THE SUNDA MEGATHRUST: PAST, PRESENT AND FUTURE

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After lying dormant for about a thousand years, sudden slippage of a 1600-km long section of the Sunda megathrust fault caused uplift of the seafloor between Aceh and Myanmar, resulting in a great earthquake and the horrific Indian Ocean tsunami of 2004. Three months later and just to the south, sudden slippage of a 350-km length of the megathrust beneath Simeulue and Nias islands caused another destructive great earthquake and lesser tsunami. Because it takes centuries for tectonic strains to build up again after such big earthquakes, these two events are unlikely to recur within the next hundred years. Farther south, however, offshore West Sumatra and Bengkulu provinces, another great earthquake and tsunami will likely occur within the next few decades. We are trying to characterize that future earthquake and tsunami, to encourage and to focus preparations for and mitigation of the coming disaster. Similar efforts need to be initiated throughout much of south and southeast Asia, if the disastrous effects of future large earthquakes and tsunamis are to be mitigated.

FROM SCIENCE TO HUMAN WELFARE

Much of the loss stemming from the great Aceh-Andaman earthquake and tsunami of 2004 could have been avoided. But achieving that goal would have required at least four things: 1) Scientific discovery that such a large earthquake and tsunami could happen, followed by 2) public education about the hazard, 3) emergency preparedness, and 4) the design and construction of resilient coastal communities. The lack of all of these prerequisites for resilience to the earthquake and tsunami fated the deaths of hundreds of thousands, large economic losses, and human suffering that continues to this day.

Similar future losses from earthquakes and tsunamis in south and southeast Asia could, in theory, be substantially reduced. However, achieving this goal would require forging a strong chain that links knowledge of why, when and where these events will occur to people's everyday lives. The *post mortem* of the 2004 disaster makes clear that the most important links in this chain are recognition and characterization of hazards through scientific research, then public education, emergency response preparedness, and improvement of infrastructural resilience (Sieh, 2006).

In this article, I focus on the first activity on this list – scientific research. Without knowledge of what is likely to happen, mitigation efforts are likely, at best, to be misdirected and ineffective or, at the worst, not undertaken at all. I use as an example recent research on the Sunda megathrust, the principal source of great earthquakes and tsunamis in the Indian Ocean. This research is yielding an understanding of the megathrust that includes an ability to anticipate where, when and how big future earthquakes and tsunamis will be. Results to date imply that a repetition of the 2004 megathrust rupture and tsunami will not occur for several hundred more years, although smaller, more local events are possible. This contrasts with our expectations for the region of coastal Sumatra south of the 2004 rupture. There we expect one or two great earthquakes and tsunamis within the next few decades. We have begun to calculate the characteristics of plausible tsunamis for that section, as a guide for emergency preparedness, public education, and land-use planning. Modest efforts by NGOs and local government to mitigate this threat are now underway in West Sumatra province.

The Sumatran example I illustrate, below, demonstrates that scientists have the tools to understand the natural threats to south and southeast Asian communities. I conclude, however, that in most places scientists do not have the public and governmental support necessary to employ those tools effectively. As a result, tragedies like the 2004 tsunami come as great surprises. Moreover, the other important links in the hazard-mitigation chain -- public education, emergency response preparedness and infrastructural resilience – do not occupy a prominent place on most agendas. Maintenance of this *status quo* throughout south and southeast Asia will prove tragic and expensive, for without strong chains from scientific discovery to mitigation, other events as profoundly disturbing to human well-being as the 2004 tsunami will strike in the coming century.

EARTHQUAKE AND TSUNAMI BASICS

Most great earthquakes occur at subduction zones—those zones of convergence between the Earth's tectonic plates, where one is slowly sliding under the other. The contact surfaces between the two plates are known as megathrust faults. These resemble the thrust faults that are found, for example, under the cities of Los Angeles and Tehran, but are vastly larger. The Sunda megathrust runs south from Bangladesh, curving around the western and southern flanks of Sumatra, Java, Bali and eastern Indonesia to northwestern Australia – all together a length of about 5500 km. Other Asian megathrusts exist offshore of the Philippines, Taiwan, Japan, and southeastern China. The biggest on-land megathrust traverses from Pakistan through India and Nepal, a distance of 2500 km along the southern side of the Himalayan mountain range.

Megathrusts commonly run from deep trenches on the ocean floor under the margins of continents. The fact that they lie under water introduces a second hazard beyond the shaking caused by the earthquake itself; the rupture may suddenly displace a large volume of the overlying ocean, thereby triggering a tsunami. This is a wave that radiates out from the site of the strongest shaking, rapidly crosses the open ocean, and comes ashore tens to thousands of kilometers away as a series of waves and surges that can be many meters to even tens of meters in height. It is ironic that any one location, great subduction earthquakes and tsunamis occur at such long intervals that there is seldom any collective memory of previous events or alertness to future potential hazards.

Figure 1 shows the basic mechanism of megathrust earthquakes and how they produce tsunamis. At the contact between the two plates, one plate (the Indian and Australian plates in this case) subducts beneath the other plate (the Sunda plate). The contact between the plates is the megathrust, a gently sloping surface that descends from a deep ocean trench for several hundred kilometers into the Earth. Over the centuries between earthquakes, this megathrust remains locked so the relative motion between the two plates expresses itself not as a movement at the interface itself, but as a gradually increasing strain or deformation of the Earth's crust surrounding it. Specifically, the advance of the subducting Indian and Australian plates causes the overlying Sunda plate to shorten and bow downward in the region above the megathrust, and thus it accumulates energy like a compressed spring or diving board (Figure

1b). When the accumulating stresses exceed the ability of the interface to withstand them, a rupture occurs; the Indian and Australian plates lurch forward and downward (by up to 10 m in case of the 2005 earthquake), and the Sunda plate lurches back to its original, 'relaxed' position (Figure 1c). In doing so, the surface of the Sunda plate drops back to its original elevation. The lurching motion of the Sunda plate delivers a 'kick' to the overlying ocean, thus triggering a tsunami.

