The Northern Sumatra Earthquake of 2004: Forty Years of Ignoring Plate Tectonics*

By

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Introduction

Discuss the significance of the calc-alkaline series.

That was the only question on my petrology mid-term examination in 1975. It was perhaps the most penetrating question I have ever been asked as a geologist. It is also the only exam question I remember from my academic years.

I went to the professor, Dr. Rudy Epis, after he returned the exams to discuss my low grade with him. I had written everything I knew about the granitic rocks that make up the calc-alkaline series and it was all correct. What I had failed to do was to answer the question. I had not discussed the significance of the calc-alkaline series.

I did not address the “granite problem.” Granite is a light-colored, relatively light-weight rock that contains a lot of quartz. Most of the Earth is made up of basaltic material, the opposite of granite: a dark, heavy rock without much quartz. Based on the overall composition of the Earth, there is just too much granite, and most of it is found on the continents. This has puzzled geologists since the science of geology began.

Epis explained that he was looking for a plate-tectonic explanation to the granite problem. Basically, the plate-tectonic model says that the Earth is a great factory. Earth is constantly recycling mostly oceanic, basaltic crust into ocean-trench subduction zones and generating granite by a kind of distillation process.

That discussion with Dr. Epis transformed me. I was awed, even overwhelmed, by the way his mind worked and the power of a scientific model—the plate-tectonic model, in this case—to collapse complexity into simplicity. I knew about plate tectonics and the calc-alkaline series separately. I had simply not connected the two in the elegant way he had. I entered his office a student concerned about a grade and left, in some way, a geologist. He made me see, perhaps for the first time, the importance of critical thinking. I promised myself to never again fail to seek the question within the question.

I thought about the conversation with Rudy Epis in early December 2004 as I began reading Simon Winchester’s Krakatoa, The Day the World Exploded: August 27, 1883.

Winchester’s book is an entertaining, popular explanation of plate tectonic theory in the context of a cataclysmic volcanic explosion that occurred in Indonesia 121 years ago. Krakatoa had a profound affect on Victorian consciousness because invention of the telegraph made news of the eruption immediately known around the world.

On December 26, 2004, the Northern Sumatra Earthquake occurred in the same tectonic neighborhood as Krakatoa. The world is stunned by the death and destruction that is coming to light from the earthquake and ensuing tsunami. The difference between the past and present seismic events in Indonesia is that we understand the current disaster because of the plate-tectonic model; in 1883, however, geology did not yet have an Earth model or context to explain Krakatoa to a frightened and confused world.

Plate Tectonics and a Restless Earth

Plate tectonics was not new in 1975 when I was studying petrology from Rudy Epis, but it was a model still considered optional by many geologists: as with all new ideas, it takes time before any but the innovator and early adopter groups embrace a new invention (Berman, 2004k). The plate-tectonic model began in 1915 when Alfred Wegener published his observations on the fit between the continents minus the intervening, present-day ocean basins (the relationship had, in fact, been previously noted as early as 1620 by Francis Bacon). Wegener supported his theory of “continental drift,” that the continents had, at one time, been connected, with abundant and convincing biological evidence. Wegener’s work was scorned and ridiculed by the scientific community presumably because there was no mechanism to de-couple the crust from the underlying mantle and core of the Earth. Thomas Chamberlin, the American geologist famous for his address Method of Multiple Working Hypotheses (HGS Bulletin, v. 47, no. 2) apparently abandoned his thesis when he commented in 1923 on Wegener’s work, “If we are to believe this hypothesis we must forget everything we learned in the last seventy years and start over again,” (Winchester, 2003).

Plate tectonics was revived after World War II due to wartime advances in measurement technology and instrumentation. A new Earth model evolved and was articulated in a series of key papers, notably by Dietz (1961), Wilson (1965), and Cox et al (1967). The breakthrough came in late 1965 when Brent Dalrymple presented findings at a meeting of the Geological Society of America: he showed an exact match between terrestrial paleomagnetic measurements and seafloor magnetic reversal bands that had been identified in post-war ocean basin surveys (Figure 1). “It was indeed a revelation...and the start of a revolution in Earth science!” (Donnenfield and Howell, 2004).

A mechanism was discovered for a crust in dynamic and perpetual motion, de-coupled from and, at the same time, interacting with the underlying mantle and core (Figure 2). Wegener’s concept was validated. The crust is divided into tectonic plates that move carrying continents along with them (Figure 3). Earth’s crust is constantly being destroyed and regenerated. On one end of a great crustal conveyor belt, new basaltic crust arises at mid-ocean ridges, spreading out the ocean basins by adding new seafloor. On the other end of the conveyor, oceanic crust is swept down into subduction zones at the peripheries of tectonic plates (Figure 4). Subducting oceanic crust is partly transformed into granitic material by partial melting and fractionation. Magmas that mix with water and carbon dioxide from sea water produce explosive volcanoes like Krakatoa.

This was the significance of the calc-alkaline series.

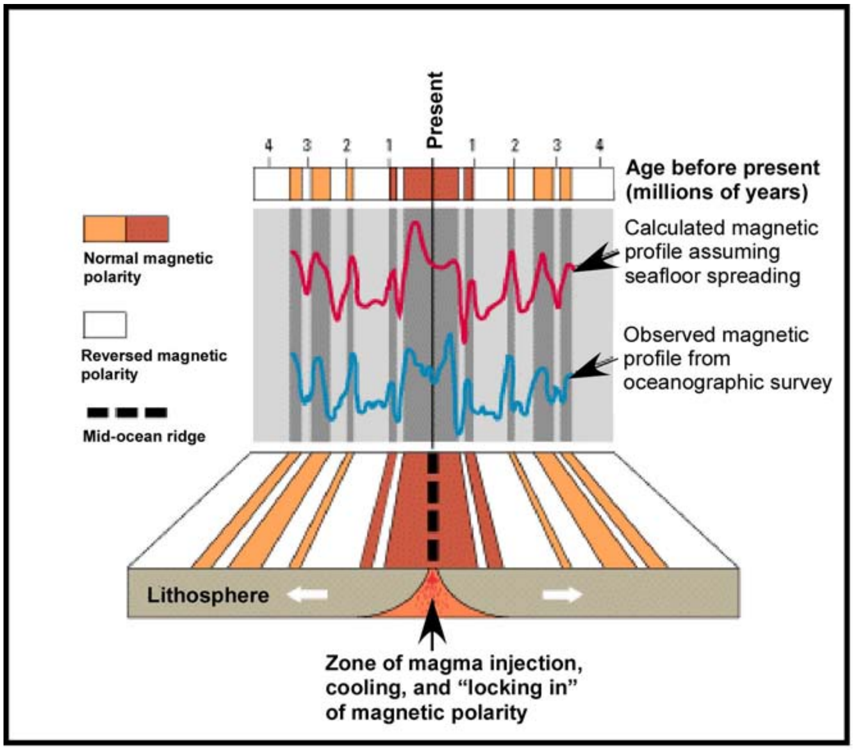

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Figure 1. Observed vs. calculated magnetic profile for the ocean floor across the East Pacific Rise (modified from Kious and Tilling, 1996).

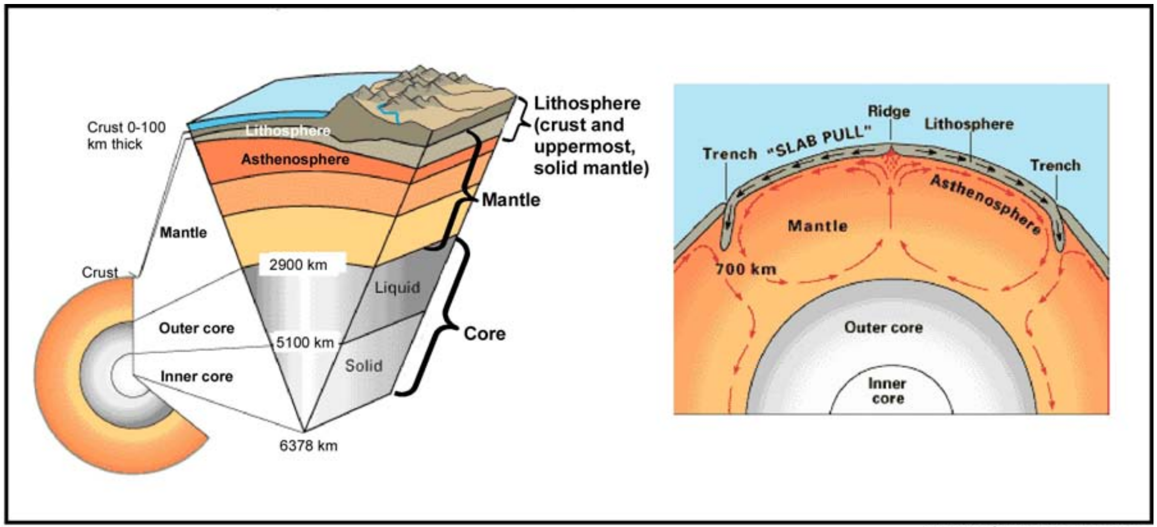

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Figure 2. Internal structure of the earth and model for convection cells in earth's mantle (modified from Kious and Tilling, 1996).

