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# Lessons from the 2004 Sumatra–Andaman earthquake

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The 2004 Sumatra–Andaman earthquake ( $M_w=9.0$ – $9.3$ ) is one of the greatest earthquakes ever recorded. In terms of its physical size, it is comparable to the 1960 Chilean ( $M_w=9.5$ ) and the 1965 Alaskan ( $M_w=9.2$ ) earthquakes. However, the damage caused by this earthquake is far greater than that caused by other great earthquakes. The 2004 Sumatra–Andaman earthquake has been studied in great detail over broad time-scales, from a fraction of seconds to hours and months, using the modern seismic data available from global seismic networks and the Global Positioning System data. We summarize the findings obtained mainly from seismic data, and discuss the unique feature of this earthquake, and possible directions of research to minimize the impact of great earthquakes on our society.

**Keywords:** Sumatra–Andaman earthquake; earthquake prediction; scenario earthquakes; tsunami warning; earthquake early warning; damaging earthquakes

## 1. Introduction

The 2004 Sumatra–Andaman earthquake (December 26, 2004, 3.30 N, 95.78 E, 10 km,  $M_w=9.2$ ) is one of the largest earthquakes instrumentally recorded. It ruptured the boundary between the Indo-Australian plate and the Eurasian plate along the northwestern Sumatra, the Nicobar Is and the Andaman Is ([figure 1](#)). The faulting occurred on a low-angle thrust fault dipping *ca*  $10^\circ$  northeast with the Indo-Australian plate moving northeast relative to the Eurasian plate. Since several papers have been already written on this earthquake (e.g. [Ammon \*et al.\* 2005](#); [Lay \*et al.\* 2005](#)), here we only summarize the results ([figure 1](#)). We first define several important earthquake parameters.

An earthquake occurs due to failure of rocks in the Earth caused by stresses produced mainly by plate motion. If the stress at a point exceeds the local strength of the rock, an earthquake occurs. A rupture initiates at a point, propagates at a speed  $V$  over a fault plane, and eventually stops when either the driving stress drops or the rupture encounters a strong obstacle. We let  $L$ ,  $S$ ,  $\tau$  and  $D$  be the rupture length, fault area, duration of rupture and the average displacement (offset) across the fault plane, respectively. The rupture speed  $V$

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varies from earthquake to earthquake. In most earthquakes,  $V$  is *ca*  $2\text{--}3.5\text{ km s}^{-1}$ , but faster and slower rupture speeds have been observed in a few cases. Ideally, it is desirable to quantify the size of an earthquake by the total amount of energy released. However, it is technically difficult even now to accurately estimate the energy release. The seismic moment  $M_0$ , defined by

$$M_0 = \mu DS \quad (1.1)$$

is used instead to represent the size of an earthquake. In the above,  $\mu$  is the shear modulus of the rock surrounding the fault (Aki 1966).

Although  $M_0$  has the unit of energy, it is not the energy released in an earthquake. Thus, we commonly use (dyne cm) or (N m) for the unit of  $M_0$  to indicate that  $M_0$  is distinct from the energy released.

In the current practice, we define the moment magnitude  $M_w$  by (Kanamori 1978)

$$M_w = (\log_{10} M_0)/1.5 - 10.7 \quad (M_0 \text{ in dyne cm}). \quad (1.2)$$

When an earthquake occurs beneath the seafloor, the resulting deformation of the seafloor displaces water. This disturbance propagates in the ocean as tsunami with long wavelengths, which propagate all the way to the coast and often cause extensive damage. The overall size of tsunami is given by the tsunami magnitude (Bryant 2001, p. 139) which is determined from the observed tsunami height. Several tsunami magnitude scales are used in practice; here we use the  $M_t$  scale introduced by Abe (1979) which is computed from the tsunami amplitude,  $H$  (in m), recorded at a station at distance  $X$  (in km) using the relation  $M_t = \log H + \log X + 5.55$  (Abe 1981). Despite its simplicity, it represents the overall size of tsunami well.

The source parameters, as defined above, of the 2004 Sumatra–Andaman earthquake can be summarized as follows:

- (i) The duration of rupture,  $\tau$ , is *ca* 500 s (Ishii *et al.* 2005; Ni *et al.* 2005) which is the longest instrumentally determined duration for any historical earthquakes. In comparison, the rupture duration of the 1960 Chilean ( $M_w=9.5$ ) and the 1964 Alaskan ( $M_w=9.2$ ) earthquakes was *ca* 350 (Houston & Kanamori 1986).
- (ii) The rupture length,  $L$ , is estimated at 1200–1300 km (Ammon *et al.* 2005; Ishii *et al.* 2005; Ni *et al.* 2005; Tsai *et al.* 2005). The rupture propagated north from the hypocenter in the south as shown in figure 1. This length is approximately the same as that of the aftershock distribution within a few days after the earthquake (figure 1). In comparison, the rupture length of the 1960 Chilean earthquake is *ca* 800–1000 km, and that of the 1964 Alaskan earthquake is *ca* 500–700 km. Thus, the Sumatra–Andaman earthquake has probably the longest rupture length ever determined instrumentally.
- (iii) The moment magnitude,  $M_w$ , estimated by various investigators ranges from 9.0 to 9.3 (e.g. Harvard CMT solution; Ammon *et al.* 2005; Park *et al.* 2005; Stein & Okal 2005; Tsai *et al.* 2005) and is comparable to the Chilean ( $M_w=9.5$ ) and the Alaskan ( $M_w=9.2$ ) earthquakes. However, the current practice of estimating the seismic moment,  $M_0$ , does not take into account the effects of the complex three-dimensional structure in the source region and, as a result,  $M_w$  is subject to considerable uncertainty.

The same situation applies to the Chilean and the Alaskan earthquakes as well. Taking this limitation into account, these three earthquakes should be regarded as comparable in size. Here, we use  $M_w=9.2$  as a representative value for the Sumatra–Andaman earthquake. The average slip is *ca* 7 m, with the maximum slip exceeding 20 m off the coast of northwestern Sumatra.

- (iv) The tsunami magnitude,  $M_t$ , is 9.1 (K. Abe 2005, personal communication). In comparison,  $M_t=9.4$  and 9.1 for the Chilean ( $M_w=9.5$ ) and the Alaskan ( $M_w=9.2$ ) earthquakes, respectively (Abe 1979). Thus, even though the tsunami was extremely devastating, its physical size is not anomalously large for an earthquake with  $M_w \approx 9$ .

## 2. Prediction and forecast of earthquakes

If we can predict the time, location and size of an earthquake accurately, we will be able to greatly reduce the impact of an earthquake on our society. For this reason, there has been a great deal of interest in earthquake prediction among the public and emergency services officials. However, the term ‘Earthquake Prediction’ is often used in two different contexts (Kanamori 2002).

