Long-Term Perspectives on Giant Earthquakes and Tsunamis at Subduction Zones*

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Annu. Rev. Earth Planet. Sci. 2007. 35:349–74

First published online as a Review in Advance on January 17, 2007

The *Annual Review of Earth and Planetary Sciences* is online at earth.annualreviews.org

This article's doi:
10.1146/annurev.earth.35.031306.140302

0084-6597/07/0530-0349$20.00

Key Words

paleoseismology, earthquake recurrence, earthquake forecasting, Sumatra, Chile, Cascadia, Hokkaido

Abstract

Histories of earthquakes and tsunamis, inferred from geological evidence, aid in anticipating future catastrophes. This natural warning system now influences building codes and tsunami planning in the United States, Canada, and Japan, particularly where geology demonstrates the past occurrence of earthquakes and tsunamis larger than those known from written and instrumental records. Under favorable circumstances, paleoseismology can thus provide long-term advisories of unusually large tsunamis. The extraordinary Indian Ocean tsunami of 2004 resulted from a fault rupture more than 1000 km in length that included and dwarfed fault patches that had broken historically during lesser shocks. Such variation in rupture mode, known from written history at a few subduction zones, is also characteristic of earthquake histories inferred from geology on the Pacific Rim.

INTRODUCTION

The Indian Ocean tsunami of 2004, which took nearly a quarter million lives in a dozen countries (International Federation of Red Cross and Red Crescent Societies 2005), has spurred efforts to improve tsunami safety around the world (see sidebar Tsunami for a definition). Most of the efforts focus on geophysical estimates of earthquake size, location, and tsunami potential; real-time detection of tsunamis in the open ocean and on the coast; delivery of tsunami warnings to officials and coastal residents; mapping of areas to be inundated and evacuated; posting of evacuation signs; and public education in the basics of tsunami survival.

TSUNAMI

An oceanic gravity wave—or more commonly a train of such waves—generated by seafloor deformation associated with a submarine earthquake, landslide, volcanic eruption, or asteroid impact. In Japanese the literal meaning is "harbor wave." The speed of a tsunami is equal to a square root of the product, ocean depth times gravitational acceleration. In the deep ocean, a tsunami travels at jetliner speed but the amplitude is commonly less than a meter. In shallower nearshore waters, the tsunami slows to automobile speed but increases its amplitude to become destructive.

Also spurred by the Indian Ocean disaster is the assessment of earthquake and tsunami hazards on geologically extended timelines. The 2004 tsunami took most of its victims by surprise not only for want of instrumental warnings and tsunami education but also because written and instrumental records of the past few centuries span too little time to provide enough perspective on the Indian Ocean's full earthquake and tsunami potential.

This review starts with the 2004 Sumatra-Andaman earthquake and the associated Indian Ocean tsunami, then proceeds to offer long-term perspectives from earthquakes and tsunamis recorded geologically on the Pacific Rim. Our Pacific examples focus on the giant 1960 earthquake in Chile, the 1700 Cascadia earthquake in western North America, and a seventeenth-century earthquake in northeast Japan (**Figures 1** and **2**). In two of these geological examples, the inferred earthquakes and tsunamis are larger than those known from in the region's written history. In all three examples, earthquake size varies from one earthquake to the next, and the earthquakes do not necessarily repeat at regular intervals. Such variability in size and repeat time, likely also in the source region of the 2004 Sumatra-Andaman earthquake, complicates the task of identifying which subduction zones are likely to produce the next giant earthquakes and tsunamis.

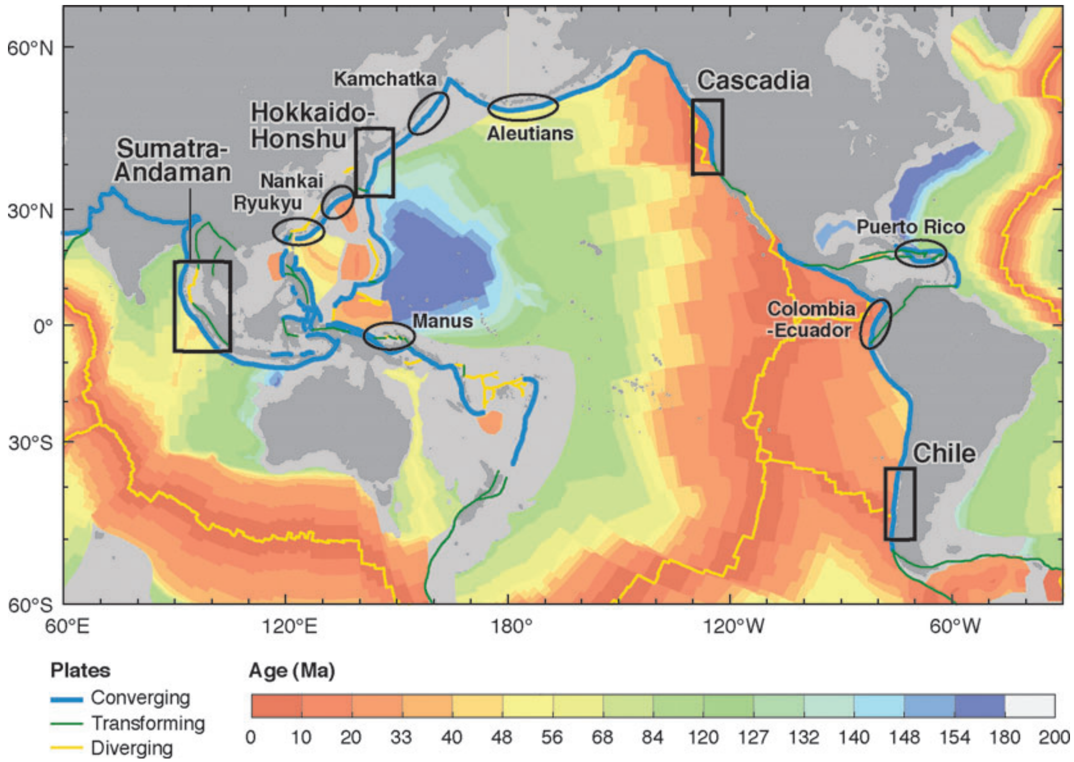

Figure 1

Plate-tectonic setting of the four subduction zones (*squares*) discussed in this review. Lines denote boundaries between the plates: blue where the plates converge, as at subduction zones; green represents transforms, such as the San Andreas Fault; and yellow for divergence. Color shading denotes seafloor ages of oceanic plates (Muller et al. 1997). Other subduction zones mentioned in the text are also shown.

PAST TSUNAMIS OF UNUSUAL SIZE

2004 Sumatra-Andaman: Less Surprising in Hindsight?

The 2004 Sumatra-Andaman earthquake, and the ensuing Indian Ocean tsunami, attained uncommon enormity (Kanamori 2006, Stein 2006). As estimated from seismic waves of several kinds and from horizontal and vertical displacement of the land, the earthquake's magnitude was in the range M_w 9.1–9.3 (Lay et al. 2005, Stein & Okal 2005, Subarya et al. 2006, Fujii & Satake 2007), where M_w denotes moment magnitude, a logarithmic measure of earthquake size. Not since the 1964 Alaska earthquake had there been an event this large (**Figure 3**). Expressed linearly as seismic moment, the 2004 earthquake was in the range 5–10 × 10^{22} Nm—equivalent to the sum of the moment of all earthquakes in the preceding decade, worldwide (Lay et al. 2005).