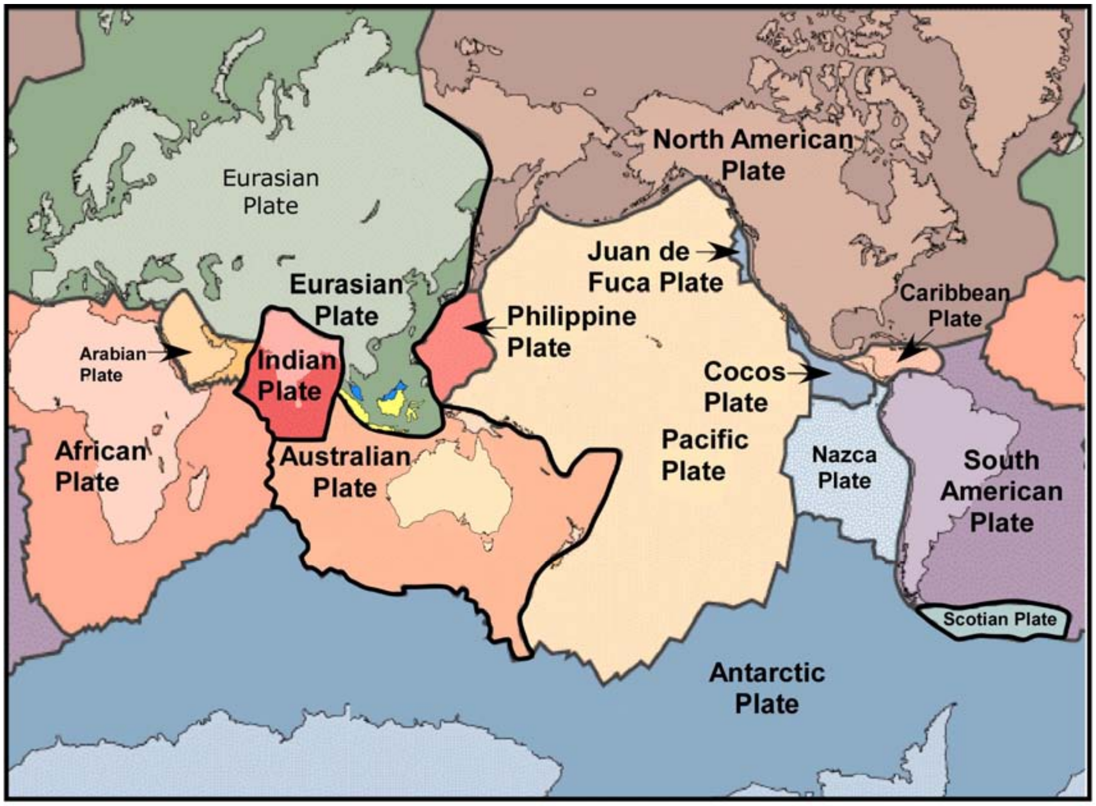

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Figure 3. Earth’s tectonic plates (modified from Kious and Tilling, 1996).

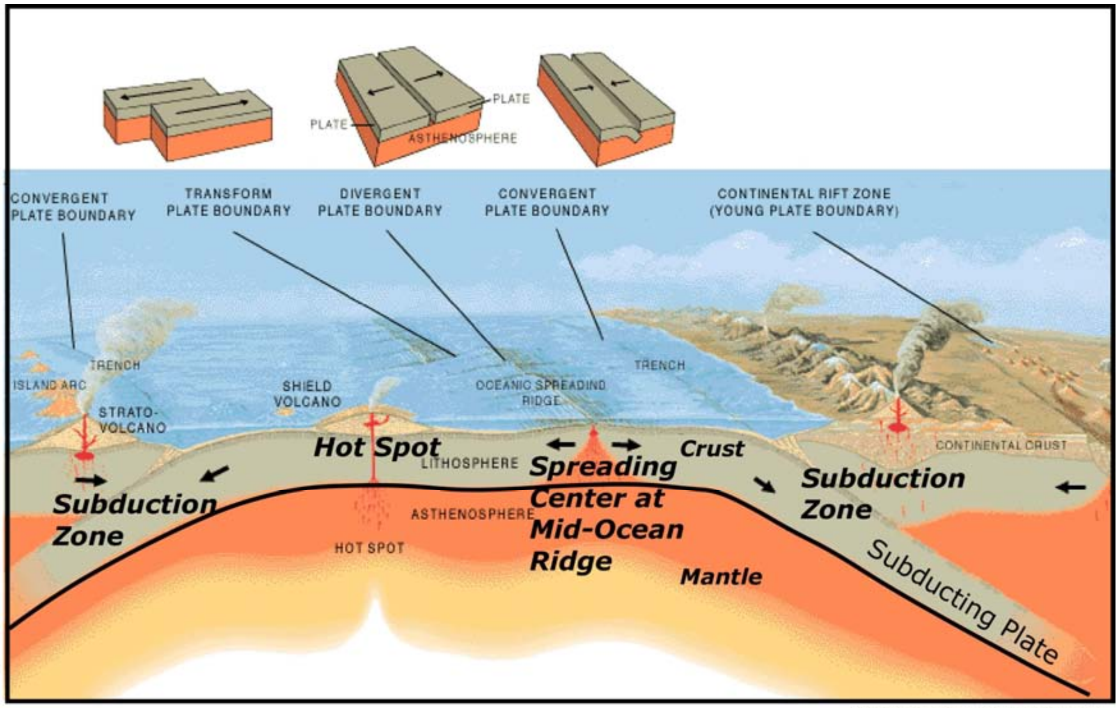

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Figure 4. Tectonic plates and plate boundary types (modified from Kious and Tilling, 1996).

Northern Sumatra Earthquake of 2004

On December 25, 18:58:53 Central Standard Time (local Indonesia time 07:58:53, December 26) an earthquake took place on the seafloor west of Northern Sumatra, Indonesia (3.267° North / 95.821° East), 255 km south-southwest of the city of Banda Aceh. The earthquake, which measured 9.0 in magnitude on the Richter scale, produced tsunamis with speeds of as much as 800 kilometers/hour (500 miles per hour) throughout much of the Indian Ocean Basin. In coastal areas of Sri Lanka, India, Bangladesh, Thailand, Indonesia, the Maldives and Malaysia, run-up heights (onshore height above sea level) of over 12.5 meters (40 feet) produced great destruction and have claimed over 150,000 lives at this writing. The tsunami's deadly force was felt as far as 5,000 kilometers (3,000 miles) away in Kenya, the Cocos Islands, Mauritius, Reunion, Seychelles and Somalia, the latter where 120 people were killed. The tsunami crossed into the Pacific Ocean and was recorded in New Zealand and along the west coasts of South and North America. This is the fourth largest earthquake in the world since 1900 and is the largest since the 1964 Prince William Sound, Alaska earthquake.

As I followed the news of the earthquake and tsunami, it was easy to place the December 26 earthquake into rather well-defined categories of scientific understanding based on the plate-tectonic model. I was amazed by the power of the World Wide Web as I acquired instantaneous information about the earthquake and saw video and digital photo images of the devastation in the Indian Ocean Basin.

The earthquake occurred in approximately 1200 m of water with a focal depth at about 30 km in the crust. The epicenter lies along the Sunda Trench in a transition zone from northwest-oriented strike-slip-dominated fault movement to more north-south-oriented compressional faulting (Figure 5). The trench is the surface expression of the plate interface between the Australia and India plates, situated to the southwest of the trench, and the Burma and Sunda micro-plate portions of the Eurasia Plate, situated to the northeast (Figures 6 and 7). In the immediate area of the earthquake, the India/Australia plate moves to the northeast at a rate of approximately 6 cm/year relative to the Eurasia Plate. This results locally in oblique convergence, expressed both as right-lateral strike-slip faulting and underthrusting. More regionally along the Sunda Trench the pattern is one of convergence and subduction (Figure 8). The Sunda Trench, in turn, is part of a circum-Pacific network of trench-subduction zones called the "Ring of Fire" (Figure 9).

Preliminary locations of larger aftershocks following the megathrust earthquake show that approximately 1200 km of the plate boundary slipped as a result of the earthquake. By comparison with other large megathrust earthquakes, the width of the causative fault-rupture was likely over one-hundred km. From the size of the earthquake, it is likely that the average displacement on the fault plane was about fifteen meters. The sea floor overlying the thrust fault would have been uplifted by several meters as a result of the earthquake. The above estimates of fault dimensions and displacement will be refined in the near future as the result of detailed analyses of the earthquake waves" (USGS Preliminary Earthquake Report, 2004).