### (a) Short-term prediction

In the common usage, especially among the public, earthquake prediction means a highly reliable, publicly announced, short-term (within hours to weeks) prediction that will prompt some emergency measures (e.g. alert, evacuation, etc.). Exactly how reliable this type of prediction should be depends on the social and economic situations of the region involved. The issue is whether the quality of prediction is good enough to benefit the society in question. In the areas where the social and economical structures are relatively simple, predictions with low reliability could be still useful, while in highly industrialized countries, predictions, if any is to be issued, must be very accurate.

### (b) Long-term forecast

In another usage, earthquake prediction means a statement regarding the future seismic activity in a region, and the requirement for high reliability is somewhat relaxed in this context. In a way, this is a more general scientific prediction of a physical system. The reliability of a specific prediction depends on the level of our understanding of the process, and the amount and quality of data we have. Since, the basic physical process of earthquakes is now reasonably well understood and high-quality geophysical data are being collected, it should be possible to make some predictions regarding the future seismic activity in a region on the basis of whatever geophysical parameters are observed and their interpretations. This type of prediction also has important social implications on time-scales of months and years. However, it is best to distinguish it from the short-term prediction described above. It should be mentioned that the term ‘prediction’ is often used for a statement on a specific earthquake, and ‘forecast’ is more commonly used for a statement on the future seismic behaviour of a region as a whole.

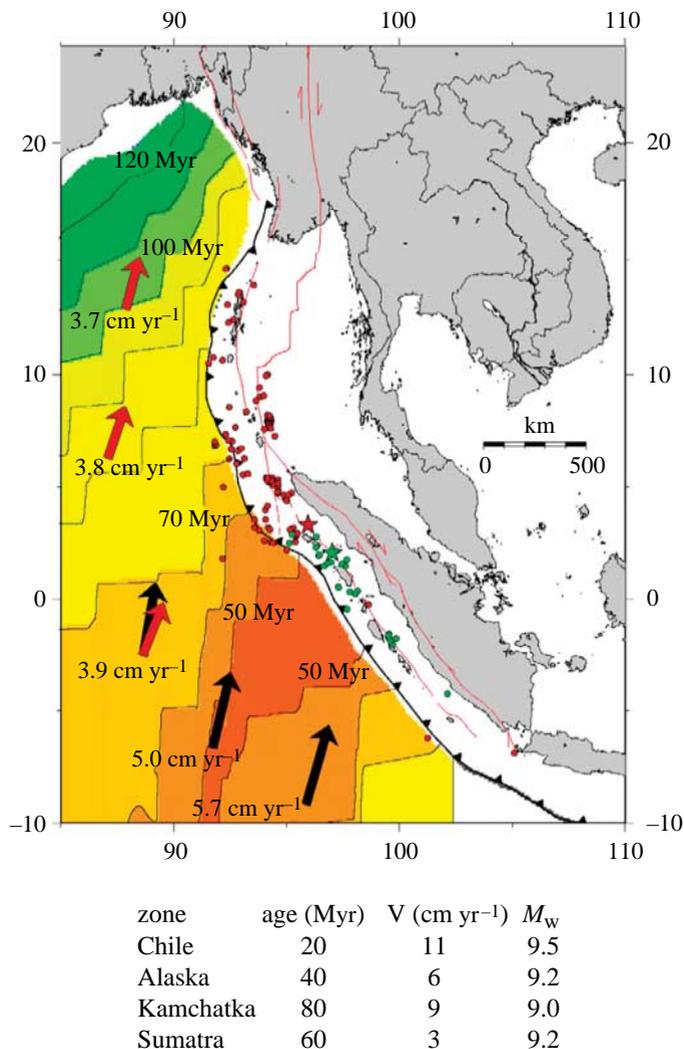


Figure 1. Age of the seafloor and plate convergence directions in the epicentral area of the 2004 Sumatra–Andaman earthquake. The red and green stars indicate the epicentre of the 2004 Sumatra–Andaman earthquake (Dec 26,  $M_w=9.2$ ), and the 2005 Nias earthquake (Mar 28,  $M_w=8.7$ ), respectively. Red and green circles are the aftershocks. Red arrows indicate the relative plate motion. Dark arrows indicate the plate motion computed from a regional kinematic model. (Courtesy of Mohamed Chlieh). Age of the subducting plate, convergence rate and  $M_w$  of the largest earthquake in four subduction zones are listed at the bottom.

### (c) *Uncertainties in prediction and forecast*

Advances have been made in understanding crustal deformation and stress accumulation processes, rupture dynamics, rupture patterns, friction and constitutive relations, interaction between faults, fault-zone structures and nonlinear dynamics. Thus, it should be possible to predict to some extent the seismic behaviour of the crust in the future from various measurements taken in the past and the present. However, the incompleteness of our understanding of

the physics of earthquakes in conjunction with the obvious difficulty in making detailed measurements of various field variables (structure, strain, etc.) in the Earth makes accurate deterministic short-term predictions difficult. Moreover, earthquakes occur in a complex crust–mantle system. This system includes some distinct structures such as the seismogenic zone and faults, as well as highly heterogeneous structures with all length scales. The distinct structures are responsible for the long-term deterministic behaviour of earthquakes, but the interactions between different parts of the complex system result in the chaotic behaviour of earthquake sequences. Several processes are especially responsible for the uncertainties. If we assume that plate motion is stationary then the stress changes due to plate motion can be estimated with relatively small uncertainties. However, the stress in the crust also changes with time on a local scale. For example, the stress on a fault can be affected by nearby earthquakes. Since earthquakes occur on a complex array of faults, the crustal stress field is irregular on a local scale and determination of future earthquake locations would be inevitably uncertain.

The strength of the crust may change as a function of time too. For example, migration of fluids in the crust could change the local strength of the crust and affect the occurrence of earthquakes (e.g. [Raleigh \*et al.\* 1976](#)). Since our knowledge of hydrological processes in the crust is limited, the temporal variation of the strength of the crust is difficult to predict, which leads to large uncertainties in the timing of occurrence of earthquakes.

Prediction of the size (magnitude) of an earthquake is also uncertain, because a small earthquake may trigger another event in the adjacent area, cascading to a much larger event. Although the extent of a stressed area may ultimately determine the maximum size of the earthquake, the growth of rupture is likely to have some stochastic elements. Any small earthquake may grow into the maximum earthquake determined by the size of the stressed area or may stop half way depending on small variations in the mechanical properties of rocks in the fault-zone. Another important process is triggering by external effects. [Hill \*et al.\* \(1993\)](#) observed significant seismic activities in many geothermal areas soon after the June 28, 1992, Landers, California, earthquake ( $M_w=7.3$ ). Although the detailed mechanism is still unknown, it appears that the interaction between fluid in the crust and strain changes caused by seismic waves from the Landers earthquake was responsible for sudden weakening of the crust. If sudden weakening of the crust resulting from dynamic loading plays an important role in triggering earthquakes, deterministic predictions of the initiation time of an earthquake would be difficult.