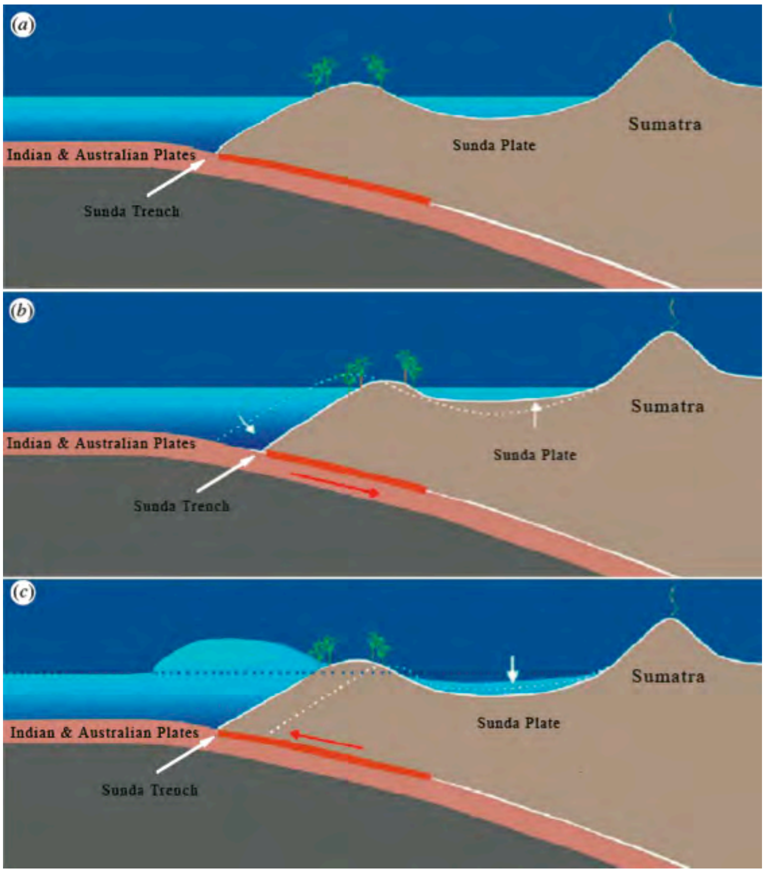


Figure 1. Idealized cross-section through the Sumatran plate boundary shows the accumulation and relief of strains associated with subduction. (a) Relationship of subducting plate (left) to overriding plate (right). The thick red line indicates the locked part of the megathrust between the two plates. (b) Since the megathrust is locked along this shallow portion, the over-riding block is squeezed and dragged downward in the decades to centuries leading up to a large earthquake. (c) Sudden relief of strains accumulated over centuries results in a large earthquake, uplift of the islands and a tsunami.

PAST GREAT SUMATRAN EARTHQUAKES AND TSUNAMIS

2004 and 2005

The Sunda megathrust is the plane of contact between the Indian/Australian oceanic plates descending beneath the Sunda plate; the two descending plates are moving north–northeast with respect to the Sunda plate at a rate of about 50 mm per year (Figure 2). Rupture of a 1600-km length of the megathrust caused the great magnitude 9.2 earthquake of 26 December

2004. Tens of meters of sudden slip relieved centuries of slowly accumulating strain across the plate boundary. Movement of GPS monuments and uplift and subsidence of corals show that slip on the megathrust ranged as high as about 20 m offshore Aceh and the Nicobar islands (Subarya et al., 2006; Chlieh et al., in review). The uplift of the seafloor caused by the slippages ranged as high as about 6 meters. Measurement of uplifted coral reefs on Simeulue island, above the southern end of the rupture (Figure 3) showed that the megathrust beneath that part of the island had slipped about 10 meters. It was these uplifts that caused the great tsunami.

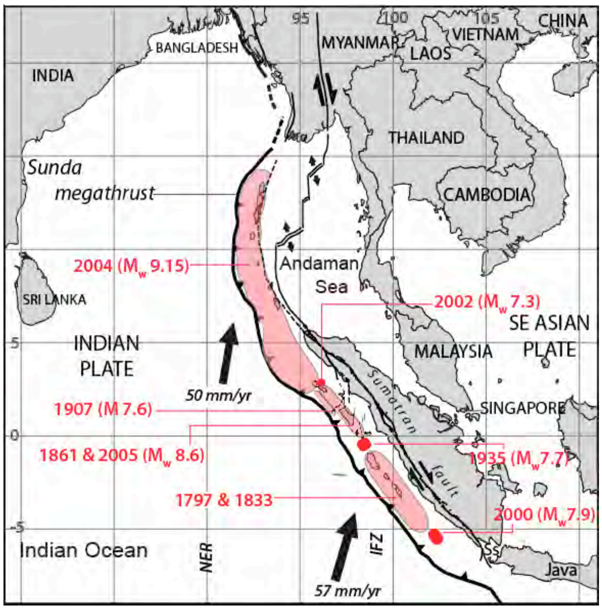


Figure 2. Setting and sources of the great 2004, 2005 and earlier earthquakes. The pink patches overlie those sections of the megathrust that have failed during large earthquakes.

Figure 3. Aerial photograph of the western tip of Simeulue island shows uplift of the fringing coral reef, evidence that the megathrust 25 km below the island slipped about 10 meters during the 2004 earthquake.

