steepening in slab dip from south to north. The downdip width of the aftershock zone of the 2004 $M_w$ 9.0 earthquake varies from $\sim$200 km at its northern end to $\sim$275 km at its southern end, and events located between 35 and 70 km focal depth occur more frequently in the southermost section of this aftershock zone. Outer-rise and near-trench normal and strike-slip faulting earthquakes also increase in frequency following the 2004 and 2005 earthquakes. Earthquake swarms triggered along the Andaman backarc spreading center both north of Sumatra and near Siberut Island, 100 km south of the Nias Island aftershock sequence, illustrate the complex and variable nature of seismicity following these great earthquakes.

Introduction

The Sumatra and Andaman subduction systems are currently one of the most seismically active regions in the world due to the ongoing aftershock sequences of the $M_w$ 9.0 26 December 2004 Sumatra–Andaman Islands and $M_w$ 8.6 28 March 2005 Nias Island great earthquakes. The history of great ($M \geq 8$) earthquakes along the Sumatra margin includes events in 1797, 1833, and 1861 (Fig. 1) (Newcomb and McCann, 1987; Sieh and Natawidjaja, 2000), but no record of prior great earthquakes exists for the Andaman Islands region (Ortiz and Bilham, 2003; Bilham et al., 2005). Over the course of the instrumental record, both subduction zones have hosted numerous mid to large magnitude earthquakes ($M_w$ 6.5–7.9). However, a comprehensive reanalysis of the reported instrumental arrival-time data for events in this region has not been attempted to date. Most detailed studies of seismicity in the region have been conducted in combination with global catalogs that are routinely produced by international agencies. Over time these agencies have used different Earth models, location methods, and data types. Moreover, the depths for many events in these catalogs, which until only recently (2005) were based almost entirely on first-arriving $P$ waves, are often not well determined. As a result, because most researchers have not been selective in their use of inhomogeneous catalog hypocenters, events that are poorly located are often presented in published articles. A goal of this article is to relocate all instrumental seismicity using the same method in order to make meaningful interpretations based on a consistent data set.

Seismicity in the Sumatra–Andaman Islands region results from subduction of the Indian and Australian oceanic plates beneath the Eurasian plate, which includes the Andaman microplate and Sunda subplate in Southeast Asia (Fig. 1) (McCaffrey, 1988; Sieh and Natawidjaja, 2000; Pubbellier et al., 2003; Curray, 2005). These oceanic plates vary in age from 60 Ma offshore Sumatra to 90 Ma along the northern Andaman Trench, and the convergence rate varies along strike from 50 to 60 mm/yr (Fig. 1) (Sieh and Natawidjaja, 2000). Due to the largely northward motion of these plates, convergence becomes increasingly oblique from south to north along the Sunda and Andaman trenches,
which results in formation of the large-scale, dextral strike-slip Sumatra fault system and the development of the Andaman microplate (Curry, 2005). The southern boundary of the Andaman microplate is defined by diffuse deformational features along the forearc from the inactive Batee fault to $-0.5^\circ$ S (Sieh and Natawidjaja, 2000). Relative plate motion becomes nearly trench parallel along the Andaman Trench, with trench-normal convergence estimated at 14 mm/yr at the northern Andaman Islands (Bock et al., 2003; Paul et al., 2001).

The 26 December 2004 $M_w$ 9.0 Sumatra–Andaman Islands earthquake ruptured the entire length of the Andaman Trench and generated the most deadly tsunami in the historic record. The earthquake was followed by an extensive aftershock sequence with a high degree of spatial and temporal variability and apparently triggered a second great earthquake, the $M_w$ 8.6 Nias Island event, along the adjacent Sunda subduction zone three months later. Coseismic rupture during the 2004 Sumatra–Andaman Islands earthquake extended $\sim$1300 km along the Andaman subduction zone (Lay et al., 2005). Initial rupture lasted over 500 sec and was very complex, with preliminary models requiring variable rupture velocities from 2.5 to 2.8 km/sec over the entire length of the aftershock zone (Ammon et al., 2005; Ishii et al., 2005; Ni et al., 2005). Subsequent detailed moment magnitude calculations using normal modes (Stein and Okal, 2005) and multiple point source centroid moment tensors (CMT) (Tsai et al., 2005) yielded $M_w$ 9.3, though we adopt $M_w$ 9.0 for consistency with the Harvard CMT catalog (Dziewonski et al., 1983, and periodic updates). Most models developed to date subset the 2004 rupture into three main segments broadly corresponding to the Andaman, Nicobar, and northern Sumatra regions (e.g., Ammon et al., 2005; Kennett and Cummins, 2005; Lay et al., 2005). Kennett and Cummins (2005) correlate transitions in rupture behavior to changes in physical properties of the subducted slab along strike such as the ratio of shear-wave speed to bulk-sound speed, but the reasons for the complex, variable rupture remain an area of active research. Relocated teleseismic aftershocks of this great earthquake occurred along nearly the entire plate interface, extending from Simeulue Island north through the Nicobar and Andaman Islands and along the backarc spreading center north of Sumatra (Fig. 1). In comparison, the 2005 earthquake to the south had a relatively simple source, characterized by thrust faulting with a CMT mechanism almost identical to the first-reported solution for the 2004 event (Fig. 1). Aftershocks of the 2005 earthquake extended from Simeulue Island to the southern tip of Nias Island (Fig. 1).

