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Sumatran megathrust earthquakes: from science to saving lives

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Most of the loss of life, property and well-being stemming from the great Sumatran earthquake and tsunami of 2004 could have been avoided and losses from similar future events can be largely prevented. However, achieving this goal requires forging a chain linking basic science—the study of why, when and where these events occur—to people's everyday lives. The intermediate links in this chain are emergency response preparedness, warning capability, education and infrastructural changes. In this article, I first describe our research on the Sumatran subduction zone. This research has allowed us to understand the basis of the earthquake cycle on the Sumatran megathrust and to reconstruct the sequence of great earthquakes that have occurred there in historic and prehistoric times. On the basis of our findings, we expect that one or two more great earthquakes and tsunamis, nearly as devastating as the 2004 event, are to be expected within the next few decades in a region of coastal Sumatra to the south of the zone affected in 2004. I go on to argue that preventing future tragedies does not necessarily involve hugely expensive or high-tech solutions such as the construction of coastal defences or sensor-based tsunami warning systems. More valuable and practical steps include extending the scientific research, educating the at-risk populations as to what to do in the event of a long-lasting earthquake (i.e. one that might be followed by a tsunami), taking simple measures to strengthen buildings against shaking, providing adequate escape routes and helping the residents of the vulnerable low-lying coastal strips to relocate their homes and businesses to land that is higher or farther from the coast. Such steps could save hundreds and thousands of lives in the coastal cities and offshore islands of western Sumatra, and have general applicability to strategies for helping the developing nations to deal with natural hazards.

Keywords: palaeoseismology; earthquakes; Sumatra; forecasts; human welfare; tsunami

1. Introduction

Great earthquakes—those with a magnitude of 8 or more—are rare events that can cause tremendous loss of life as well as widespread material damage. They may also have a long-lasting impact on the natural world. Most great earthquakes occur at *subduction zones*—the zones of convergence between the Earth's tectonic

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plates, where one plate is slowly sliding under the other. The contact surfaces between the two plates are known as *megathrust* faults—they resemble the thrust faults that are found, e.g. under the cities of Los Angeles and Tehran, but are vastly larger.

Megathrusts commonly run from 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, 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 kilometres away as a series of waves and surges that can be 10 m or more in height.

Depending on the coastal topography, tsunamis can travel several kilometres inland, destroying much in their path. In the great Aceh–Andaman earthquake of 26 December 2004, most of the estimated 280 000 deaths resulted from the associated tsunami rather than from the earthquake shaking. These deaths were distributed throughout all of the countries bordering the Indian Ocean, and even in East Africa, but the great majority occurred near the megathrust rupture, in northern Indonesia. Many other regions of the world, such as the northwest coast of North America and the west coast of South America, are exposed to the threat of similar events. However, at any one location, great subduction earthquakes occur at long intervals, so that there is seldom any collective memory of previous events or alertness to future potential hazards.

In this article, I make the case that it is possible to lessen substantially the hazards posed by great subduction earthquakes. It is possible to save hundreds and thousands of lives that will otherwise be lost in future events, and to prevent much of the material destruction that will otherwise occur. To achieve this goal, however, a chain must be forged that connects basic science with people's everyday lives. There are five vital links in this chain.

- (i) *Basic science*. We need to understand better the cyclic geological process that generate great megathrust earthquakes, as well as the hazards that these earthquakes pose to specific human populations.
- (ii) *Emergency response preparedness*. There needs to be the capability to deliver immediate assistance for search and rescue, medical aid, emergency food and housing, and the like.
- (iii) *Warning capability*. Local populations need to have warning of an impending event. In the region of the earthquake, the best warning of a tsunami is the shaking of the big earthquake itself, tens of minutes before the onset of the tsunami.
- (iv) *Education*. Local populations need to know how to act in such a way as to protect themselves ahead of and during a great subduction earthquake and tsunami.
- (v) *Infrastructure*. Changes need to be made in the basic physical attributes of at-risk communities, so that fewer people are inherently in the path of damage and destruction.

In this article I review these five themes, using as a specific example the Sumatran megathrust on the eastern flank of the Indian Ocean. I will focus on a sector of the megathrust to the south of the zones that ruptured in 2004 and 2005. I have been studying this sector since 1994 with my American and Indonesian colleagues, and we have learnt enough about its history to make meaningful predictions about its future. This sector, we believe, has a high likelihood of generating a giant 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, unless actions to reduce the scale of the disaster significantly begin now and are sustained over the coming decades.