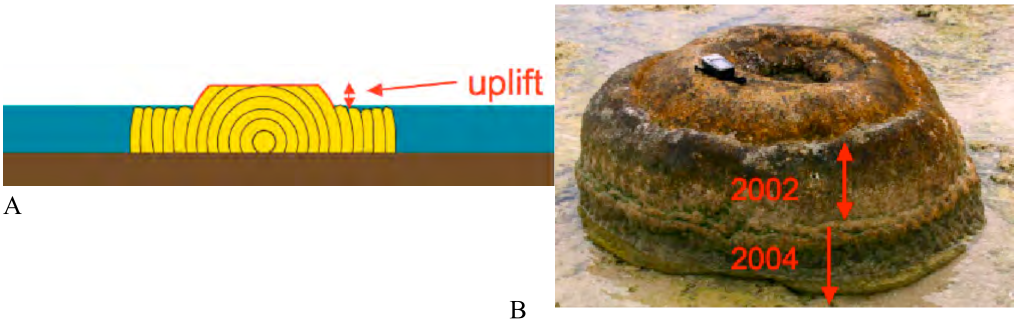
A second great earthquake occurred 3 months later, on 28 March 2005. In this magnitude 8.7 event, rupture of the subduction megathrust extended southward an additional 350 km beyond the southern end of the 2004 rupture (Briggs et al., 2006). Once again, the pattern of movement of GPS monuments and corals allowed us to determine the length, depth and slippage on the megathrust. The combined length of the 2004 and 2005 ruptures is enormous -- about 1900 km. This is roughly the distance from Kuala Lumpur to Bali or Singapore to Hanoi.

1797 and 1833

There are also historical accounts of great earthquakes on the sectors of the megathrust to the south of the 2004 and 2005 events, but the accounts are too sparse to tell us much about the details of these large ancient earthquakes. Fortunately, however, we have been able to use corals to characterize in detail these events of 1797 and 1833 (Natawidjaja et al., 2006). Moreover, we have used modern GPS geodesy to measure the current accumulations of strain that are building toward the next big megathrust failures.

We have learned enough about these great earthquakes, previous prehistorical earthquakes, and current rates of strain accumulation to make meaningful assessments of the future, including plausible effects of future tsunamis. This region has, we believe, a high likelihood of generating a great earthquake within the next few decades—probably within the lifetimes of children now living along its coastlines. The tsunami that follows the earthquake will probably devastate the coastal cities, towns and villages of this part of western Sumatra, as well as the offshore islands. Tens or hundreds or thousands of people will die in this event, and the damage suffered will have effects for decades following, unless actions to reduce the scale of the disaster significantly begin now and are sustained over the coming decades.

Most of what we know about this dangerous section of the Sunda megathrust has come to us from paleoseismic and geodetic research. To study the old earthquakes, we have turned to a biological rather than a geological record—a record kept by the large coral colonies that are common on the fringing reefs of the offshore islands west of the Sumatran mainland. Coral organisms cannot much tolerate exposure to the air. Thus, the colonies grow upward from their base as far as the waterline (specifically, up to the lowest low-tide level in a given year), after which growth continues only sideways. Once it reaches the waterline, it can only grow outward, forming a pancake-like colony, or "microatoll." If a microatoll is growing in a location that is experiencing cyclic changes in elevation related to the earthquake cycle, as described above, then these changes in elevation will be experienced by the microatoll as changes in the local water level—sinking of the Earth's crust will be experienced as a rise in water level and vice versa. If an earthquake is accompanied by dropping of the crust, the top of the microatoll will drop beneath the water level, and as a result it will be able to grow upward for several years without restraint, until it reaches the water level again. If the crust is rising, the microatoll will actually die back, if the rise is enough to lift the top of the microatoll out of the water (Figure 4a).



A

B

Figure 4. (a) Certain species of massive coral record changes in sea level, because they cannot grow above the sea surface. In this idealized cross-section through a coral colony, annual growth rings show it has grown up to sea level in 5 years. At year 7, it rose during an earthquake so the top of the coral was exposed above the sea and died. In the subsequent 5 years, the coral continued to grow outward below the new sea level. (b) This coral on Simeulue island was mostly submerged below the sea until a foreshock of the great 2004 earthquake occurred in 2002. Uplift of about 15 cm during that M 7.3 earthquake caused the central perimeter of the head (indicated by the double arrow) to die. Two years of growth of the portion still below the sea ensued, but the remainder of the head died after uplift during the giant 2004 earthquake.

With the help of underwater chainsaws, we take slab-like cross-sections of the microatolls. In these cross-sections, we can see annual growth rings, analogous to the growth rings of trees. By counting these rings, as well as by applying a radiometric dating technique, we can reconstruct the entire history of a microatoll's growth, which may extend back for well over a century. Furthermore, dead microatolls can be found that record even earlier histories. From these histories, we can deduce the dates of earthquakes reaching back for several centuries. By putting together the histories obtained from microatolls at many different locations, we can often reconstruct the extent and nature of the ruptures that caused the individual earthquakes and thus obtain an estimate of their magnitudes.

From our analysis of the 1797 and 1833 events, we see that they resulted from rupture of adjacent, slightly overlapping sectors of the megathrust, southeast of the rupture that caused the March 2005 earthquake (Figure 5).