Moment magnitude (M_w): an earthquake magnitude scale based on seismic moment (M_0), computed as $M_w = (\log M_0 - 9.1)/1.5$, where M_0 is in Nm

Seismic moment (M_0): a fundamental physical parameter to quantify earthquake size. It is the product of fault rupture area (length times width), the average seismic slip on the rupture area, and the rigidity (shear modulus) of the faulted rock

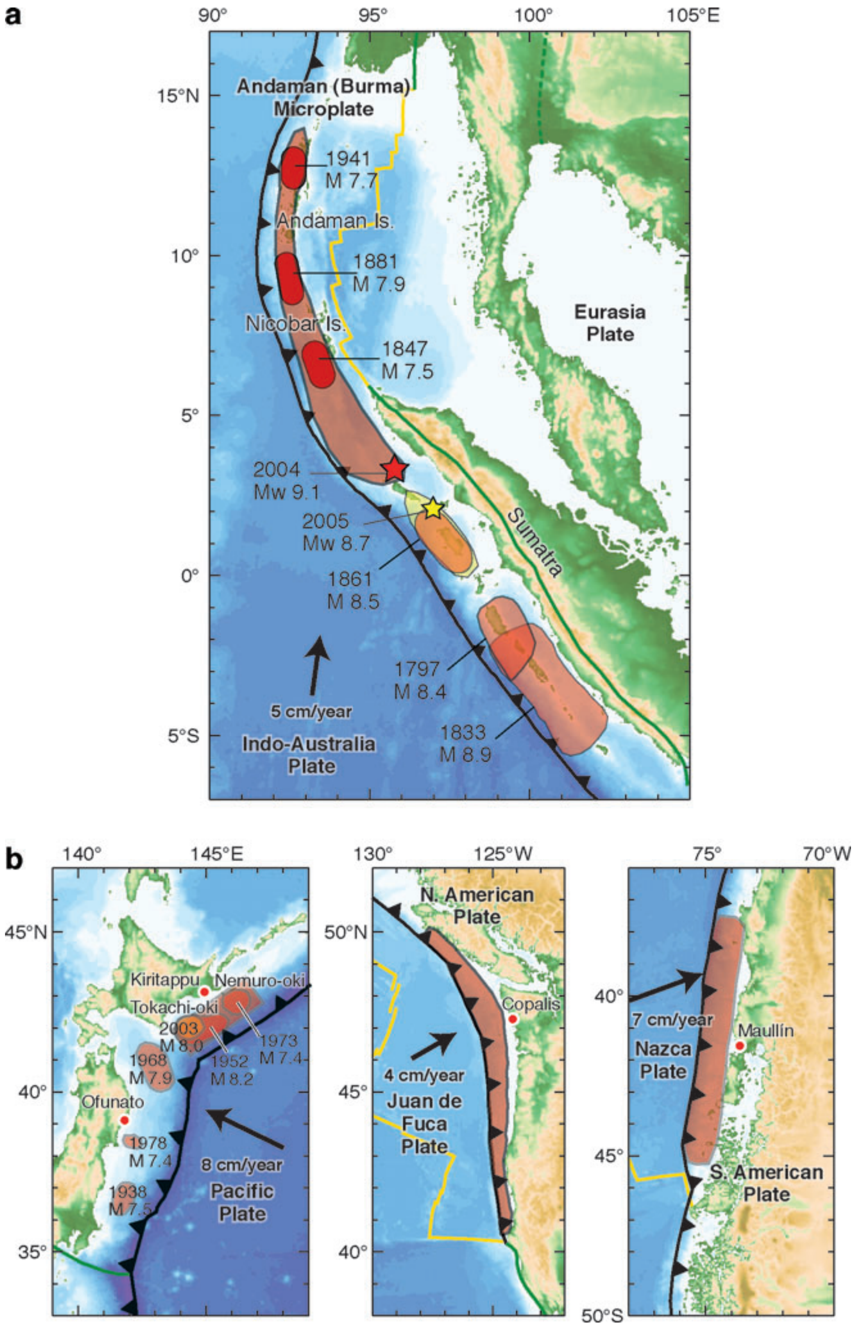

Figure 2

(*a*) Setting and rupture areas of the giant Sumatra-Andaman earthquake of 26 December 2004 and of the great Nias earthquake of 28 March 2005. Rupture areas of pre-2004 earthquakes after Bilham et al. (2005) and Natawidjaja et al. (2006). Plate boundaries from Sieh & Natawidjaja (2000) and Curray (2005). (*b*) Setting and rupture areas of great subduction earthquakes off northeast Japan (*left*), Cascadia (*center*), and south-central Chile (*right*). Rupture areas from Earthquake Research Committee (1998) and Satake et al. (2005) for Japan, Satake et al. (2003) for Cascadia, and Cifuentes (1989) and Barrientos & Ward (1990) for Chile. Plate motions from DeMets et al. (1990) and Stein & Okal (2007).

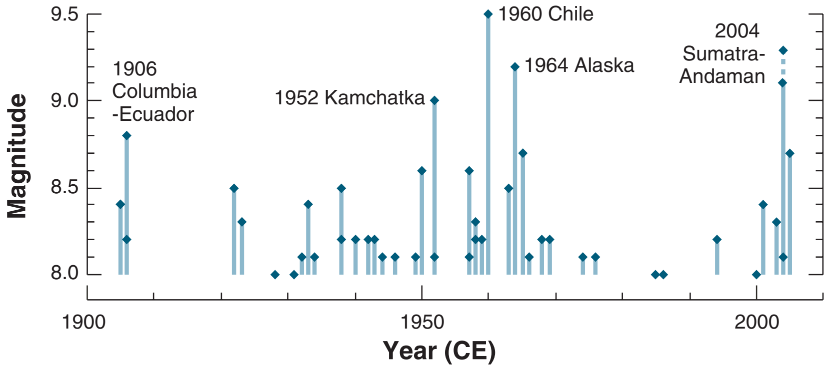

Figure 3

Sizes of largest earthquakes, 1900–2005, expressed in moment magnitude (Kanamori 1977, Johnson et al. 1994, Subarya et al. 2006).

In retrospect, the enormity of the 2004 Indian Ocean tsunami looks almost expectable. The earthquake at the tsunami's source, like most of the planet's great earthquakes (shocks of M_w 8.0 and larger), resulted from rupture of an inclined boundary between tectonic plates, a subduction zone (**Figure 1**). The Sunda subduction zone, on which the 2004 Sumatra-Andaman earthquake occurred, extends several thousand kilometers along the east side of the Indian Ocean (**Figure 2*a***). In the preceding centuries, other parts of the zone had broken in great earthquakes, including one in 1833 of estimated M_w of 8.6–8.9 (Newcomb & McCann 1987, Natawidjaja et al. 2006). This history raised concerns, before the 2004 Sumatra-Andaman earthquake, about tsunami hazards posed by the Sunda subduction zone (Cummins 2004).

Viewed another way, however, written history shows little reason to expect a giant earthquake (M_w 9.0 and above) or a transoceanic tsunami from the 2004 earthquake's source area. No pre-2004 event in the area's documented earthquake history had attained M_w 8, let alone M_w 9 (Bilham et al. 2005). That history is instead dominated by shocks of estimated magnitudes 7.5–7.9 (in 1847), 7.9 (1881), and 7.7 (1941). None of these three earthquakes likely exceeded 150 km in rupture length (Bilham et al. 2005)—one-tenth the rupture length in 2004 (Subarya et al. 2006) (**Figure 2**). All three were associated with tsunamis, but the effects of the tsunamis of 1847 and 1941 are poorly known (Murty & Rafiq 1991, Ortiz & Bilham 2003, Bilham et al. 2005), and on the tide gauges of peninsular India, the maximum amplitude of the 1881 tsunami was under 1 m (Ortiz & Bilham 2003).

The enormity of the 2004 Sumatra-Andaman earthquake also seems improbable if giant earthquakes typically happen where the subducting plate is young—several tens of million years old, at most. This generalization is based on global earthquake history from the first three quarters of the twentieth century (Ruff & Kanamori 1980). A notable exception is the 1952 Kamchatka earthquake, which attained an approximate magnitude of 9.0 (Kanamori 1977) despite the 80–million year age of the nearest well-dated oceanic crust (**Figure 1**; Stein & Okal 2007). If maximum earthquake size nonetheless varies inversely with subducting-plate age—a question we revisit near the end of this review—the Indo-Australia plate along the Sumatra-Andaman rupture seems too old, at 55–90 million years, for an earthquake of magnitude 9.

