The Tsunami Story

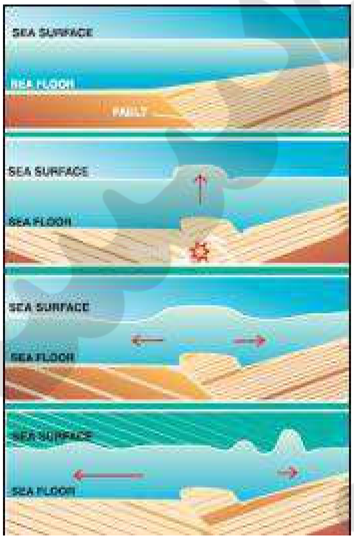

Figure 1. Click to see an animation of a tsunami generated by an earthquake.

Tsunami is a set of ocean waves caused by any large, abrupt disturbance of the sea-surface. If the disturbance is close to the coastline, local tsunamis can demolish coastal communities within minutes. A very large disturbance can cause local devastation AND export tsunami destruction thousands of miles away. The word tsunami is a Japanese word, represented by two characters: tsu, meaning, "harbor", and nami meaning, "wave". Tsunamis rank high on the scale of natural disasters. Since 1850 alone, tsunamis have been responsible for the loss of over 420,000 lives and billions of dollars of damage to coastal structures and habitats. Most of these casualties were caused by local tsunamis that occur about once per year somewhere in the world. For example, the December 26, 2004, tsunami killed about 130,000 people close to the earthquake and about 58,000 people on distant shores. Predicting when and where the next tsunami will strike is currently impossible. Once the tsunami is generated, forecasting tsunami arrival and impact is possible through modeling and measurement technologies.

Generation. Tsunamis are most commonly generated by earthquakes in marine and coastal regions. Major tsunamis are produced by large (greater than 7 on the Richter scale), shallow focus (< 30km depth in the earth) earthquakes associated with the movement of oceanic and continental plates. They frequently occur in the Pacific, where dense oceanic plates slide under the lighter continental plates. When these plates fracture they provide a vertical movement of the seafloor that allows a quick and efficient transfer of energy from the solid earth to the ocean (try the animation in Figure 1). When a powerful earthquake (magnitude 9.3) struck the coastal region of Indonesia in 2004, the movement of the seafloor produced a tsunami in excess of 30 meters (100 feet) along the adjacent coastline killing more than 240,000 people. From this source the tsunami radiated outward and within 2 hours had claimed 58,000 lives in Thailand, Sri Lanka, and India.

Underwater landslides associated with smaller earthquakes are also capable of generating destructive tsunamis. The tsunami that devastated the northwestern coast of Papua New Guinea on July 17, 1998, was generated by an earthquake that registered 7.0 on the Richter scale that apparently triggered a large underwater landslide. Three waves measuring more than 7 meter high struck a 10-kilometer stretch of coastline within ten minutes of the earthquake/slump. Three coastal villages were swept completely clean by the deadly attack leaving nothing but sand and 2,200 people dead. Other large-scale disturbances of the sea -surface that can generate tsunamis are explosive volcanoes and asteroid impacts. The eruption of the volcano Krakatoa in the East Indies on Aug. 27, 1883 produced a 30-meter tsunami that killed over 36,000 people. In 1997, scientists discovered evidence of a 4km diameter asteroid that landed offshore of Chile approximately 2 million years ago that produced a huge tsunami that swept over portions of South America and Antarctica.

Wave Propagation. Because earth movements associated with large earthquakes are thousand of square kilometers in area, any vertical movement of the seafloor immediately changes the sea-surface. The resulting tsunami propagates as a set of waves whose energy is concentrated at wavelengths corresponding to the earth movements (~100 km), at wave heights determined by vertical displacement (~1m), and at wave directions determined by the adjacent coastline geometry. Because each earthquake is unique, every tsunami has unique wavelengths, wave heights, and directionality (Figure 2 shows the propagation of the December 24, 2004 Sumatra tsunami.) From a tsunami warning perspective, this makes the problem of forecasting tsunamis in real time daunting.

Figure 2. Click to see the propagation of the December 24, 2004 Sumatra tsunami.