2. The science: learning from the past

I am a palaeoseismologist, which means that I attempt to reconstruct the history of past earthquakes by studying the traces that they have left in the earth. With recent earthquakes, these traces can be obvious, often taking the form of several metre-high scarps—miniature cliffs that record where the rupture tore across the landscape. With older earthquakes, the traces are much subtler; they may consist of slight disturbances in layers of sediment, offsets in streambeds or trees with distorted growth patterns. Starting in 1975, I have used these clues to put together a history of the San Andreas fault, the notorious strike-slip (sideways-sliding) fault that marks the boundary of the Pacific and North American plates in California. The history that we have unearthed goes back nearly two millennia and in some locations, includes sequences of as many as 12 earthquakes, each dated by the carbon-14 method or some other radiometric dating technique. This history forms the basis for our general understanding of the earthquake cycle on the San Andreas fault, for assessments of the likelihood that specific parts of the fault will rupture in the coming decades, and for estimates of the size of the earthquakes that those ruptures will generate (Liu *et al.* 2004; Weldon *et al.* 2004). This knowledge has contributed to hazard mitigation strategies that have largely eliminated exposure to earthquake hazards along the San Andreas fault.

In 1994, I turned my attention, for scientific reasons, to the Sumatran subduction megathrust, a giant earthquake fault that had been relatively little studied but that, as all the world now knows, has the capacity to unleash immense disasters. This megathrust is the plane of contact between the Indian–Australian plate and the southeast Asian portion of the Eurasian plate; the Indian–Australian plate is pushing north–northeast with respect to the Eurasian plate at a rate of about 50 mm per year (figure 1). The giant magnitude 9.2 earthquake of 26 December 2004 was caused by the rupture of a 1600 km section of the megathrust, as the two plates slid tens of meters past one another (Subarya *et al.* 2006). The rupture began near the island of Simeulue, off the northwestern coast of Sumatra; over the following 10 min the rupture propagated 1500 km northward, terminating north of the Andaman Islands in the Bay of Bengal. A second great earthquake occurred 3 months later, on 28 March 2005. In this magnitude 8.7 event, the rupture of the subduction megathrust extended southward an additional 350 km beyond the southern end of the 2004 rupture (Briggs *et al.* 2006). The total length of the two ruptures is nearly 1900 km, roughly the distance from London to St Petersburg.

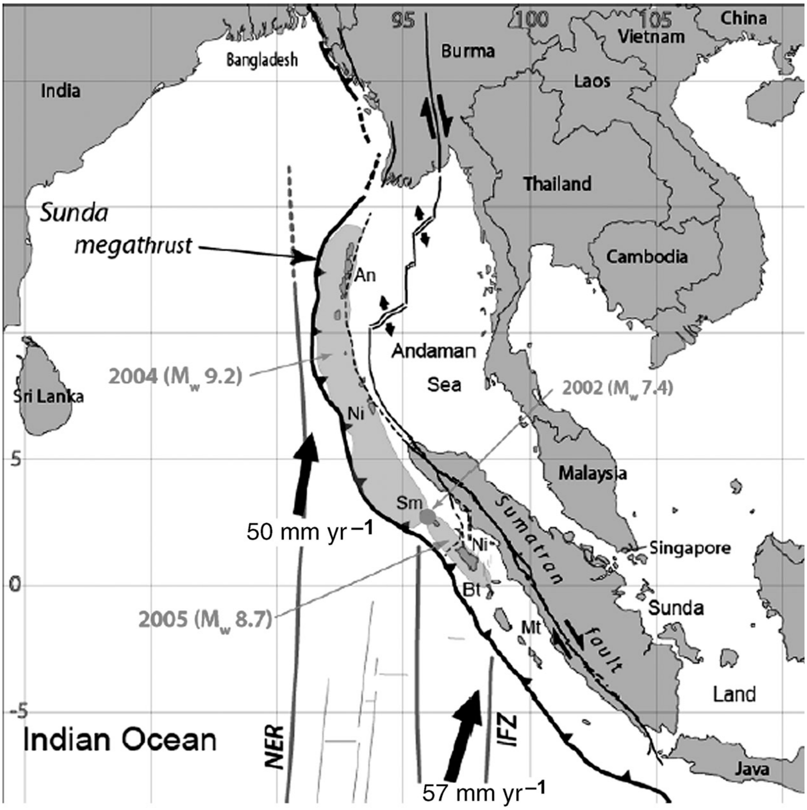

Figure 1. Setting and sources of the giant earthquakes of 2004 and 2005. Sm, Simeulue island; Ni, Nias island; Bt, Batu islands; Mt, Mentawai islands.

Figure 2 shows the basic mechanism of great earthquakes on subduction megathrusts. At the contact between the two plates, one plate (the Indian–Australian plate in this case) subducts beneath the other plate (the Eurasian plate). The contact between the plates is a gently sloping surface that decends eastward from a deep ocean trench (the barbed black line in figure 1) for several hundred kilometres into the Earth. Over the centuries between earthquakes, the interface 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 near the interface. Specifically, the advance of the subducting Indian–Australian plate causes the overlying Eurasian plate to shorten and bow downward in the region above the interface, and thus it accumulates energy like a compressed spring or diving board (figure 2*b*). When the accumulating stresses exceed the ability of the interface to withstand them, a rupture occurs; the Indian–Australian plate lurches forward and downward (by up to 15 m in the 2005 earthquake), and the Eurasian plate lurches back to its original, 'relaxed' position (figure 2*c*). In doing so, the surface of the Eurasian plate drops back to its original elevation. The lurching motion of the Eurasian plate delivers a 'kick' to the overlying ocean, thus triggering a tsunami.

