The Tectonic Framework of the Sumatran Subduction Zone

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Key Words

Sumatra, subduction, earthquake, hazards, geodesy

Abstract

The great Aceh-Andaman earthquake of December 26, 2004 and its tragic
consequences brought the Sumatran region and its active tectonics into the
world's focus. The plate tectonic setting of Sumatra has been as it is today
for tens of millions of years, and catastrophic geologic events have likely
been plentiful. The immaturity of our understanding of great earthquakes
and other types of geologic hazards contributed to the surprise regarding
the location of the 2004 earthquake. The timing, however, is probably best
understood simply in terms of the inevitability of the infrequent events that
shape the course of geologic progress. Our best hope is to improve under-
standing of the processes involved and decrease our vulnerability to them.

INTRODUCTION

The island of Sumatra (**Figure 1**) forms the western end of the Indonesian archipelago and until recently was perhaps best known to the world for its coffee, though perhaps not so much as Java, its neighbor to the east. For geologists, who learn largely from the past, it has been there that many important geologic processes have been studied and thus better understood. Some of these processes, like those leading to the recent earthquakes, have global consequences. The massive eruption of Toba Caldera ∼74,000 years ago is among the largest known and had a profound impact on the evolution of humans by modification of the Earth's climate (Rampino & Self 1992). The eruption of Krakatoa, between Java and Sumatra, in 1883 had a lesser impact on climate but possibly a large effect on the region's cultural and economic development. According to Simon Winchester in his book *Krakatoa* (Winchester 2003), the eruption and tsunami were among the first global catastrophes; that is, they occurred during the earliest days of rapid international communication networks. The December 2004 earthquake again thrust Sumatra into the world's attention with home videos, photos, and personal accounts of unimaginable human loss and tragedy.

Compared with subduction zones near developed countries like Japan and the United States, the subduction zone offshore Sumatra received relatively little attention prior to the 2004 earthquake and tsunami. In their book, *The Geology of Earthquakes*, Yeats et al. (1997) only briefly mention Sumatra in the chapter on subduction zone megathrusts. The newfound attention following the
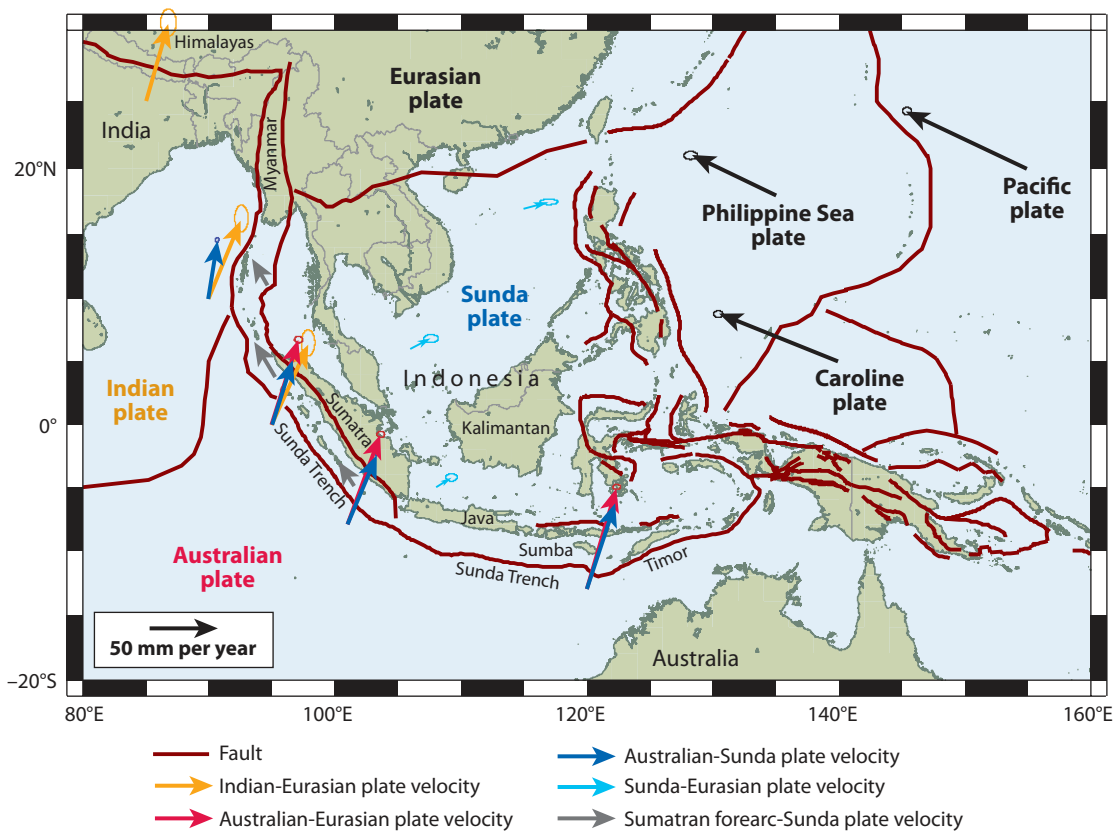

Figure 1

Plate tectonic setting of Sumatra. Vectors show relative velocities of plate pairs as labeled.

tragedy provides an important opportunity for earth scientists to educate the world on the seriousness of earthquake and tsunami hazards for many regions, especially those that may seem harmless at present, as northern Sumatra and the Andamans did before 2004.

This review is not of the great earthquake sequence, as there are many papers covering that, but is instead focused on its setting. Understanding the tectonic background and geologic history of Sumatra is useful in recognizing that great earthquakes and other catastrophic geologic events are rare only from the short-lived human perspective. Disaster stems not from the occurrence of these natural events but instead from our continued vulnerability to their effects.

SUMATRA: A GEOLOGIC TREASURE HUNT

For students of the Earth, Sumatra has long been a field laboratory for studies of important geologic processes. Reid (1913) used geodetic observations before and after the 1892 Tapanuli earthquake on the Sumatran fault to support his fledgling idea of elastic rebound that gained additional support as a result of the 1906 San Francisco earthquake. Early Dutch and Indonesian geologists used the geological and geophysical properties of Sumatra and Java to develop and promote now-out-of-date ideas about a geosynclinal cycle to explain the juxtaposition of sediments, volcanic rocks, and trench structures. Many of these ideas were applied to explain the older European Alps. Deep-water, submersible-based gravity measurements in the Sunda trench by Vening Meinesz (1954) revealed the great isostatic disequilibrium of deep-sea trenches. The gravity anomalies were later shown to be due to bending of the subducting plate and infilling by and accretion of low-density sediments, important aspects of subduction. The unparalleled exposure of the nonvolcanic forearc ridge (the offshore island chain stretching from Simeulue to Enggano) off Sumatra allowed better understanding of accretionary wedge tectonics worldwide (e.g., Moore & Karig 1980).

Starting with the work of Fitch (1972), Sumatra is often cited as the classic example of slip partitioning, which occurs when the relative motion between two obliquely converging plates is taken up on multiple, parallel faults. We now see that this process probably occurs in numerous other fault systems worldwide (Jarrard 1986, McCaffrey 1992). A study of 17th to 19th century Sumatra earthquakes by Newcomb & McCann (1987), through the written accounts of ground shaking and tsunami waves, remains one of the more thorough such works in the field of paleoseismology. More recently, the life and death of near-coastal corals of Sumatra and its western islands have revealed the detailed histories of vertical motions related to the earthquake cycle (Zachariasen et al. 1999). Finally, the rare sequence of great and large earthquakes in Sumatra starting in December 2004 has given us the best opportunity to date to observe and monitor with modern methods and instrumentation a great subduction zone earthquake and its aftereffects. No doubt many more insights into the workings of the Earth will come from continued attention to the Sumatran region.