Approximately 17 seismographic stations have monitored seismicity at local and near-regional distances ($\Delta < 20^\circ$) in the Andaman–Sumatra and Sunda regions, but these stations have inconsistent reporting histories and lie exclusively to the east of the subduction zones resulting in a highly biased station geometry. For relocation one must rely predominately on arrival times reported by stations at teleseismic distances ($\Delta > 28^\circ$). In recent years techniques developed by Engdahl et al. (1998) and Engdahl and Villaseñor (2002) have resulted in a general improvement in the
locations and focal depths of teleseismically recorded earthquakes globally (this methodology will be hereafter referred to as the EHB algorithm). We apply the EHB algorithm, with special attention to focal depth, to all teleseismically recorded earthquakes with \(\geq 10\) teleseismic arrivals and a teleseismic secondary azimuth gap of \(< 180^\circ\) in the Sumatra–Andaman and Western Sunda regions for the period 1918–2005. The aim of this study is to produce a comprehensive catalog of all instrumentally recorded events for these regions and to assess this relocated seismicity, with reliable focal depth distributions, in the context of subduction processes, regional seismotectonics, and subducting plate geometry. The patterns arising from these relocations also are compared to available focal mechanisms to gain a better understanding of the complex spatiotemporal relationships between the 2004 and 2005 great earthquakes.

**Methods**

Standard teleseismic earthquake catalogs that have been produced by the International Seismological Summary (ISS), the International Seismological Centre (ISC), and the U.S. Geological Survey’s National Earthquake Information Center (USGS/NEIC) have until only recently relied almost entirely on first-arriving \(P\) phases for locating events using the Jeffreys–Bullen (JB) travel-time tables (Jeffreys and Bullen, 1940). Engdahl et al. (1998) and Thurber and Engdahl (2000) have shown that routine hypocenter determinations can be significantly improved in several ways. First, the use of an improved one-dimensional (1D) global travel-time Earth model (ak135) (Kennett et al., 1995) allows first-arriving and later phases (\(P\), \(S\), and \(PKP\)) to be properly identified so that they can be reliably used in the iterative relocation of events with dynamic phase reidentification. Epicenter constraints are improved by the inclusion of \(S\)-wave and \(P\)-core phases because their travel-time derivatives differ significantly in magnitude from those of direct \(P\). Also, the EHB algorithm uses teleseismic \(pP\), \(pwP\), and \(sP\) phases in the relocation procedure. These depth phases, when used with theoretical probability density functions and corrections for bounce point topography or water depth, provide powerful constraints on focal depth hitherto not applied systematically by any of the international agencies routinely processing phase data. In particular, depth–origin time trade-off is reduced by the inclusion of depth phases because their travel-time derivatives are opposite in sign to direct \(P\). Third, model uncertainty is properly introduced in the relocation procedure by weighting phase data as a function of their variance with epicentral distance (Engdahl, 2006). Fourth, although single-event locations can be subject to bias of several tens of kilometers in subduction zones, use of selection criteria for teleseismic station coverage can at least ensure that the earthquakes within a localized area are well located in a relative sense (i.e., the events are uniformly biased within that area).

The EHB method has already been successfully applied to earthquakes reported by the ISC and USGS/NEIC during the modern period (1964–2005), providing a uniform database of well-constrained events with reduced hypocenter uncertainties. In addition, the application of this method to arrival times of early instrumental earthquakes (prior to 1964) listed in the ISS Bulletin has resulted in a comprehensive and homogeneous digital earthquake catalog for the entire twentieth century (Engdahl and Villasenor, 2002). In this study nearly all instrumentally recorded events in the Sumatra–Andaman and western Sunda regions prior to 1964 have been relocated to provide a catalog complete to at least \(M_s 6.5\). For the modern period our selection criteria provide a catalog that is complete to at least \(M_W 5.5\), but includes many events of smaller magnitude.

It is important to point out that EHB procedures cannot entirely remove the effects of the Earth’s lateral heterogeneity on teleseismic earthquake location. Most earthquakes occur in or near subducted lithosphere where aspherical variations in seismic-wave velocities are large (i.e., on the order of 5%–10%) (Bijwaard et al., 1998). Such lateral variations in seismic velocity, the uneven spatial distribution of seismograph stations, and the specific choice of seismic data used to determine the earthquake hypocenter can easily combine to produce bias in teleseismic earthquake locations of up to several tens of kilometers (van der Hilst and Engdahl, 1992). Bondár et al. (2004) find that catalog location accuracy is most reliably estimated by station geometry, as best expressed by the primary and secondary azimuth gaps (secondary azimuth gap is defined as the largest azimuthal gap filled by a single station). In this study we select only events that have ten or more teleseismic (\(\Delta > 28^\circ\)) observations and a teleseismic secondary azimuth gap \(< 180^\circ\). Although EHB earthquake relocations in continental areas have been shown to be accurate to 15 km or better (Myers and Schultz, 2000), it is expected that in subduction zones the effects of the higher-velocity downgoing plate can produce a larger bias. However, in our study region these plate effects are minimized because the rays to most teleseismic stations from shallow depth earthquakes are trenchward of the higher-velocity steeply dipping part of the downgoing slab.

The use of later-arriving phases in routine hypocenter determination potentially provides powerful constraints on focal depth and reduces the effects of strong near-source lateral heterogeneities. However, until 2005 both the ISC and USGS/NEIC relied almost entirely on first-arriving \(P\) waves to locate earthquakes. Thus, without further processing, residuals for high-frequency seismic phases other than \(P\) that are reported by these agencies have only limited application to research problems such as source location and the development and evaluation of Earth models. The EHB phase identification algorithm, applied to the phase group immediately following the \(P\) wave at teleseismic distances (\(pP\), \(pwP\), \(sP\), and \(PcP\)), has been shown to be particularly effective so that these phases can be confidently exploited in the relocation procedure. This is especially important for events
in the study region, as many are suboceanic, giving rise to \( pwP \) phases. In the following sections, we review comparisons of EHB free-depth determinations using the arrival times of reidentified and associated depth phases with depths determined by other independent methods.