There is no clear 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 trigger the tens of meters of slip that occurred. However, the 2005 earthquake appears to have historical precedents only 98 and 140 years earlier, in 1907 and 1861. In fact, stories of these earthquakes and tsunamis led many people on Simeulue and Nias islands to avoid the tsunami by fleeing to the hills after the 2004 and 2005 earthquakes. Hardly a life was lost to the tsunamis there.

There are records of great earthquakes on the sectors of the megathrust to the south of the 2004 and 2005 events. In 1797, an earthquake with an estimated magnitude of 8.4 generated a tsunami that severely damaged the coastal settlement that is now the city of Padang, and in 1833 an even bigger event (magnitude of about 9.0) struck further to the south, again causing a tsunami that devastated the mainland coast (Natawidjaja *et al.* in press).

To study these and earlier earthquakes, we have turned to a biological rather than a geological record—a record kept by the giant coral heads or *microatolls* 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 microatolls 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. 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 microatoll will drop beneath the water level, and as a result it will be able to grow upward without any restraint for several years, 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 3*a*).

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.

Starting in 2002, we added a second technique—the use of continuously monitoring GPS stations to detect current motions of the Earth's crust. We have set up 24 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 coast. Most of the stations transmit their data to satellites so that 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

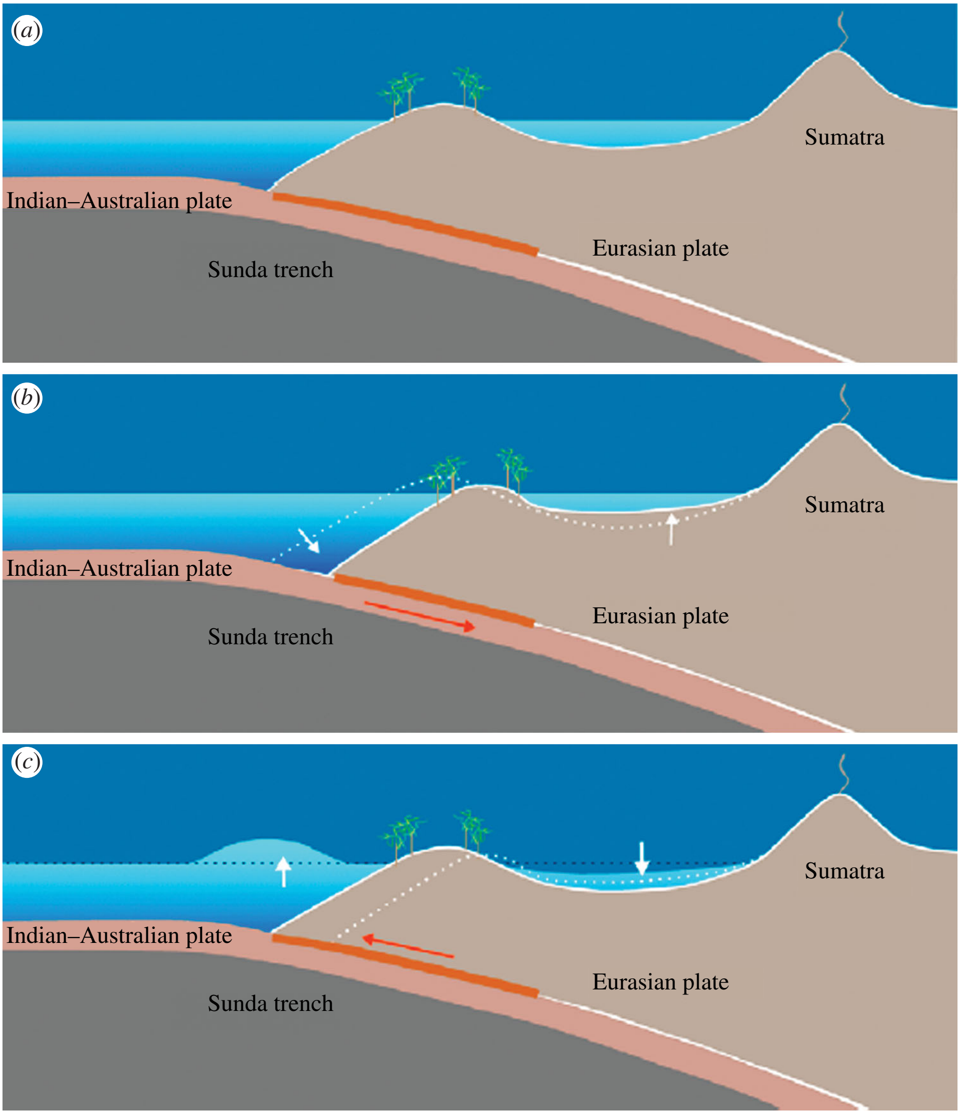

Figure 2. Idealized cross-sections through the Sumatran plate boundary show the accumulation and relief of strains associated with subduction. (*a*) Relationship of subducting plate (left) to over-riding plate (right). The brown line indicates the locked part of the megathrust between the two plates. (*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.

