A CENTURY OF EARTHQUAKES: 1906-2006

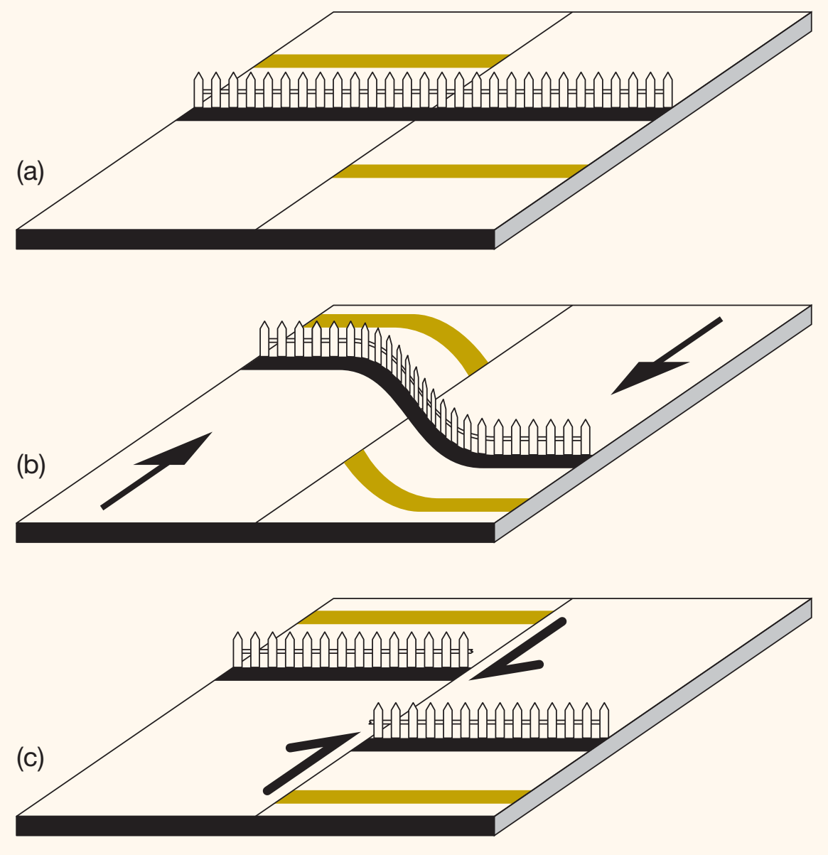
A CITY BURNS - A SCIENCE COMES OF AGE


Photo courtesy of: San Francisco Public Library

On April 18, 1906 at 5:12 AM the city of San Francisco suffered a major earthquake with a magnitude of about 7.9. After a minute of strong shaking, much of the city lay in ruins. Fires broke out and raged for three days, causing considerably more damage than the earthquake. It is estimated that 3000 deaths and $400 million in damage resulted. Scientific study of the earthquake showed that the ground had moved along a 300-km long zone, a segment of the San Andreas fault. Displaced features like fences showed that material on one side of the fault suddenly moved up to 3-6 m relative to material on the other side. Moreover, the fault showed signs of previous movements, showing that this was not the first such earthquake.

EARTHQUAKES, FAULTS, AND PLATES

As part of the investigation, H.F. Reid proposed the elastic rebound theory of earthquakes, where materials at distance on opposite sides of the fault move smoothly relative to each other, but friction on the fault “locks” each side and prevents it from slipping. Eventually the accumulated forces (stress) are more than the fault can endure, and the fault slips in an earthquake.



Motion of a fence crossing the San Andreas fault before and during an earthquake. The elastic rebound model of earthquakes assumes that between earthquakes, material on the two sides of a fault undergoes relative motion. Because the fault is locked, features across it that were linear at time (a), such as a fence, are slowly deformed with time (b). Finally the strain becomes so great that the fault breaks in an earthquake, offsetting the features (c).