**Location Error Analysis**

Although EHB depth-phase association and free-depth estimation ordinarily works quite well, problems are encountered when the starting depths are poor, there are too few depth phases and the procedure becomes unstable, or the earthquakes are complex. The problem of complex events is addressed by fixing the depth to an estimate that has been reliably determined by other means (e.g., from waveforms). However, a poor starting depth or too few depth phases usually requires a careful review of the output of the automatic processing. Subsequently, the starting depth is adjusted or fixed in order to obtain a best fit to the reported depth phases in a new hypocenter solution.

Since October 1985, the USGS/NEIC have routinely computed earthquake depths using the method of Harvey and Choy (1982) from broadband seismograms of body waves that are flat to displacement and velocity in at least the frequency range from 0.01 to 5.0 Hz, for earthquakes with \( m_b > 5.8 \). The broad spectral content in displacement and velocity waveforms often permits identification and resolution of the source functions of direct and surface reflected phases by direct inspection. If depth phases are clearly identifiable on these waveforms, the differential travel times of \( pP–P \) and \( sP–P \) are read and estimates of the focal depth are obtained by inversion of these differential times observed at several stations using the iasp91 model (Kennett and Engdahl, 1991). Since January 1996, both broadband \( P \) and transversely polarized \( S \) waves have been used to derive broadband depths for some shallow earthquakes using methods described by Choy and Dewey (1988). Figure 2 compares EHB free-depth solutions using depth phases to NEIC broadband depth determinations (adjusted to sea level) for 33 events, all of which had seven or more depth phases. The differences are no more than ±11 km.

Another source of waveform depths are CMT solutions routinely determined by Harvard for events with moment magnitudes greater than about 5.5. These solutions have been determined with long-period body and mantle waveform data (low-pass filtered) using a moment tensor inversion method. The CMT method is described in detail by Dziewonski et al. (1981), with later enhancements by Dziewonski and Woodhouse (1983). Hypocentral parameters are obtained by adding perturbations resulting from the inversion to hypocenters reported by the USGS/NEIC. If the depth is not perturbed during the inversion, it is fixed to be consistent with the waveform matching of reconstructed broadband body waves (Ekström, 1989). Default depths are 15 km and 33 km (10 km from 1981 to 1985). Recently, the CMT analysis has been extended to smaller earthquakes by analyzing teleseismic intermediate period surface waves (Arvidsson and Ekström, 1998).

The CMT data set provides an extremely valuable resource of source mechanism data, but centroid depths lack the resolution for making meaningful comparisons with EHB depths in part because the event centroid does not necessarily occur at the earthquake hypocenter (see Engdahl et al., 1998). Figure 3a shows that differences of EHB hypocenters from CMT centroid depths are often quite large. EHB depths for earthquakes with CMT default depths of 15 km and 33 km are nearly all at crustal depths in the ak135 model (<35 km). Figure 3b suggests that larger depth differences with decreasing moment magnitude for more poorly recorded events are probably a CMT resolution problem. Some of the discrepancies may be related to the differences between EHB and CMT processing techniques. However, there is an obvious danger in making these comparisons for the largest events, as we are locating the nucleation point with high-frequency arrival times whereas CMT solutions represent the centroid of fault slip (this may also be an issue for depth determination using broadband waveforms as previously described). For the seismotectonic analyses presented in this article we use CMT mechanisms compiled by Harvard (Göran Ekström, personal comm.). This ensures data homogeneity similar to that adopted for the earthquake locations.

From the depth comparisons made previously, we estimate that after review the uncertainty of our EHB depth estimates with respect to the ak135 model is on the order of ±10 km. This agrees well with an independent study (Engdahl, 2006) using a globally distributed data set of reference events (explosions and earthquakes) with epicenters and depths known to within 5 km or better. In that study, EHB free-depth procedures using depth phases resulted in an average uncertainty in depth of ±7 km. The median standard
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Figure 3. Comparison of EHB free-depth solutions to (a) CMT depths and (b) CMT depths with respect to magnitude ($M_w$).

EHB Hypocenter Analysis

Approximately 3650 instrumentally recorded earthquakes occurring in the Sumatra–Andaman and Sunda regions during the period 1918–2005 have been relocated using the EHB methodology with special attention paid to focal depth. All events are well constrained teleseismically (secondary teleseismic azimuth gap < 180°) by phase arrival times reported to the ISS, ISC, and NEIC, and EHB starting depths and the EHB assignment of teleseismic depth phases have been reviewed. The uncertainties of EHB epicsenters and focal depths are believed to be on the order of 15 and 10 km, respectively, and the azimuth gap criterion generally insures that all locations are well determined in a relative sense. We are fortunate to have the results of an Ocean Bottom Seismometer (OBS) microearthquake deployment in the nucleation region of the 2004 mainshock during February–March 2005 (Araki et al., 2006). Four events located by this network were also recorded teleseismically and met the EHB selection criteria (Table 1). EHB epicenters for these events at several possible focal depths differed from the corresponding OBS epicenters by less than 15 km in a southwest direction, contrary to what might be expected if seismic waves traveling down the higher-velocity downgoing plate had affected the locations. For shallow events in this region, EHB teleseismic epicenter bias appears to be minimal (but not eliminated) when the teleseismic station coverage is good (secondary teleseismic azimuth gap < 180°). Hence, we consider our relocations to be sufficiently accurate to resolve at the very least robust characteristics of seismicity in the study region.