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).

From our analysis of the 1797 and 1833 events, we can see that they were caused by ruptures of adjacent, slightly overlapping sectors of the megathrust, southeast of the rupture that caused the March 2005 earthquake (figure 4). The

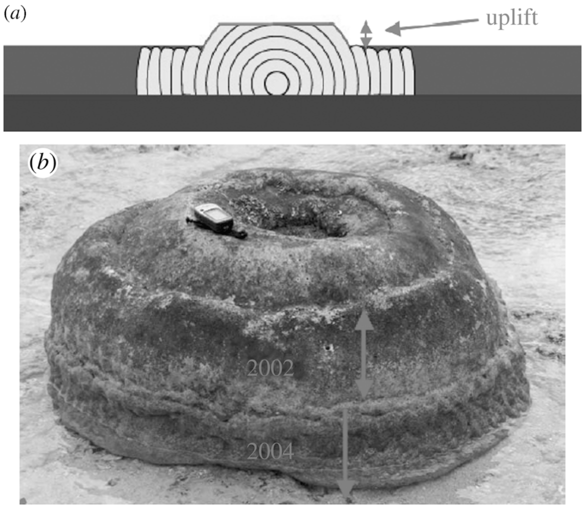

Figure 3. (*a*) Certain species of massive coral record changes in sea level, because they cannot grow above the sea surface. In this idealized cross-section through a coral head, annual growth rings show it has grown up to sea level in 5 years. At year 7, it rose during an earthquake so the top of the 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 Sumatran coral was mostly submerged below the sea until an earthquake 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.

question therefore arises, whether these sectors have been squeezed enough since 1797 and 1833 for the megathrust to rupture again in the near future. Evidently, they are not yet at the very tipping point, for if they were the March 2005 rupture would not have stopped where it did—it would have carried on southward to include all or part of the 1797 and 1833 sectors.

We can gain a better idea of where these sectors lie in their cycles by examining their past history over several earthquake cycles, as revealed in the coral records. As an example, we have reconstructed one such history for a locality on South Pagai Island, one of the Mentawai Islands that lies about 100 km west of Padang (figure 5). In this history, ruptures of the megathrust have not occurred at regular intervals, so it is not possible to predict future ruptures simply by counting off years since the last one. There is modest predictability in this sense. However, ruptures have occurred whenever a certain degree of deformation or strain has been reached. It takes variable lengths of time to reach that point because the various ruptures are accompanied by varying amounts of slip. If the slip is great, it takes a long time to re-accumulate enough strain to bring the megathrust to its threshold for rupture; if the slip is less, then less strain is relieved and it takes less time to get back to the threshold.

Frighteningly, it appears that the megathrust in the sector that ruptured in 1797 has already accumulated enough strain to bring it close to the breaking point again. Another great earthquake, therefore, is likely to occur in the near future, where ‘near’ means not necessarily weeks or months or even years, but a few decades. It could happen tomorrow or in 50 years from now, but it is not likely to be delayed much beyond that. Many residents of coastal western Sumatra are