Warning Systems. Since 1946, the tsunami warning system has provided warnings of potential tsunami danger in the pacific basin by monitoring earthquake activity and the passage of tsunami waves at tide gauges. However, neither seismometers nor coastal tide gauges provide data that allow accurate prediction of the impact of a tsunami at a particular coastal location. Monitoring earthquakes gives a good estimate of the potential for tsunami generation, based on earthquake size and location, but gives no direct information about the tsunami itself. Tide gauges in harbors provide direct measurements of the tsunami, but the tsunami is significantly altered by local bathymetry and harbor shapes, which severely limits their use in forecasting tsunami impact at other locations. Partly because of these data limitations, 15 of 20 tsunami warnings issued since 1946 were considered false alarms because the tsunami that arrived was too weak to cause damage.

Figure 3. Click to see a real-time

Forecasting impacts. Recently developed real-time, deep ocean tsunami detectors (Figure 3) will provide the data necessary to make tsunami forecasts. The November 17, 2003, Rat Is. tsunami in Alaska provided the most comprehensive test for the forecast methodology. The Mw 7.8 earthquake on the shelf near Rat Islands, Alaska, generated a tsunami that was detected by three tsunameters located along the Aleutian Trench-the first tsunami detection by the newly developed real-time tsunameter system. These real-time data combined with the model database (Figure 4) were then used to produce the real-time model tsunami forecast. For the first time, tsunami model predictions were obtained during the tsunami propagation, before the waves had reached many coastlines. The initial offshore forecast was obtained immediately after preliminary earthquake parameters (location and magnitude Ms = 7.5) became available from the West Coast/Alaska TWC (about 15-20 minutes after the earthquake). The model estimates provided expected tsunami time series at tsunameter locations. When the closest tsunameter recorded the first tsunami wave, about 80 minutes after the tsunami, the model predictions were compared with the deep-ocean data and the updated forecast was adjusted immediately…

deep ocean tsunami detection system responding to a tsunami generated by seismic activity.

These offshore model scenarios were then used as input for the high-resolution inundation model for Hilo Bay. The model computed tsunami dynamics on several nested grids, with the highest spatial resolution of 30 meters inside the Hilo Bay (Figure 5). None of the tsunamis produced inundation at Hilo, but all of them recorded nearly half a meter (peak-to-trough) signal at Hilo gage. Model forecast predictions for this tide gage are compared with observed data in Figure 5. The comparison demonstrates that amplitudes, arrival time and periods of several first waves of the tsunami wave train were correctly forecasted. More tests are required to ensure that the inundation forecast will work for every likely-to-occur tsunami. When implemented, such forecast will be obtained even faster and would provide enough lead time for potential evacuation or warning cancellation for Hawaii and the U.S. West Coast.

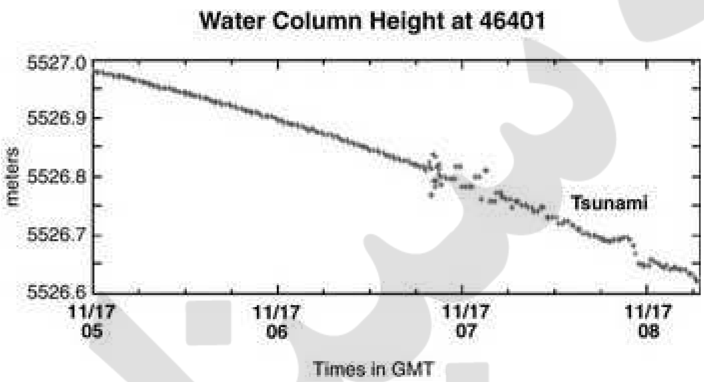

Figure 4. Rat Island, Alaska Tsunami of November 17, 2003, as measured at the tsunameter located at 50 N 171 W in 4700 m water depth.

Figure 5. Coastal forecast at Hilo, HI for 2003 Rat island, showing comparison of the forecasted (red line) and measured (blue line) gage data.