SUMATRA AND PLATE TECTONICS

The extensive descriptions and interpretations by Hamilton (1974, 1979) were among the first to put Indonesia into the context of the (then) new framework of global plate tectonics. In this view, now accepted by most geologists, the subduction zone southwest of Sumatra is part of a long convergent belt that extends from the Himalayan front southward through Myanmar, continues south past the Andaman and Nicobar Islands and Sumatra, south of Java and the Sunda Islands (Sumba, Timor), and then wraps around to the north (**Figures 1** and **2**). This trench accommodates the northward motion of the Australian plate into Eurasia. (The trench is known by several local names but here called the Sunda subduction zone in general and sometimes the Sumatran
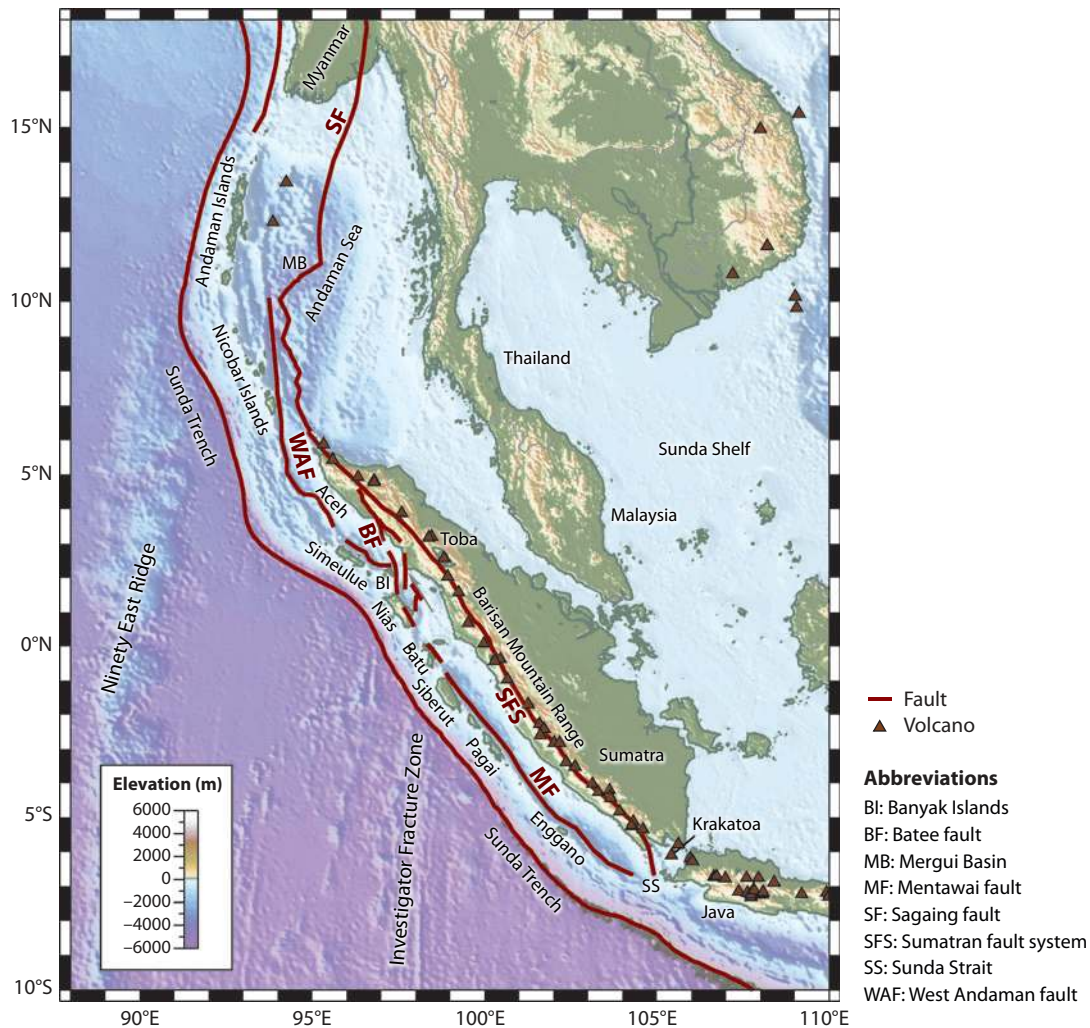
Figure 2

Physiographic map of the Sumatran region. The triangles are locations of active volcanoes. The thick red lines are faults. Data from the Global Volcanism Program, **www.volcano.si.edu.**

subduction zone when referring to the stretch offshore Sumatra.) West of Sumba, the dense lithosphere of the Indian Ocean seafloor subducts beneath the continental Sunda shelf, whereas to the east, the lighter continental Australian lithosphere thrusts beneath the oceanic lithosphere. The along-strike change in the average density of lithosphere being subducted coincides with changes in the character of the tectonics. Eastern Indonesia is outside the scope of this review and is not discussed further (see Hamilton 1979 and Bowin et al. 1980 for discussions).

Sumatra is situated on the Sunda continental margin and exposes granitic rocks as old as 240 Ma (Hamilton 1979). Broadly put, from northeast to southwest, the island's geology is characterized by oil-bearing sedimentary basins in the northeast, the Barisan mountains (**Figure 2**), which include the volcanic arc and Sumatran fault, running along the length of the island near the southwest coast, the offshore forearc basins, the forearc high (islands of the Simeulue-Enggano ridge), the

deep trench, and the subducting oceanic plate. Hamilton (1979) suggests that Sumatra was rifted from the northern edge of Australia (north of New Guinea) during the Triassic to early Jurassic (∼200–250 Ma). Sumatra would have been a stable continental margin from then until subduction began in the Cretaceous (possibly ∼100 Ma).

The 100-km-wide Barisan Mountains, the backbone of Sumatra (**Figure 2**), include pre-Tertiary rocks covered by Cenozoic volcanic rocks. The structural central graben led van Bemmelen (1949) to conclude it was a rift structure and that the Sumatran fault was dip-slip in nature. Subsequent work revealed it to be a transform (transcurrent) faulting structure (Katili & Hehuwat 1967), and modern GPS measurements reveal no extension across it (Prawirodirdjo et al. 1997). At the latitude of Toba Caldera (2°N) (**Figure 2**), the range broadens into what van Bemmelen called the Batak Tumor (named after the Batak people who inhabit the Toba region of Sumatra), a two-kilometer-high bump in the range that includes 500-m-deep Toba Lake, the surface of which is at 900 m above sea level.

The active volcanoes of Sumatra fall along the Barisan mountains (**Figure 2**) and, like most arcs, are generally parallel to the subduction zone and above the ∼100 to 150 km depth contours of the subducted plate (Hatherton & Dickinson 1969, Sieh & Natawidjaja 2000). This pattern of subduction-related volcanism has persisted since at least Oligocene time (Hamilton 1979). The modern arc rocks are andesite, dacite, and rhyodacite to rhyolite, and their strontium ratios indicate variable amounts of crustal contribution. The volcanic arc continues to the north, forming the islands of Barren and Narcondam, both ∼100 km east of the Andaman Islands (**Figure 2**). Even farther north, inactive volcanoes in Myanmar may form part of the same chain (Curray 2005). Thus the volcanic rocks reveal a long history of subduction along the entire southwestern margin of Sunda.

Approximately 74,000 years ago, more than 2800 km^3 of dacite and rhyolite were ejected from the Toba caldera complex (Chesner et al. 1991), a 100 by 30 km topographic depression in the arc. The Toba depression overlies two magma reservoirs in the shallow (<10 km) crust, one of which appears to be at least 40 by 60 km across (Masturyono et al. 2001). These reservoirs also fed caldera-forming, ash-flow eruptions at 0.5 and 0.84 Ma. The eruption at 74 ka is thought by some to have produced a near extinction of the human population (Rampino & Ambrose 2000).

SORTING OUT THE PLATE KINEMATICS

The plate kinematics of the Sumatran region is, in a broad sense, the simple interaction of the Indian-Australian and Eurasian plates (**Figure 1**). However, in detail it is much more complex than that. The subducting Indian-Australian plate comprises two separate plates that are bounded by a broad, slowly deforming region (DeMets et al. 1994) currently being subducted at the Sunda trench. The internal deformation of the subducting plate may lead to a centimeter per year or so of uncertainty in the convergence at the Sunda trench.

Deformation of the overriding plate leads to larger complexities in plate motions. Sumatra sits at the southwestern edge of the Sunda plate (Bird 2003), which moves at a few millimeters per year to a centimeter per year eastward relative to Eurasia (Chamot-Rooke & Le Pichon 1999, Bock et al. 2003) (**Figure 1**). The resulting convergence between the Sunda plate and the oceanic plates to the southwest is somewhat slower than it would be relative to Eurasia.