A comparison of EHB locations and depths to ISC values (1964–2002) for the 1431 events in common between the catalogs results in average differences of 12.0 ± 9.2 km in epicenter and +17.5 ± 30.0 km in depth (ISC with respect to EHB), with 32 ISC events more than 100 km deeper than EHB depths. A similar comparison of the EHB and USGS/NEIC catalogs (2003–2005) for 2119 common events results in average differences of 8.0 ± 5.9 km in epicenter and +4.9 ± 11.2 km in depth (USGS/NEIC with respect to EHB). The fact that differences between USGS/NEIC and EHB hypocenters are less than differences between ISC and EHB hypocenters can partly be accounted for by the recent adoption of the ak135 model and use of depth phases by the USGS in their routine processing. However, the USGS positive bias in depth is partly due to their use of $pP$ phases as $pP$ phases for the many suboceanic earthquakes in this data set. Further discussion on the USGS/NEIC hypocenters for the Sumatra and Andaman region can be found in Dewey et al. (2007).

Figure 4 summarizes the relocated and teleseismically well-constrained earthquakes occurring in the study region during the period 1918–2005. The sector boundaries shown, convenient for later discussion, are loosely based on location and depth of seismicity, moment release in time, and aftershock distribution. Depth classification shown by color-coding illuminates interplate and intraplate seismicity, extending to focal depths of nearly 300 km, associated with the downgoing slab.

The Andaman microplate, including the Andaman, Nicobar, and Sumatra sectors, appears to have been seismically active across its full extent during the 1918–2005 period of instrumental locations, including a high level of shallow-depth backarc seismicity near the eastern microplate boundary (Fig. 4a). Seismicity that occurred in the region prior to the 2004 Sumatra–Andaman Islands great earthquake is shown in Figure 4b. Most earthquakes in the Andaman microplate and Sunda regions during this period seem to have occurred downdip along the interplate zone at depths...
greater than 35 km, with a distinct near absence of seismicity trenchward, as previously noted by Lay et al. (2005). Most aftershocks of the 2004 event occurring prior to the 2005 earthquake locate trenchward at depths less than 35 km, filling in areas with an absence of previous seismicity in the Andaman microplate (Fig. 4c). We also observe that during this aftershock period many more earthquakes between 35 and 75 km in depth occurred in the North Sumatra sector (Fig. 4c) of the aftershock zone than elsewhere. This feature is discussed further below. The 2004 aftershock pattern is consistent with an ~1300-km-long mainshock rupture (i.e., Ammon et al., 2005; Lay et al., 2005) when unfolded along an arc through its point of initiation, with the downdip width of the aftershock zone varying from ~200 km at its northern end to ~275 km at its southern end (Fig. 4c). High aftershock activity along backarc ridge-transform faults, characterized by intense swarms, indicates accompanying slip partitioning along that boundary (Lay et al., 2005). Northernmost aftershocks of the 2005 Nias Island event abut the southernmost aftershock zone of the 2004 mainshock across Simeulue Island (Fig. 4d) (DeShon et al., 2005; Singh and Sumatra-Aftershocks Team, 2005). Rupture during the $M_w$ 9.0 2004 earthquake propagated with variable speed as it progressed northward, with the main component of fast rupture occurring in a 400-km-long region corresponding to our Sumatra sectors (e.g., Ammon et al., 2005; Stein and Okal, 2005). The unprecedented duration and rupture complexity of the 2004 mainshock is reflected in the temporal history of the aftershock sequence (Fig. 4) and seismic moment release (Fig. 5) along the margin. Here, seismic moment release, estimated by a logarithmic scaling of the seismic moment ($M_0$) using the formula $\log_{10}(M_0) = 17.25$ with $M_0$ in dyne cm, is presented to more realistically distinguish large earthquakes from small earthquakes. Aftershocks with $M_w \geq 6.5$ occurred primarily in the Nicobar sector. Although the Sumatra sectors had seen considerable moment release prior to the 2004 great earthquake, few $M_w \geq 6.5$ aftershocks occurred in that sector (Fig. 5a, b). In contrast the Nicobar sector experienced few prior large earthquakes, but a number of large, mostly trenchward, aftershocks with at least one very large event occurring nearly eight months later. Finally, the Andaman sector was characterized by a number of earlier large events, but not very large aftershocks of the 2004 events.

Cross-sections of earthquakes with well-determined depths for the Andaman, Nicobar, northern Sumatra, southern Sumatra, and Sunda sectors are shown in Figure 6. All cross-sections reveal a shallow-dipping seismic zone, presumably along or close to the plate interface, followed by a gradual downturn of the interplate seismic zone into the mantle at dip angles increasing from the Sumatra segment to the Andaman sector. Trenchward seismicity consists almost entirely of aftershocks of the 2004 and 2005 great earthquakes at depths mostly less than 35 km. Many of these aftershocks occurred near the trench axis and in the outer rise. A large number of aftershocks occurred in the downturn section of the interplate seismic zone in the Northern Sumatra sector (Figure 6c) at depths mostly greater than 35 km. In the southern Sumatra sector, few teleseismic aftershocks were located in the immediate vicinity of the 2004 mainshock (Fig. 6d). Shallow-depth upper-plate aftershocks were located beneath the volcanic line in the Andaman, Sumatra, and Sunda sectors (Fig. 6a, c–e). However, in the Nicobar sector along the eastern plate boundary in a region of backarc spreading, shallow-depth upper plate aftershocks occurred as intense swarms (Fig. 6b). This geometry of the seismic part of the slab in the Nicobar and Andaman region is presumably the result of slab roll back associated with the formation of the Andaman backarc basin and spreading center north of Sumatra.