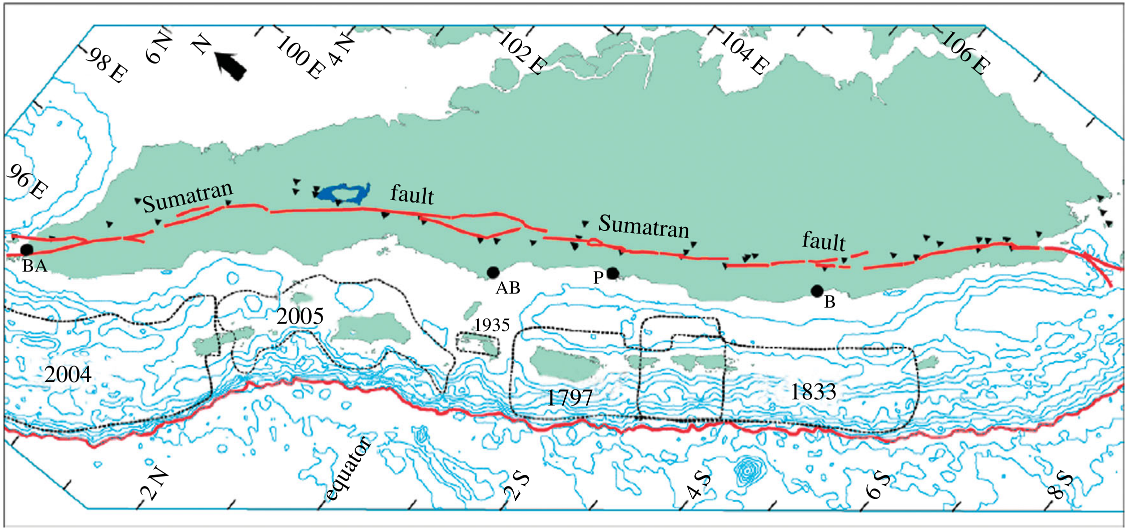

Figure 4. Great megathrust ruptures occurred in 1797 and 1833 in central western Sumatra. Coral microatolls on the islands above the ruptures help us constrain the extent and magnitude of the two events (Natawidjaja *et al.* in press). The southern extent of the 1833 rupture is poorly constrained, but 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 (Nalbant *et al.* 2005; Sieh & Natawidjaja 2000). BA, Banda Aceh; AB, Air Bangis; P, Padang; B, Bengkulu.

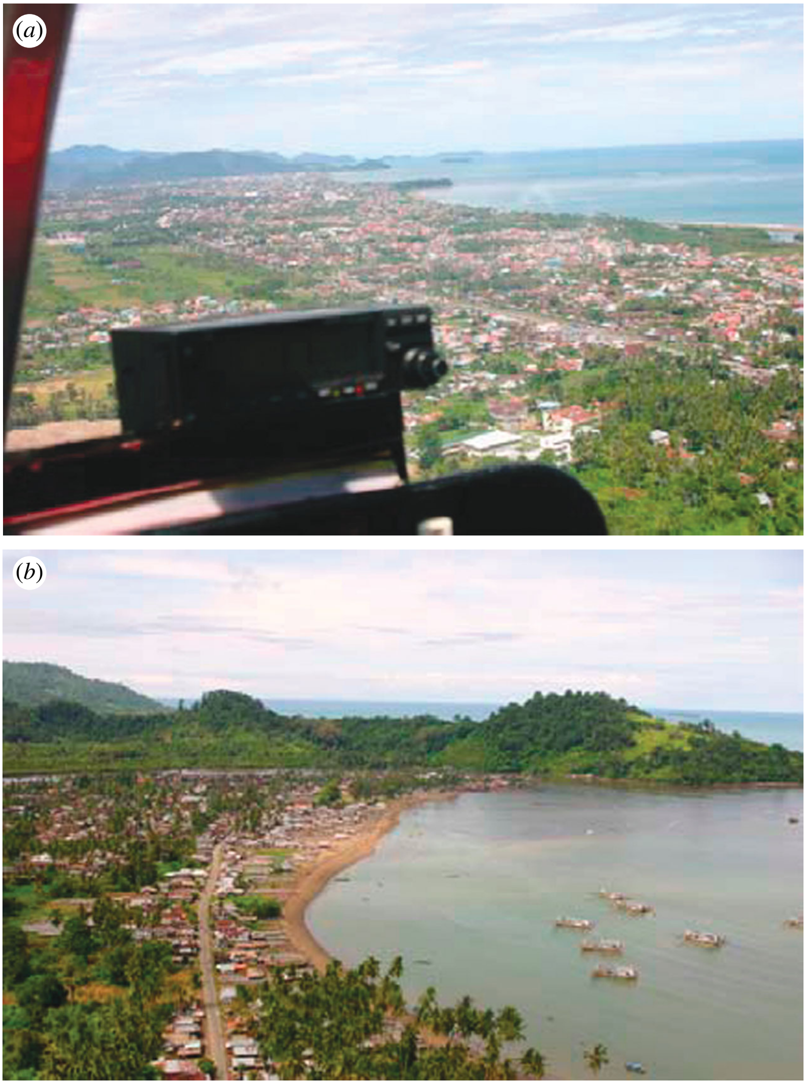

Figure 5. (*a*) Padang is now a sprawling city of about 800 000 people. Most of the town is less than 10 m above sea level. (*b*) Many smaller towns and villages along the western coast of Sumatra will also be inundated by future tsunamis. This town (Air Bangis) has begun to prepare for the possibility.

aware of this potential, because they have been told of our research. The March 2005 earthquake was followed by a cluster of smaller earthquakes whose epicentres were to the south of the rupture, right in the region where a future rupture of the Mentawai segment is anticipated. It is not too much of a stretch to consider these earthquakes as possible foreshocks to a future 1797-type event. In fact, many panicked citizens of west Sumatra thought just that and fled the city.

What would happen if the 1797 or the 1833 event recurred—or if both those sectors broke together in a single event? First, great damage and loss of life would be caused by the earthquake-induced shaking, particularly because many local buildings are inadequate to withstand such earthquakes. What about tsunamis? The March 2005 earthquake caused only a rather moderate tsunami—too small to cause as much damage as the giant December 2004 tsunami. There are at least two very specific reasons that the 2005 tsunami was smaller than the 2004 tsunami. First, the rupture occurred mostly under islands, rather than underwater. Second, the channel between the offshore islands and the mainland is relatively shallow in the region of the 2005 event, so there was relatively little water to be displaced. With respect to the first reason, the situation farther south is similar, in that there are islands above the future earthquake source; but with respect to the second reason, the situation is quite different. The water between the islands and the mainland coast is very deep. Thus, a tsunami intermediate in size between the 2004 and 2005 tsunamis should be expected.