The rate and direction of subduction of the lithosphere under the Sunda forearc, however, are further modified by the independent motion of the forearc. Fitch (1972) explained the presence of the Sumatran fault and other similar faults inboard subduction zones by the process now known as slip partitioning. That is, in some cases of oblique subduction where the two plates do not converge at a right angle to the strike of the trench, it requires smaller overall shear force to

share the shearing (trench-parallel) component of the relative motion between two separate faults (**Figure 3a**) instead of on one fault. In the case of partitioning, one fault is the subduction thrust, which takes up all of the trench-normal slip (the dip-slip component) and some fraction of the trench-parallel slip (the strike-slip component). A second fault, within the overriding plate and commonly strike-slip in nature, takes up a portion of the trench-parallel motion. The subduction thrust and strike-slip fault isolate a wedge of forearc called the sliver plate (**Figure 3a**). The slip rates on the separate faults can be inferred from their geometries and knowledge of the overall convergence (**Figure 3b**).

The motion of the Sunda forearc (sliver plate) is not known well, particularly in the Andaman section, and hence the subduction vector is highly uncertain. Earlier estimates of the relative
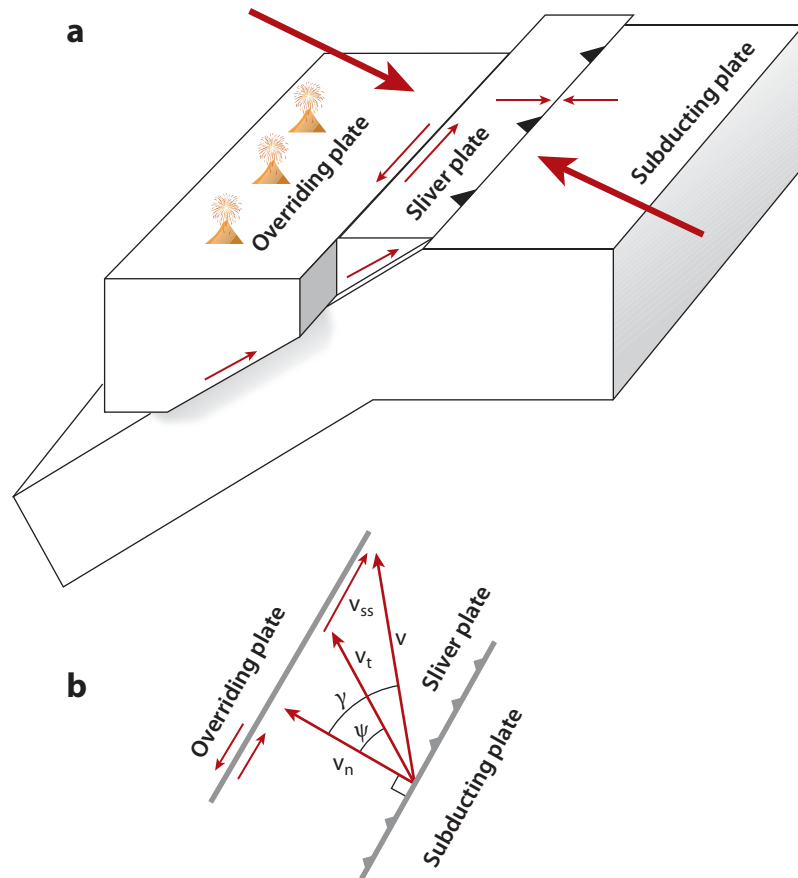

Figure 3

(*a*) Block diagram showing the geometry of the sliver plate and its motion under conditions of oblique subduction. The nonorthogonal (oblique) motion of the subducting plate under the overriding plate imparts along-strike shear stress at its base, which can detach the leading edge of the overriding plate forming the so-called sliver plate. The sliver plate slides laterally relative to the upper plate along a strike-slip fault (e.g., Sumatran fault) and thrusts over the subducting plate. (*b*) The vector geometry of such a system. Knowledge of the total relative motion vector V, the direction of V_{ss} (the strike-slip vector) from fault orientation, and the azimuth of V_t (the thrust vector) from earthquake slip vectors allows a unique solution to the triangle formed by V, V_t, and V_{ss}, providing estimates of the magnitudes of V_t and V_{ss}. ψ is the slip vector obliquity, γ is the convergence obliquity, and V_n is the velocity normal to the trench.

motions assuming a rigid forearc sliver plate failed to predict convergence in the Andaman section of the trench, which probably indicates, as is now accepted, that there is extensive internal deformation within the forearc. One possibility, evident in the change in earthquake slip directions along the margin (**Figure 4b**), is that the Andaman section (called the Burma plate) and Sumatran sections of the forearc move independently with a break near 6° to 7°N (Subarya et al. 2006).
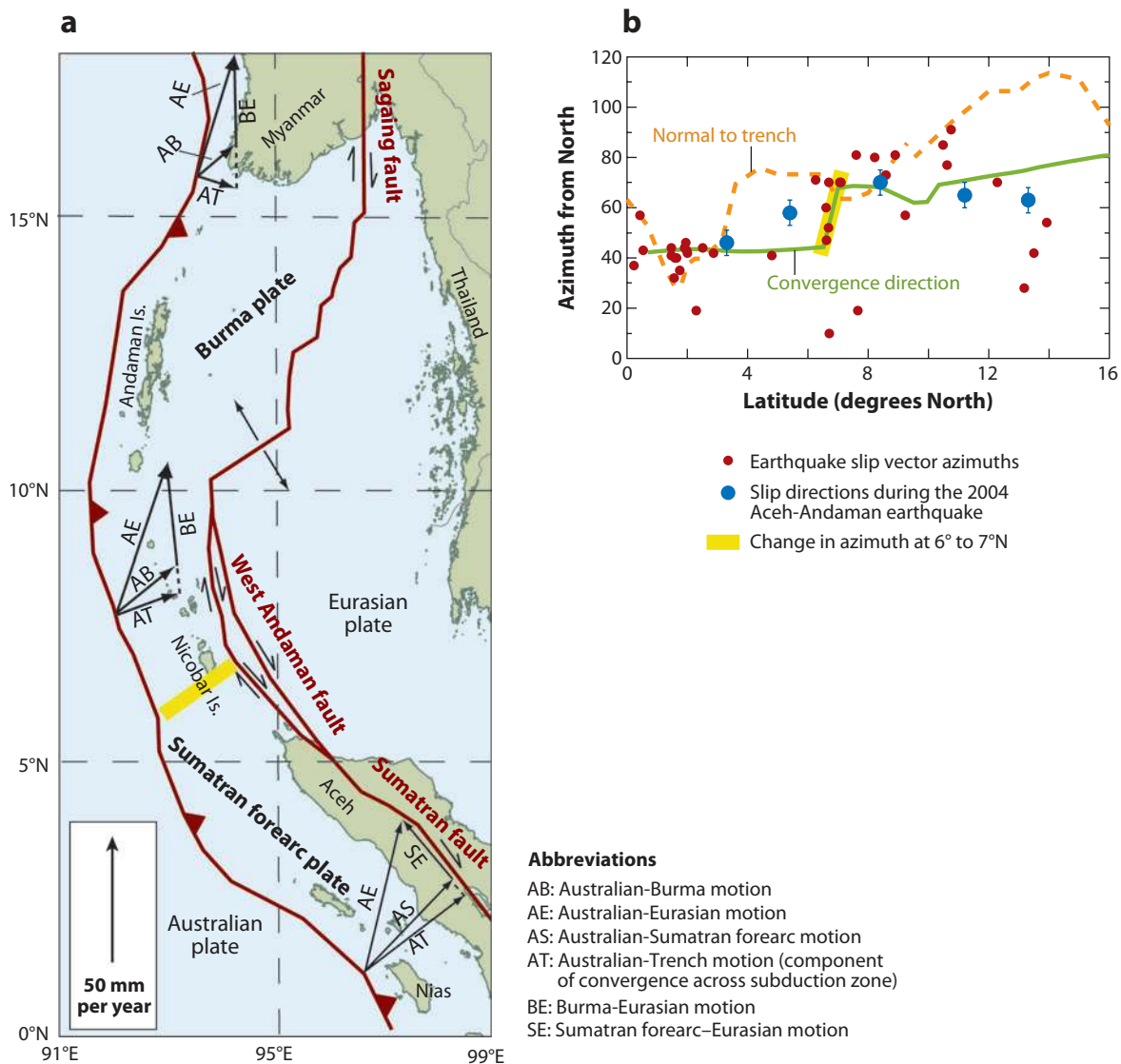
Figure 4

(*a*) Map showing possible relative motions of the Sumatran and Burma forearc plates relative to adjacent Indian-Australian and Eurasian (Sunda) plates. Adapted with permission from Curray (2005). The vector diagrams show the partitioning of the total convergence of Australia relative to Eurasia (vector AE) into components of subduction (vectors AS and AB) and strike-slip (vectors SE and BE). (*b*) Plot of earthquake slip vector azimuths (*red dots*), the direction normal to the trench and possible convergence directions based on motions of the Burma and Sumatran forearc plates. Blue dots are slip directions during the 2004 Aceh-Andaman earthquake inferred from seismograms (Tsai et al. 2005). The change in azimuths at 6° to 7°N suggests that the Sumatran and Burma forearc plates move separately.