One further indication of unusual size—displacement during an earthquake—helps explain the apparent lack of a comparable earthquake or tsunami in the region's written history. Permanent tectonic-plate deformation during the earthquake was measurable far from the fault rupture and amounted to several meters nearby. The far-field deformation, inferred from global positioning system (GPS) data, was noticeable more than 3000 km distant and included a displacement of 27 cm at Phuket, Thailand, nearly 600 km from the nearest part of the rupture area (Vigny et al. 2005). The seismic slip that occurred on the plate-boundary fault itself, from northern Sumatra to the Andaman Islands, is poorly known and is still being estimated, most recently by means of tsunami waveforms (Fujii & Satake 2007). Recent estimates based on horizontal and vertical displacement at the land surface are 30 m off northern Sumatra and as much as 20 m to the north (Subarya et al. 2006).

Such slip amounts represent centuries of plate-tectonic motion. Along the northern Sunda Trench, the Indo-Australian Plate is subducting beneath the Andaman (or Burma) microplate at 5 cm/year (Sieh & Natawidjaja 2000). If the fault slip occurs only during earthquakes, the 20 m of slip represents 400 years of plate motion and the 30 m slip represents 600 years. A South and Southeast Asian tsunami 600 years ago would predate accounts of the region's early European visitors, such as Vasco de Gama in southern India (1498) and Portuguese spice traders in the Maluka Islands of eastern Indonesia (1511).

Today, countries around the Indian Ocean want to know how often a 2004-sized catastrophe really happens. Earth scientists, seeking answers from past millennia, are searching for geological traces like those the 2004 earthquake and tsunami left behind. Chief among these are signs of land-level change and of tsunami inundation.

Land-level changes that accompanied the 2004 Sumatra-Andaman earthquake, in response to fault slip during the earthquake, are recorded geologically by emerged corals and submerged coastal lowlands. The uplift and subsidence have been mapped regionally by comparison of satellite images taken before and after the 2004 earthquake and ground-truthed by field surveys and GPS (Meltzner et al. 2006, Tobita et al. 2006). Islands nearest the Sunda Trench emerged, whereas those farther east were submerged. Maximum uplift of 1.5 m was measured with emerged corals off Sumatra (Meltzner et al. 2006) and west of North Andaman Island (Kayanne et al. 2007). Subsidence reached 1 m or more in the Nicobars and Andamans, where tides now flood former rice paddies and villages (Malik & Murty 2005**).** Farther south, in studies begun years before the 2004 earthquake, corals yielded geological records of uplift from the 1833 and 1797 Sumatra earthquakes, and from earlier earthquakes as well (Natawidjaja et al. 2006). Coastal paleogeodesy is getting underway in and around the region of the 2004 earthquake. Researchers are also looking there for stratigraphic signs of ancient coseismic uplift or subsidence and for deposits from past tsunamis, too. It is hoped that these efforts will extend the region's giant-earthquake history back 1000 years or more.

The 2004 Indian Ocean tsunami left geological traces both near and far from its Sumatra-Andaman source. Most post-tsunami surveys focused on damage (Kawata et al. 2005) and run-up—to heights of 20–30 m in northern Sumatra (Borrero 2005); 5–15 m in Thailand, India, and Sri Lanka (Tsuji et al. 2006); but less than 3 m in Myanmar (Satake et al. 2006a). However, other studies examined the tsunami's onshore sedimentary record, which is dominated by sand sheets commonly 10 cm in thickness (Jaffe et al. 2006, Moore et al. 2006). The setting, architecture, and internal properties of these deposits show how ancient Sumatra-Andaman earthquakes might be identified from the geological traces of their tsunamis, both near and far from the tsunami's source. Searches for ancient tsunami deposits are accordingly underway on Indian Ocean shores (Jackson et al. 2005, Rajendran et al. 2006).

Tsunami deposit: sediment, most commonly sand, that has been moved by a tsunami and preserved geologically. Useful in reconstructing tsunami history where distinguishable from deposits of rivers and storms

Around the Pacific Ocean, most of the long records of repeated great earthquakes are based on geological evidence of land-level changes and tsunamis. Such evidence helps explain the enormity of the giant earthquake that occurred on May 22, 1960, along the coast of south-central Chile.

1960 Chile: Too Soon for Its Size

The year 1960 belongs to a bygone era in earthquake and tsunami studies. It predates the recognition of plate tectonics, the installation of the world-wide standardized seismographic network system, the computer simulation of tsunami generation and propagation, and the establishment of international tsunami warning systems. Today's still-meager understanding of the giant 1960 Chile earthquake—of its size, tectonics, and tsunami generation—accordingly took decades to achieve. This understanding, as outlined below, now includes recognition that the earthquake's predecessors varied greatly in size, and that approximately 300 years elapsed, on average, between the largest of these earthquakes in the past 2000 years.

The giant 1960 Chile earthquake culminated a series of fault displacements that began 29 h earlier, with a foreshock of M_w 8.1 (Cifuentes 1989). The series also included a slow earthquake ~15 min before the mainshock. This puzzling precursor, which may account for a belt of uplift inland from the mainshock's coseismic subsidence (Linde & Silver 1989), had nearly as much seismic moment as did the mainshock (Kanamori & Cipar 1974, Kanamori & Anderson 1975, Cifuentes & Silver 1989). The combined seismic moment of the slow precursor and the mainshock has been estimated as $4–6 \times 10^{23}$ Nm.

The mainshock itself has a range of estimated sizes. Kanamori (1977) used 2×10^{23} Nm as an average estimate of seismic moment; the corresponding moment magnitude of 9.5 has become the widely accepted number. However, the seismic moments estimated from free oscillations and strain seismograms span the range $1–3 \times 10^{23}$ Nm, equivalent to M_w 9.4–9.6 (Kanamori & Cipar 1974, Kanamori & Anderson 1975, Cifuentes 1989, Cifuentes & Silver 1989). This range implies average slip between about 20 and 30 m if the rupture length (estimated from aftershock distribution) is close to 900 km and the rupture width is between about 60 and 290 km (Cifuentes 1989). However, as judged from land-level changes inferred to have accompanied the mainshock (Plafker & Savage 1970), the seismic moment is less than 1×10^{23} Nm, either with uniform slip of 17 m on a 850 km × 130 km wide fault, or with variable slip as great as 40 m (Barrientos & Ward 1990).

If seismic slip during the giant 1960 Chile earthquake averaged more than 10 m, the earthquake released more slip than likely accumulated since the region's previous great earthquake, which occurred in 1837 (Lomnitz 1970). That is, the 1960 earthquake was too soon for its size. This puzzle was first posed in the late 1980s (Stein et al. 1986), when geophysicists compared seismological estimates of the 1960 mainshock slip with long-term rates of plate motion—convergence of the subducting Nazca Plate with the overriding South American Plate at 7 m per century (DeMets et al. 1990, Norabuena et al. 1998, Stein & Okal 2007). The full puzzle involves a total of four historical earthquakes in the region of the 1960 mainshock: 1575, 1737, 1837, and 1960 (Lomnitz 1970). The four give an average repeat time of 128 years—equivalent to approximately 9 m of accumulated plate convergence. If all four earthquakes were similar in size, and if the 1960 mainshock had 20 m of seismic slip, each of the earthquakes expended about twice the plate-motion budget.

Geophysicists accordingly deduced that the Chilean earthquakes of 1575, 1737, 1837, and 1960 varied in size, so that earthquakes as large as the 1960 mainshock need not repeat at the 128-year average (Stein et al. 1986, Cifuentes 1989, Barrientos & Ward 1990). Variability in rupture mode at subduction zones was first identified along the Nankai Trough of southwest Japan, on the basis of written records from the past 1300 years (Imamura 1928, Ando 1975). In another historical example, from Colombia and Ecuador, a subduction fault area that broke in its entirety during a great earthquake 1906 was ruptured again, in a serial, piecemeal fashion, by three merely large shocks between 1942 and 1979 (Kanamori & McNally 1982). Such cycle-to-cycle variability is typical, rather than exceptional, for great earthquakes of the past 500 years at a dozen subduction zones around the Pacific Rim (Thatcher 1990). Variability is also evident in the contrast between the 2004 Sumatra-Andaman earthquake and its humble predecessors of 1847, 1881, and 1941 (Bilham et al. 2005).