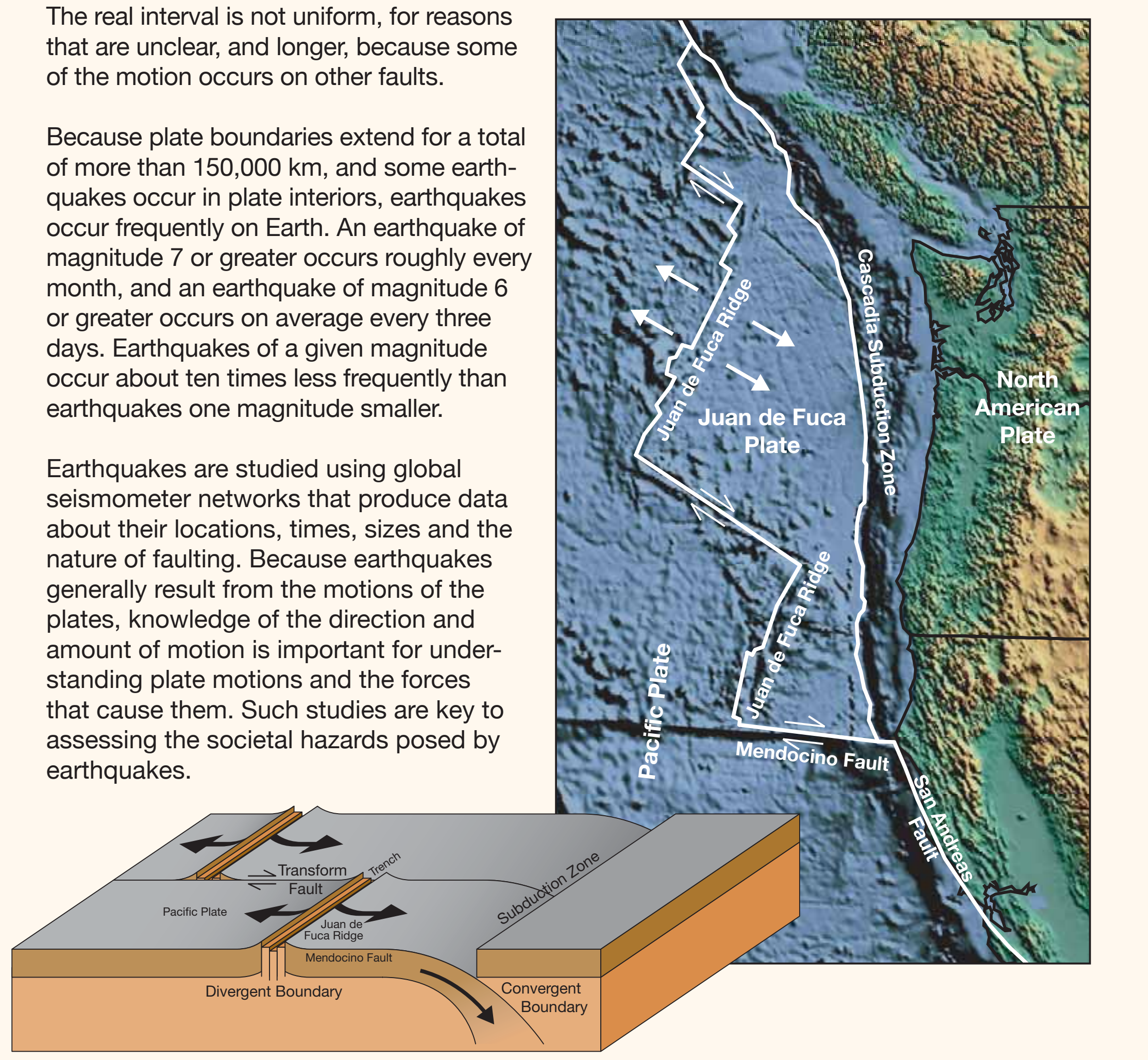
The San Andreas fault in the Carrizo plain in California, seen from the southeast. Note the displacement of stream gullies as the rocks on the left side of the fault have moved to the right (north).

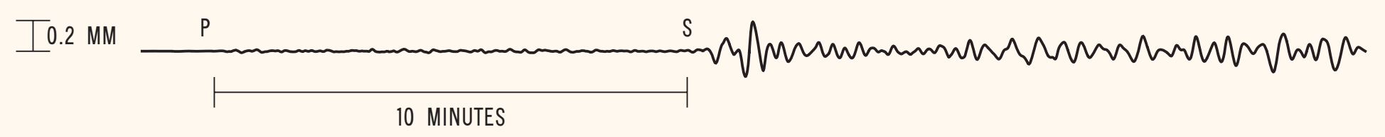
In the 1960s, geologists discovered that the Earth’s outer shell was made up of about 15 100-km thick tectonic plates that were smoothly moving by each other at speeds of a few inches (a few cm) per year (about the speed that fingernails grow). Earthquakes primarily occur at the boundaries where the plates converge, diverge, or slide past each other. At spreading centers both plates move away from the boundary, whereas at subduction zones the underthrusting subducted plate moves toward the boundary. At the third boundary type, transform faults (such as the San Andreas), relative plate motion is parallel to the boundary.

The San Francisco earthquake occurred on the San Andreas fault in northern California, part of the boundary along which the Pacific plate moves northward relative to the North American plate. Studies using the Global Positioning System satellites show that the two plates move by each other at a speed of about 4.5 cm/yr. Most parts of the San Andreas fault are “locked” most of the time, but slip several meters in a large earthquake every few hundred years. A simple calculation (earthquake slip/slip per year) suggests that such an earthquake with a 4-m slip should occur on average about 90 years. The real interval is not uniform, for reasons that are unclear, and longer, because some of the motion occurs on other faults.