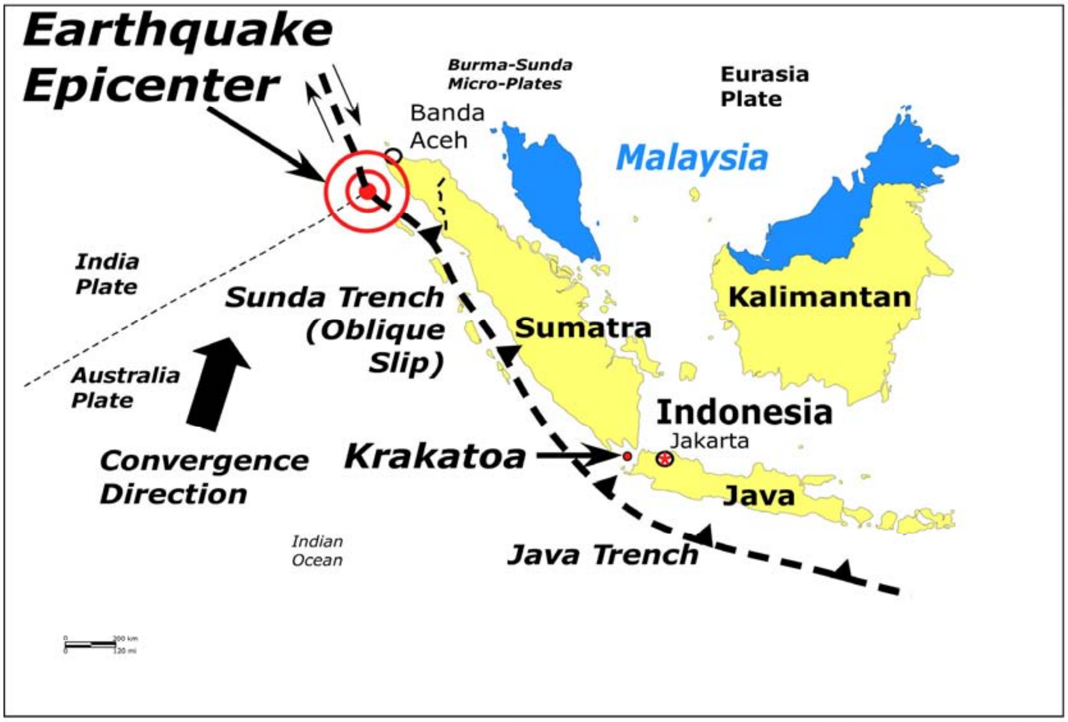

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Figure 5. 2004 Northern Sumatra earthquake epicenter and location of 1883 Krakatoa eruption.

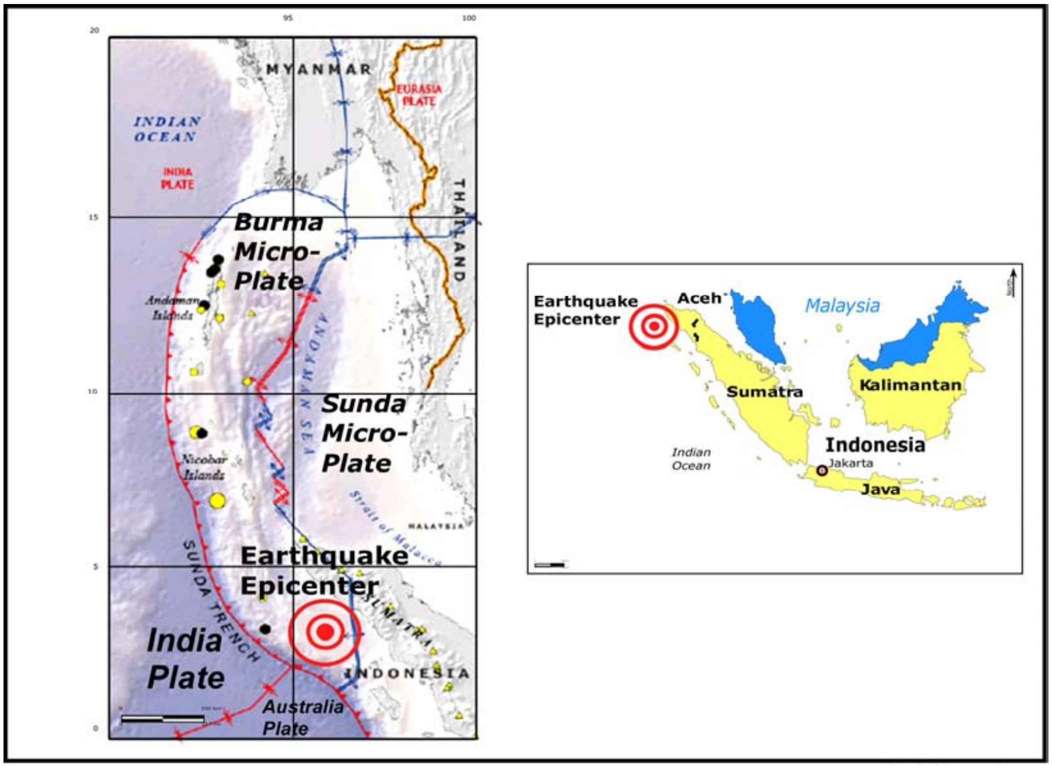

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Figure 6. Northern Sumatra earthquake tectonic setting (modified from USGS Preliminary Earthquake Report, 2004).

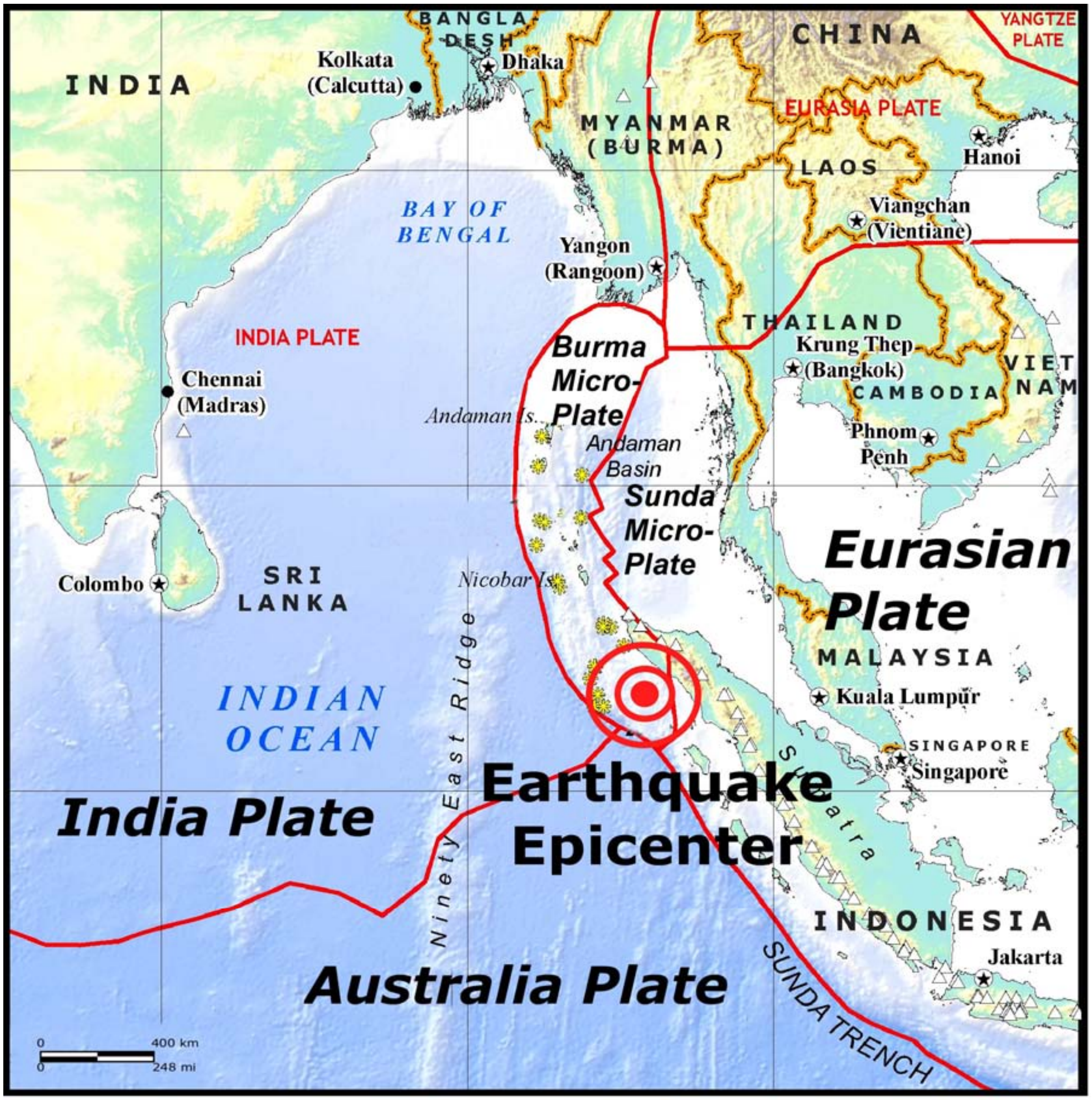

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Figure 7. Northwestern Indian Ocean tectonic setting (modified from USGS Preliminary Earthquake Report, 2004).

