PDHonline Course G384 (3 PDH)

Great Earthquakes and Associated Tsunamis

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Course Content

Course Introduction

One of the great tragedies of modern times occurred in March 2011, hitting the Northeast Coast of Japan abruptly and with very little to no advance warning. This disaster came in the form of an earthquake so powerful that it knocked the earth off its axis of rotation. This great earthquake also spawned a tsunami so overwhelming that it literally wiped out several coastal towns in Northeast Japan. This tsunami encroached inland for distances of up to 5 or 6 kilometers drowning and destroying everything in its path. It was estimated that this earthquake was the largest one to strike Japan in a thousand years.

What forces within the earth generated this epic disaster? Because Japan is so well monitored by automated sensing instruments scientists have been able to accumulate a wealth of real time data about this event, thus enabling them to reconstruct and know exactly what happened. Every detail of this tragedy was recorded real time by seismometers, Global Positioning System (GPS) instruments, strain gauges and tidal gauges. For example, to monitor earthquakes, the Japan Meteorological Agency (JMA) operates a uniquely dense earthquake observation network comprised of over 200 seismographs/seismometers. In addition, the Agency operates over 600 seismic intensity meters. It also collects data from over 3,600 seismic intensity meters managed by local governments and the National Research Institute for Earth Science and Disaster Prevention (NIED). The data thus collected are input into the Earthquake Phenomena Observation System (EPOS) at the Agency’s headquarter in Tokyo and at the Osaka District Meteorological Observatory on a real-time basis. The following figure gives a visual impression of the dense distribution of seismic monitoring devices throughout Japan.