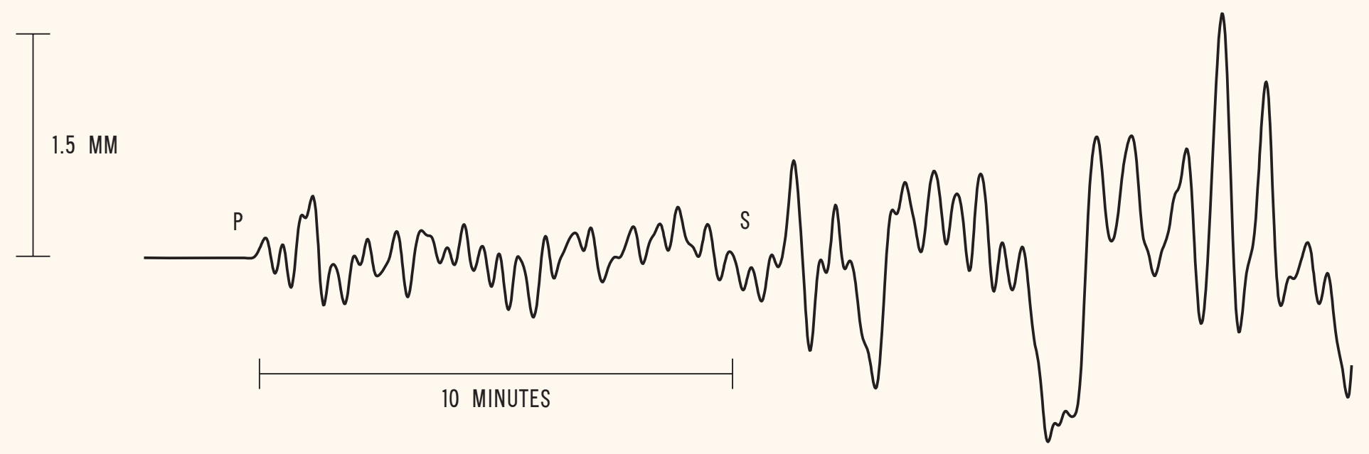
Because plate boundaries extend for a total of more than 150,000 km, and some earthquakes occur in plate interiors, earthquakes occur frequently on Earth. An earthquake of magnitude 7 or greater occurs roughly every month, and an earthquake of magnitude 6 or greater occurs on average every three days. Earthquakes of a given magnitude occur about ten times less frequently than earthquakes one magnitude smaller.

Earthquakes are studied using global seismometer networks that produce data about their locations, times, sizes and the nature of faulting. Because earthquakes generally result from the motions of the plates, knowledge of the direction and amount of motion is important for understanding plate motions and the forces that cause them. Such studies are key to assessing the societal hazards posed by earthquakes.