The forearc sliver southwest of Sumatra is bounded on the northeast by the Sumatran fault and on the southwest by the Sunda trench. At its trailing boundary in the Sunda Strait, its motion is thought to be much slower (Huchon & LePichon 1984) than at its leading edge in the Andaman Sea (Curray et al. 1979), consistent with stretching of the forearc. The along-strike forearc extension is revealed by variations in the slip directions of earthquakes on the thrust fault (McCaffrey 1991). As is discussed below, such elongation of the forearc has the consequence of causing a northward increase in the slip rate on the Sumatran fault. Southwest of central Sumatra, slip vector and GPS velocities indicate that the Sumatran oblique slip system is partitioned with ∼2/3 of the shear component on the Sumatran fault and 1/3 of the shear on the subduction fault (Genrich et al. 2000, McCaffrey et al. 2000). Diament et al. (1992) suggested that the Mentawai fault is an active strike-slip structure, similar to the Sumatran fault, connecting with the Batee fault north of Nias (**Figure 2**), but Sieh & Natawidjaja (2000) give evidence that this system is currently inactive.

Convergence at the trench off Sumatra is likely 40 to 50 mm yr^{-1} (**Figure 4a**). To the north, because the orientation of the Andaman-Nicobar section of the trench (**Figure 4a**) (Curray 2005) is nearly parallel to the direction of relative motion, convergence is thought to be much slower, <20 mm yr^{-1}. The slow convergence was among the reasons that, prior to 2004, a great earthquake was not contemplated in the Andaman section of the subduction zone.

THE SUMATRAN FAULT

Among the outstanding features of the Sumatran subduction system is the 1900-km-long Sumatran fault. This fault is purely strike-slip, similar in many, but different in important, ways to the San Andreas fault in California. It extends the entire length of the island and coincides geographically with the volcanic arc through most of its length. An extensive study and review of the Sumatran fault is given by Sieh & Natawidjaja (2000).

The Sumatran fault, unlike other great transcurrent faults, is highly segmented (Katili 1974, Sieh & Natawidjaja 2000). Most segments are less than 100 km long, and only 2 of the 19 segments identified by Sieh & Natawidjaja (2000) are longer than 200 km. The segments are separated by step-overs of a few kilometers or more. The importance of the short segments and wide step-overs is that they limit the area that can slip in a single event, and magnitudes tend to be limited to M_w ∼7.5 or smaller throughout (see Earthquake Magnitude sidebar).

Estimates of the modern slip rate on the Sumatran fault vary depending on method and location along the fault. It is now generally accepted that the obliquity of the convergence along with a moving, stretching forearc block results in an increase in the slip rate toward the northwest. Using geometric considerations and earthquake slip vector directions as indicators of the thrusting

EARTHQUAKE MAGNITUDE

Earthquake size is now defined by the moment magnitude $M_w = 2/3 (\log M_o - 9.1)$ (Hanks & Kanamori 1979), where the seismic moment M_o is given by $\mu\, d\, L\, W$. The rigidity μ is an elastic constant that varies from ∼2 to ∼7 × 10^{10} N m^{-2} within the region of shallow earthquake activity. The factor L is the length of the fault, which can reach hundreds of kilometers for thrust or strike-slip earthquakes, and W is the dimension of the fault surface in the direction of dip into the Earth. The amount of slip in the earthquake d in general scales with L by a factor of ∼10^{-5} (Wells & Coppersmith 1994) so that magnitudes are largely determined by the slip area LW.

direction, McCaffrey (1991) estimated a uniform stretching rate of the forearc at 3 to 4 $\times$ 10^{-8} yr^{-1}, which predicts an increase in the Sumatran fault slip rate from ~6 mm yr^{-1} near the Sunda Strait (Bellier & Sébrier 1994, 1995) to ~25 mm yr^{-1} near the equator (Genrich et al. 2000), to ~50 mm yr^{-1} in the Andaman Sea. Seafloor magnetic anomalies have been interpreted as showing a slip rate in the Andaman Sea that is somewhat slower than predicted, ~36 mm yr^{-1} since 10.8 Ma (Curray et al. 1979). Estimates of slip rates from geologic features offset by the Sumatran fault and from GPS are generally consistent with this northwestward increase but differ in detail. The discrepancies are likely related to the specific geometry of the deformation that is not well understood. In any case, the Sumatran fault serves as a well-documented example of a strike-slip fault with varying slip rates along it.

Sieh & Natawidjaja (2000) review and present new geological evidence for the total offset on the Sumatran fault and conclude that it is no more than 25 km, though they note that an offset of as much as 100 km cannot be definitively ruled out. The low estimate is at odds with the estimates offshore the south and north ends of Sumatra. To the south, in the Sunda Strait, Huchon & LePichon (1984) suggest that the opening is ~100 km, though Sieh & Natawidjaja (2000) argue that the reasoning for this high estimate is circular (i.e., based ultimately on a presumed offset on the Sumatran fault). Sieh & Natawidjaja (2000) make a revised estimate of ~10 km by calculating the stretching adjacent to the Sumatran fault but also note that stretching of the forearc, as a whole, away from the fault could be as much as 100 km. To the northwest, spreading in the Andaman Sea would suggest a total of ~460 km of offset in the past 10 Ma (Curray et al. 1979). The reconciliation of the low observed offsets onshore with the large offsets offshore may be related to the youth of the onland offset features, particularly the volcanics along the Sumatran fault that reveal the offsets best (Sieh & Natawidjaja 2000).

The Sumatran fault, with its rich history of damaging earthquakes, is a source of considerable hazard to communities (Sorensen 2008). The mountains of Sumatra form a long linear chain within which sit many fertile, highly populated valleys. These valleys are predominantly fault-controlled; that is, they owe their existence to the presence of the Sumatran fault (Sieh & Natawidjaja 2000). Hough & Bilham (2006) point out many examples of such cases in which geologically risky settings are also the most appealing for human habitation. As in many developing countries, the hazards from earthquakes are exacerbated by building practices that inadequately reinforce masonry structures.

Some authors have suggested that trench-parallel faults like the Sumatran fault are localized by weakening of the crust due to high temperatures associated with magmatism (e.g., Beck 1983, Tikoff 1998). However, globally only a few trench-parallel strike-slip faults coincide with volcanic arcs. Sieh & Natawidjaja (2000) show that the young Sumatran volcanoes do not coincide in detail with the Sumatran fault (only 9 of 50 are within 2 km) but instead that the fault tracks the lower plate more. The divergence of the fault and volcanic arc is particularly clear around Toba caldera where a large bow in the slab deflects the volcanic arc northeastward while the Sumatran fault continues well southwest of the caldera (Fauzi et al. 1996). Finite element modeling by McCaffrey et al. (2000) suggests that the downdip shear stress distribution on the subduction interface is the main control on where the strike-slip localizes in the overriding plate. The coincidence of the Sumatran fault with the subduction fault geometry supports the stress control model, and the straightness of the Sumatran fault might further suggest that the long-term stress on the Sumatran thrust is fairly uniform along strike.

Following the 2004 and 2005 thrust earthquakes on the Sunda subduction zone, some workers expected earthquakes to be triggered on the Sumatran fault (McCloskey et al. 2005, Nalbant et al. 2005, Sorensen 2008). The reasoning is that slip on the subduction interface decreases the stress

normal to the Sumatran fault and brings it closer to failure by increasing the ratio of the shear stress to the normal stress. Such earthquakes have yet to occur as of this writing (July 2008). One possibility for the absence of the expected Sumatran fault earthquakes is that it takes a long time for the stress changes to act in the Earth owing to fluids that modify the stress field (poro-elastic effects). Another possibility, suggested by the mechanics of oblique subduction in which both the shear and normal stress on the strike-slip fault are derived from the thrust interface (McCaffrey 1992, Platt 1993), is that the stress drop in the thrust earthquake changed the normal and shear stress on the Sumatran fault proportionally, thus bringing it neither closer nor farther from failure. Such a mechanism could explain the lack of induced seismicity on the fault following the large earthquakes.