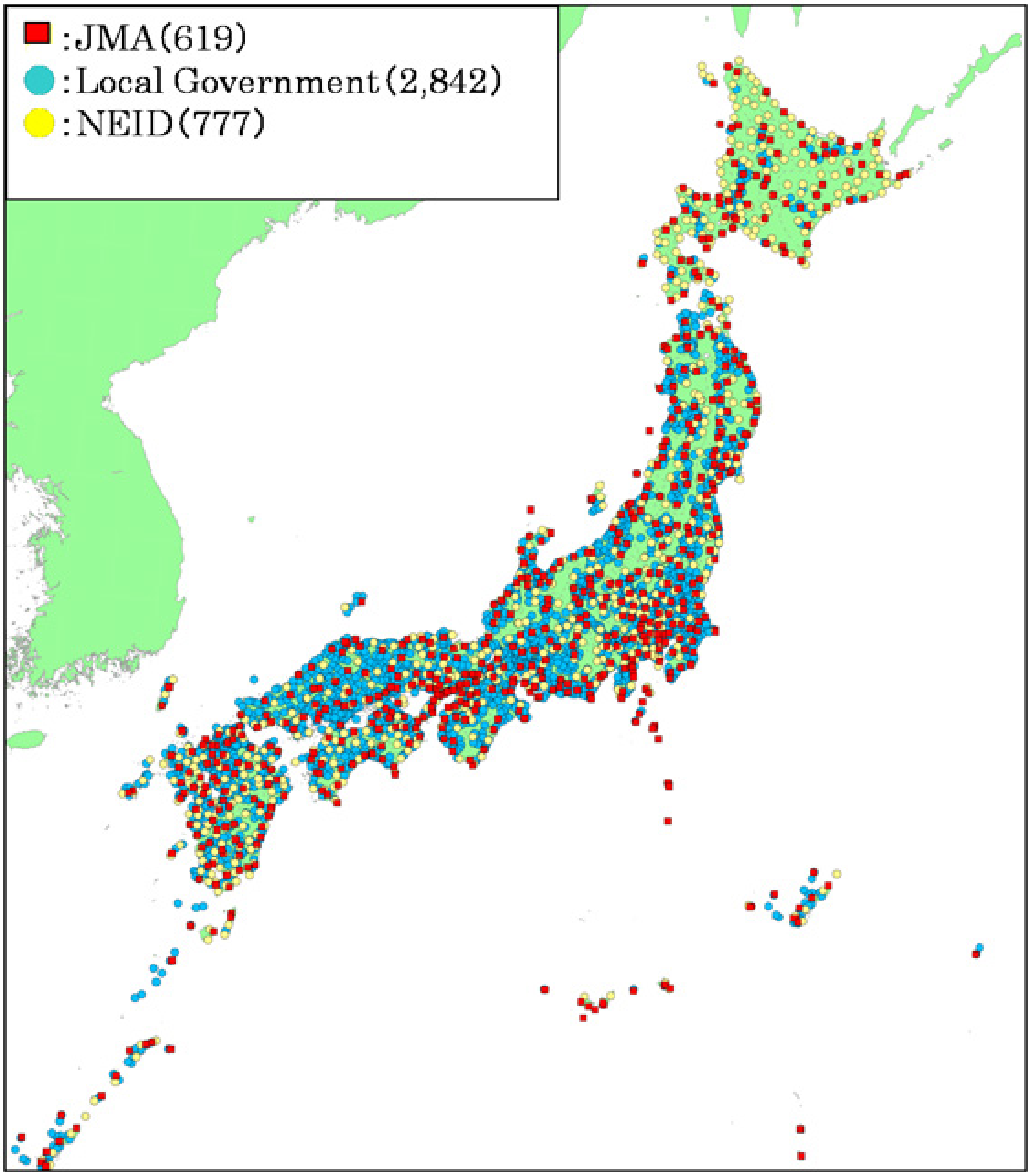

Figure 1: Sites of seismic monitoring devices deployed in Japan as of October 1, 2009 (Source: Japan Meteorological Agency).

In addition, by the time this earthquake occurred, the Geographical Survey Institute of Japan had in full operation a permanent network of over 1,000 GPS receivers deployed across the country. Each GPS receiver is housed in a 15-foot tall stainless-steel pillar. Readings are taken every 30 seconds and, using differential GPS corrections, horizontal motion of less than 0.1 inch can be readily detected. The following photograph shows one of these fully computerized GPS sensors that recorded both the amount and direction of local displacements.

Figure 2: One of Japan's permanent GPS receivers used for monitoring earth movements.

This great earthquake and ensuing tsunami laid the coastal cities, towns and industrial facilities of Northeastern Japan to complete ruin and sparked one of the worst nuclear accidents in memory. Incredibly, however, the disaster could have been much worse without the preparations that were already in place. Clearly, however, there is still much more to learn to mitigate the impact of such overwhelming natural disasters.

The Great Japan Tohoku-oki Earthquake

On March 11, 2011, at 2:46:24 pm local time, the Northeastern half of Japan was hit by a huge tremor. As determined by the United States Geological Survey (USGS), the epicenter of this event was located at latitude 38.297^{o}N, 142.372^{o}E, about 60 miles off the Coast of Honshu, Japan. The horizontal location uncertainty is +/- 13.5 km (8.4 miles). The hypocenter of the earthquake was located at a depth of 30 km (18.6 miles), and the epicenter was 129 km (80 miles) E of **Sendai**, Honshu, Japan, 177 km (109 miles) E of **Yamagata**, Honshu, Japan, 177 km (109 miles) ENE of **Fukushima**, Honshu, Japan, and 373 km (231 miles) NE of **TOKYO**, Japan. Early analyses of the seismic records estimated the event to be of magnitude 7. But, as data continued to flood into the observatories the numbers started to climb in quick succession. The initial magnitude estimate was revised in quick succession up to a magnitude of 9.0.

The following figure shows the location of the earthquake epicenter in relation to the mainland of Japan. The main tectonic features, namely the Plate Boundary and the Pacific and Eurasian Plates, are also shown on the figure.

Figure 3: Location of the earthquake epicenter in relation to the mainland of Japan. The earthquake occurred as a result of an abrupt displacement between the Eurasian and Pacific Plates along their common boundary.

The association between faults and earthquakes, and the relationship between the fault plane, the hypocenter (or focus) and the epicenter of an earthquake are explained and illustrated in Course G-175 titled: “Earthquakes: Basic Principles”. The operation of the seismograph/seismometer and the generation of seismograms that record the ground vibrations that accompany an earthquake are also explained in the same course (G-175).

Aftershocks

Earthquakes of this magnitude are usually followed by many aftershocks, and in the week that followed the main earthquake numerous aftershocks occurred. The main shock was followed by thousands of magnitude 4, hundreds of magnitude 5, dozens of magnitude 6 and a handful of magnitude 7 earthquakes. Every aftershock took a toll on an already frightened population and potentially every aftershock triggered a new one. The net effect is that the entire country just about ground to a halt as a result of these events.

The following figure delineates the region within which the aftershocks occurred over the portion of the plate boundary that was destabilized.