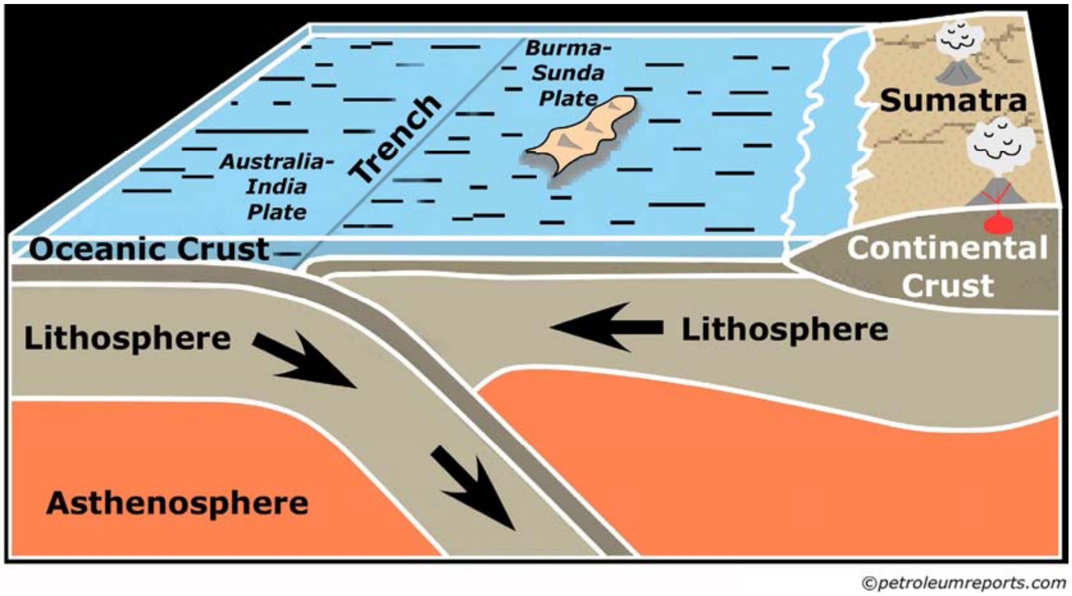

Figure 8. Tectonic model for Northern Sumatra earthquake (modified from Kious and Tilling, 1996).

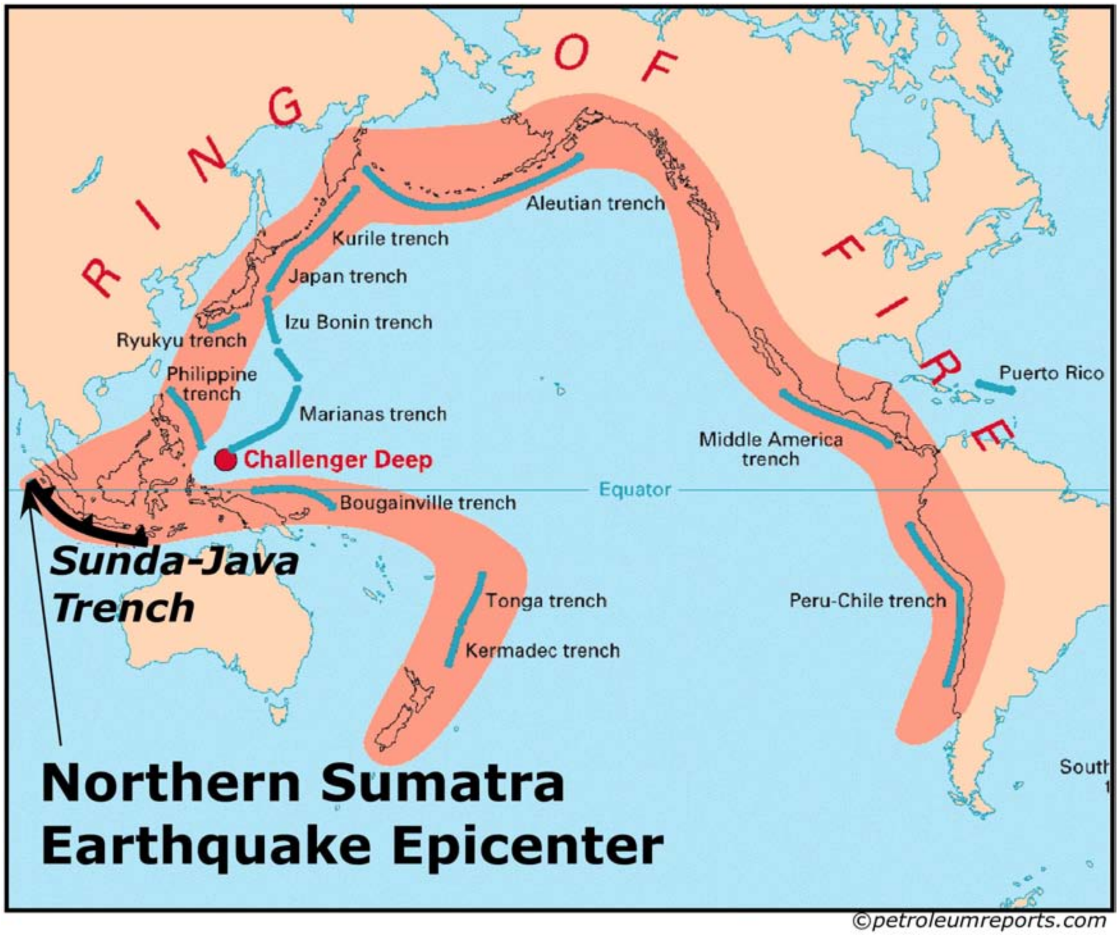

Figure 9. The Ring of Fire, a zone of frequency earthquakes and volcanic eruptions (modified from Kious and Tilling, 1996).

Tsunami Resulting from Northern Sumatra Earthquake

The December 2004 earthquake itself had little direct affect on humans because it occurred at considerable distance offshore. The tsunami (Japanese for harbor wave) that followed, however, has produced unprecedented damage and loss of life throughout the Indian Ocean region.

A tsunami is a very large ocean wave train, or series of waves, generated in a body of water by a vertical displacement of the ocean water column. A tsunami is generally triggered by underwater earthquake, volcanic activity or landslides. Sometimes a tsunami is incorrectly referred to as a tidal wave. A tsunami isn't the same as a tidal wave since it isn't caused by tides.

When earthquakes occur beneath the sea, the water above the deformed area of the ocean floor is displaced. Waves are formed as the displaced water mass equilibrates (Figure 10). The seafloor uplift, in effect, acts like a gigantic wave machine. Tsunami-induced waves have unusually long wavelengths in excess of 100 kilometers and periods on the order of one hour.

Tsunamis are generated in the open ocean and transformed into a train of catastrophic oscillations on the sea surface close to coastal zones. As the wave front reaches the shallow continental shelf, the friction of the seafloor slows the wave progressively from the bottom up. The upper part of the wave moves faster than the lower portion because of frictional drag on the rising seafloor. The wave crest lengthens and elevates until the front of the wave is steeper than the back side, and the wave breaks and collapses (Figure 11).

In the case of the Northern Sumatra earthquake, approximately 30-60 cm high deep ocean waves were produced, believed to have been traveling at about 600-800 kilometers per hour, or about the speed of a jet aircraft (National Institute of Oceanography, India, 2004). As the tsunami approached shallow coastal waters, its speed decreased to several tens of kilometers per hour. By the time it hit land, it had developed 4- to 12-meter-high waves, though there are unsubstantiated reports of much higher runups.

Preliminary information from the United States Geological Survey National Earthquake Information Center indicates approximately 15 meters of displacement along a 1200-km segment of the plate interface along the Sunda Trench (USGS Preliminary Earthquake Report, 2004). That translates into 18 million cubic meter instantaneous displacement of sea water (about four billion gallons): the equivalent of nearly 5000 olympic-sized swimming pools of water or 113, 217,000 barrels of oil, a giant field's recoverable reserves instantaneously drained and dumped upon the coastline of southern Asia! The Valdez oil spill of 1989 was approximately 1.25 million barrels, by comparison.