In a recent comparison of the 1960 Chile mainshock with its historical predecessors, scrutiny of old documents was combined with a field investigation of natural evidence for coseismic subsidence and tsunamis at an estuary midway along the length of the 1960 rupture (Cisternas et al. 2005). Both in documents and in the field, the 1575 earthquake is the one most similar to the 1960 mainshock. The estuary preserves traces of subsidence and tsunami from 1575 and 1960 but not from 1737 or 1837 (**Figure 4*a***). Also present are such traces for six earlier events from the past 2000 years. In all, the average recurrence interval is close to 300 years for earthquakes and tsunamis that left geological records at the estuary. These findings imply that variable rupture mode helped the 1960 mainshock become a giant (Cisternas et al. 2005). It is likely that the 1737 and 1837 ruptures were both narrower and shorter, and involved less seismic slip, than did the 1960 break. They thereby left the fault partly loaded with accumulated plate motion that the 1960 earthquake eventually expended (Cisternas et al. 2005).

Far from Chile, the legacy of the giant 1960 earthquake includes precautions and discoveries that its tsunami helped bring about. The 1960 Chile tsunami caused more than 1000 casualties in Chile but also took 61 lives in Hawaii and 142 in Japan (**Figure 4*b***) (Japan Meteorological Agency 1961, Atwater et al. 2005a)—far-field losses that spurred the establishment of an international tsunami warning system in the Pacific and of the Tsunami Commission in the International Union of Geodesy

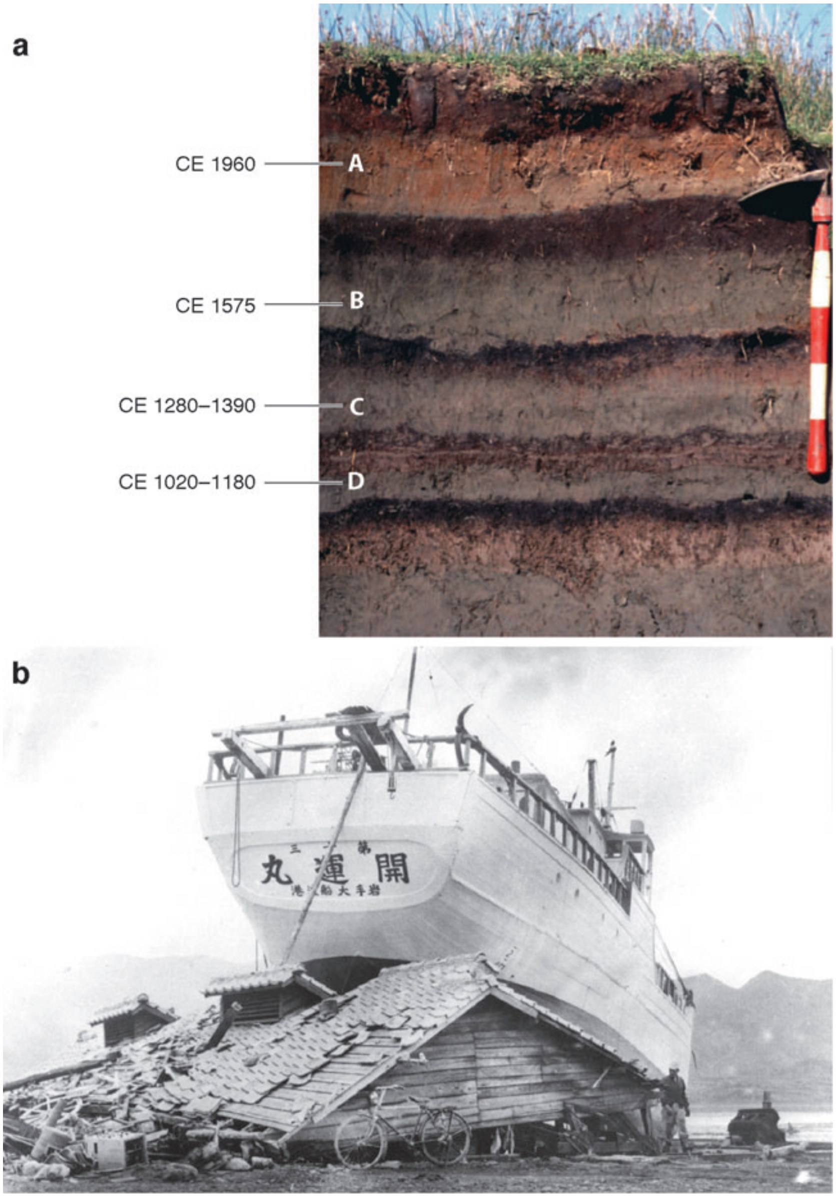

Figure 4

Chilean earthquakes and tsunamis. (*a*) In an estuarine outcrop midway along the length of the 1960 rupture (Maullin in **Figure 2*b***), sand sheets A, B, and D were laid down by tsunamis, whereas sheet C accumulated on a tidal flat above the soil of a subsided meadow (Cisternas et al. 2005). Labels give the date (or date range, at two standard deviations) of the associated earthquakes. Each stripe on the shovel handle is 10 cm long. (*b*) The 1960 Chilean tsunami brought this fishing boat ashore in Japan (Ofunato in **Figure 2*b***). (Photo from Asahi Shimbun)

and Geophysics. The 1960 tsunami also left behind sand sheets in Chile that guided geologists to such tsunami traces at the Cascadia subduction zone (Atwater et al. 2005b). In Japan, moreover, the tsunami losses in 1960 brought attention to earlier tsunamis of remote origin, one of which now provides an exact time and approximate size for Cascadia's most recent giant earthquake.

1700 Cascadia: Finding an Orphan's Parent

A quarter century ago, North America's Cascadia subduction zone (**Figure 1**) had no recognized history of great earthquakes, let alone any giant ones. Yet today, the Cascadia region is using a local earthquake of magnitude 9 as a basis for engineering design and tsunami evacuation plans (Atwater et al. 2005b).

The paradigm shift began in the early 1980s with geodetic inference that the subduction zone is locked (Savage et al. 1981) and with comparisons to subduction zones on which great earthquakes are known from instrumental records (Heaton & Kanamori 1984). The shift continued as researchers began recognizing North American evidence for the past occurrence of great Cascadia earthquakes (**Figure 5*a***).