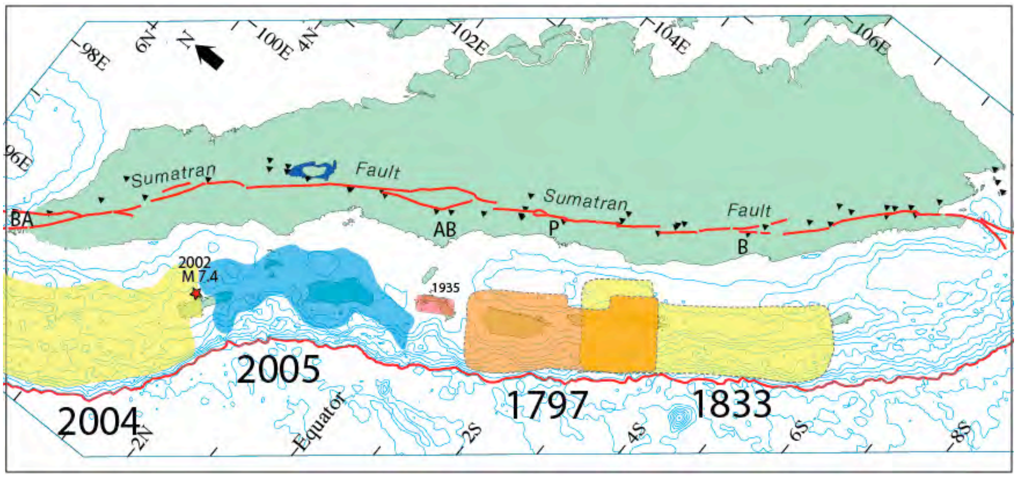


Figure 5. Great megathrust ruptures occurred in 1797 and 1833 in central western Sumatra (beneath the colored patches). Coral microatolls on the islands above the ruptures help us constrain the extent and magnitude of the two events (Natawidjaja et al., 2006). The southern extent of the 1833 rupture is poorly constrained, but the size of the earthquake was probably between 8.7 and 8.9. A repetition of rupture of these sections of the megathrust now threatens about a million inhabitants of western coastal Sumatra. The Sumatran fault, which runs through the highlands of Sumatra and through Banda Aceh, the devastated capital of Aceh province, also poses a risk to Sumatrans (Sieh and Natawidjaja, 2000; Nalbant et al., 2005). BA, Banda Aceh; AB, Air Bangis; P, Padang; B, Bengkulu.

FUTURE SUMATRAN MEGATHRUST EARTHQUAKES AND TSUNAMIS

Starting in 2002, we added geodesy to our bag of scientific tools by beginning the installation a network of continuously monitored GPS stations in Sumatra. We have set up 27 of these stations so far, most of them on the offshore islands, only 20 km or so above the megathrust, but also a few on the mainland (Figure 6). This network detects with high precisions current motions of the Sumatran crust. Most of the stations transmit their data to us via satellites, so we can monitor the data daily. The GPS data allow us to follow the ongoing slow deformations of the Earth's crust that go on between earthquakes—in fact, they are better than the microatolls in that they record motions in both the vertical *and* horizontal directions. In addition, they detect the sudden displacements associated with the earthquakes themselves, such as the December 2004 and March 2005 events (Briggs et al., 2006).

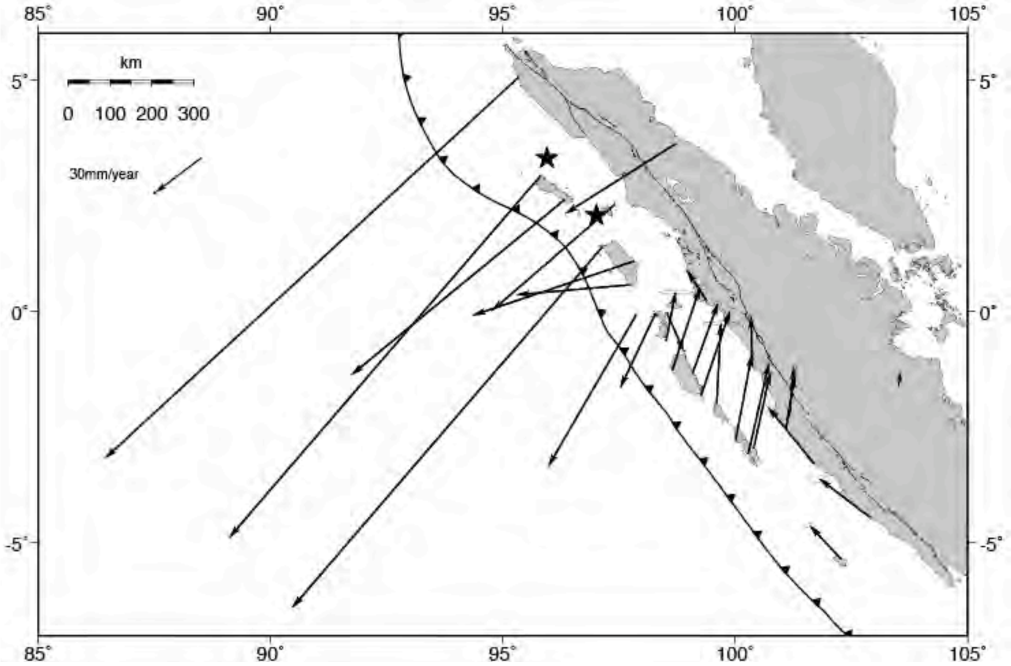


Figure 6. The Sumatran GPS Array currently consists of 27 continuously recording GPS stations. Stations from the Equator north continue to show rapid adjustments to the great earthquakes of 2004 and 2005; large vectors pointing southwestward reflect after-slip on the megathrust throughout the year after the 2005 earthquake (Hsu et al., 2006). Stations south of the Equator show ongoing accumulations of strain that will be suddenly released during future great earthquakes there. Vectors from these stations show that the Mentawai islands and southern mainland coast are still squeezing because of the locking of the underlying megathrust. Corals show that this has been going on since at least the mid-20th century, and in all likelihood strains have been accumulating since the great earthquake of 1833.