What is more, records of the 1797 earthquake give us some idea of the tsunami that followed it. Padang was a tiny place at the time; in fact, the coastal strip itself was largely uninhabited, at least by colonists. The settlement was 1–2 km inland, centred on a harbour on the banks of a small river. Nevertheless, the tsunami ran up the river, and according to contemporary accounts, it seized a 150 ton English sailing vessel that was moored there, carried it up the river and deposited it over the river bank in the middle of town. Padang is now a city of about 800 000 people.

The 1833 earthquake was likewise followed by a destructive tsunami. It had less effect at Padang, which lay at 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 other coastal cities, towns and villages of western Sumatra.

3. Emergency response preparedness

There are many ways in which countries such as Indonesia, though impoverished by Western standards, can effectively prepare themselves for future megathrust earthquakes and tsunamis. Most importantly, they need to set up a multi-tiered administrative structure that is devoted to this one issue. In the aftermath of the December 2004 tsunami, the Vice-President of Indonesia was assigned the task of administrating relief efforts. Laudable though his efforts have been, much more could be achieved by having a permanent cabinet-level official whose responsibility is not merely to respond to disasters that have already happened but also to plan mitigation strategies for future ones. This official would run an agency like the United States' Federal Emergency Management Agency (FEMA) that would coordinate planning and relief efforts. The agency would establish and maintain permanent lines of communication with foreign governmental and non-governmental agencies—agencies that, in the past, have come forward mainly in the wake of disasters. The Indonesian agency would oversee and provide support and communications for planners at the provincial and city level. It would also be responsible for developing long-range plans for how and where to rebuild after foreseeable disasters.

The need for joint advance planning with relief agencies and foreign governments can hardly be overstressed; typically, in past disasters, a great deal of time and effort has been wasted as a diverse array of national and international organizations struggle to communicate and to direct their relief efforts rationally. Foreign governments can greatly help such planning efforts by committing to work with the Indonesians over the long term.

It is also important that scientific research be brought to bear, ahead of disasters, in order to identify the at-risk zones and the kinds of problems that are likely to be encountered. With sufficient support, it is possible to develop models that, for a given megathrust earthquake, predict the likelihood of the event and the size of the tsunamis to be expected at a given locale as well as the likely zones of inundation. Such predictive models require detailed analysis of such factors as fault location and orientation, past history, seafloor bathymetry and coastal topography. A large number of such models need to be developed both for advance planning and also for use in the wake of an earthquake, in order to direct relief efforts where they are most likely to be needed. It is my understanding that in the wake of the 2004 tsunami, several governments have established funding for such research efforts.

There need to be regular practice exercises for disaster response, supported by the Indonesian government and international organizations and governments. These drills should involve local administrators, emergency responders and citizens. Many westerners are familiar with evacuation drills at their places of employment. Indonesians need to become familiar with evacuation drills that involve large sectors of coastal communities. There also need to be rehearsals at the national and international level, so that government and relief agencies learn to communicate effectively with each other and understand what is expected of them and what they can expect of others.

As an example of what is already being done, I can cite efforts in the coastal town of Air Bangis, about 200 km north of Padang (figure 5*b*). After discussions between members of our group and local officials, an *ad hoc* organization has laid out walking/running paths that lead from various low-lying parts of the town up to higher ground. Similarly, in Padang, private groups have started the planning of evacuation routes, including the construction of earthquake-resistant footbridges across waterways. Financial support for such efforts from overseas governments and other agencies could be enormously helpful.

Yet another important aspect of disaster preparedness is the stockpiling of food, medical supplies, tents and so on, as well as the allocation of suitable sites for emergency shelter. Devastated coastal communities cannot afford to wait for days or weeks after a disaster for relief supplies to be hauled from the capital or shipped from overseas, enough supplies for immediate relief should be stored locally.

Although the Indonesian government has very limited means, there are a host of organizations known as *yayasans*, founded by wealthy families as a part of a Moslem tradition of charitable action. Since many of these organizations are local, they are in a good position to participate in emergency response planning. For foreign governments desiring to contribute to this effort, it could be a very effective strategy to send specialists to assist these groups with their work and to provide a channel for international financial assistance.

4. Warning capability

There currently exists no means of giving short-term warnings of impending earthquakes, since there are no dependable signs that earthquakes are about to happen. The situation with tsunamis is quite different. A tsunami warning system, though incomplete, has been operational in the Pacific Ocean for many years.