FOREARC RIDGE

A fortuitous feature of the Sunda subduction zone is the nonvolcanic forearc ridge that pops up above sea level forming many islands between the trench and the mainland. The islands allow near-trench, land-based observations that are not possible at most other subduction zones. The forearc ridge is the top of a thick sequence of sediments and sections of sea floor, known as the accreted wedge, that are folded, faulted, and plastered onto the upper plate (**Figure 5**). The presence of the Andaman and Nicobar Islands and those off Sumatra is likely a consequence of the large volume of sediment that comes southward from the Indian-Eurasian collision and uplift of the Himalayas. Southwest of Sumatra, the islands from Enggano in the southeast to Simuelue in the northwest form the portion of the ridge within Indonesian territory (**Figure 2**). Farther to the north, the Nicobar and Andaman Islands form the outer arc ridge. (These islands are politically Union Territories of India.) The rocks of the Andaman and Nicobar Islands are ophiolites (upper sections of the oceanic lithosphere) and seafloor sediments scraped off the subducting Indian plate that are folded and faulted into the ridge structure (e.g., Curray 2005). The islands also expose younger sediments deposited in the forearc setting. The islands may have been formed in Oligocene or late Eocene, ~35 Ma, though subduction may have started much earlier (Curray et al. 1979). Active deformation of the incoming sediments at the trench attests to ongoing convergence.
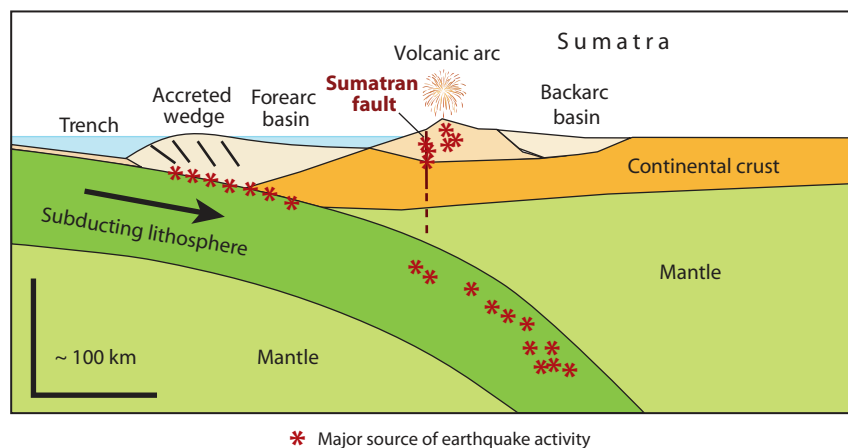

✳ Major source of earthquake activity

Figure 5

Schematic cross-section of the Sumatran plate boundary.

The islands offshore southwestern Sumatra probably have a similar origin. The best-studied of these is Nias, whose southwest coast is ~90 km from the subduction deformation front and ~20 km above the dipping plate interface. Southwest of Nias, the oceanic seafloor is seen dipping at a uniform angle of ~6° to 7° toward Nias for a horizontal distance of 25 km under the accretionary wedge, where it reaches a depth of just over 10 km (Moore & Curray 1980). From there, the interface may dip at 8° to reach a depth of 19 km beneath the coast of Nias (Kieckhefer et al. 1980). The wedge above the dipping plate interface comprises packages of trench sediments separated by thrust faults (imbricate thrust structure). Moore & Curray (1980) suggest that most of the incoming sediment is scraped off to form the wedge.

On Nias itself, the lowest exposed units are tectonic mélanges. These are highly deformed bodies containing angular sedimentary inclusions within a sheared matrix. Moore & Karig (1980) interpret these to be "deformed trench-fill turbidites and slices of oceanic crust and sediments that were accreted to the base of the inner trench slope." The mélanges are overlain by deformed Neogene strata interpreted to be uplifted sediments that formed in trench-slope basins. Thus, Nias is seen as a product of the uplift and thickening of the incoming oceanic crust and sediments at the Sunda trench.

SEISMICITY

Indonesia is among the most active regions of the Earth in terms of earthquakes, owing to the confluence of multiple plates moving at very high relative speeds. Earthquake activity around Sumatra has multiple sources: thrust earthquakes on the subduction fault, strike-slip earthquakes on the Sumatran fault, deeper earthquakes within the subducting lithosphere, and volcanic earthquakes (**Figures 5–9**).

The largest of these earthquakes are associated with subduction thrust faults, where slip on the boundary between the subducting and overriding plate can take place over a very wide area. The maximum depth to which slip occurs during crustal earthquakes may be temperature limited, and thus, under normal conditions, crustal earthquakes are shallow. Hence, for a near-vertical strike-slip fault like the Sumatran fault, W will at most be ~20 km, and the earthquake magnitude M_w is typically less than ~8.0. In fact, M_w for earthquakes on the Sumatran fault appears to be limited at ~7.6, possibly also due to the high degree of segmentation (i.e., limiting L) as noted earlier. Earthquakes on the Sumatran fault are shallow strike-slip events and reveal right lateral motion (**Figure 8**); that is, the southwest side of the fault moves northwest relative to the northeast side. In the past two centuries, the Sumatran fault has produced more than a dozen notable and damaging earthquakes (**Figure 10**).

Because subduction thrust faults dip at much lower angles (<30°) into the Earth and because the sliding of the cold upper portions of the oceanic lithosphere deep into the Earth cools the fault to greater depths, W in subduction thrust earthquakes can reach hundreds of kilometers, thus allowing much larger earthquakes to take place. For this reason, most earthquakes around the world that reach magnitudes in excess of 8.0 are at subduction zones.

The Sumatran subduction zone has many underthrusting earthquakes (**Figures 6–8**). The average dip angle of the thrust fault estimated from the earthquakes is ~20°, and the earthquakes are observed down to depths of ~50 km or greater. Hence, the potential slip width W in a great earthquake is ~50 km/sin (20°) ≈ 150 km, or ~10 times larger than on the Sumatran fault. In a global study of 19 subduction zones, Pacheco et al. (1993) estimated that W was the largest for the Sumatran subduction zone.

To digress briefly, Pacheco et al. (1993) also found that the deepest underthrust earthquakes of the zones studied were found south of Java. The Java section, in pre-2004 thinking based on

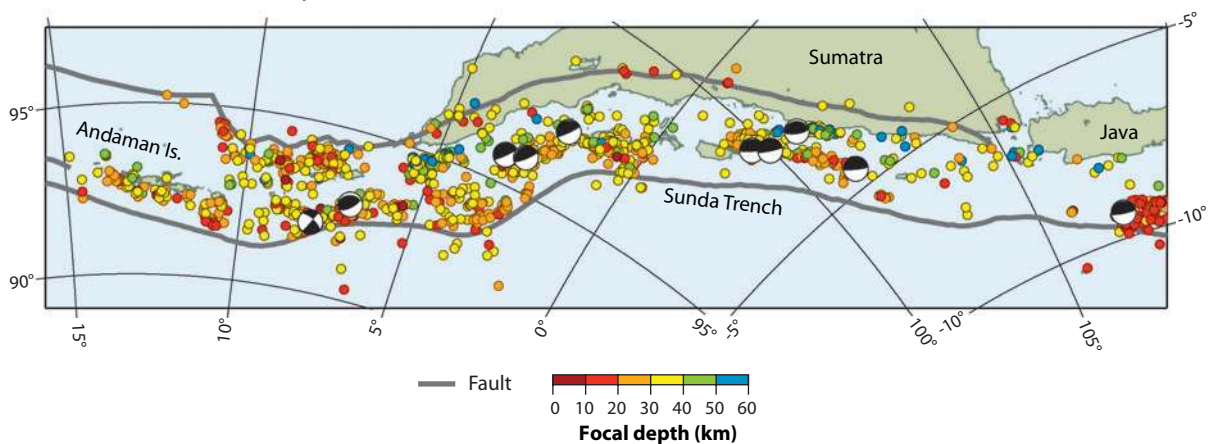**a**   **January 1973 to December 2004**
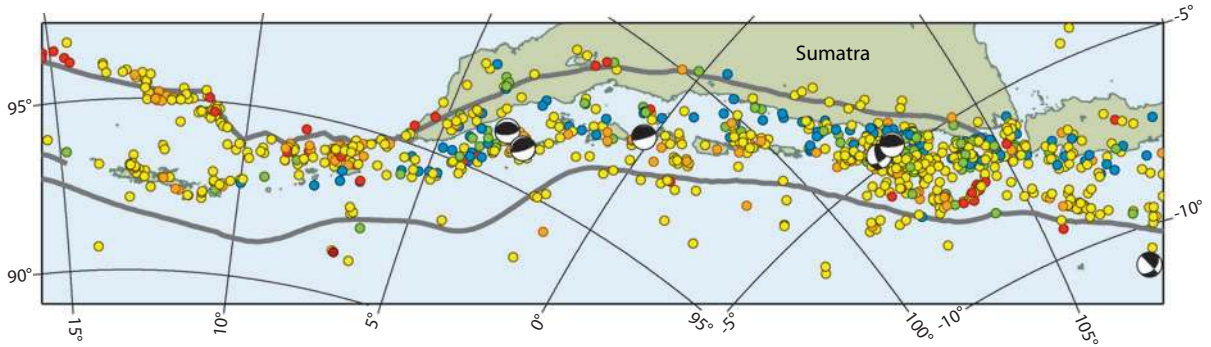
b   **December 2004 to July 2008**