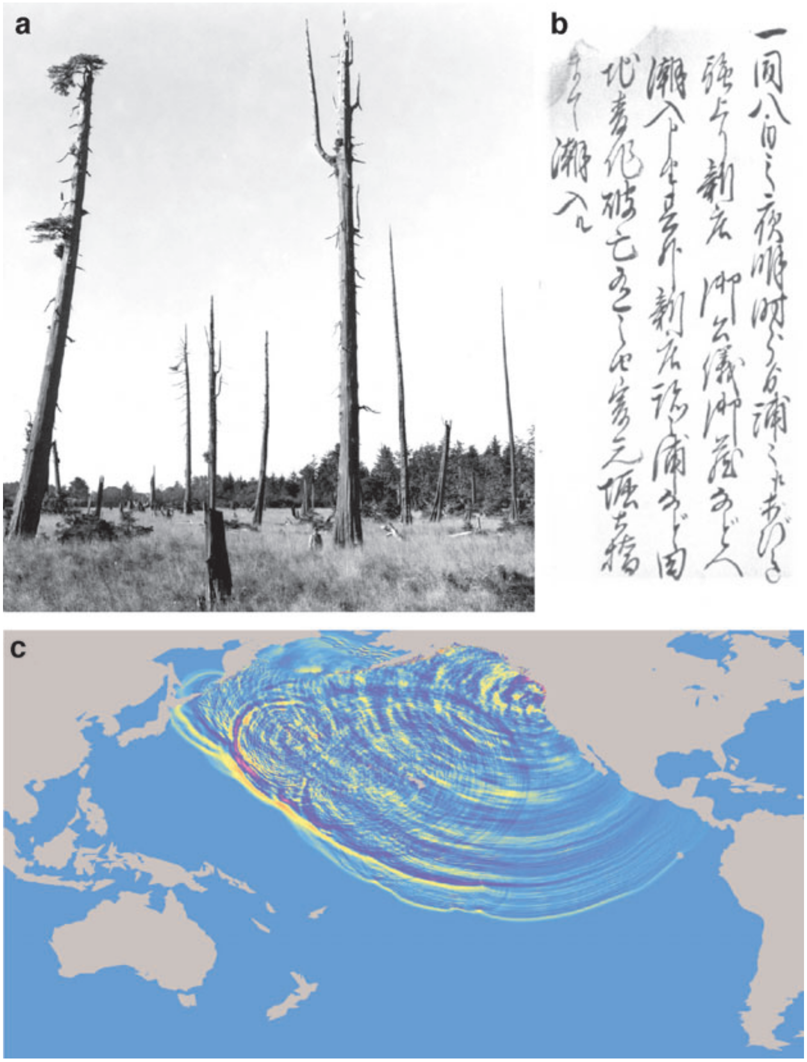

Figure 5

1700 Cascadia earthquake. (*a*) Durable trunks of western red cedar along Washington's Copalis River mark a forest killed by tides after an earthquake lowered land along hundreds of kilometers of North America's Pacific coast between the 1699 and 1700 growing seasons (Atwater et al. 2005b). (*b*) Official records of Tanabe, on the Pacific coast of southwest Japan, describe flooding and damage by unusual seas noticed at Tanabe in the morning of January 28, 1700. For a character-by-character translation of these columns of text, see Atwater et al. (2005b). (*c*) In a numerical simulation, the 1700 tsunami approaches Japan 9 h after its origins at the Cascadia Subduction Zone (Satake et al. 2003).

Some researchers identified estuarine evidence for coseismic subsidence and tsunamis; others interpreted deep-sea turbidites as evidence for shaking; the average recurrence intervals, in most cases, were close to 500 years (reviewed in Atwater et al. 2005b; on the turbidites, see also Goldfinger et al. 2003). Meanwhile, geodesists began using GPS to assess coupling between the subducting Juan de Fuca Plate and the overriding North American Plate, and in 1995 this work demonstrated that the plate boundary is indeed locked (Dragert & Hyndman 1995). However, North American scientists were still facing an impasse in defining Cascadia's great earthquake hazards. Is the subduction zone capable of giant earthquakes that rupture its entire 1100-km length, or must it break piecemeal, in lesser shocks? By 1995, geologists had succeeded in showing, from radiocarbon-dated evidence for coseismic subsidence and tsunami, that at least 900 km of the Cascadia subduction zone ruptured after 1660. However, even the most precise of this dating leaves a broad window, 1690–1720, as the time of rupture in southern Washington and northern California (Nelson et al. 1995). Such a window provides ample time for piecemeal, serial rupture without precluding the alternative of a single full-length break.

In 1996, Japanese researchers resolved this ambiguity by means of a tsunami that had been recognized decades earlier as one separated from its parent earthquake. Japan's written history of orphan tsunamis dates back to the year 799, and many of these orphan tsunamis have been linked securely to earthquakes and tsunamis in South America, beginning in 1586 and including, of course, the 1960 Chile tsunami (Ninomiya 1960). However, a tsunami in January 1700, although identified in the 1940s as waves of remote origin (Mombusho Shinsai Yobo Hyogikai 1943), had never been traced to its source. In their 1996 report, Satake et al. (1996) showed that this orphan lacks an obvious parent in Kamchatka, the Aleutians, or South America. Citing North American evidence for a great earthquake (or series of great earthquakes) between 1690 and 1720, they concluded that the tsunami originated at the Cascadia subduction zone. They further inferred that the tsunami was generated by the Cascadia earthquake at about 9 PM on January 26, 1700. This dating passed subsequent tree-ring tests in North America, the most demanding of which limited the time of rupture to the months between August 1699 and May 1700 at four estuaries along 90 km of coast along the north-central part of the Cascadia subduction zone (**Figure 5*a***) (Jacoby et al. 1997, Yamaguchi et al. 1997).

The Japanese documents (**Figure 5*b***), which have now been parsed in Japanese (Tsuji et al. 1998) and English (Atwater et al. 2005b), also provide decisive clues about the earthquake's size (Satake et al. 1996). The most rigorous estimates, reported a few years ago (Satake et al. 2003), show that the 1700 Cascadia earthquake was likely in the range of M_w 8.7–9.2. This range is based on computations of coseismic seafloor deformation with an elastic dislocation model that includes curvature of the fault plane and consequent variation along the fault rupture in the seafloor deformation that drives the simulated tsunami. The range is further based on numerical models of the trans-Pacific tsunami from this deformation, three sets of tsunami height estimates inferred from reported damage and flooding, and comparison of these estimates with heights computed from the models (**Figure 5*c***).

Diatoms: unicellular algae of microscopic size. Typically limited to wet environments. Species assemblages vary with environment; therefore, they are useful in inferring paleoenvironments

Not every great Cascadia earthquake is a giant. According to a recent coastwise comparison of radiocarbon ages for coseismic subsidence and tsunamis (Nelson et al. 2006), approximately two thirds of Cascadia's great earthquakes in the past 5000 years may have resulted from full-length ruptures or from swift series of shorter ruptures. However, other earthquakes in the past 5000 years produced paleoseismological records that are demonstrably limited to the northern, central, or southern part of the subduction zone. These probably short ruptures add Cascadia to the list of subduction zones where rupture mode characteristically varies: southwest Japan, Colombia and Ecuador, south-central Chile, Sumatra-Andaman, and, as shown in our final example, a part of northeast Japan where variable rupture mode recently solved a longstanding geodetic puzzle.

Seventeenth-Century Hokkaido: Rising After the Waves

On the Pacific coast of eastern Hokkaido, which faces the southern Kuril Trench, twentieth-century geodesy and Pleistocene geology show conflicting vertical movements. Tide-gauge and leveling data show chronic subsidence, unreversed during historical earthquakes, at rates of 5–10 mm/year in the past hundred years. By contrast, Pleistocene marine terraces dating from the last interglacial period, when sea level was approximately as high as it is today, show slight net uplift, at an average rate of 0.1–0.4 mm/year, for the past 125,000 years. How did the terraces rise?

Historically, the terraces failed to rise either during or between the region's ordinary plate-boundary earthquakes. Plate-boundary earthquakes in the range of M_w 7.8–8.2 are the largest known from the region's 200 years of written records (**Figure 2*b***). They occurred in 1843, 1952, and 2003 off the Tokachi coast (Tokachi-oki earthquakes) and in 1894 and 1973 to the east, off Nemuro (Nemuro-oki). Coastal land-level changes known to have accompanied these ordinary earthquakes are limited to subsidence, in amounts of a few tenths of a meter at most. Transient uplift after the 1973 earthquake was predicted to have been large enough to help erase the historical deficit in uplift. Instead, however, it barely negated the coseismic subsidence before the chronic interseismic subsidence resumed (Kasahara & Kato 1981).

How the terraces rose remained a matter of conjecture until coastal geology provided two lines of evidence for earthquakes much larger than those of the past 200 years. When these lines of evidence came together in 2004, they showed that the unusually large earthquakes were followed by transient uplift—a phenomenon that helped raise the terraces.

One of the lines of evidence, found mainly on lowlands and lake bottoms along the open coast, consists of tsunami deposits. Prehistoric sand sheets in eastern Hokkaido demonstrate that during the past 7000 years, the southern Kuril Trench repeatedly produced tsunamis larger than those recorded in the region's 200 years of written history (Nanayama et al. 2003). These sand sheets underlie lowlands and lagoons along 200 km of eastern Hokkaido's Pacific coast. At Kiritappu they extend as much as 3 km inland across a beach-ridge plain, where the tsunami from the 1952 Tokachi-oki earthquake terminated 1 km from the coast (Central Meteorological Agency 1953) and left sand only within a few hundred meters of the beach (**Figure 6*a***). Diatoms