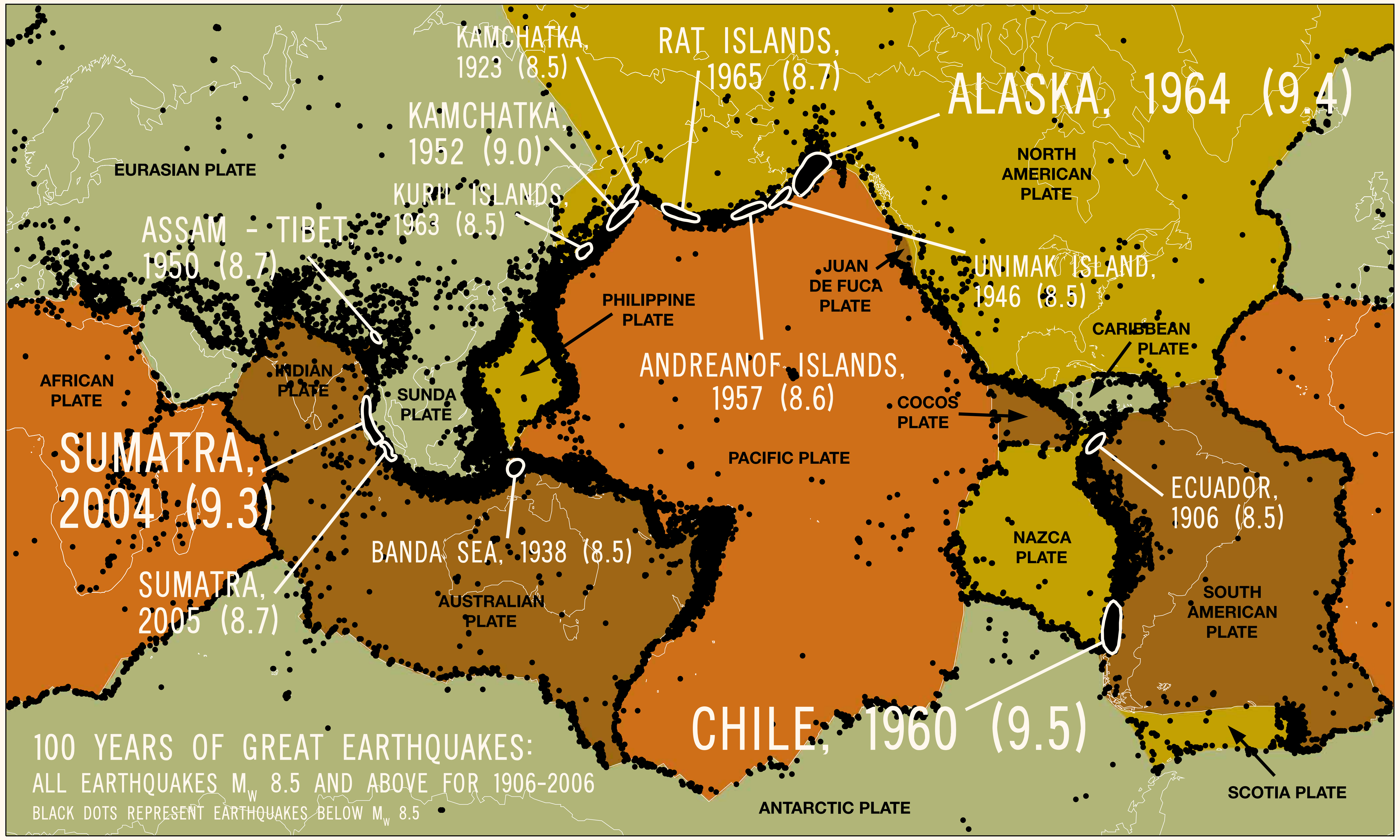




1906 San Francisco Earthquake (M_w = 7.9) seismogram (N-S ground motion) recorded in Göttingen, Germany (9080 km from epicenter).



2004 Sumatra Earthquake (M_w = 9.3) seismogram (vertical ground motion) recorded in Kevo, Finland (8850 km from epicenter).



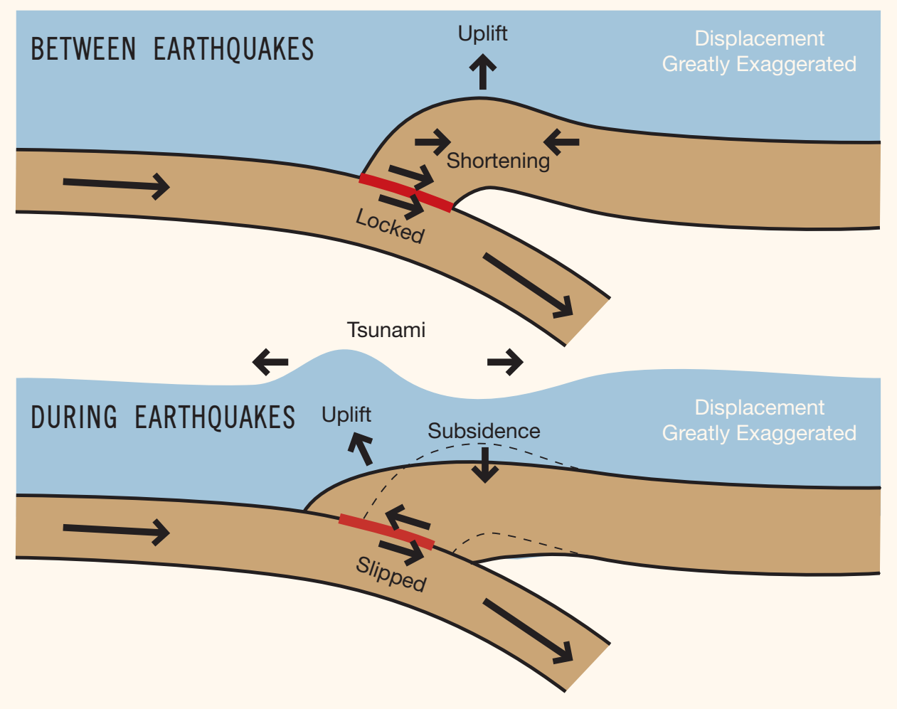
100 YEARS OF GREAT EARTHQUAKES:

ALL EARTHQUAKES M_W 8.5 AND ABOVE FOR 1906-2006

BLACK DOTS REPRESENT EARTHQUAKES BELOW M_W 8.5

THE KILLER WAVE

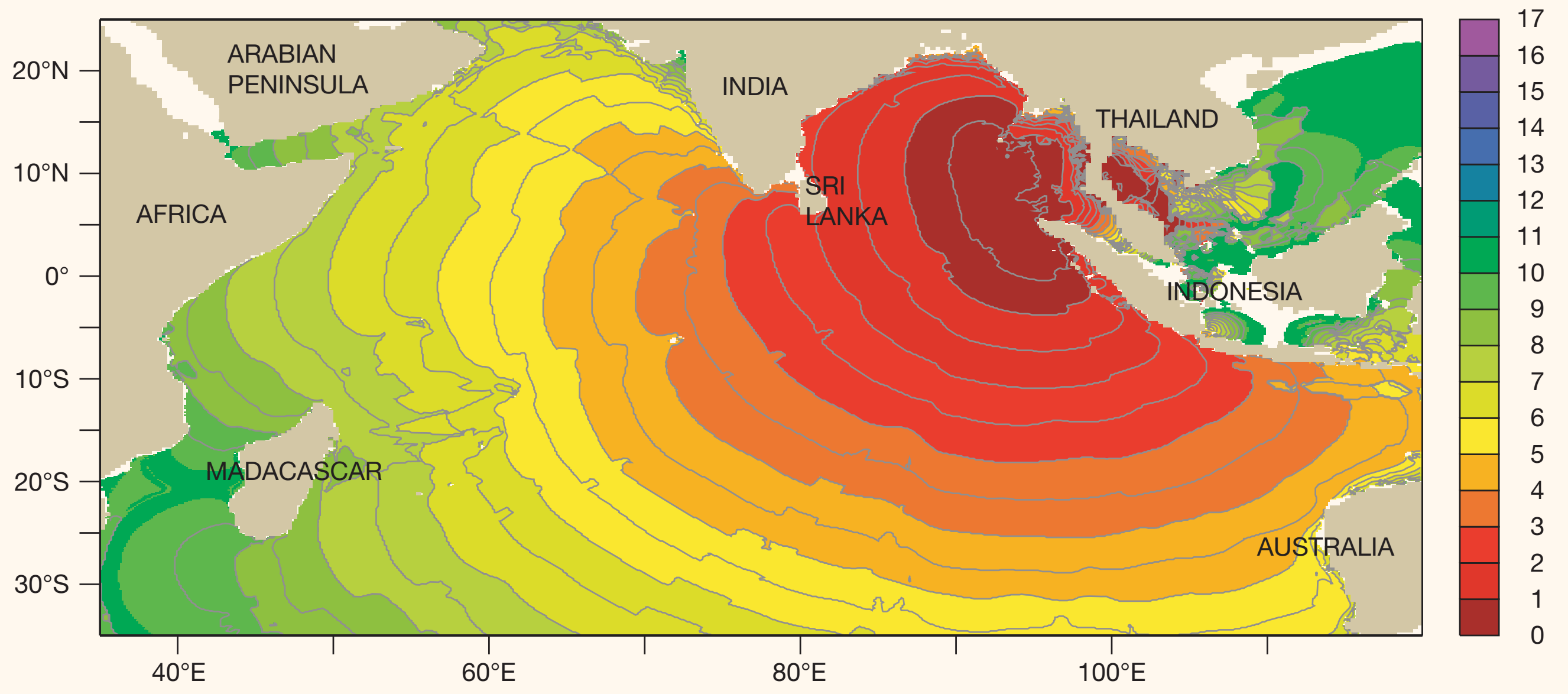
On December 26, 2004 the world saw yet again how the stress built up over hundreds of years by slow and almost imperceptible motions of tectonic plates can be released with devastating effect. A great earthquake beneath the Indonesian island of Sumatra generated a massive sea wave, or tsunami, that raced across the Indian Ocean at the speed of a jet plane, wreaking destruction along seacoasts and causing at least 300,000 deaths. Tsunami heights grow substantially as they approach the shallow ocean near the coast, and they can be enormously destructive.



An earthquake occurs when the accumulated stresses on the fault exceed the fault strength. Beneath Sumatra, the overriding plate that had been dragged down since the last major earthquake rebounded over the course of a few minutes and suddenly displaced many cubic kilometers of ocean, causing the devastating tsunami.