Comparable large earthquakes in recent history include: 1) the magnitude 9.5 1960 Chile earthquake, 2) the magnitude 9.2 1964 Prince William Sound, Alaska, earthquake, 3) the magnitude 9.1 1957 Andreanof Islands, Alaska, earthquake, and 4) the magnitude 9.0 1952 Kamchatka earthquake (USGS, 2004).

Submarine Telegraph Cables: the Launch of the World Wide Web

Many people across the world quickly learned of the devastation wrought by the Northern Sumatra earthquake over the World Wide Web News of the Krakatoa eruption also spread quickly, through the precursor technology of telegraphy. In 1825, British inventor William Sturgeon invented the electromagnet and five years later American Joseph Henry sent a current over one mile of wire to activate an electromagnet that caused a bell to strike. In 1835, Samuel Morse used pulses of current to deflect an electromagnet, which moved a marker to produce written codes on a strip of paper—the invention of Morse Code (Bellis, 2004). In 1844, Morse successfully sent an electronic message from Washington D.C. to Baltimore What hath God wrought?"—representing the first binary encoding of information that traveled over a network.

The Atlantic and Pacific coasts of the United States were connected by telegraph later the same year. Most Americans knew about the end of the Civil War two hours after the South's surrender. By contrast, Andrew Jackson fought the battle of New Orleans 20 days after a peace treaty ended the War of 1812.

In the first half of the 19th century, electricity and electrical applications, beyond scientific research and novelty, were in their infancy. There was no reliable source of electricity. The voltaic cell could generate electricity only for a short time before accumulated hydrogen on the copper pole blocked the flow of current. It was not until the advent of the Daniell cell in 1836 that storage batteries became a possible source of electricity (Katz, 2004) and many years later before it was generally available.

Batteries," notes Bill Burns, an expert on telegraph history, were used on the early cable systems because there was no alternative. Useful generators (dynamos) were not developed until the 1870s but, even after that, the systems ran on batteries because of their reliability" (personal communication).

The telegraph was really the first commercial application of electricity. No precedents for long distance, much less submarine, electrical transmission existed before the telegraph. The technology of electrical conductors and application of electrical signal propagation theory were at primitive levels in the 1840s when the first land telegraph cables were laid. Submarine cables required refinements in copper metallurgy and corresponding conductivity efficiency, development of Gutta Percha gum insulation (interestingly, discovered in the Malay Archipelago) and sophisticated approaches to cable armoring before early efforts were successful (Burns, 2004).

Submarine telegraph cable networks began the World Wide Web of electronic communication. 1851 marked the first successful international telegraph cable, from Dover to Calais, and 1866 saw the first successful transatlantic cable, from Ireland to Newfoundland (Burns, 2004). In this 15-year period, telegraphic communication evolved from isolated national landline systems to a submarine cable network connecting much of the world (Figure 12).

David Dudley Field remarked in 1879 on the 25th anniversary of his company's contract to lay the Transatlantic Telegraph Cable:

Though we then knew something of what we were doing, we did not know all. Events have outrun the imagination. Little did I dream that, within twenty years, I should stand beneath the Southern Cross and send from Australasia a message to my northern home, which, almost while I stood, passed over half the globe, darting with the speed of thought across the nearly two thousand miles of Australian desert, through the Arafura Sea, past the Isles of Ternate and Tidore (Indonesia), across the Bay of Bengal and the of Sea of Arabia, along the Red Sea coast, under the Mediterranean and Biscay’s sleepless bay, and finally beneath our own Atlantic to this island city (New York)” (Sprague, 1884).

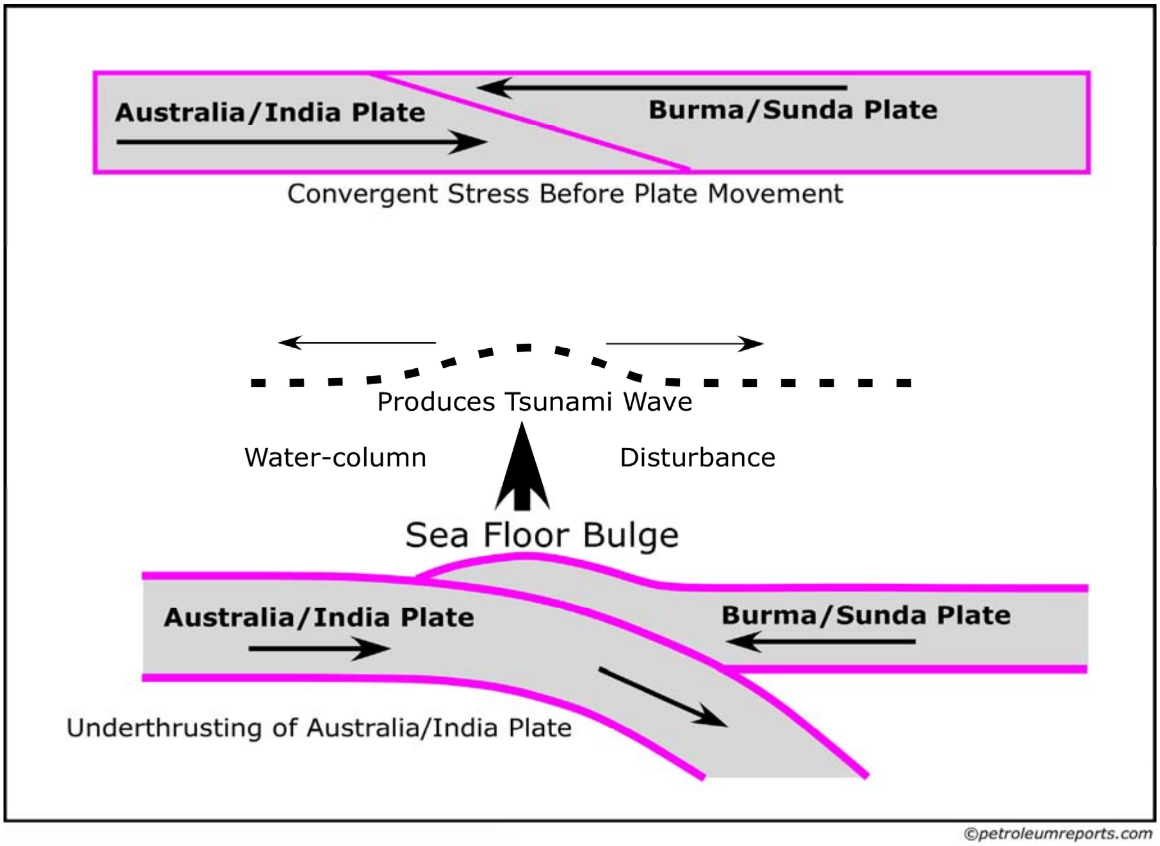

Figure 10. Seismic model for tsunami generation.

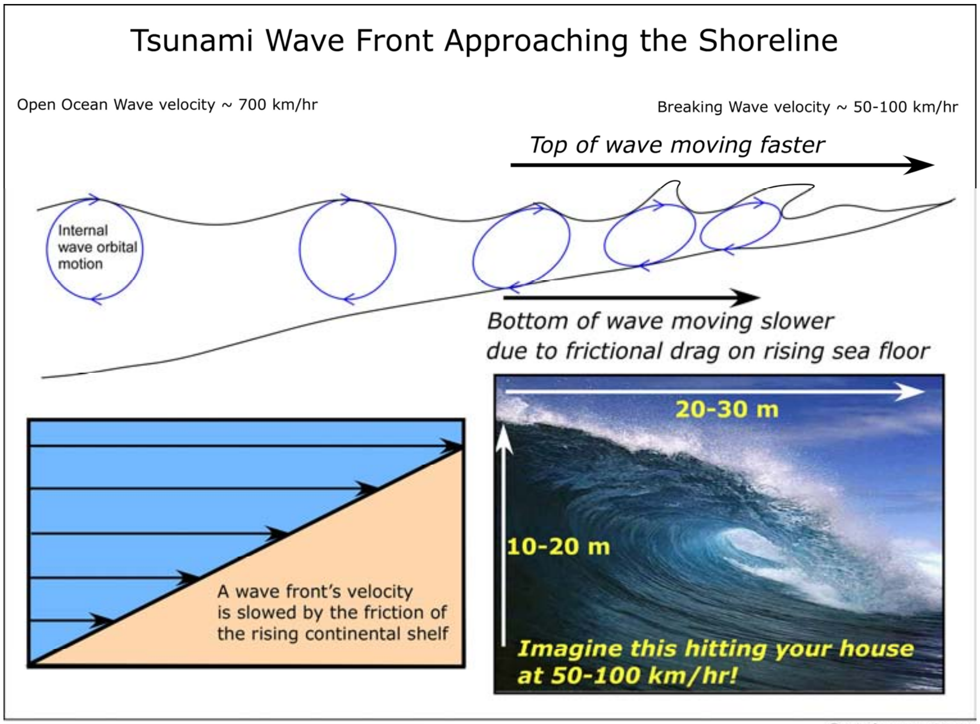

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Figure 11. Effect of tsunami approaching shoreline.