North of the Equator

There is no historical record of an event comparable to the 2004 Aceh–Andaman earthquake. This is hardly surprising because, at the rate of steady plate convergence, it would have taken hundreds of years to accumulate enough strain to be relieved by the tens of meters of slip that occurred in 2004. Archeological evidence on the east coast of India, in fact, suggests that the penultimate great tsunami occurred about a thousand years ago (Rajendran et al., 2007).

In contrast, the 2005 earthquake appears to have an historical precedent 140 years earlier, in 1861 (Newcomb and McCann, 1987). This 140-year interval is almost precisely the interval one would expect, given the average amount of slip that occurred in 2005 (6 m) and the rate of convergence of the plates there (45 mm/yr). Even though this interval between quakes is far shorter than the many hundreds of years between 2004-like earthquakes, it seems that a repeat of the great 2005 earthquake is very unlikely within the next hundred years.

There is another type of earthquake, however, that may pose a risk to coastal residents of Nias and Simeulue. In 1907, an earthquake of modest magnitude (7.6, according to Gutenberg and Richter, 1954), produced a tsunami on the west coasts of those islands that was far higher there than the tsunamis of 2004 or 2005. In fact, it was recollection of this tsunami that motivated people on Simeulue and Nias islands to flee to the hills after the 2004 and 2005 earthquakes -- an action that ensured their survival. The source of the infamous 1907 tsunami is debated. Two sources, both west of the islands, are plausible: Sudden rupture of the shallowest part of the megathrust, which has been creeping rapidly since the 2005 earthquake (Hsu et al., 2006; Tilmann et al., 2006), or rupture of a fault west of the Sunda trench on the oceanic seafloor. Recent mapping of bathymetry by our German colleagues (Schauer et al., 2006) shows that the oceanic seafloor is broken by numerous normal faults as it bends in preparation for descent into the subduction zone. Both of these sources must be regarded as potential sources of a locally damaging tsunami in the century.

South of the Equator

The question now arises, whether the sector of the megathrust south of the Equator has been squeezed enough since 1797 and 1833 for it to rupture again in the near future. Evidently, it was not yet at the tipping point in 2004 or 2005, for if it had been, the March 2005 rupture would not have stopped where it did—it would have carried on southward past the Equator.

We can gain a better idea of where this sector lies in its cycle by examining its history over the past several earthquake cycles, as revealed in the coral records. These records show that uplifts as large as those in 1797 and 1833 also occurred in the late 14th century and in the century centered on AD 1600. Thus it appears that great earthquakes (or earthquake couplets, as in 1797 and 1833) occur about every two centuries. This implies that we are in the last years or decades of the current dormant period and that another great earthquake is likely to occur in the near future, where 'near' means not necessarily weeks or months or even years, but a few decades. The great earthquake could happen tomorrow or 30 years from now, but it is not likely to be delayed much beyond the next few decades.

Many residents of coastal western Sumatra are aware of this potential, because they have been told of our research. The March 2005 earthquake was followed by a cluster of moderate earthquakes whose epicenters were far to the south of the rupture, right in the region where a future rupture of the Mentawai segment is anticipated. These moderate earthquakes caused many people to flee the coastal city of Padang.

Estimating tsunamis south of the Equator

What would happen if the section of the megathrust south of the Equator were to rupture suddenly? First, significant damage and loss of life would likely be caused by the earthquake, itself, particularly because many local buildings are inadequate to withstand the several minutes of strong shaking that would occur. But what about tsunamis?

In 1797 Padang was a tiny English colonial settlement 1–2 km upstream from the coast on the banks of a small river. The tsunami ran up the river, and according to contemporary accounts it seized a 150-ton English sailing vessel that was moored near the river mouth, carried it up the river and deposited it over the river bank in the middle of town. That would have required an overland flow depth of several meters (Natawidjaja et al., 2006). Padang is now a city of about 800 000 people that occupies nearly all of the first few kilometers from the coastline (Figure 7a) – clearly the effects of a 1797-sized tsunami today would be horrific. The 1833 earthquake was likewise followed by a destructive tsunami, but it had less effect at Padang, which lay beyond the very northern end of the rupture zone. However, it did destroy the waterfront at Bengkulu, about 400 km to the south. Then a tiny settlement, Bengkulu now has a population of about 300 000. Altogether, there are more than a million individuals exposed to future megathrust earthquakes and tsunamis in Bengkulu, Padang and the other coastal cities, towns and villages of western Sumatra.

Figure 7. (a) Padang is now a sprawling city of about 800 000 people. Most of the town is less than 10 m above sea level. (b) Many smaller towns and villages along the western coast of Sumatra will also be inundated by future tsunamis. The town of Air Bangis, near the Equator, has begun to prepare for the possibility.

To date, the modest yet laudable post-2004 efforts by local NGOs and local government to mitigate tsunami hazard in Padang and the surrounding region (http://multiply.com/i/xqeWVamMRpEvgXAiTyIvjw) have relied on simple assumptions about future tsunamis. They have assumed that land lower than 5 m above sea level is dangerous, land between 5 and 10 m above sea level is relatively safe and that land above 10 m is safe. More-precise information from scientists is sorely needed to aid in mitigation efforts.

To assess the specific effects of future tsunamis along this part of the coast, one needs to start with a plausible set of sources, that is, reasonable ruptures on the megathrust that produce uplift of the seafloor. Then one must calculate the effects of the uplift of the seafloor on the sea itself. We have made an initial attempt at this (Borrero et al., 2006). First, we calculated the on-land effects of the 1797 and 1833 tsunamis, using the slips implied by the coral uplift during those earthquakes. The results were comparable to the sparse historical record of tsunami inundation and overland flow depths during those events. Armed with this success, we then calculated the effects for two plausible future scenarios: In one case, the entire 700-km length of the megathrust breaks, with 10 m of slip – an amount similar to that of the 2005 Nias-Simeulue earthquake, north of the Equator. In the other case, slip is 20 m along this 700-km length – an amount similar to that of the 2004 Aceh-Andaman earthquake (Figure 8). The latter scenario can be considered a plausible worst-case scenario. In that case, a 700-km long welt several meters high develops on the sea surface west of the Mentawai islands (Figure 8f). That welt spreads southwestward into the Indian Ocean and northeastward to the Sumatran coast.