Reduction of impact. The recent development of real-time deep ocean tsunami detectors and tsunami inundation models has given coastal communities the tools they need to reduce the impact of future tsunamis. If these tools are used in conjunction with a continuing educational program at the community level, at least 25% of the tsunami related deaths might be averted. By contrasting the casualties from the 1993 Sea of Japan tsunami with that of the 1998 Papua New Guinea tsunami, we can conclude that these tools work. For the Aonae, Japan case about 15% of the population at risk died from a tsunami that struck within 10 minutes of the earthquake because the population was educated about tsunamis, evacuation plans had been developed, and a warning was issued. For the Warapa, Papua New Guinea case about 40% of the at risk population died from a tsunami that arrived within 15 minutes of the earthquake because the population was not educated, no evacuation plan was available, and no warning system existed.

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Tsunami Vocabulary and Terminology

Tsunami - Tsunamis are ocean waves produced by earthquakes or underwater landslides. The word is Japanese and means "harbor wave," because of the devastating effects these waves have had on low-lying Japanese coastal communities. Tsunamis are often incorrectly referred to as tidal waves, but a tsunami is actually a series of waves that can travel at speeds averaging 450 (and up to 600) miles per hour in the open ocean.

In the open ocean, tsunamis would not be felt by ships because the wavelength would be hundreds of miles long, with amplitude of only a few feet. This would also make them unnoticeable from the air. As the waves approach the coast, their speed decreases and their amplitude increases. Unusual wave heights have been known to be over 100 feet high. However, waves that are 10 to 20 feet high can be very destructive and cause many deaths or injuries.

From an initial tsunami generating source area, waves travel outward in all directions much like the ripples caused by throwing a rock into a pond. As these waves approach coastal areas, the time between successive wave crests varies from 5 to 90 minutes. The first wave is usually not the largest in the series of waves, nor is it the most significant. Furthermore, one coastal community may experience no damaging waves while another, not that far away, may experience destructive deadly waves. Depending on a number of factors, some low-lying areas could experience severe inland inundation of water and debris of more than 1,000 feet.

Tsunami Watch - An alert issued to areas outside the warned area. The area included in the watch is based on the magnitude of the earthquake. For earthquakes over magnitude 7.0, the watch area is 1 hour tsunami travel time outside the warning zone. For all earthquakes over magnitude 7.5, the watch area is 3 hours tsunami travel time outside the warning zone. The watch will either be upgraded to a warning in subsequent bulletins or will be cancelled depending on the severity of the tsunami.

Tsunami Warning - Indicates that a tsunami is imminent and that coastal locations in the warned area should prepare for flooding. The initial warning is typically based on seismic information alone. Earthquakes over magnitude 7.0 trigger a warning covering the coastal regions within 2 hours tsunami travel time from the epicenter. When the magnitude is over 7.5, the warned area is increased to 3 hours tsunami travel time. As water level data showing the tsunami is recorded, the warning will be cancelled, restricted, expanded incrementally, or expanded in the event of a major tsunami.

Life of a Tsunami

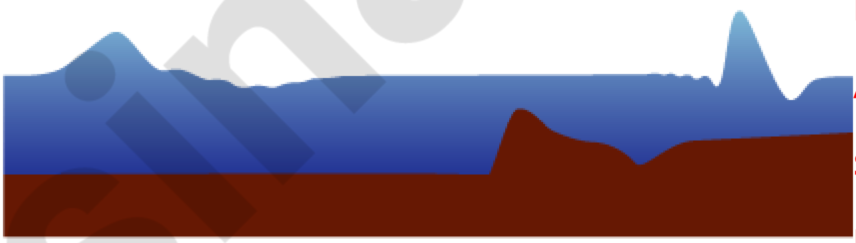
Panel 1—Initiation: Earthquakes are commonly associated with ground shaking that is a result of elastic waves traveling through the solid earth.

However, near the source of submarine earthquakes, the seafloor is "permanently" uplifted and down-dropped, pushing the entire water column up and down. The potential energy that results from pushing water above mean sea level is then transferred to horizontal propagation of the tsunami wave (kinetic energy). For the case shown above, the earthquake rupture occurred at the base of the continental slope in relatively deep water. Situations can also arise where the earthquake rupture occurs beneath the continental shelf in much shallower water.

Note: In the figure, the waves are greatly exaggerated compared to water depth. In the open ocean, the waves are at most several meters high spread over many tens to hundreds of kilometers in length.