The shallow dip angle of trenchward aftershocks (<10°), the thickness of the aftershock zone (~10 km), the increased dip angle (15°–20°) of intense interplate aftershock activity landward, with a downdip depth limit of ~50 km at a distance of ~240 km inward from the trench axis, and the lack of deeper aftershocks in the subducting slab, noted in the teleseismic event locations shown in Figure 6d, are consistent with the local earthquake locations calculated using
Figure 4. EHB seismicity in the Sumatra–Andaman region relocated and color classified by depth: (a) 1918 through September 2005; (b) 1918 to 26 December 2004, mainshock; (c) 2004 mainshock to 28 March 2005, Nias Island earthquake; and (d) 2005 Nias Island earthquake through September 2005. Sector boundaries are indicated. Upper red star is 2004 $M_w$ 9.0 mainshock and lower orange star is 2005 $M_w$ 8.6 Nias Island earthquake. The thick black line (teeth on overriding plate) indicates the trench location, and gray triangles represent Holocene volcanoes. Faults in the upper plate backarc and forearc are shown in blue.
Figure 5. Logarithmically scaled moment release of earthquakes at focal depths of 70 km or less, with sector boundaries corresponding to Figure 4: (a) Map showing moment release of earthquakes prior to the 2004 Sumatra–Andaman great earthquake (white circles), and aftershock moment release during the period between the 2004 and 2005 mainshocks (light shaded circles) and during the period after the 2005 mainshock (dark shaded circles). Magnitude scale indicates equivalent moment magnitude; (b) Space–time plot of moment release. Vertical axis is arc distance in kilometers unfolded along a small circle through the point of initiation of the 2004 event with respect to a center of arc curvature and horizontal axis is time in years. (c) Cumulative moment release across the Andaman, Nicobar, northern Sumatra, and southern Sumatra sectors for earthquakes at focal depths of 70 km or less. Vertical axis is moment release and horizontal axis is time in years. Moment release from the $M_w 9.0$ 2004 mainshock ($3.5 \times 10^{22} \text{ N m}$) and the $M_w 8.6$ 2005 mainshock ($8.9 \times 10^{21} \text{ N m}$) are not shown.

OBS data offshore northern Sumatra (Araki et al., 2006). Araki et al. (2006) concluded that the lack of larger aftershocks suggests complete strain release and possibly little afterslip near the 2004 earthquake source. They also note that the microearthquake distribution shows a correspondence with steep slopes in seafloor topography and suggest that shallow seismicity there might be associated with splay faults, though the resolution of the telesismic data set can neither confirm nor disprove this hypothesis.

Focal Mechanism Analysis

Higher-resolution earthquake locations and focal depths permit an improved interpretation of focal mechanism data. The patterns arising from relocated hypocenters can, for example, be compared to available focal mechanisms to more clearly distinguish interplate and intraplate seismicity, as it is not a valid assumption that all aftershocks or relocated earthquakes occurred along the plate interface. Figures 7–10
Figure 6. Cross sections (no vertical exaggeration) of hypocenters that have depth constraints: (a) Andaman; (b) Nicobar; (c) northern Sumatra; (d) southern Sumatra; and (e) Sunda sectors. Plotted are early instrumental (pre-1964) earthquakes (large white circles with thick outline), pre-mainshock (1964–2004) earthquakes (small white circles), 2004 Sumatra–Andaman aftershocks (gray circles), and aftershocks of the 2005 Nias Island earthquake (black circles). Stars indicate 2004 and 2005 mainshock hypocenters. Inverted triangles are digital trench points, and upright triangles are volcanoes.
Figure 7. Selected mechanisms from the Harvard CMT catalog (Harvard Seismology) for the Sumatra–Andaman region. Beach balls (in lower hemisphere projection) are plotted at the location of the EHB epicenter, and their compressional quadrants are color coded according to EHB depth. Other tectonic features and symbols are as in Figure 4.
Figure 8. Orientation of $P$ axes of Harvard CMT mechanisms (Harvard Seismology) shown in Figure 7. The bar length is proportional to the projection of the $P$ axis on the horizontal component (the bar corresponding to a vertical $P$ axis would have zero length). Other tectonic features and symbols are as in Figure 4.
Figure 9. Orientation of $T$ axes of Harvard CMT mechanisms (Harvard Seismology) shown in Figure 7. The bar length is proportional to the projection of the $T$ axis on the horizontal component (the bar corresponding to a vertical $T$ axis would have zero length). Other tectonic features and symbols are as in Figure 4.
Figure 10. Orientation of $B$ (null) axes of Harvard CMT mechanisms (Harvard Seismology) shown in Figure 7. The bar length is proportional to the projection of the $B$ axis on the horizontal component (the bar corresponding to a vertical $B$ axis would have zero length). Other tectonic features and symbols are as in Figure 4. The purple line and gray box define the orientation and events used to construct the cross section shown in Figure 11.
show Harvard CMT solutions for the period 1976 through July 2005, and associated pressure, tension, and null axes, respectively, that are well constrained following the criteria proposed by Frohlich and Davis (1999). These criteria are based on three statistical parameters: (1) the relative error \( E_{\text{rel}} \), which is the ratio of the scalar moment of the reported error tensor normalized by the moment tensor itself; (2) \( f_{\text{CLVD}} \), which is a measure of the strength of the non-double-couple component of the moment tensor; and (3) \( n_{\text{free}} \), the number of elements not fixed at zero during the inversion (if no element was fixed then \( n_{\text{free}} = 6 \)). With selected values for the three statistical parameters \( E_{\text{rel}} \leq 0.15, |f_{\text{CLVD}}| \leq 0.20, \) and \( n_{\text{free}} = 6 \), these rules reduce the CMT catalog by half. However, the earthquakes selected have \( T, B, \) and \( P \) axes with uncertainties of \( 5^\circ-10^\circ \) or less in their azimuth and plunge angles, and these uncertainties also apply to the strike, dip, and rake of the nodal planes. This means that differences in dip and/or strike of \( 5^\circ-10^\circ \) or more are significant and can be interpreted. The following observations are contingent on using only these well-constrained CMT focal mechanism solutions in conjunction with EHB hypocenters.