Results of the models imply that much of the Sumatran coast south of the Equator would suffer destructive waves. At Padang and Bengkulu the first cresting waves would strike about a half hour after the beginning of the earthquake (Figure 9). Bengkulu, unprotected by large offshore islands, experiences one long-lasting initial cresting wave, several meters high. By contrast, Padang experiences a set of three slightly smaller waves in that same time period, because the sea has to pass through the straits between large offshore islands on its journey to the city. Note that large waves also hit more than two hours after the earthquake. These are “edge” waves that move slowly along the coast in shallow waters. Movies of the simulated tsunamis can be downloaded from www.pnas.org/cgi/content/full/060469103/DC1 and www.tectonics.caltech.edu/sumatra/tsunami_models.html.

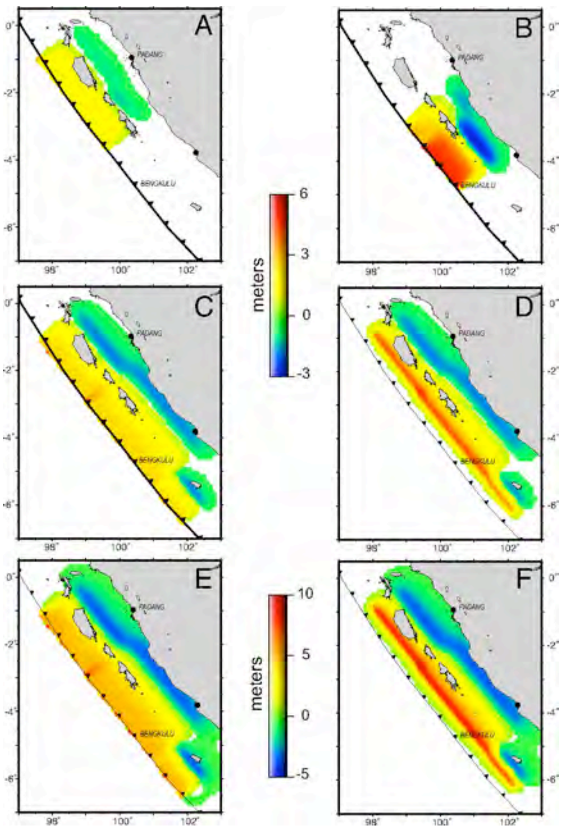
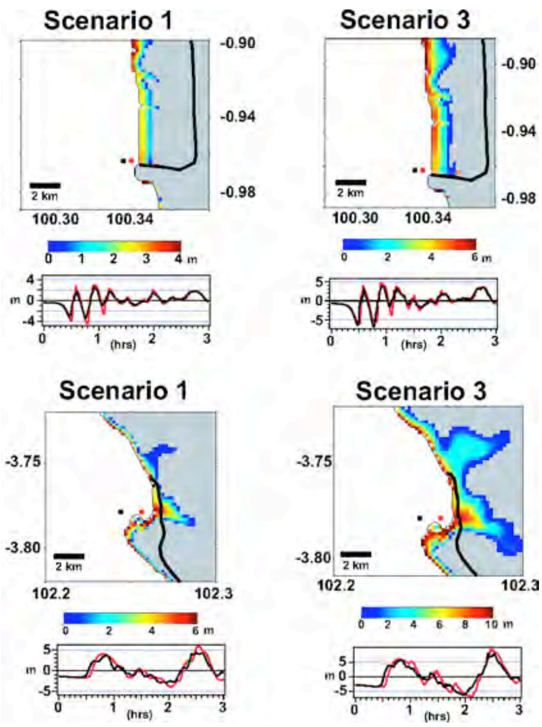


Figure 8. Uplift of the seafloor produced by the six megathrust ruptures used in the study by Borrero et al. (2006). (*A* and *B*) Dimensions of the 1797 (*A*) and 1833 (*B*) ruptures from Natawidjaja et al. (2006). (*C*) In scenario 1, uniform slip of 10 m extends to trench. (*D*) In scenario 2, uniform slip of 10 m extends up-dip only to a depth of 15 km. (*E*) In scenario 3, uniform slip of 20 m extends to trench. (*F*) In scenario 4, uniform slip extends up-dip only to a depth of 15 km, and the sea floor bulges up about 8 m southwest of the Mentawai islands.

These simulations are just the beginning of what scientists must produce in order to aid mitigation of the tsunami hazard along western Sumatran shores. Refinement of the tsunami source will be realized through ongoing studies of the deformations now being recorded by the SuGAr array of continuously recording GPS instruments. Already, the new GPS data are suggesting that the sources used by Borrero et al. (2006) are too large. Chlieh et al. (in review) use the GPS data and the coral record of the past 50 years to show that the locked patch of the megathrust offshore Bengkulu and Padang is no more than 600 km long, not the 700 km assumed in the models of Figure 8. This implies sizes for future west Sumatran tsunamis somewhat smaller than in those models.



The topography and shallow bathymetry used in tsunami modeling also play critical roles in determining the local characteristics of tsunamis. The models in Figure 9 use the most detailed topography and bathymetry that are readily available – bathymetry from standard hydrographic charts and topography from NASA's Shuttle Topography Radar Mission (SRTM). Higher-resolution data would enable significant improvements in estimating future inundation distances and overland flow depths. Our German colleagues have announced plans to collect such data for use in a next generation of tsunami maps. This effort promises to provide still more precise and reliable data from which to construct tsunami hazard maps.