Shallow earthquakes of $M_b \geq 5.0$. (*a*) Earthquake activity in the 31 years leading up to the December 2004 earthquake. Focal mechanisms are from the CMT catalog 1976 to December 2004 for all earthquakes of $M_w \geq 7.0$. (*b*) Same as in part *a*, except for the period after the December 2004 earthquake. The Andaman-Nicobar segment of the subduction plate boundary was very quiet prior to 2004. Earthquake data from the U.S. Geological Survey, National Earthquake Information Center, **http://neic.usgs.gov/neis/epic/**.

subducting plate age and convergence rate (Ruff & Kanamori 1980) and a short earthquake history, like the Andaman section, was among the subduction zones unlikely to produce a great earthquake. The island of Java, with ∼130 million people, is the most populous island and is among the most densely populated in the world. Its subduction segment should instead, in a post-2004 view, be considered among the most hazardous.

Earthquakes deeper than ∼50 km at a subduction zone are generally within the subducted lithosphere (**Figure 9**) and reveal its location within the mantle. Along the Sunda margin, we see that the deepest earthquakes, those at depths in excess of 500 km, are plentiful beneath Java and form a near-vertical zone, revealing a very steeply dipping slab. West of ∼105°E longitude, the bottom of the deep seismic zone shallows to ∼300 km, and farther northwest, beneath the Andaman Islands, it reaches a depth of only 150 km. The maximum depth of earthquakes in the subducting slab appears to correlate with the rate of subduction perpendicular to the
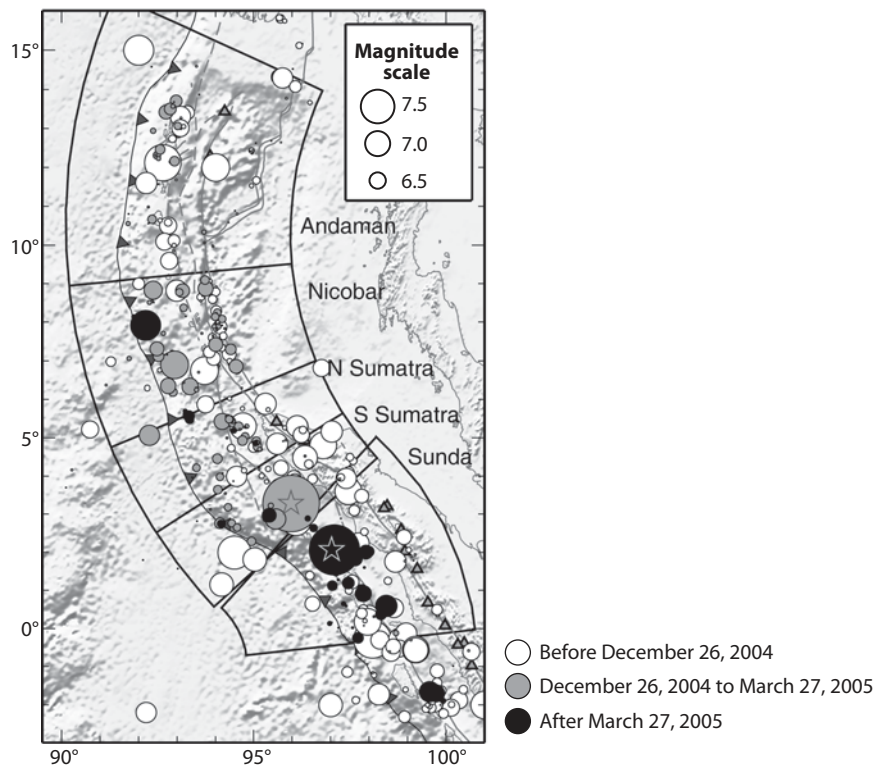
Figure 7

Map of earthquake sizes before and after the great earthquakes of December 2004 and March 2005.
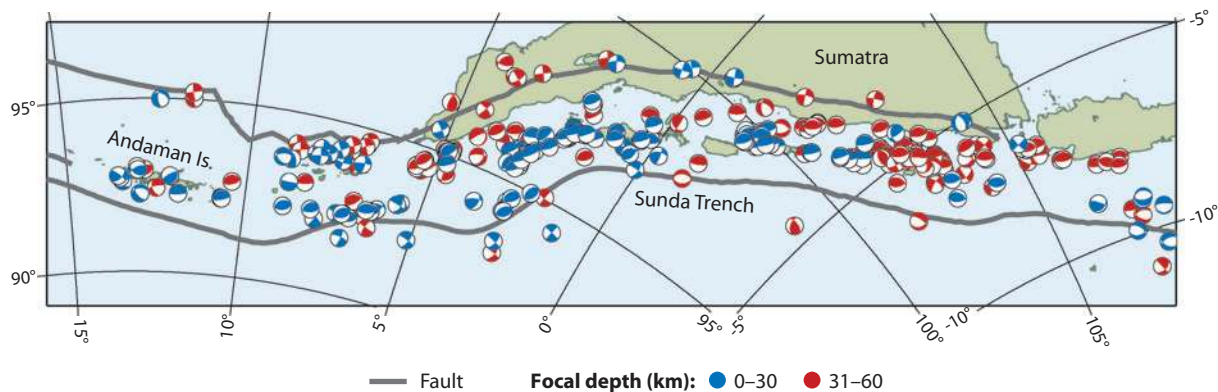Reproduced with permission from Engdahl et al. (2007).

Figure 8

Centroid moment tensor solutions for shallow depth earthquakes of $M_w \geq 5.7$ along the Sunda margin from 1976 to 2008. Earthquakes along the subduction zone are predominantly thrust earthquakes, and those along the Sumatran fault and the Andaman Sea are right-lateral strike-slip earthquakes. Data from Global CMT Project **http://www.globalcmt.org/**.
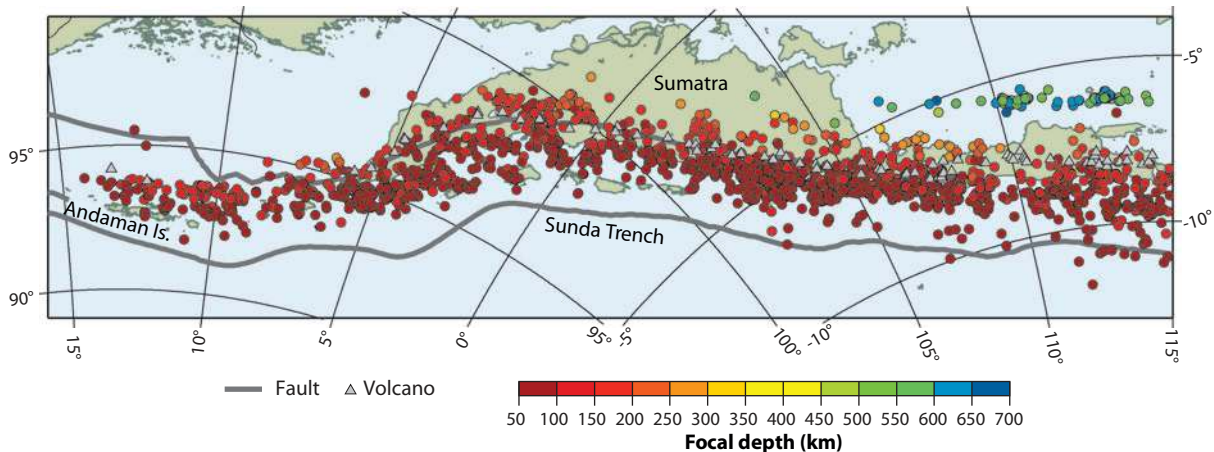
Figure 9