Figure 4: Red line delimits the region of aftershocks that occurred during the week that followed the main event. The area over which the epicenters of the aftershocks are distributed gives a feeling for the extent of the plate boundary fault that ruptured to generate the main event.

Cause of the Great Japan Tohoku-oki Earthquake

It is now known that the crust of the earth is subdivided into a number of rigid plates, known as tectonic plates, which move and interact with each other along their boundaries. The following figure shows the individual plates that cover the surface of the earth.

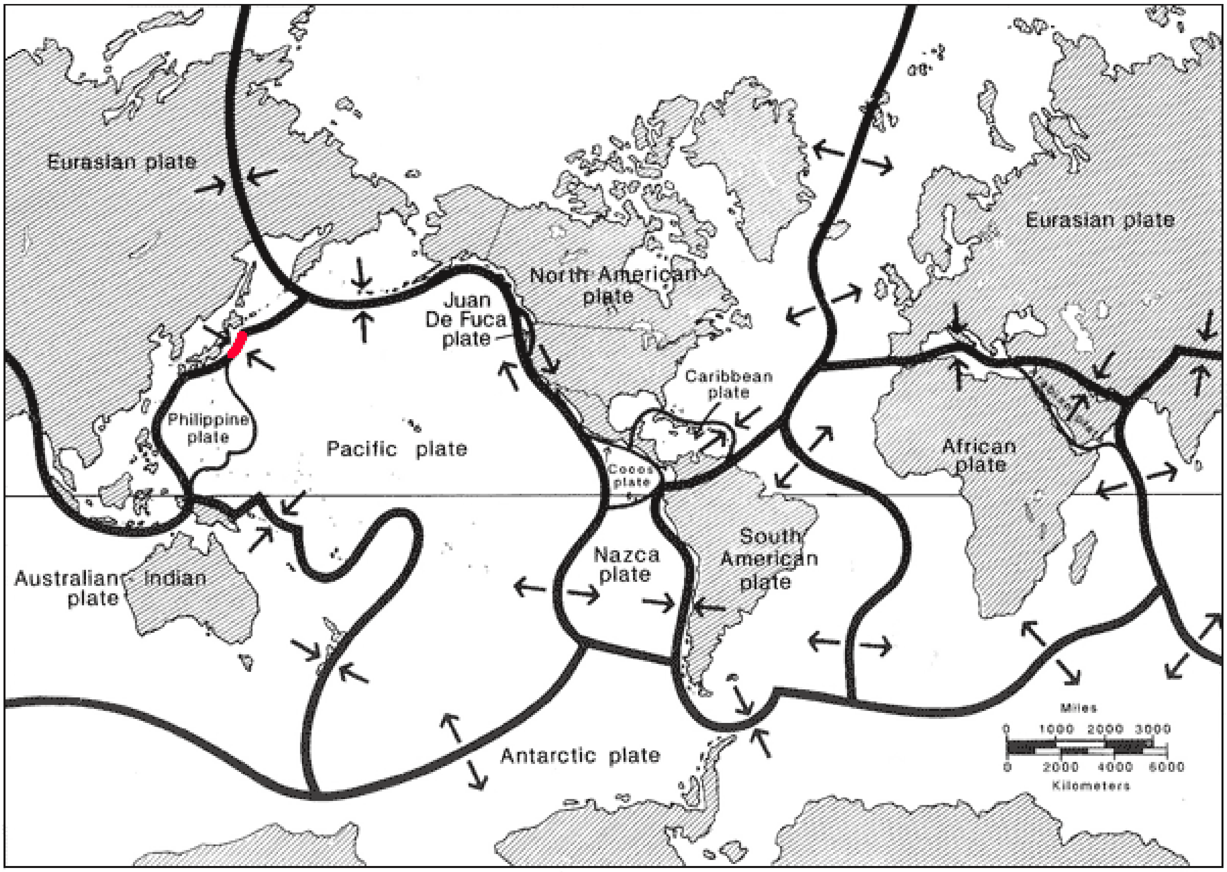

Figure 5: Map showing how the surface of the earth is broken into tectonic plates. The arrows indicate the relative movements between plates. The small Juan De Fuca plate is moving towards North America. The red segment is the plate boundary that generated the Great Japan Tohoku-oki Earthquake and spawned the powerful Tsunami.