Figure 9. Maps of computed tsunami flow depths and inundations over local coastal topography near Padang (*Upper*) and Bengkulu (*Lower*) for model scenarios 1 and 3. Pixel dimension is 200x200 m. Below each map is the corresponding tsunami time series. Each begins at the time of fault rupture and are for offshore locations at water depths of 5 m (red dot) and 10 m (black dot). Solid black line represents the extent of densely populated urban areas. The simulations of 1797 and 1833 tsunamis are consistent with sparse historical accounts. Simulations of plausible future events (Scenarios 1 and 3) show that both Padang and Bengkulu could be seriously impacted by future tsunamis. The effects at Bengkulu, unprotected by offshore islands, will likely be more severe than at Padang.

PUBLIC EDUCATION

It is beyond the scope of this paper to discuss in any detail the aspects of earthquake and tsunami hazard mitigation that should follow on the heels of the basic scientific definition of the problem, summarized above. I have, however, explained my views about this in a previous paper (Sieh, 2006). Still, let me mention briefly what our group has done in the way of public education in Sumatra. In a nutshell, we have tried to teach people there why earthquakes and tsunamis occur and to keep our work in public view, to encourage preparations, preparedness and change.

In the course of many visits to Sumatra, we have developed friendships with and admiration for many of the people of Sumatra, as well as an awareness of the hazards to which they are exposed. Starting in 2004, my colleagues and I began a program of public education in the Mentawai Islands, which is where much of our research has been focused. The program has had several elements. One is a set of posters that we have had distributed and put up in public spaces such as offices and businesses. These posters are in three languages—English (for the tourists and surfers), Mentawai (the local language) and Indonesian. They explain in a straightforward way about the research we are doing and our main findings, and what these findings mean in terms of earthquake and tsunami hazards. A small part of the posters introduce some of the steps can be taken to reduce these hazards. Literacy rates are high, so these posters reach much of the population in the villages that we visit. Copies of the posters are available for downloading at www.tectonics.caltech.edu/sumatra/public.htm. Figure 10 is our most recent poster, which is aimed at the populations on the mainland coast of Sumatra.

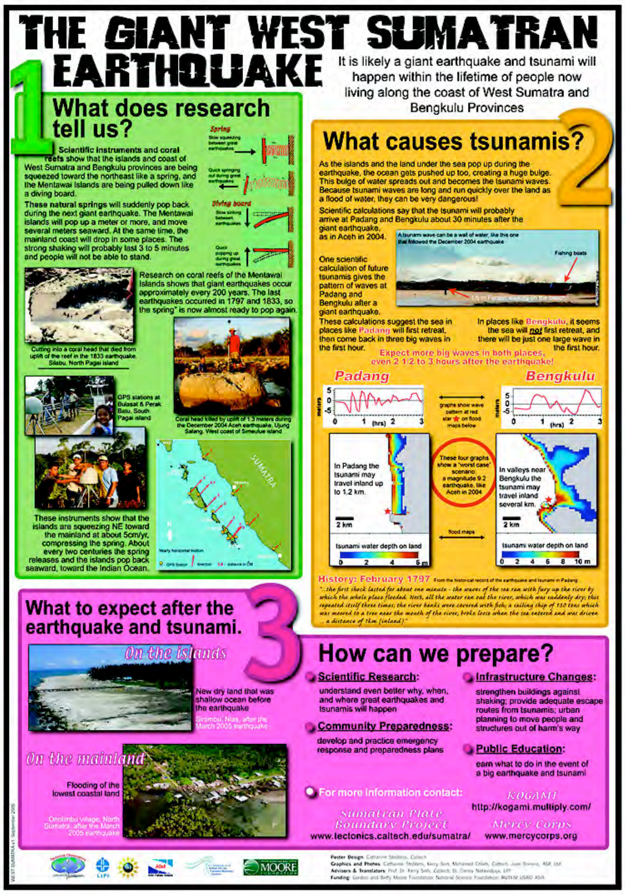


Figure 10. The English version of the latest in our series of educational posters is aimed at coastal residents of mainland Sumatra. These posters present the science behind the earthquake and tsunami hazard. Additional efforts will be necessary to mitigate the hazards.

The 2004 and 2005 disasters have greatly aided our educational efforts. Sadly, it has taken disasters of this magnitude to draw public attention to earthquake and tsunami hazards and to the connection between them. The population of Padang has in fact been put in a state of great anxiety by the events to the north. The sequence of aftershocks mentioned earlier, which were situated close to Padang, caused great distress there -- I have been told that some people even died in traffic accidents while attempting to leave the coastal zone. Of course, this state of anxiety will gradually abate.

Thus it is critically important to seize the opportunity brought about by the 2004 and 2005 disasters to educate local communities about the actions they can take to protect themselves from the next giant Sumatran earthquakes. The main message that needs to be communicated is that people should respond to a long-lasting earthquake—say one lasting 45 s or more—by running or cycling to high ground or inland, but that this is not necessary with the more-frequent small earthquakes that typically last 10–15 s. In addition, people should be urged to support programs for changes in infrastructure and development of emergency response capabilities.

THE INFRASTRUCTURE—BUILDING AND PLANNING FOR SAFETY

Another critically important aspect of hazard mitigation in western coastal Sumatra is dealing effectively with the enormous exposure of communities to shaking and tsunami inundation. The current situation is akin to an overnight campout in the middle of a not-so-busy street. Most of the night, the campers slumber peacefully. When a pair of headlights appears up the street, someone is supposed to wake everyone up so that they can flee before the car plows through the tents. Far better if the tents had been pitched in the front yard rather than in the street! Thus, the two key questions concerning how to build safely in coastal regions exposed to megathrust earthquakes and tsunamis are first, where to build and second, how to build.