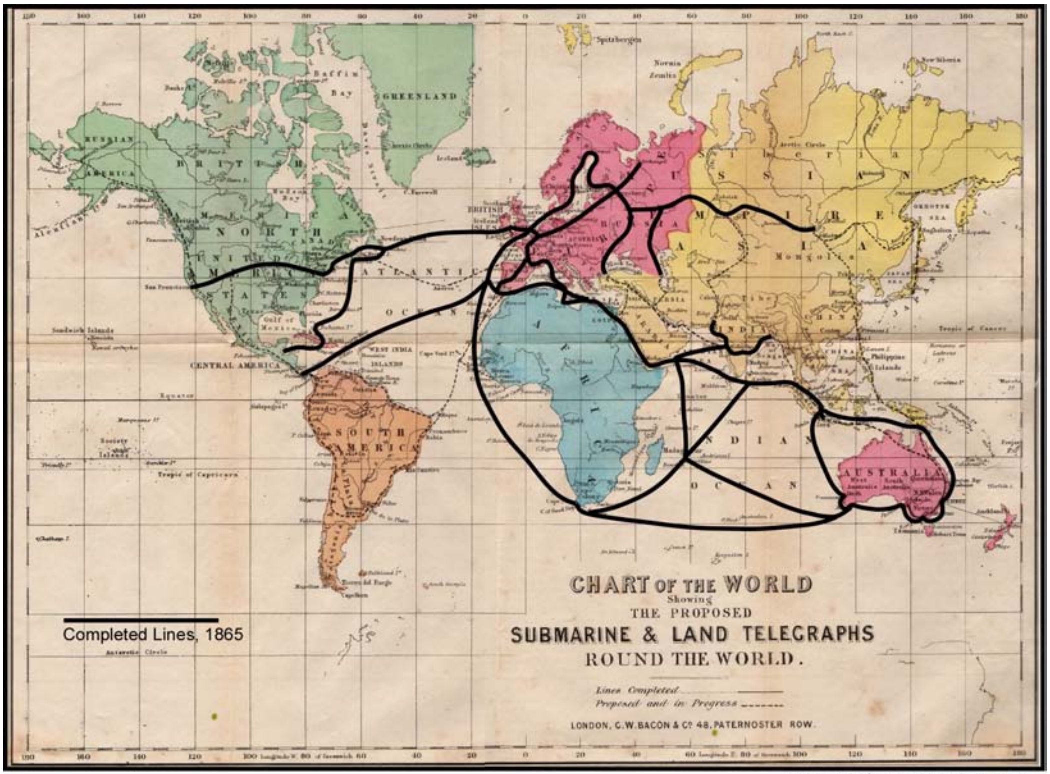

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Figure 12. 1965 chart of world showing proposed submarine and land telegraphs around the world, emphasizing cable routes from the Far East to North America. Image by permission of the atlantic-cable.com website.

Krakatoa Eruption, August 1883

The same telegraph cable network that Field mentioned in his 1879 address was used four years later to spread news of the Krakatoa explosion almost instantaneously around the world. Boston newspapers were printing the story within four hours of the eruption (Brianstorms, 2004). This was the first time in history that news of a catastrophe reached the whole world simultaneously and became, in some ways, a shared global experience..

On August 27, 1883, a volcanic explosion vaporized the island of Krakatoa in the Indian Ocean. The eruption blew apart that island in the Sunda Strait between Java and Sumatra (Figure 5) and produced modern history's most powerful explosion—30 times stronger than the largest thermonuclear bomb. The blast was heard in Australia and Burma, thousands of kilometers from Krakatoa. The ash and pulverized rock blasted into the air circled the globe for a year, and the Earth's weather patterns were disrupted for several years. A 40-meter tsunami inundated at least 100 villages on both sides of the Sunda Strait, killing an estimated 37,000 people (the death toll from the 2004 tsunami suggests this may have been a low estimate, based mostly on local effects of the tsunami, and not taking into account coastal regions elsewhere in the Indian Ocean). Until recently, a rusting Dutch warship could be seen 4 kilometers inland on a hillside on Java where the tsunami wave deposited it (Lekic, 2004).

By any reckoning, Krakatoa was one of the largest explosive volcanic eruptions in the history of the planet (Figure 13) based on the volcanic explosivity index (VEI), a combination of measures shown in Table 1.

A special committee of the Royal Society of London was established in early 1884 to document the eruption and explosion of Krakatoa and to provide some explanation. The committee's final report was published in 1888 and contained nearly 500 pages of accounts of pressure and current measurements that permitted calculation of the speed of the tsunami that followed Krakatoa's eruption: it was approximately 1125 km/hour the average speed of sound. The nearly 25 cubic kilometers of Krakatoa Island were gone, either blown into the atmosphere or collapsed into the ocean (Winchester, 2003). A great deal of the Society's report is dedicated to accounts of the sunsets and pumice rafts produced by the explosion. The reasons for the explosion were not resolved by the Royal Society of London.

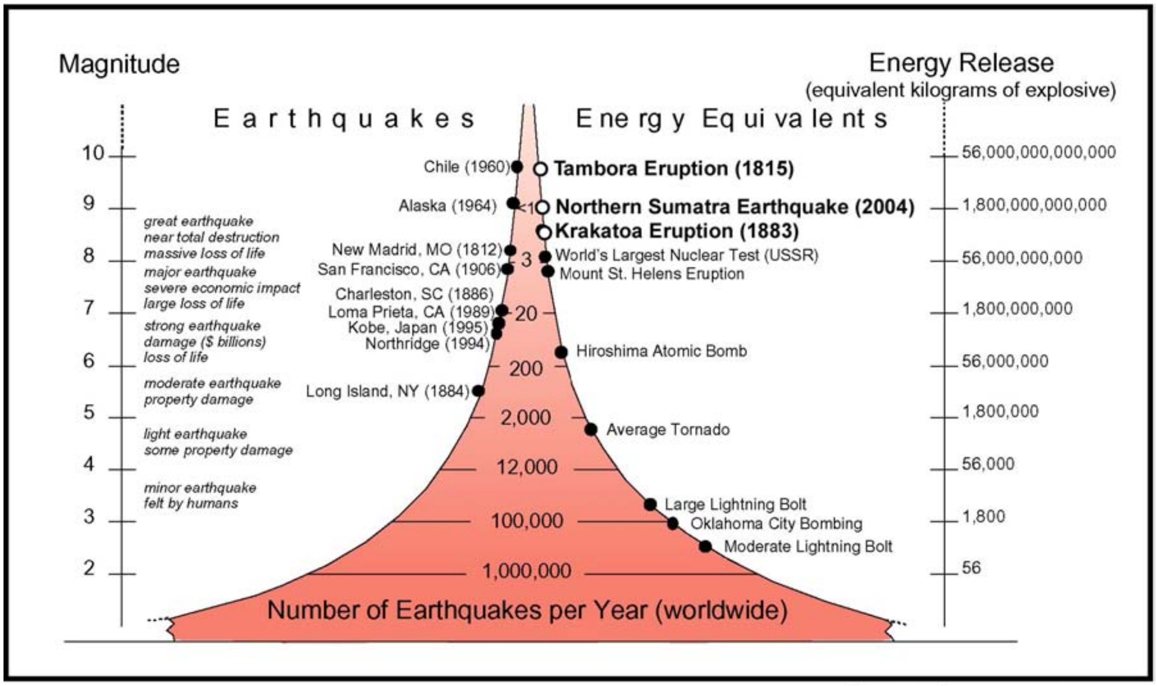

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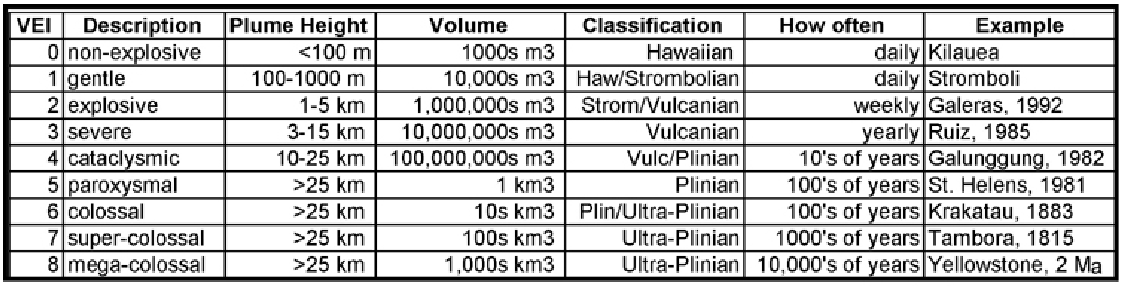
Figure 13. Earthquakes magnitudes (modified from Incorporated Research Institutions for Seismology,Washington, D.C., http://www.iris.edu/edu/onepagers/no3.pdf).