Many of these tectonic plates meet and interact with each other beneath the ocean floor, in relative proximity to continental masses. The spatial interactions between the oceanic and continental plates and the resulting stages of strain accumulation and sudden slippage, that manifest itself as earthquakes, is explained and illustrated in Course G-207 titled: “Tsunamis: Basic Principles”. In summary, the point in time when the edge of the Eurasian continental plate, east of Japan, started to spring back from its forced buckling under the push of the Pacific Plate (location and direction of movement shown on Figures 3 and 5, above) is the moment at which the great earthquake was initiated.

The Manifestation of Earthquakes

The sudden shaking or trembling of the earth, which occurs during an earthquake, is caused by the propagation of various kinds of elastic waves that travel through the earth and along its surface from the source (focus/hypocenter) of the earthquake to more distant places. The waves that travel through the earth are referred to as “body waves” and those that travel along its surface are referred to as “surface waves”. In other words, it is the seismic waves that carry the energy from the point of origin (focus/hypocenter) to the other distant points around the earth at which the earthquake effects are felt.

It takes time for a wave to travel from one point to another. That is waves have velocity and seismic waves (body waves and surface waves) travel at various speeds that depend on the type of wave and the medium through which the waves move through. In fact, our understanding of the causes of earthquakes and the nature and internal structure of the earth is based almost entirely on our ability to record and interpret the behavior of these earthquake waves.

Types of Seismic Waves

When rocks snap or break, causing an earthquake, the energy that is released travels away from the point of origin in the form of waves. These waves are similar to those generated by a pebble dropped in a quiet pond. The concentric ripples that move away from the point of impact, carrying part of the energy imparted by the pebble when it struck the water, are known as “surface waves”. In addition, if listening devices are placed at some depth below the water surface we can detect noise produced by the pebble striking the water. This noise is carried through the body of water by “body waves” that can be detected by these listening instruments.

Similar to the water-born waves, there are two types of earth-born waves that are generated by earthquakes:

1. Body waves, which travel through the interior mass of the earth, and
2. Surface waves, which travel only along the surface of the earth.

Body Waves

One type of body waves, also known as compression waves, move particles forward and backward along their travel path by successive compression and relaxation. This means that the molecular structure of materials in their path are alternately compressed and relaxed. These compression waves can travel through solid, liquid or gas. Because they travel at great speeds and normally reach the surface first, they are called “Primary Waves”, and are referred to simply as “P” waves.

The second type of body waves that move particles from side to side at right angle to their direction of propagation are known as transverse or shear waves. The rock will be distorted, or sheared, but no compression or stretching will take place. These shear waves can travel through solids but not through liquids. Shear waves do not travel through the earth’s crust as rapidly as compression waves. Because they normally reach the surface later they are called “Secondary Waves”, and are referred to simply as “S” waves.

“P” waves travel about 1.7 times faster than “S” waves. Therefore, the first “P” wave always arrives at a seismic recording station before the first “S” wave. In addition, “S” waves are usually larger in amplitude than “P” waves since faulting, which causes earthquakes, is a shear phenomenon. The following figure is an illustration of these two fundamental types of body waves.

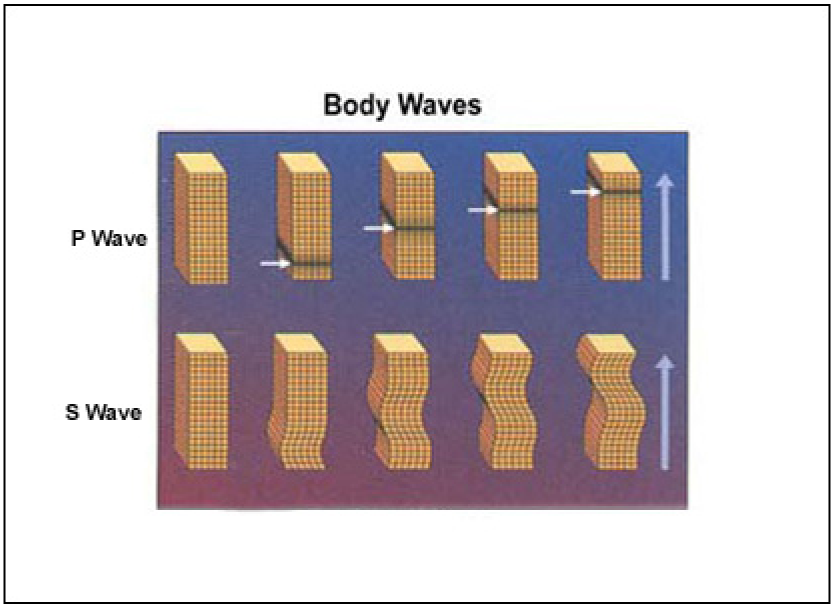

Figure 6: Diagram of particle motions within the body waves as they travel in the direction indicated by the light blue arrows (right). Source: modified from a US Geological Survey illustration.