In the wake of the 2004, Aceh–Andaman tsunami, plans have been laid to deploy a comparable early-warning system in the Indian Ocean. I believe that these plans are largely misdirected. It is true that, if such a system had been in place in the Indian Ocean, and if appropriate communication channels and programs of public education had been developed; many of the tsunami deaths outside of Indonesia could have been averted. For many more of the victims of the 2004 tsunami, however, the warning would not have come early enough, because most of the deaths occurred on the coast of Aceh province, which was reached by the tsunami just tens of minutes after the rupture of the megathrust. For many that would not have been enough time to walk or run the necessary 1–3 km from the coast, even if the warning had been delivered instantaneously.

As for other locations in the Indian Ocean, such as Sri Lanka, which are more remote from the megathrust, it is true that their populations could be warned of future tsunamis by the system that is now being planned. However, it is too late; the 1500 km stretch of the megathrust that threatened them has now ruptured. Given the enormous size of the slip during the December 2004 event—up to 25 m or even more in places—it is highly unlikely that this section of the megathrust has the capacity to deliver another giant tsunami in this century, and probably not even for several centuries more. It is simply a poor allocation of resources to put in place a warning system that in effect, locks the barn door on a horse that has already bolted. Funds for tsunami warning systems would be better allocated to other parts of the world where they are clearly needed. (It is possible that the northernmost part of the megathrust, near Myanmar (Burma), still has the capacity to cause a damaging tsunami, but this possibility should be fully investigated with palaeoseismic and palaeotsunami research before spending money on guarding against it.)

The likely future tsunamis are those that will be generated by the sectors of the subduction megathrust to the south—the sites of the 1797 and 1833 events. These tsunamis will radiate out in two opposite directions from the subduction zone. One tsunami will head out into the southern expanses of the Indian Ocean, where there are few inhabited coasts to be protected. Another tsunami will head from the subduction zone toward the mainland coast of western Sumatra, swamping the offshore islands on the way. The tsunami will reach both the islands and the coast within tens of minutes after the earthquake.

Like the Aceh tsunami, however, this tsunami will come with its own, instantaneous warning signal—the giant earthquake. Unlike what happened in countries like Sri Lanka and Thailand in December 2004, where the affected coasts were too far away from the rupture for the inhabitants to feel the earthquake itself, the inhabitants of the offshore islands and the mainland Sumatra coast will experience very strong and long-lasting ground motions. It is necessary only that they make the connection between the earthquake and the likelihood of an impending tsunami, as we will discuss subsequently.

Figure 6. The English version of one of the educational posters that our research group has developed to teach coastal Sumatrans why they have earthquakes and tsunamis. This and additional materials can be accessed through our website at www.tectonics.caltech.edu/sumatra/public.

5. Public education

In the course of many visits to Sumatra, I have developed friendships with, and admiration for, many of the people of Indonesia, as well as an awareness of the hazards to which they are exposed. Starting in 2004, I began a program of public education with my American and Indonesian colleagues in the Mentawai Islands, which is where much of our research has been focused (figure 1).

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 (figure 6). 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.

Another element consists of meetings we have with local officials and lectures that we present to ordinary citizens, normally in churches or schools. These presentations are intended to educate them about what we know and to involve them in the process of public education and response preparedness.

The beginnings of these outreach programs were funded by seed money from the Tectonics Observatory at Caltech. I planned to submit a grant proposal to the National Science Foundation to continue the work, but in late 2004, about a month before the 24 December earthquake, my application was rejected, sight unseen, because it got caught up in the complex rules over the funding of such overseas educational programs. Hopefully it will become easier in the US to tie useful research to outreach programs, for much scientific research can be used to the benefit of citizens outside of my own country.

One way or another, we will continue and extend this program. But, it will take a much larger infusion of funds and professional expertise to carry additional educational efforts with the necessary breadth and intensity. In particular, public-outreach programs in the mainland cities like Padang are far more demanding than on the islands, where there is far less competition for the attention of the population. To run an education program at the scale that is needed will take much more time and energy, which can be provided by a single research team; it must be a national or international enterprise specifically focused on this one issue. The seeds for this kind of effort have already been sown by non-governmental groups that came together spontaneously in the aftermath of the 2004 and 2005 earthquakes, as described above.

One factor has greatly aided our educational efforts, and that is the 2004 earthquake and tsunami. Sadly, it has taken a disaster of this magnitude to draw public attention to the earthquake and tsunami hazards and the connection between them. The population of Padang has in fact been put in a state of excessive anxiety by the events to the north. The sequence of aftershocks mentioned earlier, which were situated farther to the south than the two megathrust ruptures of 2004 and 2005, caused panic in Padang and other coastal communities, and I have been told that some people died in traffic accidents while attempting to leave the coastal zone. Of course, this state of anxiety will gradually abate over time. It is critically important to seize the opportunity posed by the 2004 and 2005 disasters to educate local communities in a positive way 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.