VEI	Description	Plume Height	Volume	Classification	How often	Example
0	non-explosive	<100 m	1000s m3	Hawaiian	daily	Kilauea
1	gentle	100-1000 m	10,000s m3	Haw/Strombolian	daily	Stromboli
2	explosive	1-5 km	1,000,000s m3	Strom/Vulcanian	weekly	Galeras, 1992
3	severe	3-15 km	10,000,000s m3	Vulcanian	yearly	Ruiz, 1985
4	cataclysmic	10-25 km	100,000,000s m3	Vulc/Plinian	10's of years	Galunggung, 1982
5	paroxysmal	>25 km	1 km3	Plinian	100's of years	St. Helens, 1981
6	colossal	>25 km	10s km3	Plin/Ultra-Plinian	100's of years	Krakatau, 1883
7	super-colossal	>25 km	100s km3	Ultra-Plinian	1000's of years	Tambora, 1815
8	mega-colossal	>25 km	1,000s km3	Ultra-Plinian	10,000's of years	Yellowstone, 2 Ma

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Table 1. University of North Dakota Volcanic Explosivity Index (VEI) tabulation of major volcanic eruptions, http://volcano.und.nodak.edu/vwdocs/eruption_scale.html.

Forty Years of Ignoring Plate Tectonics

The plate-tectonic model now allows us to understand what the Royal Society could not. Krakatoa was located where the Australia/India Plate is subducting beneath the Burma/Sunda portion of the Eurasian Plate. Krakatoa was, in all respects except perhaps its magnitude, typical of subduction-related volcanoes: violent, highly explosive, granitic in composition and prone to ash, pumice and mud rather than to lava. Krakatoa was part of a chain of active volcanoes that includes the islands of Sumatra and Java (Figure 5). 94 percent of all active volcanoes in the world today are concentrated along subduction zones and Indonesia has more active volcanoes than any other country on Earth; there are 21 fully active volcanoes on the island of Java alone (Winchester, 2003).

For decades, all that marked the site of the original 825-meter-high (2,640 feet) island was a tiny islet, renamed Rakata, that had survived the explosion. In 1930, a new volcano—Anak Krakatau, or the Child of Krakatau—broke through the water at the center of the old volcano, where the tectonic forces that led to the 1883 eruption are pushing magma upward at a rapid pace. Anak Krakatau is now growing almost 2 meters per year and has already reached a height of nearly 410 meters (1,320 feet) (Lekic, 2004). The dynamic subduction system is rapidly repairing the results of Krakatoa's mighty blast.

The North Sumatra earthquake of 2004 and the Krakatoa eruption of 1883 are related geologically because they occurred within the same subduction complex. The 2004 earthquake is in a region of predominantly oblique convergence and is characterized by both strike-slip and dip-slip faulting. Where Krakatoa once stood, 1400 kilometers to the southeast in the Sunda Strait, the subduction complex is classically convergent and dip-slip in nature.

The 2004 and 1883 events are also related because the world learned about and experienced them almost immediately. News of Krakatoa was available as a result of advances in telegraph technology. The Northern Sumatra earthquake and tsunami is one of many catastrophes and crises that humankind has learned about more or less as a community since Krakatoa through modern telecommuncations technology and the Internet. Other than natural disasters these events include wars, ethnic cleansing, terrorist attacks and HIV/AIDS.

Improvements in our ability to understand and communicate about earthquakes and eruptions have done little to diminished the tragic impact of these events. The December 2004 tsunami reached Sumatra's shores in less than an hour after the earthquake and at least 80,000 are known dead on that island; it arrived in Sri Lanka within two hours and killed at least 27,000; it struck Thailand about an hour after the earthquake occurred and 2,400 were killed; India's east coast was reached in about 2 hours, where about 7,400 were killed; Seychelles and Somalia were reached in about 7 hours where 117 people were killed (Figure 14).

Some would say advances in science and technology have gained nothing because geological disasters such as the Northern Sumatra earthquake of 2004 cannot yet be predicted or prevented. The fact that the earthquake can be placed in an understandable tectonic context, and that we can transmit information about and images of the event, provides no benefit to mankind.

I believe there was sufficient time to have warned people in many of the locations affected by the tsunami following the earthquake. Figure 15 shows a map of 128 earthquake monitoring stations that are part of the Global Seismographic Network. Information about the magnitude and epicenter of the Northern Sumatra Earthquake was available in at least 128 places on Earth within moments of the event. Several monitoring stations are located on the island of Sumatra itself. Stations are also located in Thailand, Sri Lanka and India. Tsunamis commonly result from earthquakes of magnitude 8.0 or greater (some sources say 6.5). No sophisticated modeling effort is needed to quickly plot a series of concentric circles around the epicenter of an earthquake and apply velocities based on abundant data on historical tsunamis(including the arrival times noted in the Royal Society's 1888 report on Krakatoa!).

Many of the regions affected most by the tsunami are rural and technologically backward. For populations without general access to telecommunication technology and automotive transportation warnings may not have been effective, especially given the short time between awareness of the earthquake and arrival of the tsunami. There is, however, no evidence that any attempt was made to warn people anywhere in the Indian Ocean Basin.

I believe there have been at least 40 years to prepare for an event like the Northern Sumatra earthquake of 2004. Leaders in the Indian Ocean region chose to ignore advances in plate tectonics and now their people are paying the price.

The plate-tectonic model clearly identifies subduction zones such as the Malay Archipelago as regions of frequent earthquake activity. Indonesia has the greatest frequency of earthquakes and volcanic eruption of any nation on the Earth. There were 10 earthquakes of magnitude 7.0 or greater in Indonesia between 1975 and 2002 (Table 2).

According to the USGS National Earthquake Information Center, there were four earthquakes with magnitude 7.0 or greater in the Sunda-Java Trench region of Indonesia in 2004 alone, before the Northern Sumatra Earthquake (Figure 16)! Based on nothing more statistically valid than the Tambora and Krakatoa eruptions, one could estimate that mega-earthquakes and tsunamis occur at about a 75-year interval in this region. Because there had not been a seismic event on this scale in 121 years, the region was overdue. With the addition of the 2204 data point, the recurrence interval appears to be about 60 years.

It should be part of every Indian Ocean country's national emergency plan to expect tsunamis produced by earthquakes in the Sunda-Java Trench Subduction Zone. The fact that this is not the case should be cause for serious debate and discussion after the initial phase of relief work has been achieved in the aftermath of the recent earthquake and tsunami.

Our knowledge and understanding of the earth have grown exponentially in the past 100 years," noted Andrew Pulham while reviewing this document. I think we choose not to apply this knowledge, preferring to be impotent rather than being smart. Earth science is a global resource and one that is mostly open and shared. Perhaps we need global leaders to apply it to greatest effect. National leaders will unfortunately always default to the near in time and space" (personal communication, 2005).

The history of science shows that discovery and invention is itself beyond prediction. It is impossible to know when science will be able to accurately anticipate earthquakes and related tsunamis. We have, however, made significant advances in understanding Earth's tectonic behavior and can say with considerable accuracy where and within what ranges of magnitude seismic events are likely to occur. It is understandable that the typical victim of the recent tsunami disaster in the Indian Ocean may not have anticipated the tragic events that are still unfolding. It is inexcusable that their leaders and governments did not make efforts to inform and prepare their citizens for the inevitability of these occurrences at some point since the articulation of the plate-tectonic model 40 years ago.