#### (d) *Precursor*

Some earthquakes are known to have been preceded by distinct seismic activity, called foreshocks. These observations led some seismologists to believe that earthquakes can be predicted by observing some precursors like foreshocks.

The term ‘precursor’ means two different things. In a restricted usage, precursor implies some anomalous phenomenon that always occurs before an earthquake in a consistent manner. This is the type of precursor one would wish to find for short-term earthquake prediction. As far as we know, universally

accepted precursors that occur consistently before every major earthquake have not yet been found.

In contrast, precursor is often used in a second sense to mean some anomalous phenomena that may occur before large earthquakes. Since an earthquake may involve nonlinear preparatory processes before failure, it is not unreasonable to expect a precursor of this type. However, it may not always occur before every earthquake, or even if it occurs, it may not always be followed by a large earthquake. Thus, in this case, the precursor cannot be used for a definitive earthquake prediction. Some large earthquakes were preceded by a distinct foreshock activity, but many earthquakes do not have distinct foreshocks. Also, a group of small earthquakes can occur without any major earthquake following it. These precursors may be identified in retrospective studies, but it is very difficult to identify some anomalous observations as a precursor of a large earthquake before its occurrence.

### 3. Lessons from the Sumatra–Andaman earthquake

The occurrence of such a large earthquake as the 2004 Sumatra–Andaman earthquake at this particular location was surprising to many seismologists. In general, past great earthquakes have occurred in the areas with certain tectonic characteristics. In general, such great earthquakes happen where one tectonic plate collides against another. One plate is pushed into the Earth's interior along a huge thrust fault (often called a megathrust). This process is called subduction. The world's largest earthquakes occur along subduction zones.

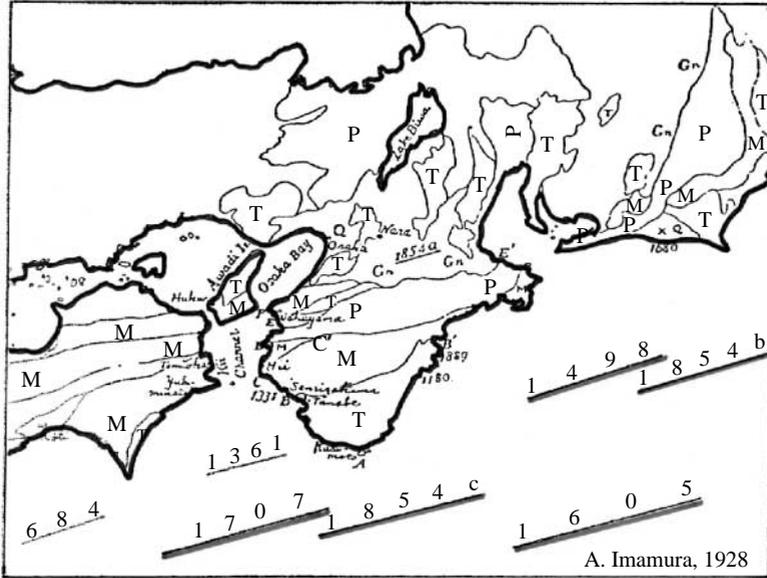
Great earthquakes in the past like the 1960 Chilean and the 1964 Alaskan earthquakes have generally occurred on the plate boundary, where the subducting oceanic plate is relatively young. The age of the subducting oceanic plate is *ca* 20 Myr for Chile and 40 Myr for Alaska. When the subducting plate is young, it is more buoyant leading to strong coupling between the subducting oceanic plate and the continental plate. As shown in [figure 1](#), in the case of the Sumatra–Andaman earthquake the age of the subducting plate in the southernmost portion of the rupture zone is *ca* 55 Myr which is relatively young, but in the northernmost portion it is almost 90 Myr, much older than that of the subduction zones where great earthquakes have occurred in the past.

In each of these instances the trench-normal convergence rate is large, 11 cm yr<sup>-1</sup> for Chile and 6 cm yr<sup>-1</sup> for Alaska. In the case of the Sumatra–Andaman earthquake, however, the trench-normal convergence rate is *ca* 3 cm yr<sup>-1</sup> in the south, and almost zero in the north. The relation summarized by [Ruff & Kanamori \(1980\)](#) suggests an empirical formula

$$M_w = -0.00953T + 0.143V + 8.01, \quad (3.1)$$

where  $M_w$  is the magnitude of the expected event,  $V$  is the trench-normal convergence rate in cm yr<sup>-1</sup>, and  $T$  is the age of the subducting plate in million years ([Kanamori 1986](#)). Using this relationship, we get  $M_w=8.2$  for the southernmost part of the rupture zone of the Sumatra–Andaman earthquake. Thus, in the framework of this empirical relationship, an occurrence of  $M_w=8+$  earthquake in the southernmost part of the rupture zone of the Sumatra–Andaman earthquake is not unexpected, but it is surprising to have an  $M_w=9+$  event.

(a) Nankai trough



(b) earthquake sequence along the Nankai trough

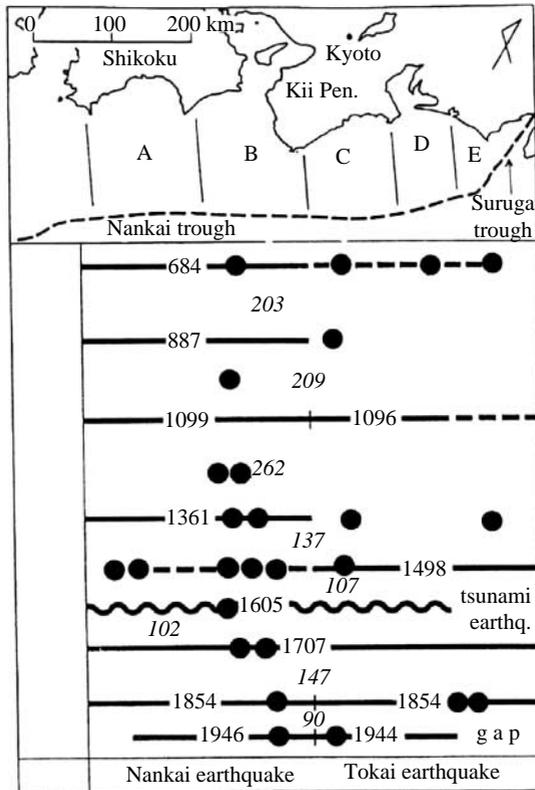


Figure 2. (a) The rupture zones of large historical earthquakes in the Nankai trough (Imamura 1928). (b) Rupture sequence along the Nankai trough (Ishibashi & Satake 1998).