Panel 2—Split: Within several minutes of the

earthquake, the initial tsunami (Panel 1) is split into a tsunami that travels out to the deep ocean (distant tsunami) and another tsunami that travels towards the nearby coast (local tsunami). The height above mean sea level of the two oppositely traveling tsunamis is approximately half that of the original tsunami (Panel 1). (This is somewhat modified in three dimensions, but the same idea holds.) The speed at which both tsunamis travel varies as the square root of the water depth. Therefore, the deep-ocean tsunami travels faster than the local tsunami near shore.



Panel 3—Amplification: Several things happen as the

local tsunami travels over the continental slope. Most obvious is that the amplitude increases. In addition, the wavelength decreases. This results in steepening of the leading wave--an important control of wave run up at the coast (next panel). Note that the first part of the wave reaching the local shore is a trough, which will appear as the sea receding far from shore. This is a common natural warning sign for tsunamis. Note also that the deep ocean tsunami has traveled much farther than the local tsunami because of the higher propagation speed. As the deep ocean tsunami approaches a distant shore, amplification and shortening of the wave will occur, just as with the local tsunami shown above.

Panel 4—Run up: Tsunami runup occurs when a peak in the tsunami wave travels from the near-shore region onto shore. Run up is a measurement of the height of the water onshore observed above a reference sea level.

Except for the largest tsunamis, such as the 2004 Indian Ocean event, most tsunamis do not result in giant breaking waves (like normal surf waves at the beach that curl over as they approach shore). Rather, they come in much like very strong and fast-moving tides (i.e., strong surges and rapid changes in sea level). Much of the damage inflicted by tsunamis is caused by strong currents and floating debris. The small number of tsunamis that do break often form vertical walls of turbulent water called bores. Tsunamis will often travel much farther inland than normal waves.

Do tsunamis stop once on land? No! After runup, part of the tsunami energy is reflected back to the open ocean and scattered by sharp variations in the coastline. In addition, a tsunami can generate a particular type of coastal trapped wave called edge waves that travel back-and forth, parallel to shore. These effects result in many arrivals of the tsunami at a particular point on the coast rather than a single wave as suggested by Panel 3. Because of the complicated behavior of tsunami waves near the coast, the first runup of a tsunami is often not the largest, emphasizing the importance of not returning to a beach many hours after tsunami first hits.

Preliminary Analysis of the April 2007 Solomon Islands Tsunami, Southwest Pacific Ocean

The tsunami that was triggered by a magnitude 8.1 earthquake on April 1, 2007, in the Solomon Islands caused significant damage and loss of life. In the hopes that disasters such as this can be avoided in the future, we attempt to understand the mechanism and impact of this tsunami. The information presented here is focused on geologic aspects of the disaster.

Links for More Information on Earthquake from the National Earthquake Information Center:

Event page for April 2007 M=8.1 Solomon Islands Earthquake

Earthquake Summary Poster

Links for More Information on Tsunami from NOAA Center for Tsunami Research:

Event page for April 2007 Solomon Islands Tsunami

Tectonic Background

The M=8.1 earthquake that occurred in the Solomon Islands on April 1, 2007 (UTC), was located along the Solomon Islands subduction zone, part of the Pacific "Ring of Fire". A subduction zone is a type of plate tectonic boundary where one plate is pulled (subducted) beneath another plate. For most subduction zones that make up the western half of the Ring of Fire, the Pacific plate is being subducted beneath local plates. In this case, however, the Pacific plate is the overriding or upper plate. There are three plates being subducted along the Solomon Islands subduction zone: the Solomon Sea plate, the Woodlark plate, and the Australian plate (see figure below). A spreading center separates the Woodlark and Australian plates. More detailed information on the plate tectonics of this region can be found in Tregoning and others (1998) and Bird (2003).

Plate tectonics of the Solomon Islands region.
Water depth shown in color (cool colors-deeper water) (metadata).
Approximate area of fault that ruptured during April 2007 earthquake shown in hachure pattern.
(See a larger version of this image, 404 kb.)

In 1982 and 1984, the USGS, as part of the CCOP/SOPAC Australia-New Zealand-United States Tripartite Agreement, conducted marine geologic investigations of the Solomon Islands region. This resulted in the acquisition of multi channel seismic reflection data aboard the R/V *S.P. Lee* across the Solomon Islands subduction zone. A track line map of one of the seismic reflection lines (line 401, cruise L-6-84-SP) is shown below. Both cruises L-7-82-SP and L-6-84-SP acquired seismic reflection and other data along the Solomon Islands subduction zone.