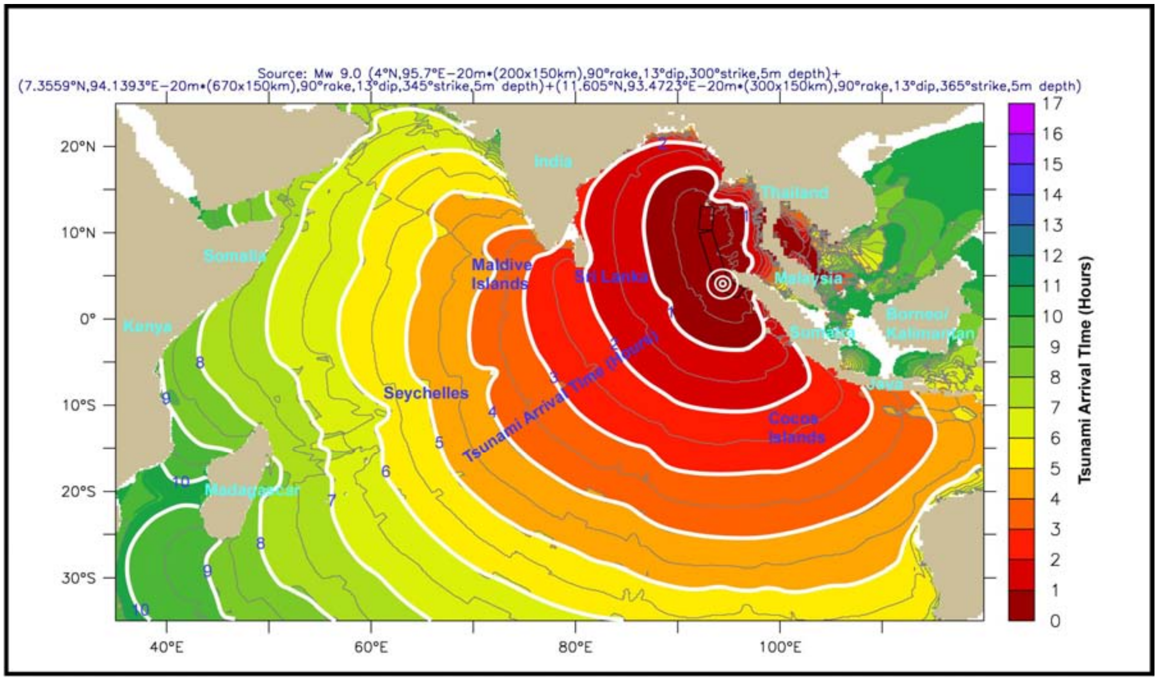


Figure 14. Tsumani arrival map in hours from earthquake epicenter (modified from Facility for Analysis and Comparison of Tsunami Simulation (FACTS), 2005, http://www.oceanonline.com/tsunami_travel_timechart.pdf, and from NOAA, http//wcatwc.arh.noaa.gov/IndianOSite/IndianO12-26-04.htm.)

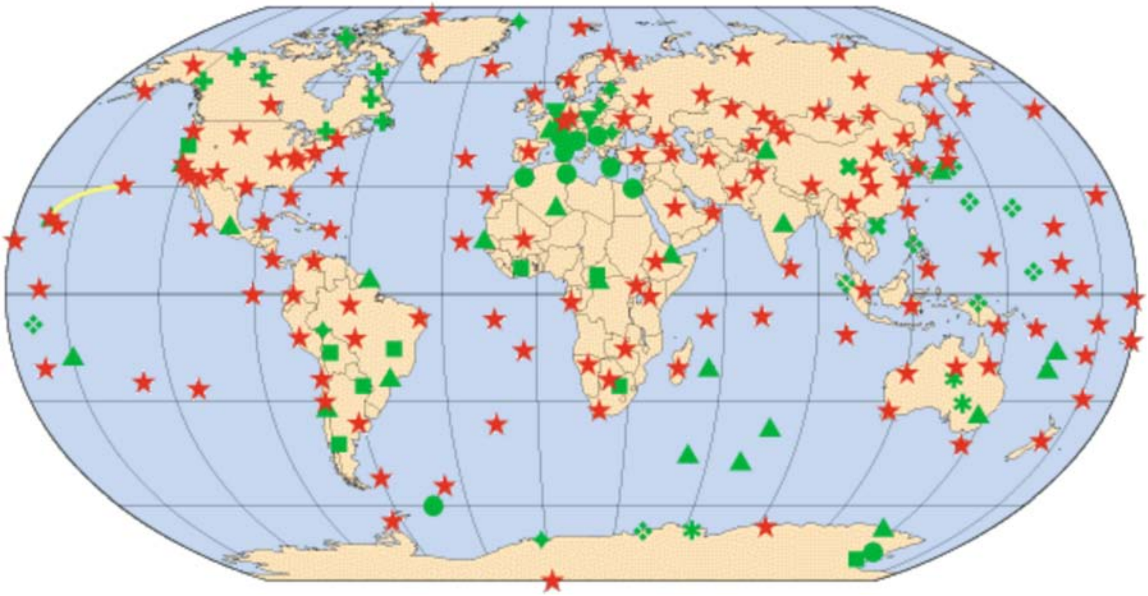


Figure 15. Global Seismic Network of earthquake monitoring stations, modified from Incorporated Research Institutions for Seismology, http://www.iris.edu/about/GSN/.

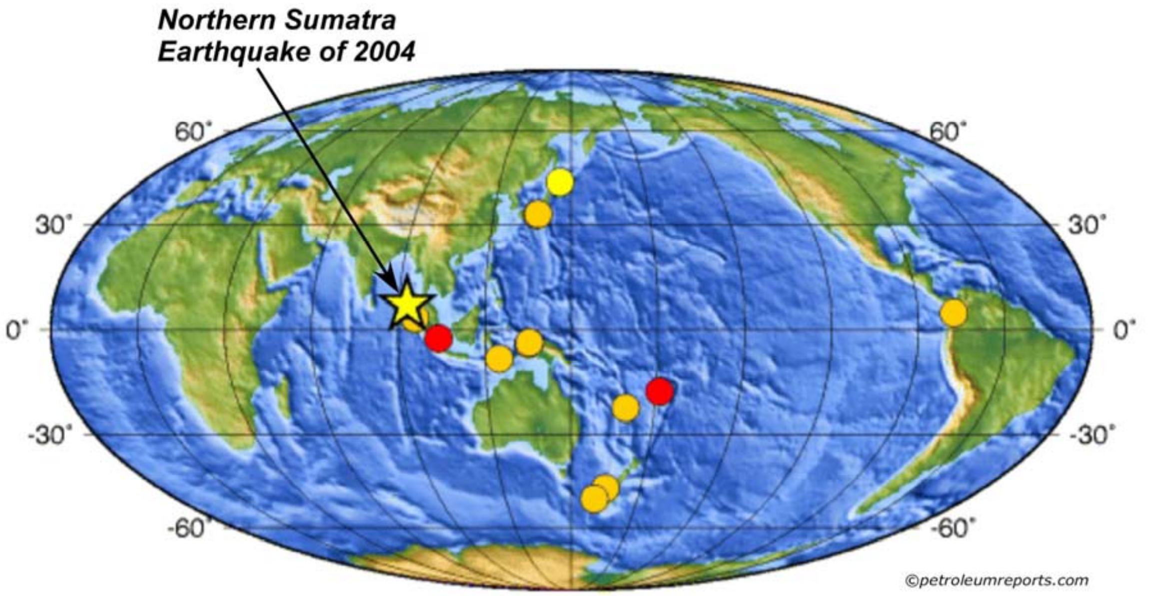
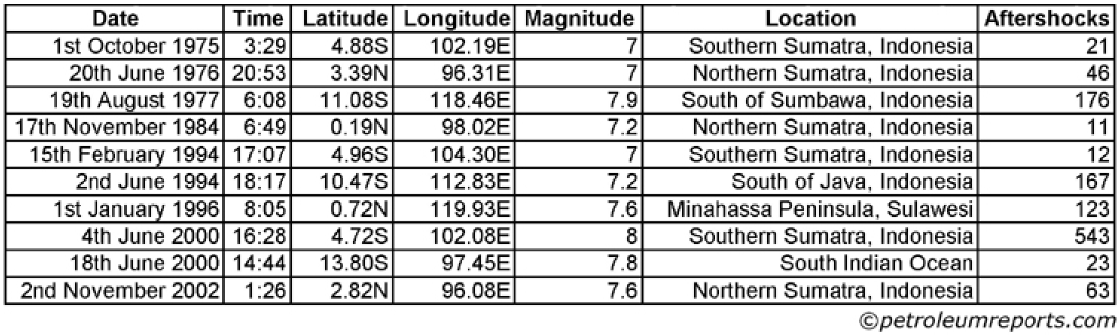


Figure 16. Earthquakes of magnitude 7.0 and greater in 2001 (modified from USGS National Earthquake Information Center).



Date	Time	Latitude	Longitude	Magnitude	Location	Aftershocks
1st October 1975	3:29	4.88S	102.19E	7	Southern Sumatra, Indonesia	21
20th June 1976	20:53	3.39N	96.31E	7	Northern Sumatra, Indonesia	46
19th August 1977	6:08	11.08S	118.46E	7.9	South of Sumbawa, Indonesia	176
17th November 1984	6:49	0.19N	98.02E	7.2	Northern Sumatra, Indonesia	11
15th February 1994	17:07	4.96S	104.30E	7	Southern Sumatra, Indonesia	12
2nd June 1994	18:17	10.47S	112.83E	7.2	South of Java, Indonesia	167
1st January 1996	8:05	0.72N	119.93E	7.6	Minahassa Peninsula, Sulawesi	123
4th June 2000	16:28	4.72S	102.08E	8	Southern Sumatra, Indonesia	543
18th June 2000	14:44	13.80S	97.45E	7.8	South Indian Ocean	23
2nd November 2002	1:26	2.82N	96.08E	7.6	Northern Sumatra, Indonesia	63

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Table 2. Indonesia earthquakes of magnitude 7.0 or greater 1975-2002, University of Edinburgh Earthquake Prediction & Analysis Site, http://tsunami.geo.ed.ac.uk/localbin/quakes/mapscript/front_page.pl.

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[+] Some online references may not be available with time.

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