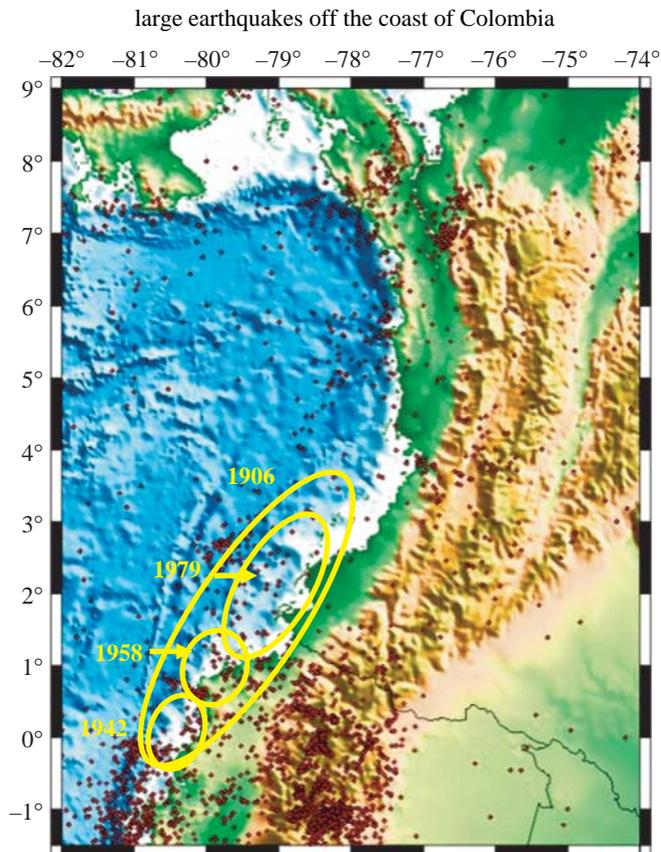


Figure 3. Earthquake sequence along the Colombia–Ecuador subduction zone (Kelleher 1972; Kanamori & McNally 1982).

What is special about the Sumatra–Andaman earthquake? Why did we have such a large earthquake at the place where we did not expect very large events? The empirical relationship as it is used above may approximately hold in the general sense, but we need to realize that significant deviations can happen in complex systems like earthquakes where interactions between different segments could cause triggering of rupture over an extended area. Physical discontinuities or interruptions to the fault surface may halt or interrupt rupture propagation, and the resulting stress increase at the fault ends may trigger rupture on the adjacent segment. In a way, large earthquakes are in fact multiple smaller earthquakes where several segments have been triggered sequentially.

Exactly how the different parts of the rupture zones interacted during the Sumatra–Andaman sequence must await further investigations. Nevertheless, it is possible that the rupture in the southernmost segment triggered the ruptures in the north. Such triggering may not happen all the time. If it does not happen, the event may end up being a moderate earthquake, but if it does happen the event may become a great earthquake. As a result, the rupture pattern along a given subduction boundary can vary from sequence to sequence. We will present several examples of complex ruptures that have occurred in several different tectonic regions.

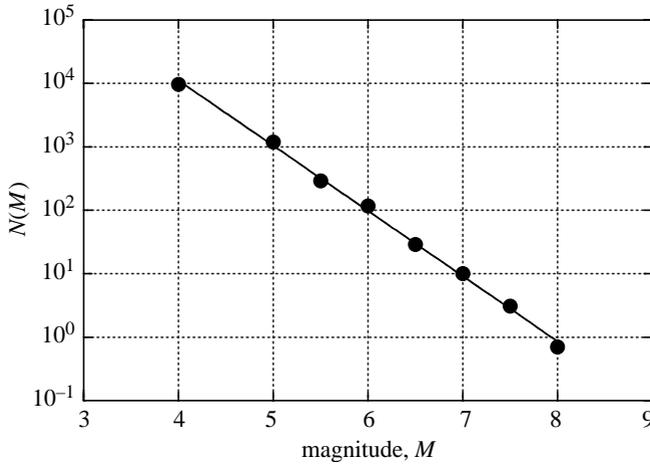


Figure 4. Magnitude–frequency relationship for earthquakes in the world for the period 1904–1980.  $N(M)$  is the number of earthquakes per year with the magnitude greater than or equal to  $M$ . Note that, on the average, approximately one earthquake with  $M \geq 8$  occurs every year (Kanamori & Brodsky 2004).

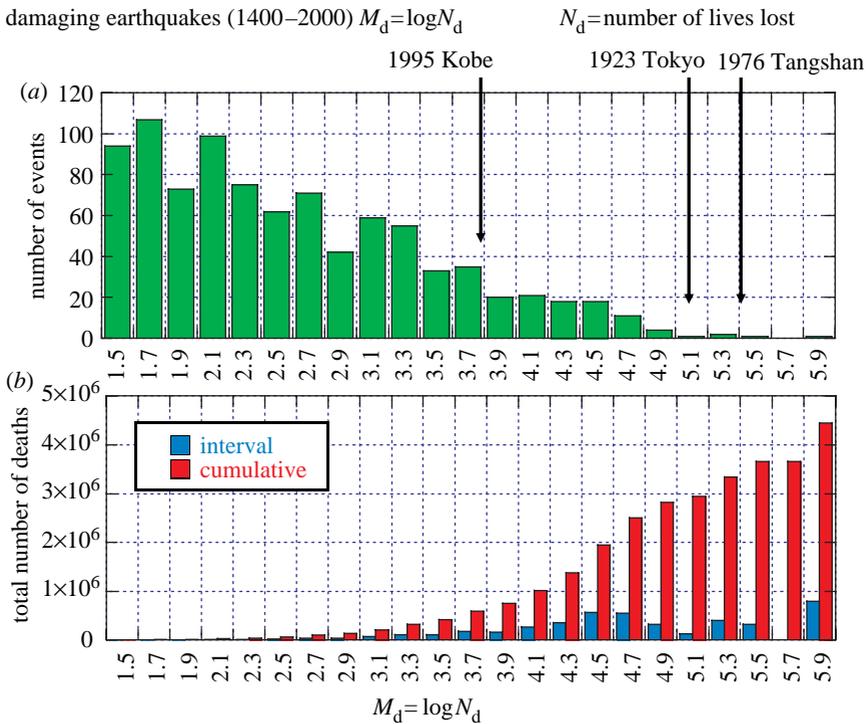


Figure 5. The frequency of damaging earthquakes,  $N$  (a) and the number of deaths,  $N_d$ , caused by them (b). The blue columns show the number for a 0.2 interval of  $M_d (= \log N_d)$  and the red columns show the cumulative numbers, i.e. the number of deaths in events equal to or smaller than  $M_d = \log N_d$ . The data are from Utsu (2002).