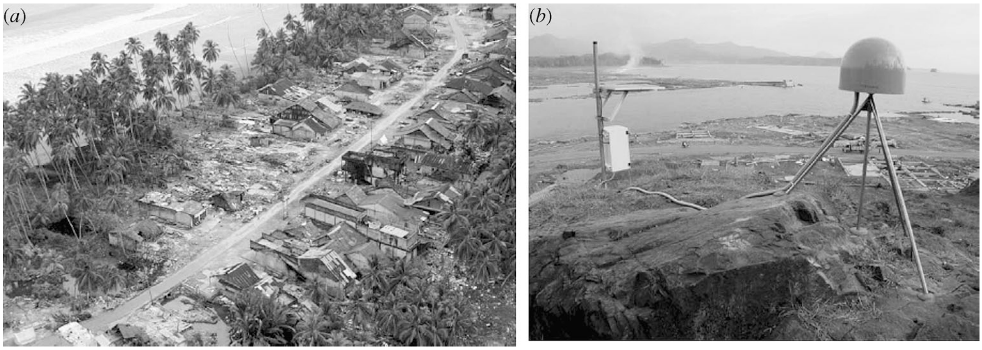

Figure 7. (*a*) The most damaging tsunami wave of 26 December 2004, at Sirombu village on the west coast of Nias island, Sumatra, arrived about 8 h after the earthquake. This tardy arrival probably means it was reflected off the Maldives in the central Indian Ocean and came back to flood western Sumatra. Only a few residents died, because they fled when the smaller, first wave arrived, soon after the earthquake. (*b*) One of our new continuously recording GPS stations on the west coast of Aceh province overlooks the former site of Lamno village, where most residents lost their lives in the 26 December 2004, tsunami. The largest waves here arrived about half an hour after the strong shaking of the earthquake. Many could have escaped, if they had been trained to leave the coastal region immediately after a large earthquake.

6. The infrastructure—building and planning for safety

The two key questions concerning how to build safely in the zones 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, i.e. in 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 (figure 7). 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.

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.

Building coastal defences, such as seawalls, to protect populations from tsunamis is not a practicable strategy in most cases. Even in such pro-active countries as Japan, such approaches are not common. Such seawalls could only protect against average-sized tsunamis, not the giant tsunamis that occur during some megathrust earthquakes. Furthermore, the expense of such construction would be far beyond the means of countries like Indonesia. A much more practicable solution is to relocate vulnerable populations away from high-risk areas, or at least to decrease population density within them. Such a strategy has been taken to a limited degree in other tsunami-prone regions. After a 1960 tsunami that killed 61 people in Hilo, Hawaii, which destroyed over 500 buildings in the downtown business district, much of the affected area was permanently cleared and turned into an attractive waterfront park.

The same kind of strategy, on a far wider scale, must be adopted in the vulnerable coastal zones and islands of western Sumatra. In large cities such as Padang, where topography is basically flat, a strip extending at least 1 km wide needs to be re-configured. Of course, this will be a capital intensive program requiring international assistance, for property owners will need to be recompensed at a rate that permits them to rebuild farther inland. For most people living in the vulnerable areas, there is no compelling economic need for them to live where they do; most residents do not have occupations related to fishing or tourism that make it necessary for them to live near the water—they have simply come to live there because that is where land was available. Furthermore, land is available farther inland that would be suitable for habitation.

As to the question of *how* to build, the issue is not tsunami resistance, which is difficult or impossible to achieve, but *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 inch into the ground.

In the coastal cities, there are more substantial buildings, such as two and three-storey concrete office and apartment buildings, as well as hotels. Adequate building codes need to be in place and enforced to ensure that new construction of this type is able to withstand the level and duration of shaking that accompany a megathrust earthquake. One advantage of having multi-storey buildings standing in the coastal strip is that they can be used in the hours following the earthquake for vertical evacuation of the population, out of the reach of the tsunami surge.

7. Conclusions

When we see how poorly the United States has coped with a recent major disaster, Hurricane Katrina, the prospects for dealing effectively with much larger disasters that threaten impoverished countries like Indonesia seem daunting. However, that very difference in economic status makes it easier for us to act effectively for good, because so much can be achieved with so little. To foundation-bolt a typical California woodframe home—the simplest and most effective step that most homeowners can undertake to protect themselves from earthquakes—costs in the order of US$5000. Anchoring a typical Indonesian home to concrete footings, as described earlier, costs in the order of US$50. Similarly, educational programs are extraordinarily cost-effective. Thus, international assistance programs, if well focused on the issues that truly require action, could save hundreds and thousands of lives.

There really is no such thing as a natural disaster, whether we are talking about earthquakes, tsunamis or hurricanes. For nature, these events are not *disasters*—they are merely a makeover or just an occasional activity that relieves pent-up strain. Nor for us, are they *natural*. We are complicit in bringing them about, to the extent that we expose ourselves to hazards by the choices we make in our everyday lives—choices about where and how we live, and what we do or fail to do in the face of known risks. Research, infrastructure changes, warning systems, emergency preparedness and public education, if taken seriously and generously supported, could transform natural hazards into natural wonders.

One test of whether humanity acts differently 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 second, then there will continue to be more tragedies like that of 26 December 2004.

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