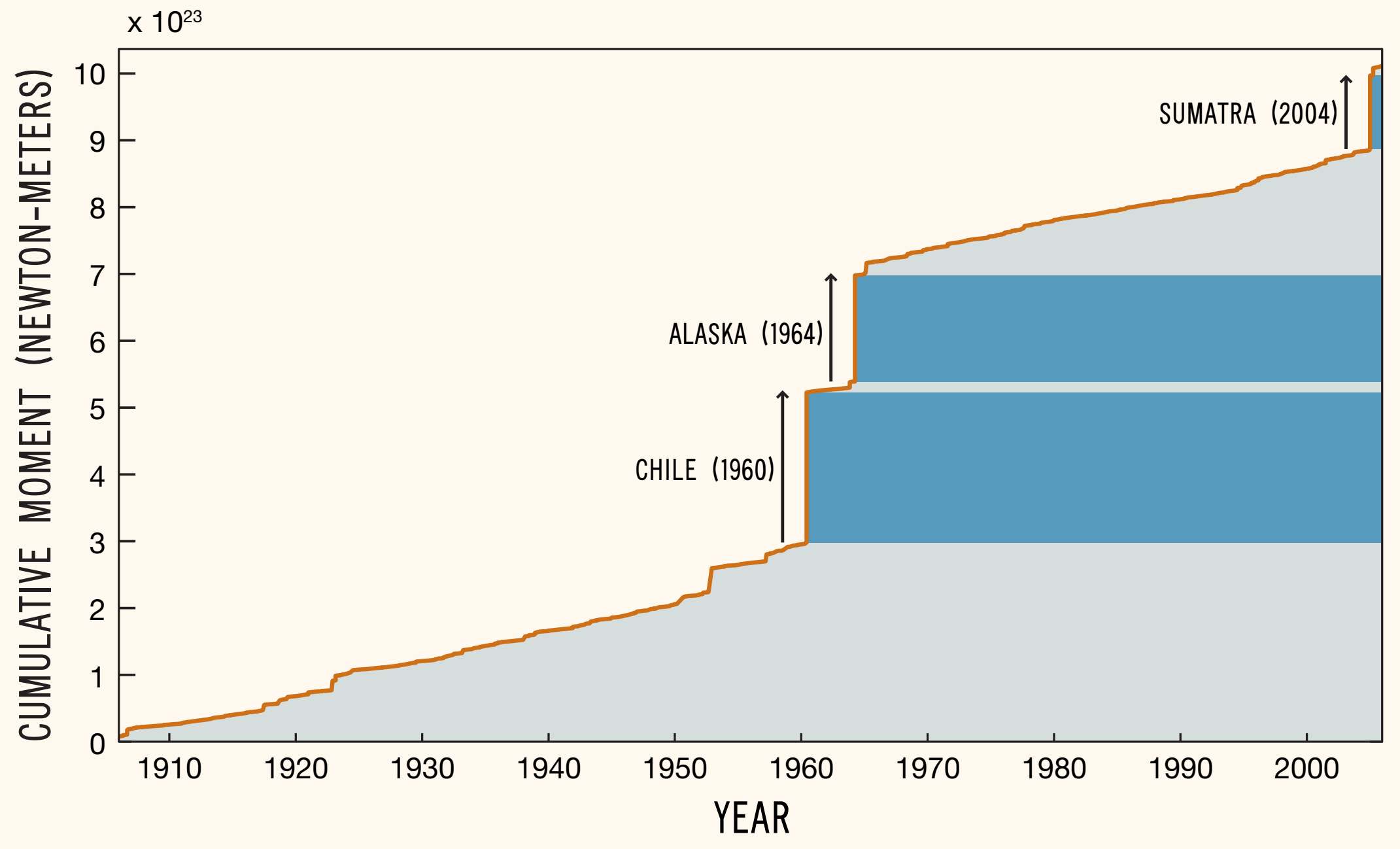
The cause of this event can be traced back over 120 million years ago, when the subcontinent of India separated from Antarctica and started its steady motion northward. 50 million years ago it collided with Asia, raising the Himalayas and forming the Tibetan plateau. The plate collision continues today as the Indian plate moves northward. Part of the plate boundary extends along the subduction zone on the west coast of Sumatra, where an oceanic part of the Indian plate subducts beneath the Burma plate, a small sliver or microplate between the Indian plate and the Sunda plate that includes much of southeast Asia. Every year, about 35 mm of convergence occurs between the Indian and Burma plates. However, the fault is locked, so stress builds up on it. Eventually the accumulated stress exceeds the strength of the fault, and it slips. During the Sumatra earthquake a huge area of this plate interface slipped, generating seismic waves that inflicted major damage near the earthquake. Moreover, because this plate boundary occurs at an underwater trench, the overriding Burma plate that had been dragged down since the last major earthquake rebounded and displaced many cubic kilometers of ocean, causing the devastating tsunami.