Table 1. The number of deaths caused by earthquakes, 1400–2004 (Utsu 2002).

year	event	$M$	number of deaths
1556	China, Shaanxi Province	8.0	830 000
1737	India, Calcutta		300 000
1976	China, Tangshan	7.8	242 800
1920	China, Ningxia	8.5	220 000
1923	Japan, Tokyo (Kanto)	7.9	142 807
1908	Italy, Messina	7.1	82 000
1668	Azerbaijan, Shemakha	7.0	80 000
1727	Iran, Tabriz	7.2	77 000
1970	Peru	7.8	66 794
1755	Portugal, Lisbon E.	8.5	62 000
1935	Pakistan, Quetta E.	7.5	60 000
1693	Italy, Catania E.	7.4	54 000
1789	Turkey, Palu	7.0	51 000
1780	Iran, Tabriz	7.4	50 000
1739	China, Ningxia	8.0	50 000
1868	Ecuador, Ibarra	7.7	40 000
1797	Ecuador, Quito	8.3	40 000
1754	Egypt, Grand Cairo		40 000
1721	Iran, Tabriz	7.4	40 000
1718	China, Gansu Province	7.5	40 000

#### 4. Examples of complex rupture

##### (a) *Nankai trough*

One of the most complete examples is that of the sequences along the Nankai trough in southwest Japan (Imamura 1928; Ando 1975). Along the Nankai trough, large earthquakes are known to have occurred repeatedly along several distinct segments (figure 2*a,b*). In 1707, two of the segments ruptured simultaneously producing one of the largest earthquakes in Japan. In 1854, the same two segments ruptured 32 h apart, producing two  $M=8+$  earthquakes. In 1944 and 1946, the two segments ruptured *ca* 2 years apart, each producing an  $M\approx 8$  earthquake. It would be very difficult to predict exactly how the different segments rupture and how they interact. This type of unpredictability is inevitable for complex processes like earthquakes.

##### (b) *Colombia–Ecuador*

Another example is the sequence along the subduction zone off the coast of Colombia and Ecuador. As shown in figure 3, a large earthquake ( $M_w=8.8$ ) occurred in 1906 on a 600 km segment along the subduction zone, but the same segment ruptured in three smaller earthquakes in 1942, 1958 and 1979 (Kelleher 1972; Kanamori & McNally 1982).

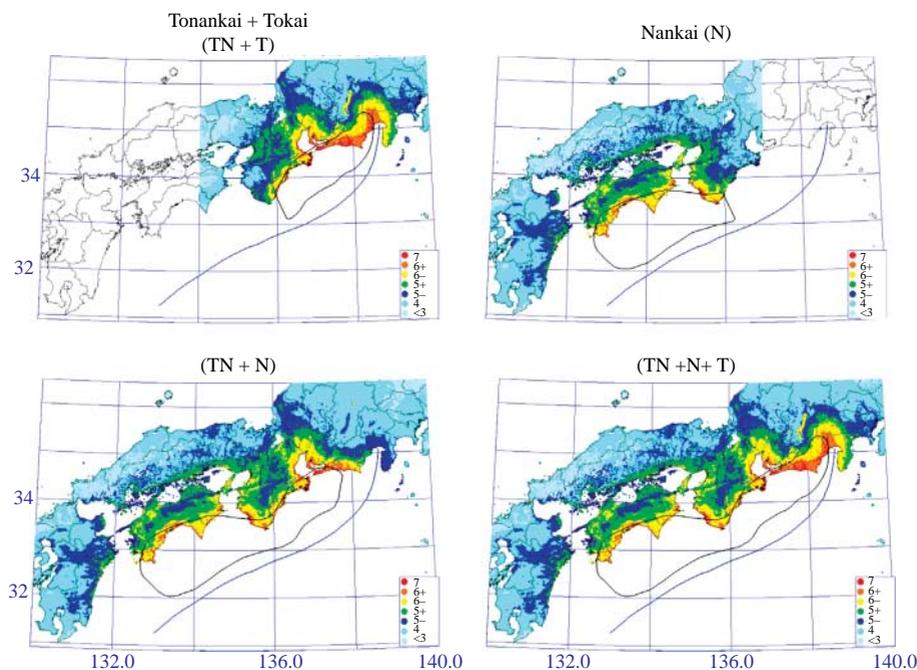


Figure 6. Four scenario earthquakes along the Nankai trough, and the estimated intensity (Japanese scale) distribution (Courtesy of Central Disaster Management Council, Japan). JMA intensity scale: the Japanese Meteorological Agency (JMA) Scale runs from 0 to 7, with 7 being the strongest. 7, in most buildings, wall tiles and windowpanes are damaged and fall. In some cases, reinforced concrete-block walls collapse. 6+, in many buildings, wall tiles and windowpanes are damaged and fall. Most un-reinforced concrete-block walls collapse. 6-, in some buildings, wall tiles and windowpanes are damaged and fall. 5+, in many cases, un-reinforced concrete-block walls collapse and tombstones overturn. Many automobiles stop due to difficulty in driving. Occasionally, poorly installed vending machines fall. 5-, most people try to escape from danger, some finding it difficult to move. 4, many people are frightened. Some people try to escape from danger. Most sleeping people awake. 3, felt by most people in the building. Some people are frightened. 2, felt by many people in the building. Some sleeping people awake. 1, felt by only some people in the building. 0, imperceptible to people.

### (c) Kurile trench

Large earthquakes with  $M \approx 8$  repeatedly occurred during the nineteenth and twentieth centuries along the Kurile trench off the coast of Hokkaido, Japan. Nanayama *et al.* (2003) investigated the tsunami deposits in Hokkaido and concluded that some earlier events, including the one in the seventeenth century, were much larger than the typical recent events, and occurred with an interval of *ca* 500 years. These larger earthquakes were probably caused by simultaneous rupture of multiple segments.

## 5. Impact of rare large events

How rare is a great earthquake like the 2004 Sumatra–Andaman earthquake?

*(a) Magnitude–frequency relationship*

In general, small earthquakes are more frequent than large earthquakes. More precisely, the number of earthquakes,  $N(M)$ , which have a magnitude greater than or equal to  $M$  is given by the relation

$$\log N(M) = a - bM, \quad (5.1)$$

where  $a$  and  $b$  are constants (Gutenberg & Richter 1941). Figure 4 shows this relation for the world (Kanamori & Brodsky 2004). Approximately one earthquake with  $M \geq 8$  occurs every year somewhere in the Earth. If we extrapolate the trend to  $M=9$ , we would expect one  $M \geq 9$  earthquake once every 10 years on the average. During the last 100 years, only four earthquakes with  $M \geq 9$  (1952, Kamchatka,  $M=9$ ; 1960 Chile,  $M=9.5$ ; 1964 Alaska,  $M=9.2$ , 2004 Sumatra,  $M=9.2$ ) have occurred. This number is considerably smaller than the expected 10 from the relation shown in figure 4, but whether this difference is significant or not is unclear. Equations like (5.1) generally hold for a highly complex system without any dominant length scale. However, extrapolating it to the large magnitude range requires caution. Since the physical dimension of an earthquake increases with its magnitude, there should be an upper limit in the magnitude as the fault length of an earthquake approaches the maximum length of tectonic structures of the Earth. The fault length of  $M_w \approx 9.5$  earthquake exceeds 1000 km, which is comparable to the length of the longest straight section of subduction zones. Thus, the maximum magnitude would be *ca* 10, and the number of events with  $M_w > 8.5$  becomes too small to have a meaningful statistics.