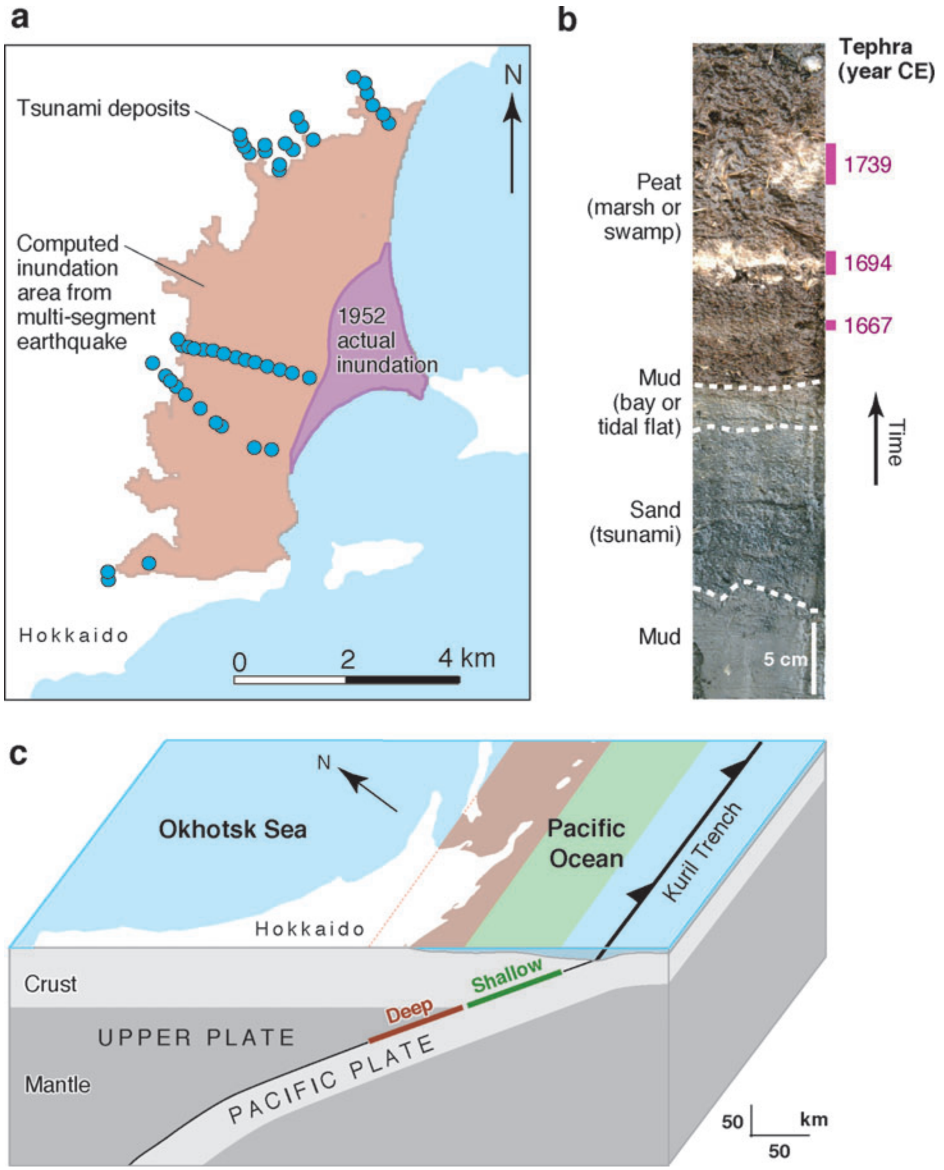

Figure 6

Evidence for an unusually large earthquake in the seventeenth century along the southern Kuril Trench off Hokkaido, Japan. (*a*) At Kiritappu marsh, tsunami deposits from a seventeenth-century tsunami (Nanayama et al. 2003) extend much farther inland than did waters of the 1952 Tokachi-oki tsunami (Central Meteorological Agency 1953). At a nearby estuary, the vertical slice in (*b*) implies postseismic emergence best explained, in diagram *c*, by deep postseismic slip in the first decades after a shallow rupture that produced a tsunami (Sawai et al. 2004). This shallow rupture probably encompassed, at a minimum, the rupture areas of the earthquakes of 1952 and 1973 (**Figure 2*b***).

Volcanic ash: widely distributed volcanic ash can be used, through analysis of color, texture, and chemical composition, as a key layer to correlate geological sections at different locations and to estimate a deposit's age

in the prehistoric sheets demonstrate a marine origin for the sand. At Kiritappu and elsewhere, the time intervals between the extensive sand sheets average approximately 500 years (Nanayama et al. 2003). Volcanic ash layers aid in the correlation and dating (**Figure 6*b***). The youngest of the prehistoric sand sheets shortly predates ash layers from 1663 (Usu volcano) and 1667 (Tarumai). A second, earlier sand sheet postdates a tenth-century ash that erupted from Baitoushan on the border of China and North Korea. Three to five sand sheets are commonly found between the tenth-century ash and a Tarumai ash approximately 2500 years old. The great inland extent of the prehistoric sand sheets is most simply explained, according to geophysical models, by multisegment earthquakes with slip amounts larger than occurred in the historical Tokachi-oki and Nemuro-oki earthquakes (Nanayama et al. 2003, Satake et al. 2005).

The second line of evidence, found in the sheltered arms of estuaries, consists of interbedded freshwater peat and brackish-water mud (Sawai 2001). Each upward change from mud to peat records rapid emergence, amounting to a meter or so, that converted bay bottoms to freshwater wetlands. This postseismic uplift far surpasses any associated with the region's ordinary plate-boundary earthquakes. Repetition of meter-scale emergence in the past 2500 years is evident from interbedded peat and mud along the 100 km coast from Kushiro to Nemuro (Kelsey et al. 2006). Volcanic ash layers date the most recent of the emergence events to the seventeenth century (Atwater et al. 2004), the same time window as the most recent of the outsize tsunamis. Did this emergence coincide with the tsunami, as coseismic uplift, or did it follow the tsunami, as a postseismic transient?

This question about the timing and cause of the episodic uplift was recently answered from the intersection of two lines of evidence at coastal sites where the sand sheets extend into the interbedded peat and mud (Sawai et al. 2004). At these sites, a combination of stratigraphy and diatom paleoecology shows that eastern Hokkaido's seventeenth-century uplift occurred in the first decades after the corresponding outsize tsunami. It was such postseismic uplift that evidently helped the terraces rise. The episodic postseismic uplift of eastern Hokkaido implies creep on the plate boundary downdip from seismic rupture of unusually large length and width (**Figure 6*c***). In the region of the giant 1960 Chile earthquake, such postseismic creep probably explains why areas near the inland limit of coseismic subsidence in 1960 have gradually risen 1–2 m in the ensuing decades (Barrientos et al. 1992).

These discoveries about eastern Hokkaido's earthquake and tsunami history led the Japanese government to revise its official treatment of the region's earthquake and tsunami hazards. Variable rupture mode, in this application, has been simplified into two rupture modes: ordinary earthquakes close to magnitude 8, with average recurrence intervals less than a century; and extraordinary earthquakes of much greater size, averaging 500 years apart. The two kinds of earthquakes are expected to differ greatly in the losses their associated tsunami causes, as illustrated for winter evening scenarios by the Central Disaster Management Council (2006). For an ordinary earthquake, the Council has estimated that the tsunami will destroy 1700 houses and cause 270 fatalities. For an extraordinary earthquake, however, the estimates are 5600 houses and 850 lives.

FORECASTING FUTURE EARTHQUAKES

Knowledge of the past can help reduce losses in the future by identifying and defining earthquake and tsunami hazards. This task can be called forecasting. Earthquake and tsunami forecasts operate at various timescales: in the few minutes between fault rupture and the arrival of seismic waves (ground-shaking warning); in the tens of minutes to hours between fault rupture and the first tsunami wave (tsunami warning); in the hours, days, or months before the fault rupture itself (earthquake prediction); and in years to decades before an earthquake or tsunami (a long-term forecast). Both a ground-shaking warning and a tsunami warning depend on quick retrieval and analysis of seismic data (Kanamori 2005, see also sidebar on Tsunami Warning System). Earthquake prediction depends on the still-elusive discovery of reliable precursory phenomena that can be monitored. The extended timescales discussed in this review yield long-term forecasts that are most commonly expressed, like weather forecasts, as probabilities of occurrence in a stated period of time. Successful earthquake

TSUNAMI WARNING SYSTEM

A tsunami warning system uses the velocity difference between seismic waves (several kilometers per second) and tsunami waves (up to 0.2 km/s for the deep ocean). These waves are generated from the same source, but the larger the distance, the longer the arrival time difference. For trans-oceanic tsunamis, such as those in the Pacific or Indian Oceans, hours may elapse between an earthquake and the tsunami arrival. The earthquake location and size can be quickly and accurately estimated by seismological observations (Kanamori 2005), and the actual tsunami generation and propagation can be confirmed by an offshore sea level monitoring system such as bottom pressure gauges (Bernard 2005) if the data are transmitted and monitored in real time. Numerical computation of tsunamis can be also utilized (Geist et al. 2006). In the case of the 2004 Sumatra-Andaman earthquake, the Pacific Tsunami Warning Center (PTWC) in Hawaii issued the first information bulletin approximately 15 min after the earthquake. This bulletin gave the correct epicenter but vastly underestimated the magnitude as 8.0. PTWC upgraded the magnitude estimate to 8.5 69 min after the earthquake and warned of the possibility of a tsunami. This warning came approximately an hour before the tsunami reached the coasts of Thailand, Sri Lanka, and India.