Based on focal mechanisms and EHB hypocenters, all aftershocks of the 2004 and 2005 events are confined to depths less than 70 km but not all occurred in the subduction megathrust fault (Fig. 4c,d). Most aftershocks of the Sumatra–Andaman Islands and Nias Island earthquakes are consistent with underthrusting along the megathrust fault and with the focal mechanisms of the mainshocks, with \( P \) axes normal to and \( B \) axes parallel to the local strike of the trench (Figs. 8 and 10, respectively). Prior to the 2004 mainshock, we located only one event with a thrust-faulting mechanism east of the trench in the Nicobar sector (Fig. 7b). Following the 2004 earthquake, many thrust earthquakes occurred at or near the trench in all sectors except the northern Sumatra sector (Fig. 7c). After the occurrence of the \( M_w 8.6 \) Nias Island event, only underthrusting and normal-faulting aftershocks occurred in the trench along the southern portion of the Sunda sector (Fig. 7d). Near-trench thrust-fault events continued to occur in the Sumatra sectors following the 2005 event as part of the ongoing aftershock sequence of the 2004 mainshock. Interplate earthquakes are not normally observed along the shallowest (<10 km) portion of subduction megathrusts (e.g., Byrne et al., 1988; Scholz, 1998; Pacheco et al., 1993; Hyndman et al., 1997), though rupture has been shown to propagate to the trench during large and great earthquakes or during tsunami earthquakes (earthquakes that generate larger than expected tsunamis based on magnitude calculations) (Kanamori, 1972; Bilek and Lay, 2002, and references therein). Similarly, the Andaman Trench had not hosted significant shallow seismicity prior to the 2004 earthquake (Figs. 4b and 7b), but rupture during the \( M_w 9.0 \) earthquake extended to the Andaman Trench along much of the rupture length (i.e., Lay et al., 2005).

Intermediate depth seismicity (70- to 300-km depth) along the Sunda and Andaman subduction zones prior to the 2004 earthquake exhibited along-strike variable focal mechanism solutions but no apparent temporal relationship with the 2004 and 2005 great earthquakes (Fig. 7). Events between 70 and 150 km depth in the Andaman sector have downdip \( T \) axes oriented slightly southeast of trench normal (Fig. 9). No events meeting the parameters used in this study occur below 150-km depth along the Andaman sector. There are two events at >150-km depth in the Nicobar sector whose focal mechanisms are not consistent with downdip tension (Fig. 9), unlike the two events at >150-km depth in the southern Sumatra sector, near the offset in the volcanic arc, which have downdip \( T \) axes roughly normal to the local strike of the trench. In the Sunda sector, all events in the 70-to 300-km-depth range have downdip \( T \) axes (Fig. 9).

Many events at or immediately adjacent to the trench to the east, prior to and following the Sumatra–Andaman great earthquakes, are characterized by both normal and strike-slip faulting (Fig. 7). Near-trench shallow normal fault earthquakes may be due to intraslab bending stresses (Fig. 7b–d). Following the 2004 earthquake there is an increase in shallow, normal-faulting events both to the west and slightly to the east of the deformation front from Nias Island north through the Andaman Islands. The increase in the number of outer-rise earthquakes with normal fault mechanisms following large megathrust earthquakes is a well-known phenomenon (Christensen and Ruff, 1983; Lay et al., 1989). Pre-2004 near-trench seismicity had primarily strike-slip mechanisms oriented with the north–south trends of many features on the incoming Indian plate. The 2005 aftershock sequence also contains three strike-slip earthquakes along the southern boundary of the aftershock zone, and some strike-slip events occurred near the Andaman Islands following the 2004 earthquake. Dewey et al. (2007) suggest, based on NEIC/USGS hypocenters, that the range of mechanisms near the trench likely reflects the intraplate stresses due both to the bending and the highly oblique convergence of the downgoing plate. Due to the depth resolution of both teleseismic datasets, however, we cannot say for certain if the normal-faulting and strike-slip earthquakes are occurring entirely within the oceanic plate or if the upper plate is involved in deformation.