Also, if the Earth's tectonic structures happen to have some characteristic lengths, then we would expect earthquakes with the magnitudes corresponding to that length scale. If this happens, the magnitude–frequency relation (5.1) is violated. These earthquakes are called the characteristic earthquakes. In any case, we should expect to have several of these great earthquakes in a century.

*(b) Statistics of damaging earthquakes*

Were the other great earthquakes as damaging as the Sumatra–Andaman earthquake? Actually, in terms of the number of deaths, they are not (Utsu 2002). The numbers for the four earthquakes with  $M_w \geq 9$  during the last 100 years are: 1952 Kamchatka (not listed), 1960 Chile (5700), 1964 Alaska (131), 2004 Sumatra (280 000). The direct damage caused by an earthquake depends on not only its physical size but also many other factors, e.g. the total population in the affected area, the types of construction etc. In addition, significant damage can occur from secondary hazards like fire, landslides and flooding. Statistics show that earthquakes with an extremely large number of deaths are relatively few in number, but the total number of deaths in these few earthquakes is very large (Table 1). Figure 5 which is constructed from the catalogue of damaging earthquakes for the period of 1400–2004 (Utsu 2002) illustrates the situation. The quantity plotted on the horizontal axis is  $M_d = \log N_d$ , where  $N_d$  is the number of deaths. In a way,  $M_d$  can be regarded as ‘Damage’ magnitude. The top figure shows the number,  $N$ , of events which fall in an interval between  $M_d - 0.1$  and  $M_d + 0.1$  as a function of  $M_d$ . The events with an extremely large number of deaths like the 2004 Sumatra–Andaman earthquake are very rare. The bottom figure shows the product  $N \cdot N_d$ . The blue columns show  $N \cdot N_d$  for each interval

and the red columns show the cumulative numbers, i.e. the number of deaths in events equal to or smaller than  $M_d = \log N_d$ . This figure shows that out of nearly 4 million people who died in earthquakes in the last 600 years, nearly half died in *ca* 40 really damaging earthquakes out of the 900 events shown in figure 5. These 40 events include the 1976 Tanshang, China, earthquake and the 1923 Kanto, Japan, earthquake. The 2004 Sumatra–Andaman earthquake belongs to this category. These rare but extremely damaging events have a profound impact on our society.

## 6. Hazard estimation using scenario earthquakes

Given the difficulty in making precise short-term predictions, the uncertainty involved in long-term forecast and the huge impact of rare but extremely damaging earthquakes, how should we deal with the hazard caused by such rare events?

One way of dealing with these large earthquakes is to consider scenario earthquakes, assess their hazard and prepare for them. This approach has been extensively used in Japan by the Central Disaster Management Council, Cabinet Office, Government of Japan and the Headquarters for Earthquake Research Promotion, Government of Japan. Since the details have been published in many reports (e.g. [Central Disaster Management Council 2003](#); [National Research Institute for Earth Science and Disaster Prevention 2003](#)), here we summarize the results of a study for the Nankai trough (figure 2*b*). As we discussed earlier, several segments (i.e. Tokai, segment E; Tonankai, segments C and D; and Nankai, segments A and B) ruptured sometimes independently and sometimes jointly (see figure 2*b*). Thus, the scenario earthquakes must be constructed for several different cases. Figure 6 shows four scenarios, Tonankai+Tokai, Nankai alone, Tonankai+Nankai and Tonankai+Nankai+Tokai.

Simple conceptual rupture models are used for estimating the intensity, the extent of damage and tsunami height for these scenario earthquakes. For each scenario earthquake, the fault area and the total seismic moment are assumed. The slip on the fault plane is not uniform, and is assumed to occur in patches. The patches where slip occurs are called asperities. A suite of fault models is constructed with random distributions of asperities. The distribution is determined by trial and error such that the computed intensity distribution can explain the general feature of historical events. The wave field is then computed for each model using appropriate three-dimensional basement structures. The general methodology is described by [Irikura & Miyake \(2001\)](#) and [Irikura \*et al.\* \(2004\)](#). The effects of shallow underground structures are included by superposing empirically estimated site response. Figure 6 shows the seismic intensity distributions for these four scenario earthquakes. The scale used in figure 6 is the Japanese seismic intensity scale defined by the Japan Meteorological Agency. Figure 7 shows the estimated number of damaged houses (per 1 km<sup>2</sup>) and figure 8 shows the distribution of the estimated tsunami height for the largest scenario event (T+TN+N).

Although this practice involves many assumptions regarding the source and propagation effects, it provides useful guidelines regarding what might be expected of future large earthquakes, including very rare events. The next important step is to start preparing for them by retrofitting structures, upgrading building codes, constructing infrastructures for efficient emergency services, etc.

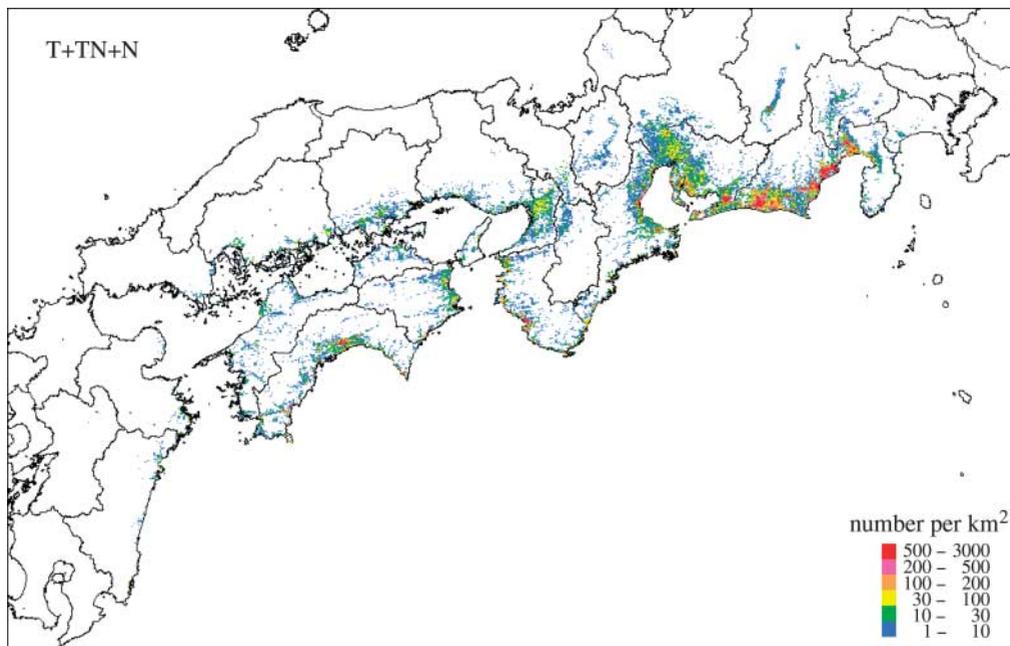


Figure 7. Estimated number of damaged houses (per km<sup>2</sup>) for a scenario earthquake simulating the 1944 Tonankai+1946 Nankai+Tokai earthquakes (Courtesy of Central Disaster Management Council, Japan).