Surface Waves

As the P and S waves approach the earth's surface, derivative waves are generated. These new waves are guided in their travel by the earth's surface, and are consequently known as surface waves. There are two types of surface waves: Rayleigh waves and Love waves and they can both travel through any type of material.

When surface waves are generated in rock, one common type of particle motion is in small circles (forward, up, back, and down) at right angles to the direction of wave propagation. In other words, this type of surface waves would cause the earth's surface to move up and down as well as back and forth. This form of motion is similar to that of a fisherman's float in a wavy body of water. The bobbing action keeps the float essentially in place as the waves move past the float. These waves are referred to as "Rayleigh Waves", after Lord Rayleigh, the English physicist who predicted their existence. They are referred to simply as "R" waves.

The second type of surface waves is generated entirely by S waves and is known as "Love Waves". They have a horizontal particle motion that is transverse to the direction of propagation of the wave front and their velocity depends on the density and rigidity of the material through which they travel. These waves are named after A. E. H. Love, the English mathematician who discovered them. They are referred to simply as "L" waves.

Because body waves spread out in all directions from the point of origin (hypocenter), while the surface waves spread out only in horizontal directions, surface waves do not dissipate as much as body waves after long travel. This is the reason why the seismograms of distant seismic stations are dominated by surface waves.

Surface waves are slower than body waves and are the last to reach a seismic recording station. Surface waves are also of lower frequency and are less attenuated along their travel path. In fact, surface waves may travel many times around the earth before they dissipate and become invisible. Both the Rayleigh and Love waves have relatively long wavelengths, compared to the body waves. For this reason, they are sometimes collectively referred to as "L" waves, for long waves. The following figure is an illustration of these two types of surface waves.

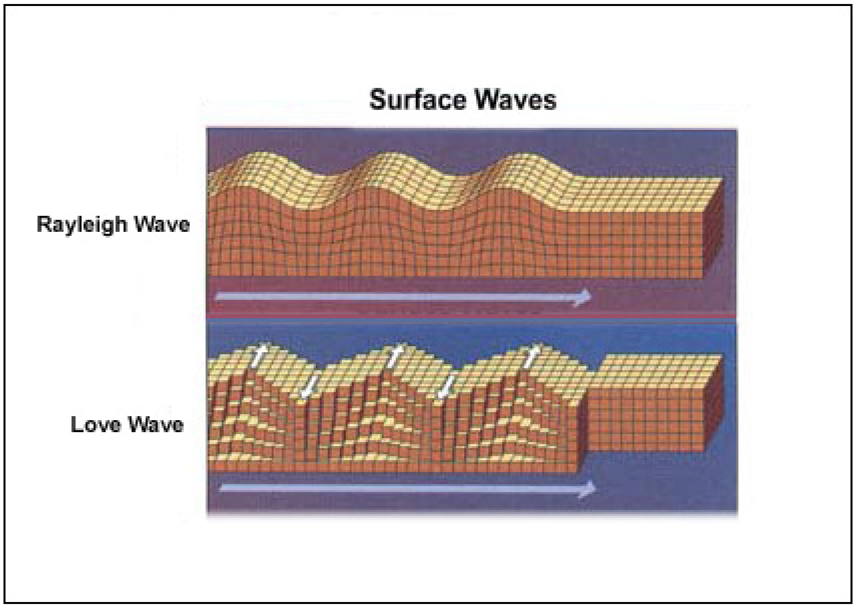

Figure 7, Diagram of particle motions within the surface waves as they travel in the direction indicated by the light blue arrows. Source: modified from a US Geological Survey illustration.

The surface waves travel through the sedimentary rocks near the earth's surface and along the interface between the sedimentary and crystalline layers that occur somewhat deeper within the crust.

Travel Times of Seismic Waves

Making use of the fundamental linearity of waves Sir Harold Jeffreys and Professor Keith Bullen, of Cambridge University, England, generated the first set of travel time curves that recorded in a graphical format how long it takes for a particular earthquake wave to travel a certain distance. As mentioned earlier, P-waves travel faster than S-waves and they both travel faster than the L-waves. This difference is made quite evident by the travel time curves presented in the following figure, which is a plot of travel times of first arrivals of P, S, and L waves from a given earthquake focus to seismographs located at different distances.