For a tsunami of nearby origin, the parent earthquake provides the most effective warning to coastal residents. In Japan, a tsunami warning based on seismology is issued 2 to 5 min after the earthquake, and is immediately relayed to coastal residents by the media or other methods. Such instrumental warnings, to be effective, depend on infrastructure to disseminate warning information, prior assessment of tsunami hazards by means of tsunami-inundation mapping, and relentless education of coastal residents and tourists.

forecasting at any timescale requires specification of three factors: where, when, and how big. Here, with regard to giant earthquakes at subduction zones, we briefly review simple hypotheses about the plate tectonics of "where," the patterns of earthquake recurrence that may influence "when," and variability of earthquake size related to "how big."

Where: Which Subduction Zones Produce Giant Earthquakes?

Where will the next giant earthquake take place? Can it happen at any subduction zone? It is difficult to answer these questions with written records alone because historical writings rarely span as much time as do the recurrence intervals for successive giant earthquakes at a subduction zone. Along the Japan Trench, for instance, no giant earthquake has occurred in 1000 years of written history. But is 1000 years enough time to demonstrate that region's full range of earthquake sizes? Moreover, even with the extended timescale provided by paleoseismology, as in the Cascadia example above, geological evidence alone may not suffice to define the size of the largest expectable earthquake.

Thus seismologists have sought to estimate maximum earthquake size at some subduction zones by means of plate-tectonic analogies. An early clue to Cascadia's great earthquake potential, for example, was this subduction zone's similarity to zones where great earthquakes are known from seismograms (Heaton & Kanamori 1984). At these zones, particularly at southern Chile and southwest Japan, the age of subducting oceanic crust (~10 million years old; **Figure 1**) and the rates of subduction (4–8 cm/year) are similar to those at Cascadia.

Today, such analogies do not seem as strong as they used to be. Although many of the largest twentieth-century earthquakes occurred at zones of fast subduction (**Figure 7*a***; Ruff & Kanamori 1980), this dependence on convergence rate may be just an artifact of recurrence intervals; written history has a greater chance of including an unusually large earthquake where subduction is fast and recurrence intervals are consequently short (McCaffrey 1997). According to an updated appraisal of age and rate dependence among the giant ($M_w \sim 9$) earthquakes known from written records or from geological inference, all occurred at subduction zones where the subducting plate is less than 80 million years old and where the plate convergence rate is between 30 and 70 mm/year (**Figure 7*b***; Stein & Okal 2007). Such reappraisals, spurred by the 2004 Sumatra-Andaman earthquake, now extend to subduction zones—including Puerto Rico, Manus, and Ryukyu—that have little or no recognized history of great earthquakes (**Figure 1**, Geist et al. 2006).

When: Do Subduction Zones Obey Simple Models of Earthquake Recurrence?

In theory, a subduction zone might produce its largest earthquakes on a regular schedule. The recurrence of earthquakes on plate boundaries, both convergent and transform (**Figure 1**), can be explained by elastic rebound: An earthquake occurs when the stress accumulation at the boundary reaches a certain limit (Reid 1910).

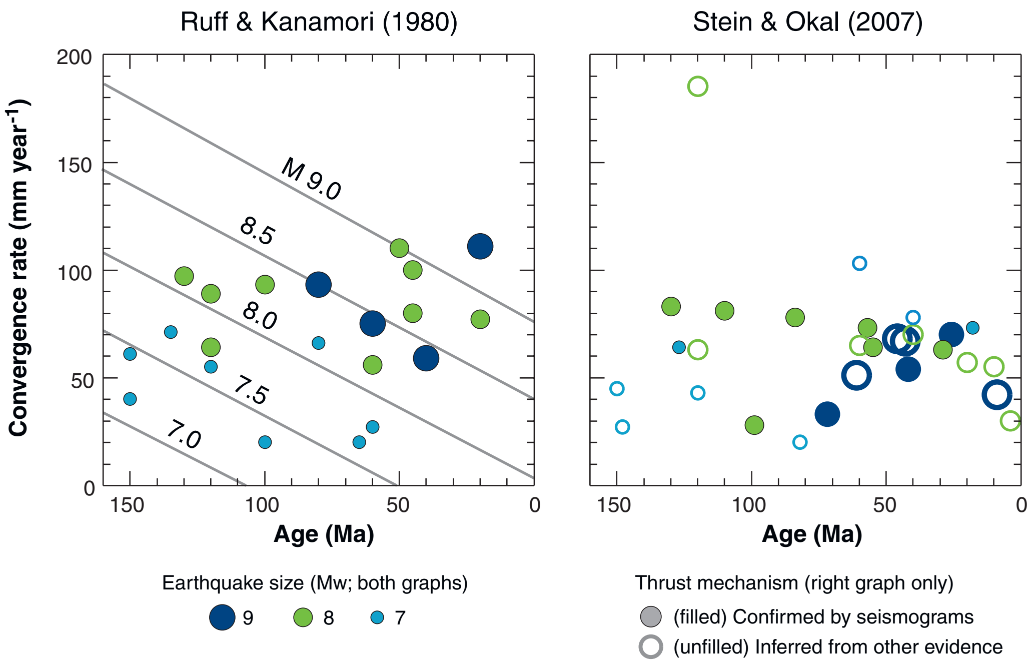

Figure 7

Two views of maximum earthquake size (M_w) as a function of the age (in millions of years, Ma) and convergence rate of subducting plates at subduction zones. (*a*) Among earthquakes of the twentieth century, as compiled in 1980, the largest earthquakes seem to occur at subduction zones where the subducting plate is young and the rate of subduction is high (Ruff & Kanamori 1980). (*b*) Plate age and convergence rate have less predictive value according to this update, which includes earthquakes since 1980 and the 1700 Cascadia earthquake (Stein & Okal 2007). The color code for earthquake size is the same as in *a*. The unfilled circles denote earthquakes for which the thrust mechanism was not determined from seismograms.

Were fault rocks perfectly elastic, and were they unfettered by a complicated history of previous ruptures, the fault might be expected to produce earthquakes of similar size predictably, at regular intervals.

This expectation is difficult to test for most faults owing to the small number of earthquakes in most great earthquake histories (Stein & Newman 2004). Accordingly, it has been common practice to base seismic hazard assessments on simplifying assumptions about the statistical distribution of recurrence intervals (Clague et al. 2006). The simplest of these assumptions, a Poisson distribution, grants a fault no memory of when the previous earthquake occurred; the probability of the next earthquake is constant through time, dependent solely on the average recurrence interval. Alternatively, earthquake probabilities increase with time, as described by statistical distributions of renewal process such as log-normal distribution or Brownian passage model (Nishenko & Buland 1987, Matthews et al. 2002).