To extend scenario earthquake studies to other earthquake-prone areas, investigations of: (i) the general characteristics of historical earthquakes; (ii) the crust–mantle structures; and (iii) the site responses of the areas involved using modern seismological methods are required.

## 7. Real-time seismology

With the availability of high-quality seismic data, seismologists can quantitatively determine many of the important physical characteristics of earthquakes rapidly. However, for the Sumatra–Andaman earthquake, it took seismologists many hours to recognize how large the event really was, partly because the present global observation systems are not specifically designed for such ‘off-scale’ events (Kerr 2005). A very rapid determination of the size is useful for various warning purposes, such as tsunami warning. Needless to say, establishing an effective tsunami warning system requires a comprehensive program including the monitoring of seismic waves, crustal deformations, water waves, infrastructure for information transfer and logistics, and education and training of residents. Here, we illustrate a simple seismological method that can rapidly distinguish truly great earthquakes from large earthquakes. Figure 9 compares very long-period displacement seismograms, one from the 2004 Sumatra–Andaman earthquake (i.e. truly great earthquake,  $M_w=9.2$ ) and the other from the nearby 2005 Nias earthquake which occurred on March 28, 2005 (i.e. large earthquake,  $M_w=8.6$ , see figure 1 for location). The difference in the amplitude of the very long-period (500–1000 s) wave preceding the  $S$  wave is

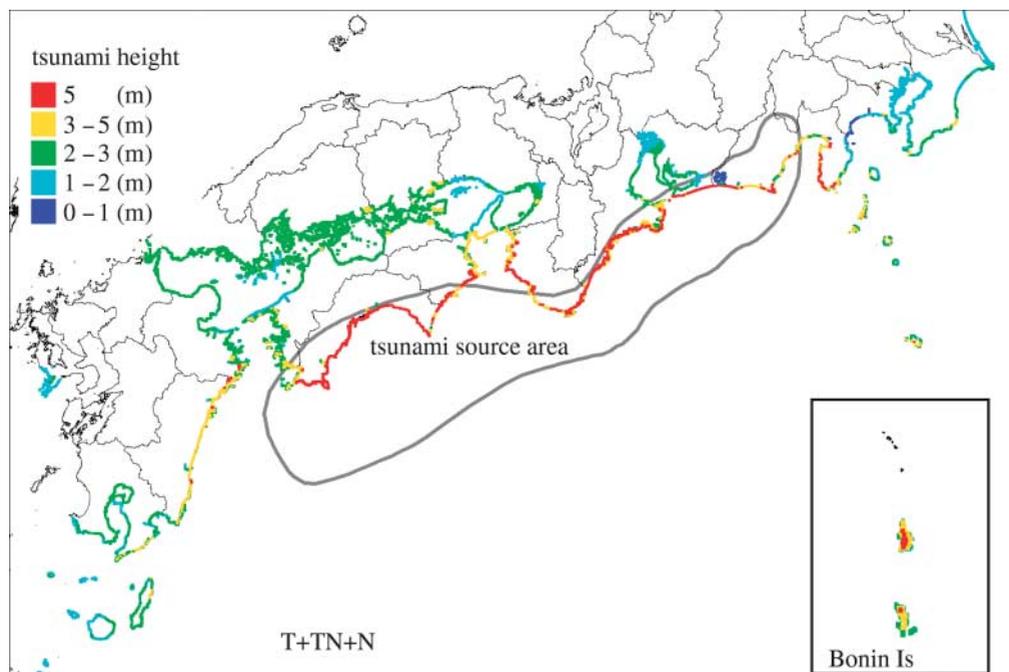


Figure 8. Estimated tsunami height for a scenario earthquake simulating the 1944 Tonankai + 1946 Nankai + Tokai earthquakes (Courtesy of Central Disaster Management Council, Japan).

apparent. This long-period wave is the *W* phase (Kanamori 1993), which can be interpreted as a superposition of overtone Rayleigh waves or of multiply reflected phases like PP, PPP, etc. It carries the information on the long-period deformation at the source at a group velocity faster than the S wave, and can be effectively used for rapid tsunami warning. This phase can be effectively used for identifying events larger than  $M_w=9$ . If  $M_w \geq 9$ , the event is most likely a subduction-zone event, and will almost certainly excite large tsunamis. How this distinctive seismological characteristic of truly great earthquakes is to be used for practical purposes should be considered in the context of a more comprehensive system. Lockwood & Kanamori (in press) performed a wavelet analysis on these seismograms with the aim of improving tsunami warning for great earthquakes.

Progress has also been made on earthquake early warning in many countries including Japan, Taiwan, Mexico, USA, Turkey, Italy, and Romania. After the occurrence of an earthquake, if the event size is estimated rapidly and its information is sent by radio (or other electronic methods) to places some distance away from the source before shaking begins there, precautionary measures can be taken to protect lives and properties. Since the details can be found in recent review papers (e.g. Lee & Espinosa-Aranda 2002; Kanamori 2005), we focus on only one aspect. A basic scientific question is, ‘At what point in time after the beginning can we estimate the damaging potential of the earthquake?’. At first glance, the chaotic behaviour of large earthquakes suggests that it would be difficult to estimate the overall behaviour from the beginning. However, we can utilize the following two general properties of earthquakes. (i) An earthquake source is a shear faulting and excites larger S (shear) wave than P