ARRIVAL TIME OF FIRST WAVE (HRS) 12/26/2004 INDONESIAN TSUNAMI



GREAT EARTHQUAKES

Charles Richter introduced the first earthquake magnitude scale in 1935 for small California earthquakes. However, the Richter and similar magnitude scales are inadequate for characterizing extremely large earthquakes. Seismologists now use a magnitude scale designed to blend with the original Richter scale, but based on the seismic moment, which relates directly to three key physical properties of the fault: stiffness of rock, fault area, and fault slip. Seismic moment is a quantity used by seismologists to measure the amount of energy released by an earthquake. The seismic moment generated by a slipping fault is:



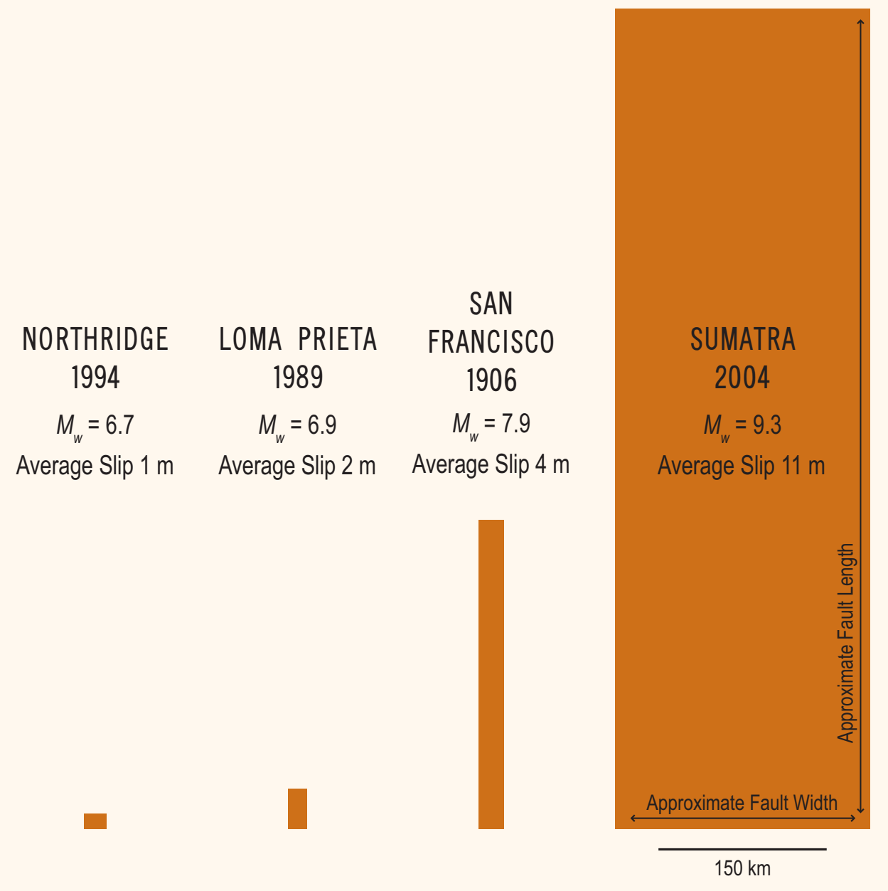
Between 1906 and 2006 about half of all global moment release occurred in just three great earthquakes: Sumatra (2004), Alaska (1964) and Chile (1960).

M_o = *rigidity x fault area x fault slip*

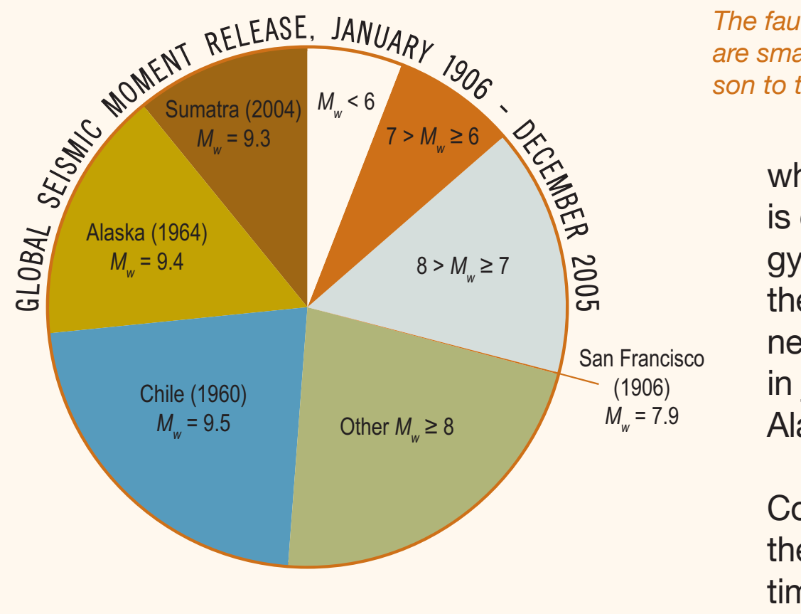
The rigidity is a number that characterizes the stiffness of rocks near the fault. Fault area and fault slip can be estimated from the analysis of seismograms. For a seismic moment expressed in units of Newton-meters (which is a unit of force times distance), the corresponding moment magnitude, M_w, is:

$$M_w = (2/3) \times (\log_{10} M_o - 9.1)$$

The constants in the equation allow the moment magnitude scale to describe great earthquakes while matching other magnitude scales at smaller magnitudes. An earthquake with M_w greater than or equal to 8.0, which on average occurs about every 1.5 years, is classified as a great earthquake. The total energy release on Earth is dominated by the largest of the great earthquakes; between 1906 and 2006 nearly half of all global moment release occurred in just three great earthquakes: Sumatra (2004), Alaska (1964) and Chile (1960).