Track line for seismic reflection line 401 (metadata).

Yellow circle is epicenter for April 2007 M 8.1 earthquake.

(Download Google Earth kmz file of cruise L-6-84-SP seismic reflection lines).

Line 401 in particular images the shallow part of the interplate thrust that is the boundary between the downgoing Woodlark plate and the overriding Pacific plate. The fault at this latitude most likely ruptured during the April 2007 M=8.1 earthquake. An interpretation of the data based on Bruns and others (1989) is shown below.

Multichannel seismic reflection line 401, cruise L-6-84-SP,

crossing the Solomon Islands subduction zone.

(See a larger version of this image, 2.3 Mb, as originally interpreted by Bruns and others, 1989.)

Several splay faults (secondary faults) that come off the shallow part of the interplate thrust, or subduction décollement, are evident in this profile. One or more of these faults may have been activated during the April 2007 earthquake.

Seismological Background

The Solomon Islands subduction zone is noted for producing an unusual pattern of earthquakes called "doublets". These are two earthquakes of similar magnitude that occur close to each other in space and time. Most of the historic doublets in the Solomon Islands have occurred north of the 2007 earthquake in the vicinity of Bougainville Island and along the New Britain subduction zone. The largest of these doublets are a pair of M=8.0 and 8.1 earthquakes that occurred 12 days apart in 1971 (Schwartz and others, 1989). The portion of the fault that ruptured in the first earthquake of the 1971 doublet re ruptured in a different manner during an M=7.7 earthquake in 1995 (Schwartz, 1999). Other doublets have occurred in 1919 and 1920, 1945 and 1946, and 1975 (both occurred in the same year), all in the M=7-8 range. In the southeastern part of the Solomon Islands subduction zone, there were doublets in 1931, 1939, and a triplet in 1977 (Lay and Kanamori, 1980). It is unclear what mechanism causes earthquake doublets to occur, although stress triggering from the first earthquake of the doublet is likely a significant a factor. Timing between earthquakes that compose doublets is discussed in general by Kagan and Jackson (1999).

From the inversion of waveforms from the April 2007 earthquake recorded on seismograph stations around the world, rupture started at a point on the inter plate thrust fault known as the hypocenter and broke approximately 250 km of the fault to the northwest. Bathymetric ridges entering the subduction zones (the Woodlark Rise and Woodlark Ridge in figures above) appear to influence the distribution of slip during the earthquake. It is interesting to note that the fault ruptured directly across where an active spreading center is being subducted. In contrast, subduction of the Woodlark rise to the northwest may have been a factor in arresting rupture.

Over geologic time, ridge subduction contributes to the uplift of the overriding plate and the creation of islands such as Simbo, Gizo, and Ranunga very near the Solomon trench (see Geist and others, 1993, for ridge subduction models). As ridges are subducted, scars in the overriding plate called "re-entrants" are left that can often be identified in the bathymetry and seismic reflection profiles (see above figures). Many of these processes can affect tsunami generation and will be investigated in the future.

Preliminary Simulation of tsunami

To create a preliminary simulation of the April 2007 tsunami, we start with the fault mechanism determined by the Global CMT Project. The length of the fault that ruptured can be determined from the distribution of aftershocks or from the seismic inversion. In this case, however, we used the results from Shake Map soon after the event to obtain an estimate of rupture length. Shown below is the preliminary simulation of the tsunami as viewed from different directions. The source and propagation model is based on an earlier study (Geist and Parsons, 2005) [Download PDF (6.5 MB)] that investigated tsunamis from the November 2000 New Ireland earthquake sequence (tsunami also observed at Gizo for the New Ireland event).

The islands near the trench are located in a region that is uplifted during the earthquake. The onset of the tsunami, therefore, will be very rapid and there might not be a withdrawal of the ocean prior to the initial wave peak. For islands such as Choiseul and Bougainville (Papua New Guinea), which are located at a typical distance from the trench for a subduction island arc, the first tsunami peak will often be preceded by withdrawal of the ocean.

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