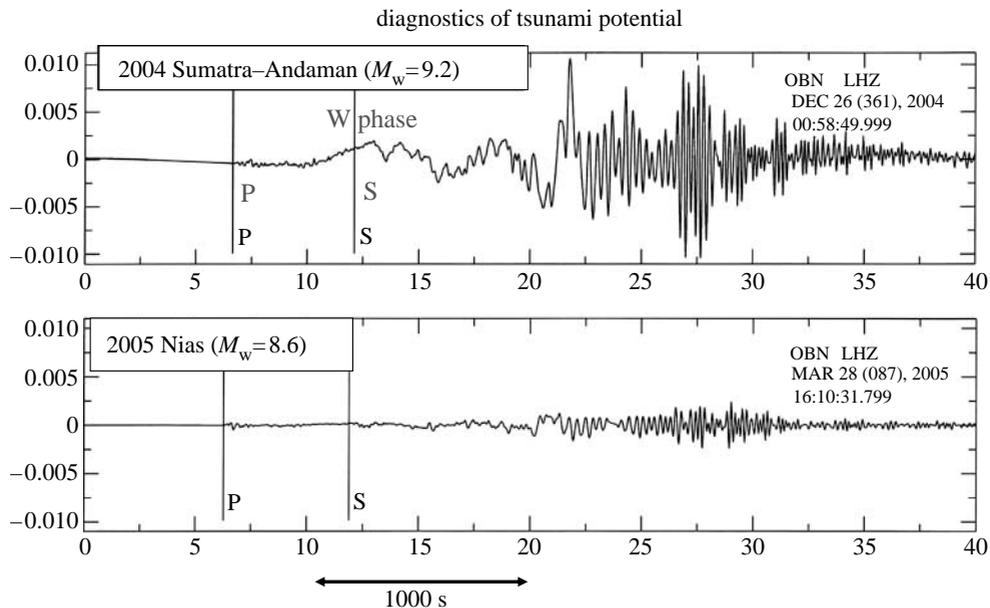


Figure 9. Comparison of the displacement seismograms of the 2004 Sumatra–Andaman earthquake ( $M_w=9.2$ ) and the 2005 Nias earthquake ( $M_w=8.6$ ) on the same scale.

(compressional) wave, which is faster by 70% than S wave. P wave carries the information about the source, but seldom causes damage. In contrast, S wave and even slower surface waves are responsible for damage. Thus, in principle, if we can estimate the event size using the information carried by P wave, we can predict the damaging power of S wave, i.e. P wave carries information and S wave carries energy. (ii) In general, as the event size increases, the duration of faulting increases, and the period of radiated seismic waves increases. Several methods have been developed since Nakamura's (1988) work to estimate the period of the initial P wave. Figure 10 illustrates how this method works. The vertical axis is a period parameter  $\tau_c$  which is determined from the first 3 s of the P wave. The parameter  $\tau_c$  is not the ordinary period, but is an effective period determined as a spectrally weighted period (Nakamura's 1988; Kanamori 2005). The longer the P wave record used, the more reliable is the estimate of the event size, but the drawback is that the warning is delayed. The 3 s duration used here is a compromise between speed and reliability. For events smaller than  $M=6.5$ , the duration of fault motion is about a few seconds so that the first part of P wave carries a fairly reliable information about the source size. Thus, the trend shown in figure 10 for  $M \leq 6.5$  is not surprising. However, as the event size increases beyond  $M=6.5$ , the source duration becomes much longer than a few seconds, and we cannot estimate the size reliably from the initial part of the P wave. Nevertheless, figure 10 shows that the limited data indicate that  $\tau_c$  keeps increasing with  $M$ . Although, the reason for this trend for large  $M$  is not fully understood yet, this method can be used at least for threshold warning of events with large magnitude, i.e. a warning can be issued that the event is larger than  $M=6.5$ , and is most likely damaging. Exactly, how we can use this information for practical earthquake early warning requires further research, but considering

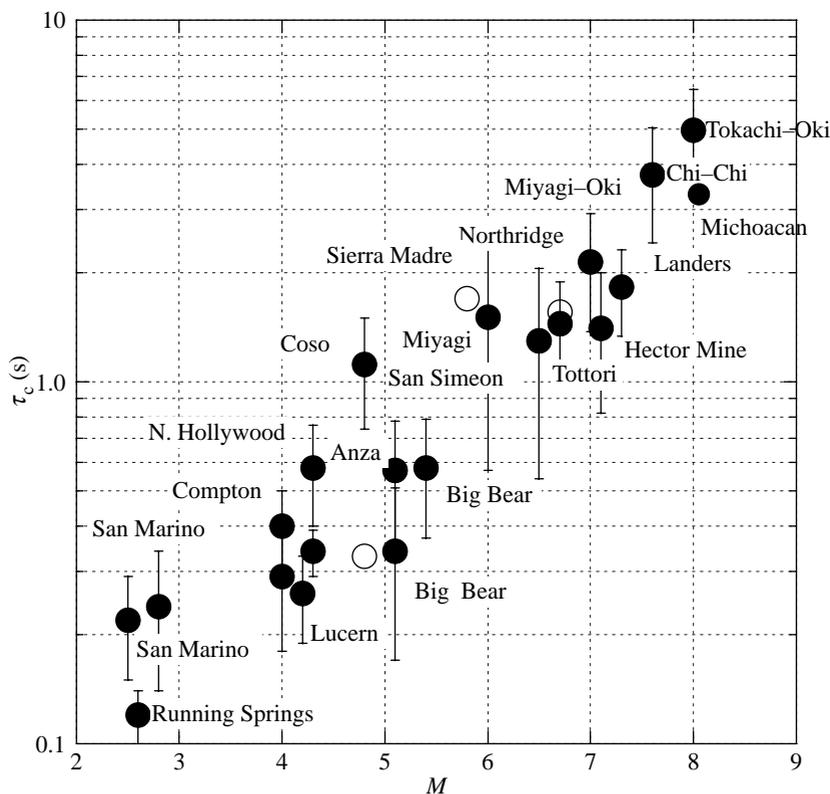


Figure 10. Relationship between the magnitude and a period parameter  $\tau_c$  which is determined from the first 3 s of P wave (modified from Kanamori (2005)).

the inherent unpredictability of earthquakes, this type of methodology will be useful for protecting large modern cities against rare large earthquakes in the future. To use early warning information effectively for damage mitigation purposes, it will be eventually necessary to interface the warning system with automated engineering practices.

## 8. Conclusion

The 2004 Sumatra–Andaman earthquake was a rare but extremely damaging earthquake. Given the difficulty in making accurate short-term earthquake predictions, the following will help minimize the impact of such a rare event on our society. (i) Understanding the nature of long-period ground motions from rare great earthquakes which will have significant impact on modern large structures such as high-rise buildings and bridges. These structures have not yet experienced long-period ground motions from such large earthquakes. (e.g. Heaton *et al.* 1995; Krishnan *et al.* in press). (ii) Development of real-time information systems, which should eventually be interfaced with automated engineering practices. (iii) Development of scenario earthquakes and implement counter measures for them. (iv) Development of low-cost construction and retrofit methods for densely populated developing countries. We did not

explicitly touch on the last point in this paper, but it is an obviously important issue for minimizing the impact of frequent medium-size earthquakes in densely populated areas with inadequate construction practices.

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