Following the 2004 mainshock, most events between 35- and 70-km depth occurred in a spatially limited region offshore northern Sumatra (Fig. 7), referred to by Dewey et al. (2007) as the Offshore Banda Aceh region. These events are consistent with thrust faulting along a plane, possibly the plate interface, dipping 27 ± 4° and extending to ~60-km depth (Fig. 11). Over the instrumental history of the margin, thrust events at these depths have been recorded along all of the Sunda and much of the Andaman subduction system (Fig. 7). These aftershocks also exhibit a large range of apparent stresses (computed as the ratio of the radiated energy to the moment multiplied by the rigidity at the source) (Dewey et al., 2007). They interpret these events as breakage of both low-strength preexisting faults and of new or immature faults within a region of the downgoing plate.
and megathrust that may have been bypassed by the 2004 mainshock rupture, an interpretation supported by our data. The steeper dip of the downing plate indicated by the focal mechanisms may help explain the normal mode recordings of the 2004 earthquake; Park et al. (2005) argue for a more steeply dipping fault plane than the 8°–10° of the Harvard CMT solution in order to efficiently excite the observed high-amplitude long period modes. Also notable in Figure 11 is a cluster of events between the deformation front (DF) and the West Andaman fault (WAF) in which earthquakes with normal-faulting mechanisms appear (within the limits of a ± 10 km EHB depth resolution) to form a lower plane of seismicity below earthquakes that have strike-slip mechanisms.

For oceanic subduction zones such as the Andaman Trench, Hyndman et al. (1997) suggest that the downdip limit of subduction zone megathrust activity occurs when the downgoing plate encounters the upper forearc mantle before temperatures reach 350°C, the onset of ductility in common subduction component materials. Previous studies along the Sunda Trench have shown that the locked portion of the seismogenic zone extends to 35- to 57-km depth (Bock et al., 2003; Simoes et al., 2004; Subarya et al., 2006). The upper plate Moho intersects the oceanic plate at ~30-km depth along Sumatra but at temperatures below 350°C (Simoes et al., 2004). Using average shear stresses between 20 and 40 MPa and a range of slab dips, Subarya et al. (2006) estimate the 350°C isotherm occurs at 40-km depth from northern Sumatra to the northern Andaman Islands. The aftershock sequences of the 2004 and 2005 mainshocks are consistent with the observation that the subduction megathrust extends below the Moho/plate interface intersection (Simoes et al., 2004). Understanding how seismicity nucleates at these depths where the downgoing slab should be intersecting usually fractionally stable upper mantle remains an area of future research.

At ~5.5° N there is a marked transition in the distribution of aftershocks of the 2004 earthquake that broadly corresponds to changes in the physical properties of the plate interface (Kennett and Cummins, 2005). However, it is not clear how this transition corresponds to the second region of significant slip apparent in many mainshock rupture models (e.g., Ammon et al., 2005; Ishii et al. 2005). To the south in the northern Sumatra sector, from the trench axis to more than 100 km landward, only small magnitude aftershocks developed (Fig. 4c, 5), while further landward we find the dense cluster of thrust-fault aftershocks at 35- to 70-km depth discussed previously. North of 5.5° N the situation reverses. The large magnitude earthquakes occur closer to the trench axis, and there are few aftershocks farther than ~75 km from the trench (Fig. 4c, 5). These aftershocks display a wide range of focal mechanisms. North of 9° N the aftershock activity associated with the subduction interface decreases noticeably before increasing again in the Andaman Islands.

The 2004 Ms 9.0 underthrusting earthquake triggered along the Andaman backarc north of Sumatra one of the largest earthquake swarms instrumentally recorded (Lay et al., 2005). This region is a transition area between the Sumatra fault and developing Andaman backarc spreading center (Figs. 1, 4). Temporally, the events extended from late January 2005 through mid February 2005, although activity has continued there through September 2005 (albeit at a lower rate). The swarm included many moderate magnitude events with well-constrained CMT solutions in the 0- to 35-km-depth range (Fig. 12). Prior to the 2004 event, seismicity was characterized by strike-slip focal mechanisms consistent with features accommodating right-lateral oblique convergence, such as the West Andaman fault and the Sumatra fault (Fig. 7b). Most of the earthquakes following the 2004 event are consistent with right-lateral strike slip, but there are also a number of normal-faulting mechanisms oriented perpendicular or near perpendicular to the predominant strike-slip faults in this region (Figs. 7c, 12). The normal-faulting events occur along a linear trend between 10- and 20-km depth. The orientation of the normal-faulting events within the developing transform fault strands is consistent with formation or reactivation of a small ocean spreading feature. This swarm of events may alternately represent an injection event such as dike formation at depth, an incipient spreading event at the seafloor, or a pull-apart basin. The relative locations of the events in the EHB catalog should be fairly good within such a small region, but the absolute depths may
ern extent of the Andaman microplate and the northern boundary of the diffuse deformation that marks the formation of the microplate (e.g., Sieh and Natawidjaja, 2000). Subarya et al. (2006) suggest the boundary is related to a north–south trending fracture zone on the subducting plate, and Singh (2005) suggests the West Andaman fault in the upper plate plays a role in directing 2004 mainshock rupture to the north. An offset of ~150 km in the volcanic line between the northern and southern Sumatra sectors (Fig. 4) is mirrored by an apparent similar offset in the seismic zone of the downgoing plate, as well as by a change in its dip angle (Fig. 6). An offset or bend in the downgoing plate is suggested as it transitions into the southern boundary of the Andaman microplate (see also Dewey et al., 2007), perhaps also giving rise to higher stresses leading to major events in this region, such as the 2002 earthquake.