As to the where, it is all too apparent that many Sumatrans now live in what at the time of a great tsunami are the wrong places -- low-lying areas close to the ocean, estuaries or rivers. In the December 2004 tsunami, in particular, but also in the March 2005 tsunami, low-lying areas in Aceh and North Sumatra were utterly devastated. In some coastal towns on the northwest coast of Aceh barely a trace of human habitation remained after the tsunami; in such towns, 90% or more of the inhabitants died. It will take decades or longer to recover from these immense losses.

The damage caused by these events was not limited to the destruction during the tsunami itself. In addition, the drop in the land surface that accompanied the rupture has left many coastal areas permanently under water, as can be seen in satellite images of Aceh and North Sumatra provinces after the 2004 and 2005 earthquakes. These changes in the coastline will lead, over years or decades, to further destructive effects. The sea continues to eat away at the subsided coastal plain, moving the coastline even farther inland. Rivers, finding themselves flowing too steeply down to the ocean, will respond by flooding more widely and by cutting new channels.

All these processes, though completely natural and inevitable, will be very disruptive to the populations that are attempting to rebuild in the affected areas. How far away from the beach must a new coastal road be built? Where should bridges be located? How close to a riverbank can homes be safely built? To answer questions of this kind requires the expertise of coastal and fluvial geomorphologists, combined with a detailed understanding of local conditions. Nations with scientific and engineering capabilities in these areas could provide such experts, who would assist in the development of land-use plans and train Indonesian scientists in these fields.

As to the question of how to build, the issue is not tsunami resistance – rather, it is seismic resistance. Currently, building techniques on the islands, and to some extent on the mainland coast, are so elementary that quite inexpensive steps can be taken to strengthen people's homes against earthquakes. Most notably, a typical island home is supported by posts that are simply perched on blocks of coral that are laid on the ground. In even a moderate earthquake such structures come off their 'foundations' and, very often collapse. This failure mode can be prevented by anchoring the posts to inexpensive concrete footings set 18 inches into the ground.

CONCLUSIONS

I hope I have convinced you that scientific understanding of earthquakes and tsunamis provides the foundation for mitigating the baleful effects of future earthquakes and tsunamis in Sumatra. The discovery of the potential for great earthquakes and tsunamis along the coast of Sumatra south of the Equator has laid the foundation for efforts at mitigation. Although more scientific work is needed, we have already identified, to first order, which megathrust patches offshore Sumatra are currently locked and therefore storing strain. And we have begun to calculate the characteristics of plausible tsunamis generated by future failure of these patches.

Most of the large, active megathrusts throughout south and southeast Asia are not as well known as the one offshore western Sumatra. It should come as no surprise then that the hazards posed by these megathrusts are too poorly known to give much insight into the levels and specifics of preparation, education and change required. Here are just a few glaring examples:

How great is the danger posed by the section of the Sunda megathrust off the southern shore of Java, one of the most densely populated coasts on Earth? Isn't it astonishing that no one really knows? We know from the tsunami disaster of July 2006 that even moderate earthquakes there have the potential to generate locally dangerous tsunamis. But is it possible that the megathrust south of Java could also generate a much larger earthquake, say an 8.5 or 9, which would produce a far more devastating tsunami along one of the most densely populated coasts on Earth? A program of continuous geodetic monitoring would be one simple step toward answering this question.

Which sections of the Himalayan megathrust will break next? It is well known that this giant fault produces great earthquakes from Pakistan through India and Nepal to Bangladesh

(Bilham, 2006), but next to nothing is being done to address the vulnerabilities of the populations it threatens. One can hope that a greater level of specific scientific information would lead to more specific information that would, in turn, motivate serious mitigation activities. Lacking such efforts, one can only wonder which megacity of the Gangetic plain will be the first to lose the gamble that it has placed by virtue of its inattention to the problem.

What is the potential of the Manila megathrust, which traverses 1200 km of the South China Sea from the Philippines to Taiwan? If its entire length were to rupture in one event, the earthquake and ensuing tsunami would rival the Indian Ocean event of 2004. Yet no one knows whether this is possible. Paleotsunami studies of coastal Vietnam and southern China could begin to address this question. Geodetic investigations would be more difficult, because there are no islands near the megathrust upon which to site GPS stations. Nonetheless, the prospect is important enough to communities on the coast of the South China Sea (such as Macau and Hong Kong) that an expensive submarine GPS system might be warranted.

Throughout south and southeast Asia, scientists do not have the public and governmental support necessary to effectively evaluate the potential for large earthquakes and tsunamis. As a result, tragedies like the 2004 tsunami come as great surprises. Moreover, the other important links in the hazard-mitigation chain -- public education, emergency response preparedness and infrastructural resilience – do not occupy a prominent place on most agendas. Maintenance of this *status quo* throughout south and southeast Asia will prove tragic and expensive, for without strong chains linking scientific discovery to mitigation, other events as profoundly disturbing to human well-being as the 2004 tsunami will strike elsewhere in the coming century.

Even along the western coast of Sumatra, where scientific studies are well advanced, the links between science and mitigation efforts are weak. For although scientific discovery there has shown that a large earthquake and tsunami are very likely within the next few decades, activities aimed at reducing the exposure of the coastal communities are too meager to make more than slight progress in solving the problem.

One test of whether humanity acts responsibly in the next millennium is this: can we marshal the visionary persistence needed to take charge of our future? Or will we carry on as we did throughout most of the past—simply reacting to tragedies as they happen? If the answer is the latter, then there will continue to be more tragedies like that of 26 December 2004.

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