Such forecasts, like a 10% chance of rain, can of course succeed whether the forecast event actually happens or not. An example of a forecast earthquake that actually

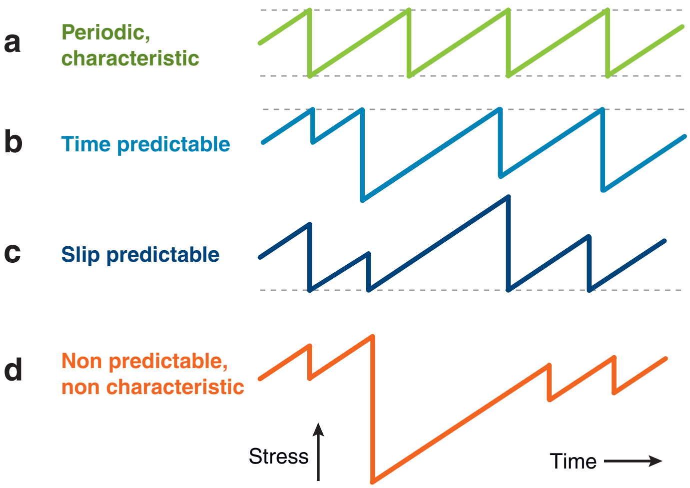

Figure 8

Four models of earthquake recurrence. (*a*) Earthquakes with similar size occur at regular intervals (characteristic earthquakes). (*b*) In the time-predictable model, the time of the next earthquake can be predicted from the size of its predecessor; the larger the predecessor, the longer the recurrence interval. (*c*) Conversely, for the slip-predictable model, the size of the next earthquake increases with the length of the recurrence interval that it terminates. (*d*) With additional complexity, neither time nor slip can be predicted. Modified from Shimazaki & Nakata (1980).

happened is the great Tokachi-oki event of September 2003 (**Figure 2*b***). The previous March, the Japanese government issued a long-term forecast for great earthquakes along the Kuril Trench (Earthquake Research Committee 2004). The forecast was based on the assumption that the southern Kuril Trench off eastern Hokkaido produces, at regular intervals, earthquakes of similar size and rupture area—the periodic, characteristic model in **Figure 8**. The committee estimated the probability in the next 30 years (starting March 2003) as 60% in Tokachi-oki and 20%–30% in Nemuro-oki, based on the recurrence of great earthquakes in the nineteenth and twentieth centuries. A half year later, a Tokachi-oki earthquake, M_w 8.0, occurred in the area of highest probability along the southern Kuril Trench. However, this earthquake violated the assumption of characteristic behavior in that the fault rupture area, as inferred from tsunami data, differed from that of the 1952 shock (**Figure 2*b***) (Satake et al. 2006b).

Attempts to accommodate such differences include the time-predictable and slip-predictable models (**Figure 8**), proposed a quarter century ago (Shimazaki & Nakata 1980). Historical earthquakes on the Parkfield segment of the San Andreas Fault are not time-predictable (Murray & Segall 2002), and paleoseismological records elsewhere along the fault have been interpreted as slip-predictable in one area (Liu-Zeng et al. 2006) and neither time-predictable nor slip-predictable in another (Weldon et al. 2004). Great earthquakes at the Nankai Trough have been found time-predictable, as judged from seismic moments estimated for great earthquakes of the past 1300 years, most of them known from written records but others inferred from archaeological excavations (Kumagai 1996). Neither time-predictability nor slip-predictability has been compared with the best-dated geologic records of great Cascadia earthquakes. These earthquakes show marked variation not just in earthquake size but also recurrence interval, which averages close to 500 years but ranges from a few centuries to a millennium (Nelson et al. 2006).

How Big: Is Magnitude Uniform or Variable?

The next earthquake on some faults may be much larger than any in the faults' instrumental or documentary history. The 2004 Sumatra-Andaman earthquake taught this lesson, known also from paleoseismological evidence at Cascadia and Hokkaido.

Such potential for a historically unprecedented earthquake is just part of a natural variability in earthquake size (**Figure 9**), such as that known from instrumental recordings of subduction earthquakes off Colombia and Ecuador (Kanamori & McNally 1982), the Aleutians (Johnson et al. 1994, Tanioka & Gonzalez 1998), and the Nankai Trough (Ando 1975). It would be simpler if a subduction zone characteristically produced an earthquake of a single size. However, in these several examples, variability is characteristic.

The causes of such variability probably include fault segments. A relatively small earthquake results from the rupture of a single segment; larger earthquakes represent breaks of multiple segments. Individual segments commonly correspond to sedimentary basins (Sugiyama 1994, Wells et al. 2003).

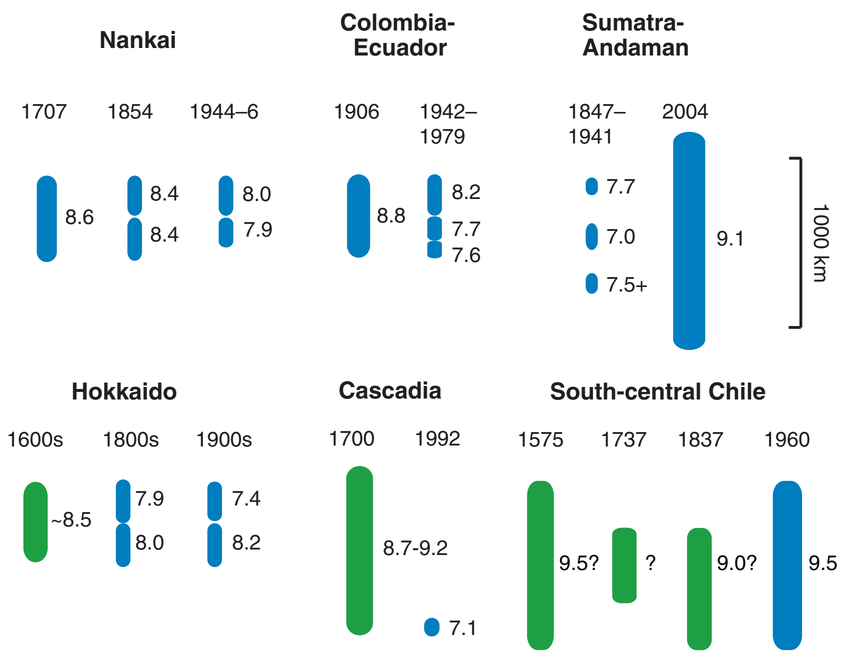

Figure 9

Variability of earthquake size in subduction zones. The colored bars represent estimated rupture area, simplified geometrically: blue, inferred solely from instrumental and written records; green, includes paleoseismic evidence. Numerals denote moment magnitude. Nankai (Ando 1975), Colombia-Ecuador (Kanamori & McNally 1982), Sumatra-Andaman (Bilham et al. 2005), Kuril (Satake et al. 2005), Cascadia (Satake et al. 2003), Chile (Cisternas et al. 2005).

SUMMARY

1. The giant 2004 Sumatra-Andaman earthquake ($M_w \sim 9$) occurred in a subduction zone where only smaller ($M_w < 8$) earthquakes were historically recorded.
2. Paleoseismological studies indicate similar variability in earthquake size at subduction zones off Chile, Japan, and western North America. For example, among three historical predecessors of the 1960 Chilean earthquake (M_w 9.5), only the earliest, in 1575, likely rivaled the 1960 earthquake in size. In Hokkaido, along the southern Kuril subduction zone, M_w 8 earthquakes in a written history 200 years long contrast with larger earthquakes, at intervals averaging about 500 years, that were recently inferred from coastal geological evidence of tsunamis and postseismic uplift.
3. At North America's Cascadia subduction zone, the past occurrence of great earthquakes went unnoticed in modern times until the last decades of the twentieth century, when the earthquakes were discovered from an unusual combination of North American geology and Japanese writings.
4. Simple geophysical hypotheses about maximum earthquake size at subduction zones, and about patterns of earthquake recurrence, appear to be of limited value in the long-term forecasting of the time and size of great subduction zone earthquakes.

FUTURE DIRECTIONS

1. Paleoseismological surveys are needed to help assess earthquake and tsunami hazards at subduction zones, particularly around the Indian Ocean. The assessments should include searching for the traces of giant earthquakes unknown from written history.
2. Geophysical models are needed to explain variability in maximum size and recurrence intervals of great earthquakes at subduction zones, in relation to plate tectonic setting and in relation to variability in the properties of fault rocks (Kanamori 2006).

ACKNOWLEDGMENTS

Hiroo Kanamori, Seth Stein, Eric Geist, and Wayne Thatcher reviewed the manuscript and provided valuable comments that improved the paper. Seth Stein and Emile Okal kindly shared their data (**Figure 7*b***) before publication.

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Annual Review of
Earth and
Planetary Sciences

Volume 35, 2007

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