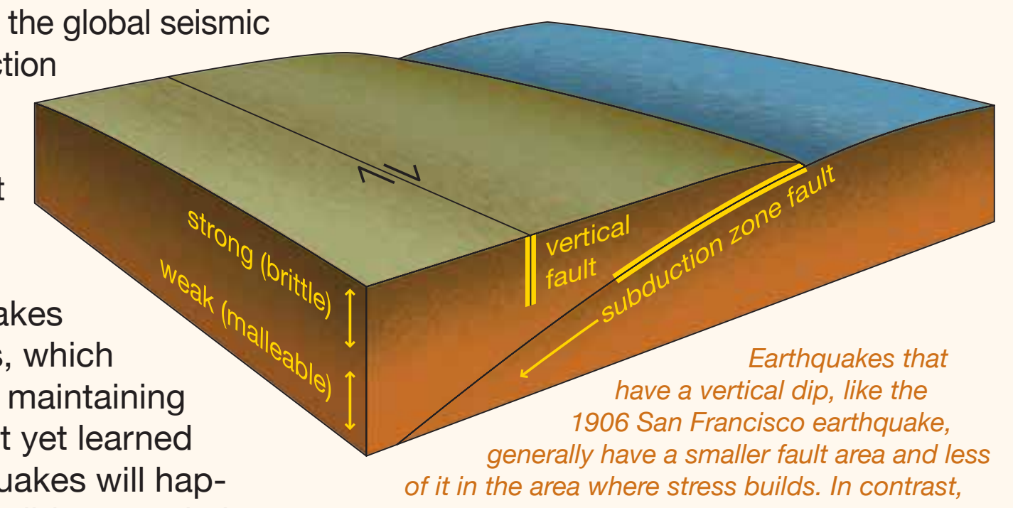
The fault sizes of more recent damaging earthquakes in California are small compared to the 1906 earthquake and tiny in comparison to the Sumatra earthquake.



The energy release of the 1906 earthquake is barely visible in the above plot of seismic energy released during the past century.

Compared to the 1906 San Francisco earthquake, the 2004 Sumatra earthquake had roughly three times the average slip on a fault with about 60 times the area, which corresponds to an increase in moment magnitude of about 1.4. As seen in the formula above, fault area, slip and rigidity of the rock constrain how large an earthquake can be. Rock type and depth account for how rigid the rocks are and how much stress can build up. The more stress that builds up, the more energy can be released when the rocks slip. In California, rocks that are deeper than 20 km are weak and do not let stress build up over time. In contrast, earthquakes in subduction zones have large surface areas in zones of stronger rocks, which allow more stress to be built up over time. Because of these factors, about 80% of the global seismic moment is released by subduction zone earthquakes.

We need to understand great earthquakes and live with them. In fact, we can’t live without them. Great earthquakes are a result of plate tectonics, which keeps the Earth habitable by maintaining our atmosphere. We have not yet learned to predict when great earthquakes will happen. The best we can do is build our societies to minimize the damage from earthquakes. This can be done by earthquake resistant construction, systems to warn of imminent tsunami waves, and other measures. Deciding how to do this is a challenging and important task.



Earthquakes that have a vertical dip, like the 1906 San Francisco earthquake, generally have a smaller fault area and less of it in the area where stress builds. In contrast, subduction zone earthquakes occur on faults that dip shallowly into the earth, which can have much larger fault areas with more of it capable of building stress. Compare the yellow (brittle) section of the vertical and subduction zone faults in the diagram.

Global earthquake data provided by the IRIS/USGS Global Seismographic Network, Meredith Nettles (Harvard University) and Lynn Sykes (Lamont-Doherty Earth Observatory). 1906 seismogram provided by Dave Wald (USGS). Sumatra seismogram provided by the IRIS/USGS Global Seismographic Network. Juan de Fuca map provided by Bill Schultz (Institute for the Application of Geospatial Technology). Additional figures derived after NOAA and Hyndman & Wang. Produced by Richard Aster (New Mexico Institute of Mining and Technology), Seth Stein and Emile Okal (Northwestern University), Michael Wysession (Washington University), John Taber, Gayle Levy (IRIS Consortium). Designed by Jason Mallett (IRIS Consortium). IRIS Consortium; www.iris.edu