Deep earthquakes of $M_w > 4.5$ from January 1973 to July 2008 along the Sumatran margin are color coded by focal depth ranges. Data from the U.S. Geological Survey, National Earthquake Information Center, **http://neic.usgs.gov/neis/epic/**.

margin—maximum earthquake depth in kilometers is ~10 times the subduction rate in mm yr^{-1}. This correlation of earthquake depth with convergence rate has been observed at many subduction zones and led to the notion in the early days of plate tectonics that deep earthquakes are thermally shut down after the slab has spent ~10 Ma in the mantle (Isacks et al. 1968).
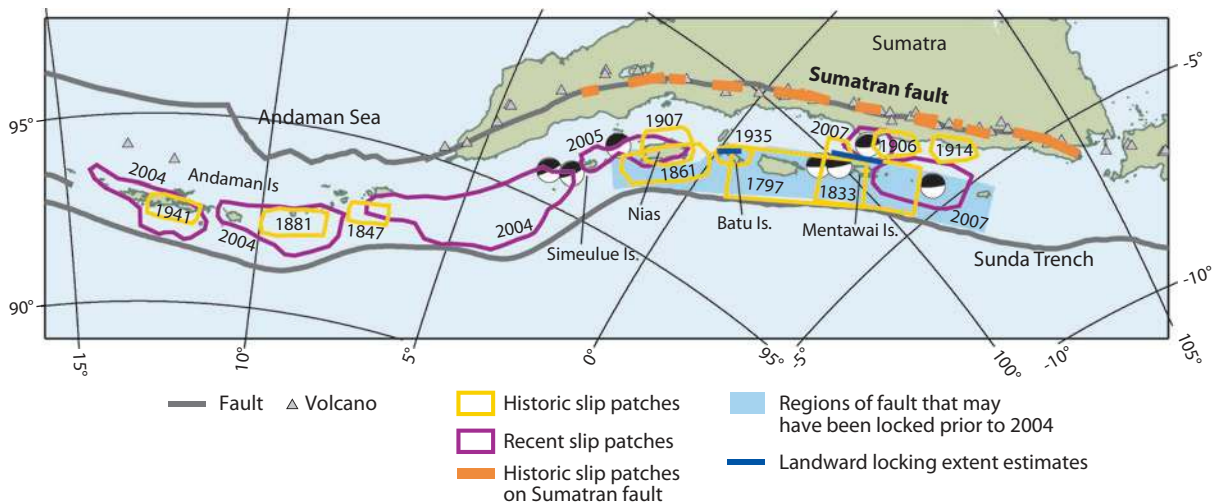
Figure 10

Map of the Sunda margin showing approximate regions of coseismic slip and regions where the subduction fault may have been locked prior to 2004. Slip patches are labeled by year of earthquake occurrence. Regions of fault that may have been locked prior to 2004 are compiled from Prawirodirdjo et al. (1997) and McCaffrey (2002). Landward (downdip) locking extent estimates (*thick blue lines*) are from Zachariasen et al. (1999) and Natawidjaja et al. (2007) for the Mentawai Islands region and from Natawidjaja et al. (2004) for the Batu Islands region. Earthquake slip sources: 1847, 1881, and 1947 Andaman from Bilham et al. (2005); 1861, 1906, 1907, and 1914 Sumatran forearc from Newcomb & McCann (1987); 1797 and 1833 from Natawidjaja et al. (2006); 2004 slip from Subarya et al. (2006); 2005 slip from Briggs et al. (2006); 2007 slip from USGS seismological slip models at **http://earthquake.usgs.gov/regional/world/historical.php**. Historic slip patches on the Sumatran fault are from Sorensen (2008).

A PLACE TO LEARN ABOUT GREAT SUBDUCTION EARTHQUAKES

The history of great subduction earthquakes along the Sunda margin was well documented even before the disastrous event of December 2004 (**Figure 10**). Newcomb & McCann (1987) studied newspapers and other accounts of shaking and tsunami waves dating back to the late seventeenth century. They characterized several suspected thrust events on the subduction zone offshore Sumatra along with a few south of Java. The full extent of the slip in these earthquakes cannot be known with great accuracy, but enough information can be found to document events of huge proportions, though none were suspected to be of the magnitude of what happened in 2004. The largest earthquakes were assigned very approximate magnitudes of 8.9 (in 1833) and 8.5 (in 1861). Farther north, along the Andaman section of the margin, evidence for moderate sized ($M_w < 8.0$) subduction earthquakes in 1847, 1881, and 1941 (**Figure 10**) was presented by Bilham et al. (2005). The 1881 event produced a tsunami that was recorded in the Bay of Bengal (Ortiz & Bilham 2003).

Among the important questions that seismologists can address regarding the hazard posed by pending great subduction earthquakes is the depth to which slip may occur. The types of information used to this end are geodetic [modern fault locking estimates (see Fault Locking sidebar)], seismologic (depths of smaller, interface thrust quakes and coseismic slip in past quakes), thermal (depth to certain frictional transitions), and structural (depth of the upper plate Moho) and also include other proxies. The subsequent section is a review of estimates of pre-earthquake fault locking on the Sunda subduction zone, followed by a brief comparison to slip in the recent earthquakes.

As noted earlier, Pacheco et al. (1993) showed that Sumatra led all subduction zones in what they inferred to be the width of the seismogenic zone W, based on moderate magnitude thrust earthquakes on the plate interface that reached 60 km depth. The occurrence of such events may tell us how deep brittle failure can occur along the thrust fault and, as such, may be a proxy for the extent of slip in great earthquakes. However, it is also possible that the deeper of these earthquakes are not along the plate interface at all but instead within the subducting plate. Most of the slip in the great earthquakes of 2004 and 2005 was above 35 km depth, likely on the plate interface, and probably did not reach the 60 km depth where background seismicity has been seen.

The increase in temperature with depth in the Earth is one of the limiting factors for the depth of earthquake slip. Our understanding of the controls that temperature has on the frictional stability fields comes in part from laboratory studies of natural Earth materials, although their applicability to subduction rocks may be questioned. In general terms, stick-slip occurs in granites at temperatures below ~350°C, and stable sliding occurs above 450°C (e.g., Blanpied et al. 1995, Tse & Rice 1986) or higher in gabbro (He et al. 2007). Estimates of the temperatures at which the deepest thrust earthquakes occur at many subduction zones are consistent with these numbers (Hyndman & Wang 1993, Tichelaar & Ruff 1993, Oleskevich et al. 1999). Thus, it is generally accepted that rocks at temperatures in excess of ~500°C slide stably (no stick-slip), and below 350°C, brittle stick-slip occurs, with a transition between these temperatures. Like all simple pictures, this one is complicated by the recent observations of shallow slow-slip events, thought

FAULT LOCKING

In the time between earthquakes, parts of the fault surface can be stuck due to friction, which is called fault locking. When an earthquake occurs, a section that was previosuly locked slips suddenly. Hence, finding the locked sections may tell us where the earthquake slip is likely to occur.

to occur only in the transition from stick-slip to stable-sliding, at temperatures as low as 100°C at the Hikurangi subduction zone in New Zealand (McCaffrey et al. 2008).

The steady-state temperature at depth along the fault depends on the temperature distribution within the subducting plate, usually approximated by an age-dependent lithosphere cooling function, the rate and angle at which it descends, and the thermal properties of the rocks (Molnar & England 1995). Using this simple approach, McCaffrey (1997) estimated average temperatures for the world's major subduction zones and compared them with earthquake histories. Those calculations suggested that both the Sumatran and Andaman subduction zones were in a thermal state comparable to other subduction zones (Alaska and Chile, respectively) that had produced M > 9 earthquakes in the preceding 50 years. Thermal modeling by Simoes et al. (2004) suggests that beneath the Batu Islands the downdip end of the locked zone, inferred from surface deformation data to be the transition region (**Figure 10**), is at a temperature of ∼260°C, which is somewhat below the expected value of ∼350°C. Simoes et al. (2004) also infer that the maximum depth of slip below the Batu Islands extends into the upper mantle, contrary to the notion that serpentinization of the mantle rocks prevents slip below the Moho (Peacock & Hyndman 1999).