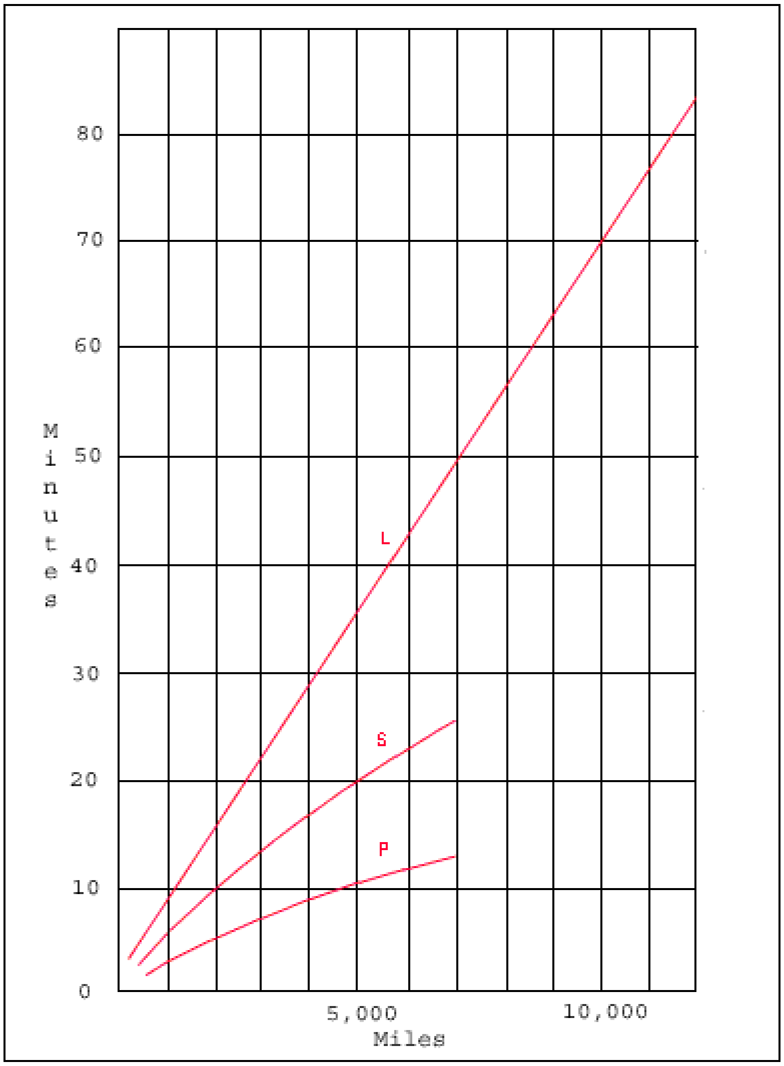

Figure 8: Time-Distance graph for P, S, and L seismic waves

The velocities of the P- and S-waves increase gradually with depth within the earth's crust. For P-waves the change is from about 3.5 miles per second for rocks near the surface to about 4.5 miles per second at depth. For the S-waves the equivalent change is from 2.1 to 2.7 miles per second. The equations used to calculate the velocity of seismic waves are given in the Appendix.

Interior Structure of the Earth

When the information about the velocity of seismic waves from a large number of seismic events is pieced together, the following picture of the structure of the earth emerges:

- Below a thin veneer of sediments the crust of the earth extends downwards to a depth of 30 to 70 km in continental areas and only to a depth of 6 to 8 km in oceanic areas. The velocity of P-waves is generally between 5 and 6.8 km/sec, increasing downward.