Following the March 2005 Nias Island earthquake, a cluster of eight $M_w \geq 5.5$ events occurred near Sibemet Island (Fig. 4d). Many of the earthquakes were aftershocks of an $M_w \geq 6.7$ event on 10 April 2005. This region is relatively seismically active compared to the remainder of the Andaman and Sunda margin, with prior $M 7+$ events in 1935, 1946, 1984, and 1998 that are notable in the cluster of seismicity seen in Figure 4b near Sibemet Island. This increase of seismicity occurs at the northern end of the apparent rupture limits of the 1797 and 1833 great earthquakes and southern end of the 1861 great earthquake (Fig. 1). The region also overlies the subducting north–south trending Investigator Fracture Zone, which may serve as a barrier to along-strike rupture during great earthquakes offshore southern Sumatra (Fauzi et al., 1996; Sieh and Natawidjaja, 2000; Rivera et al., 2002). The most recent earthquakes exhibit a small degree of spatial separation from the pre-2004 seismicity. In map view, pre-2004 seismicity is centered in the northern part of the larger island immediately to the south of Sibemet, while post-2005 seismicity lies due east of the southern tip of Sibemet (Fig. 4b,d). There are also notable differences in focal mechanism solutions between the two seismicity clusters. Both time periods are dominated by shallow-dipping thrust mechanisms, but the post-2005 seismicity has a steeper shallow-dipping plane by ~36° (Figs. 8b,d, 9b,d, 10b,d). In depth, post-2005 seismicity in the Sunda sector shows little overlap with prior underthrusting seismicity in the region (Fig. 6e).

Summary

The spatially extensive, and ongoing, aftershock sequence of the $M_w \geq 9.0$ Sumatra–Andaman Islands earthquake will potentially reveal many complex details about subduction zone processes and microplate formation. In this study, well-constrained teleseismic, earthquake locations of the 2004 and 2005 aftershocks and prior seismicity, combined with well-constrained CMT solutions, help to clarify how strain is accumulated and released along the subduction zone during a great earthquake sequence.
The Andaman microplate appears to have been seismically active across its full extent during the 1918–2005 period of teleseismic instrumental locations, including a high level of shallow-depth backarc seismicity near the eastern microplate boundary. As noted in previous studies, most earthquakes in the Andaman microplate and Sunda regions occurring during the period prior to the 2004 and 2005 great earthquakes are located downdip along the interplate zone at depths greater than 35 km, with a distinct near absence of seismicity trenchward. Aftershocks of the 2004 event, but occurring prior to the 2005 earthquake, locate trenchward at depths less than 35 km, filling in areas with an absence of previous seismicity in the Andaman microplate. The 2004 aftershock pattern is consistent with a ~1300-km-long mainshock rupture when unfolded along an arc through its point of initiation, with the downdip width of the aftershock zone varying from ~200 km at its northern end to ~275 km at its southern end. Northernmost aftershocks of the 2005 Nias Island event abut the southernmost aftershock zone of the 2004 mainshock. This boundary may represent a large-scale upper or lower plate structure that controls 2004 and 2005 mainshock rupture extent and the directivity of the 2004 earthquake (DeShon et al., 2005; Singh, 2005; Subarya et al., 2006).

In this study we observe a number of new features in seismicity along the Andaman and Sunda margin, including the following:

- The unprecedented duration and rupture complexity of the 2004 mainshock is reflected in the temporal history of the aftershock sequence and seismic moment release along the margin. At ~5.5°N there is a marked transition in the distribution of aftershocks of the 2004 earthquake that broadly corresponds to changes in the physical properties of the plate interface (Kennett and Cummins, 2005).
- Cross sections reveal a trenchward shallow-dipping seismic zone, presumably along or close to the plate interface, followed by a gradual downturn of the interplate seismic zone into the mantle at dip angles increasing from northern Sumatra to the Andaman Islands.
- The shallow dip angle of trenchward aftershocks (<10°), the apparent thickness of the aftershock zone (~10 km, but limited by the EHB depth uncertainty), the increase landwards of the dip angle (15°–20°) of intense interplate aftershock activity, with a downdip depth limit of ~50 km at a distance of ~240 km inward from the trench axis, and the lack of deeper aftershocks in the subducting slab are consistent with the local earthquake locations calculated using OBS data offshore northern Sumatra.
- Most aftershocks of the 2004 and 2005 events are confined to depths less than 70 km, are consistent with underthrusting along the megathrust fault, and are also consistent with the thrust focal mechanisms of the mainshocks, with P axes occurring normal to and B axes occurring parallel to the local strike of the trench.
- Following the 2004 earthquake, there was an increase in outer-rise normal-faulting earthquakes and many thrust earthquakes occurred at or near the trench.
- Most aftershocks between 35- and 70-km depth occurred in a spatially limited region offshore northern Sumatra and were consistent with thrust faulting along a plane, possibly the plate interface, dipping 27 ± 4° and extending to ~60-km depth.
- High aftershock activity along backarc ridge-transform faults indicates accompanying slip partitioning along that boundary. An intense earthquake swarm occurring about a month after the 2004 mainshock along the Andaman backarc north of Sumatra was characterized by shallow-depth earthquakes consistent with right-lateral strike-slip, but also including a number of normal-faulting mechanisms oriented perpendicular or near perpendicular to the predominant strike-slip faults in this region along a linear trend.
- Following the 2005 Nias Island earthquake, a cluster of eight \( M_w \geq 5.5 \) events occurred south of the mainshock near Siberut Island in a region overlying the subducting north–south trending Investigator Fracture Zone, which may serve as a barrier to along-strike rupture during great earthquakes offshore southern Sumatra.

The resolution of the current study has been limited by the nature of the teleseismic catalog data used. Future work on earthquake relocation including, but not limited to, relative event location and waveform cross-correlation could further illuminate the broadscale features discussed in this study.

Data Sources

A compressed hypocenter data file (SUMA.HDF.gz) of relocated earthquakes occurring in the Sumatra region during the period 1918–2005 and a format description (FOR-MAT.HDF) can be obtained by e-mail request to the first author at engdahl@colorado.edu.

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