Measurements of the ongoing deformation at the Earth's surface can be used to infer fault friction at depth. To this end, modern-day, high-accuracy Global Positioning System (GPS) measurements were started in central Sumatra in 1989 when surveyors from Indonesia, the United States, and Japan occupied several dozen marks between 3°N and 2°S, including many on the offshore islands (Bock et al. 1990, Prawirodirdjo et al. 1997). That survey also recovered and reoccupied several of the nineteenth century geodetic monuments established by Dutch and Indonesian surveyors (Prawirodirdjo et al. 2000). The marks were intermittently surveyed, and the network was expanded over the next two decades. Continuous GPS sites were first operated in the Sumatra area by the Indonesian mapping agency BAKOSURTANAL starting in 2002, and the 2004 earthquake prompted additional continuous sites and more frequent survey-mode occupations. In the Andaman region, GPS coverage began in 2002 but was very sparse prior to the 2004 earthquake (Jade et al. 2005).

Using a method they dubbed paleogeodesy, Sieh and coworkers (1999) studied corals to obtain more detailed temporal information on past earthquakes and ongoing deformation (Sieh et al. 1999; Zachariasen et al. 1999, 2000; Natawidjaja et al. 2004). The corals' growth patterns provide information on whether they were emerging, submerging, or remaining stable relative to the sea surface. By making corrections for regional changes in sea level, they were able to estimate the vertical tectonic motions of the land on which the corals grew. These studies provide a rich history of vertical motions in the Sumatran forearc region. Some motions are directly correlated with past, known earthquakes, while others are not, which is not a great surprise in light of abundant evidence for slow-slip events (that is, earthquake-like surface motions without the shaking) at many subduction zones (Schwartz & Rokosky 2007).

Before proceeding, it should be noted that the depth of earthquake slip is difficult to estimate directly from any type of surface measurement. For large tsunamigenic quakes, the tsunamis themselves are evidence that slip extended upward to very shallow, near-seafloor depths but do not provide strong evidence constraining the maximum slip depth. Estimating slip depth from far-field seismic waves depends on certain interactions with the free surface above—for very long source durations this information can be lost or very difficult to extract. There is considerable trade-off between the depth of the slip and the fault area or amplitude of the slip or both, even with nearby observations, when using geodetic data. This trade-off is exacerbated when all the geodetic observations are to one side of the source, as was the case for the 2004 Aceh-Andaman earthquake. Aftershocks may outline the slip area but do not reveal the slip amplitudes.

Commonly, slip modeling starts with an assumed fault structure. The depth of slip is estimated by projecting the slip distribution, which is often relatively well constrained geographically, onto that structure at depth. For example, Subarya et al. (2006) show that the maximum depth of slip inferred from the same geodetic data for the 2004 Aceh-Andaman earthquake is either 50 km, if the planar fault structure adopted by seismological studies is used, or 25 km, if a more realistic structure of a fault that increases dip with depth is employed. Geographically, in map view, the slip distributions are similar and match the observations to a similar degree. Hence, our understanding of the depth of slip ultimately depends on how well we know the fault structure.

The original GPS observations took advantage of the many islands in the Sumatran forearc to monitor strain changes over a subduction zone. However, north of Simeulue, where most of the slip in 2004 occurred, there are no more exposures of the forearc ridge until the Nicobar Islands, resulting in poor geographic coverage. As a consequence, little knowledge of the locking on the subduction thrust fault in the region subsequently ruptured by the 2004 Aceh-Andaman earthquake was available.

Conversely, in the region around Nias and the slip area of the March 2005 earthquake, the geodetic network was dense, and a better idea of the prequake locking was available. Prawirodirdjo et al. (1997) utilized GPS data collected from 1989 to 1993 to show that the plate boundary was approximately fully locked to ~50 km depth south of 0.5°S (south of the Batu Islands) and less locked (approximately half locked down to 50 km, or fully locked to ~25 km depth) between 0.5°S and Simeulue. The change in the orientation of the GPS vectors was quite abrupt over a few tens of kilometers, suggesting a short wavelength change in locking on the fault beneath.

The vertical motions of corals on the Batu Islands (Sieh et al. 1999) that form a chain crossing the forearc for ~150 km provide additional insight into the locking distribution. The idea is that if the plates are stuck together at the fault, the subducting plate will pull down and flex the overriding plate. The shape of the bending provides information on how deep, or how far from the trench, the plates are stuck together. From this exercise, Sieh et al. (1999) concluded that the plates were locked to a distance of 133 km from the trench, below which they inferred the plate interface to be at ~30 km depth. The Sieh et al. (1999) results, based on vertical motions, were consistent with inferences of Prawirodirdjo et al. (1997), who used horizontal motions only. Prawirodirdjo et al. (1997) suggested the locking depth beneath the Batu Islands is ~25 to 50 km, a depth range that encompasses the estimate by Sieh et al. (1999). McCaffrey (2002) inverted the horizontal GPS velocities and vertical coral velocities simultaneously and, like Prawirodirdjo et al. (1997), found a transition from shallow locking northwest of the Batu Islands to deeper locking southeast of them. However, another transition from shallow to deep locking was seen trending through Nias. Farther south, on the Pagai Islands (**Figure 10**), vertical motions inferred from corals are also consistent with the horizontal GPS that suggests full plate locking to a distance of ~150 km from the trench (depth ~ 35 km) (Prawirodirdjo et al. 1997, Zachariasen et al. 2000). What is known of the pre-2004 subduction interface locking area is summarized in **Figure 10** by the shaded blue region.

Although the three great earthquakes within four years along the Sumatran subduction zone represent an unprecedented look at slip during huge earthquakes, our knowledge of the slip distributions from local geodetic data is still limited. As mentioned earlier, the 2004 earthquake slip occurred seaward of northernmost Sumatra, the Andaman and Nicobar Islands, where site coverage was poor (Jade et al. 2005, Gahalaut et al. 2006, Subarya et al. 2006, Vigny et al. 2005). As a consequence, in the slip region of the 2004 earthquake, the preseismic locking is unknown and the coseismic slip distribution, in detail, is poorly constrained, except locally for the downdip edge. Seismological slip estimates revealed only part of the slip, possibly because of an abundance of slip at low rupture speed that is poorly sensed by seismometers (Ammon et al. 2005, Stein

& Okal 2007). Nevertheless, the geodetic and seismologic estimates are consistent in showing that slip on the plate boundary during the earthquake was up to tens of meters in places, and that it was also quite heterogeneous along strike—throughout the rupture length of ~1500 km, some regions barely slipped while others had large displacements.

The 2005 Nias earthquake had much better coverage and appears to have ruptured below Nias, toward the downdip direction (Briggs et al. 2006) (**Figure 10**). The rupture is farther downdip than the part of the fault that was thought to be locked prior to 2004. Newcomb & McCann (1987) also noted that the 1861 earthquake may have ruptured seaward (updip) of Nias, as evidenced by the large tsunami along Nias's southwest coast. Hence, the 2005 Nias earthquake ruptured that part of the fault that would be considered to be within the frictional stability transition zone based on these earlier observations. If this is the case, it is an important observation because it is thought that the transition region is where slip in large earthquakes propagating from above dies out at depth, but the transition region does not nucleate isolated earthquakes. Much is left to be learned about the earthquake slip process, and continuing these types of observations in settings like Sumatra is critical to that end.

SUMMARY POINTS

1. Sumatra has long been a site of subduction. While the $Mw > 8$ earthquakes of the past few years are unprecedented from the human perspective, they are business as usual for the Earth. Such events have probably occurred tens of thousands of times in Sumatra's geologic history.

2. The Andaman section of the subduction boundary, given its low convergence rate, probably has one of the longer repeat times for $Mw \sim 9.0$ earthquakes. The 2004 event reminds us that such estimates are simply statistics and do not provide practical information about when an event will strike.

3. The Sumatran region holds other proven and significant geologic hazards such as earthquakes on the Sumatran fault and volcanic eruptions.

FUTURE ISSUES

1. Sumatra provides an accessible setting for studies of subduction processes. The likelihood for another $Mw > 8.0$ earthquake there is high and monitoring should continue.

2. Geodynamic and geologic studies of the Sumatran fault should be continued to understand its physical connection to the subduction zone.

3. Serious attention should be paid to the Java section of the subduction zone. Its lack of large earthquakes in recorded history does not preclude it from rupturing in a similar event—and the high population density of Java may result in yet another leap in the enormity of earthquake disasters.

DISCLOSURE STATEMENT

The author is not aware of any biases that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

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