- At the top of the mantle the velocity of P-waves is commonly about 8.1 km/sec. This speed, however, varies regionally. For example it is about 7.7 to 7.9 km/sec under the Western US and about 8.2 km/sec under the Eastern US.
- In the upper 200 km of the mantle, the velocity of S-waves seems to decrease with depth, at least locally, pointing to the existence of a low velocity layer in the mantle. The velocities of both P- and S-waves vary regionally, being somewhat different under oceans and continents.
- From the depth of about 200 to 1,000 km the velocities of both P- and S-waves increase rapidly. There may be two zones around 400 and 600 km depths, respectively, where the rate of increase of the velocity of P-waves is particularly large.
- There is a major discontinuity at a depth of 2,900 km, separating the mantle from the core. At the core boundary the velocity of P-waves drops from about 13.7 km/sec (lower mantle) to about 8.1 km/sec (top of the core). The velocity of S-waves drops from 7.2 Km/sec to 0, indicating that the outer core must be liquid.
- In the outer core, from about 2,900 to 5,000 km, the velocity of P-waves increases slowly, while the S-waves are not transmitted at all, indicating that the outer core is presumably liquid.
- There is a relatively small inner core, radius about 1,200 km, which is probably solid and may have a complex internal structure.

The following figure shows how, at large distances from the focus of an earthquake (hypocenter), the initial P- and S-waves will be accompanied by a number of reflected and refracted waves that travel through the crust, mantle and core of the earth.

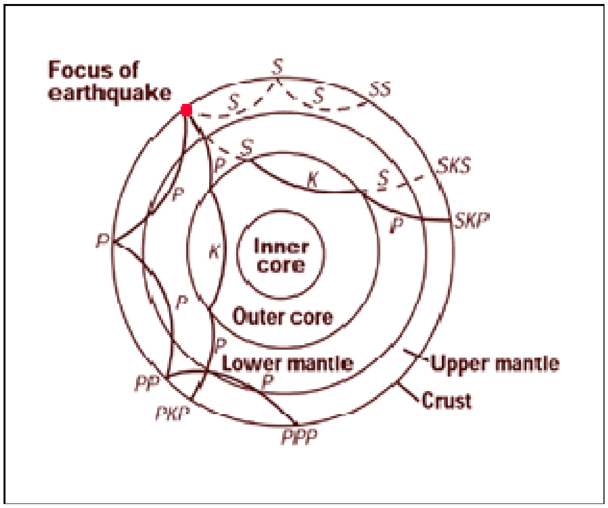

Figure 9: Possible paths of seismic waves through the earth. The focus of the earthquake is at the red dot. The symbol K designates a wave refracted through the outer core; thus PKP is a P-wave that traveled through the outer core. SKS and SKP represent an S-wave that traveled through the mantle

with a derivative compression component refracted through the outer core as K which then emerges from the mantle as both an S-component and a P-component.

It is important to note that the above figure shows that the P- and S-waves produced at the point of origin generate at an interface where they are reflected or refracted both new P- and S-waves. These derivative waves travel at different speeds and arrive therefore to their destinations at different times. As an example of these principles, the following figure presents a seismogram of the Great Japan Tohoku-oki Earthquake recorded by a seismic instrument located at Northern Illinois University, literally on the other side of the world. The arrival of the P-waves (and P-wave derivatives) is clearly shown (higher frequency, smaller amplitude waves). These were followed by the train of L-waves (lower frequency, higher amplitude surface waves).

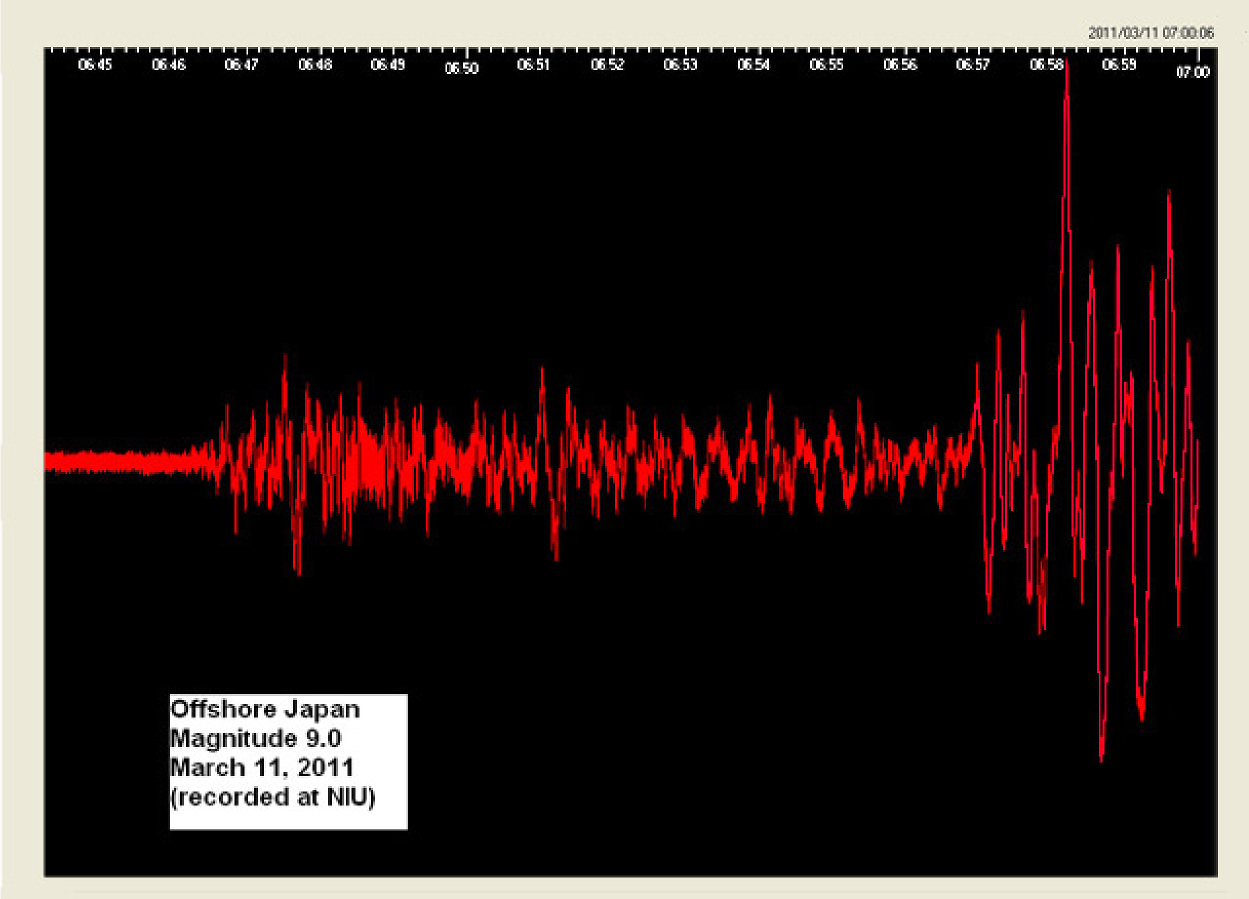

Figure 10: Seismogram of the Great Japan Tohoku-oki Earthquake as recorded by a seismometer located at Northern Illinois University. The smaller amplitude waves are the P-waves and P-wave derivatives followed by the S-waves and S-wave derivatives and finally followed by the arrival of the higher amplitude surface waves (L-waves).

Propagation of the Great Tohoku-oki Earthquake

At the moment the great earthquake struck, its seismic waves (body waves and surface waves) started racing towards shore. The fastest P-waves, which travel at about 4 miles per second, took about 15 seconds to reach the shore. The automated national detection system picked them up instantly and warnings began to flash across the country. The computer generated announcement even interrupted the broadcast of a parliamentary session in progress. Nonetheless, the coast between Sendai and Fukushima had only between 15 and 25 seconds of warning. The following figure shows the locations of Sendai and Fukushima.

Figure 11: Locations of Sendai and Fukushima, along the northeastern shore of Japan

There was very little time before the slower, but much more destructive S-waves, followed-up on the heels of the P-waves. These waves shake the ground from side to side and are the ones that make earthquakes so damaging. Already Northeast Japan was descending into chaos.

The seismic waves travelled 93 miles southwest of the epicenter and reached the Fukushima Daiichi plant, home of an aging nuclear power station housing 6 reactors, in less than 25 seconds. Sensors at the plant automatically shut down all the reactor cores. So the reactors were already in shutdown mode when the S-waves hit the plant site. The problem, however, was that the intense heat generated by the nuclear reaction does not simply dissipate instantly and the reactor cores remained extremely hot. In addition, when a reactor stops, there is no power to drive the cooling pumps and the reactor core continues to heat up. However, at this point the emergency generators, powered by conventional fuels, were automatically activated and took over the pumping of cooling water. As a result, the Fukushima Daiichi plant survived the initial earthquake hit intact. However, the station remained exposed and vulnerable to the next natural disaster that was about to unleash its full destructive force on the site.

Cascading Effects

As time ticked away scientists 3,800 miles away, at the Pacific Tsunami Warning Center in Hawaii, began receiving emergency alerts from their deployed sensors. Researchers around the world could now see the event unfold in real time. Early analyses of the records estimated the event to be of magnitude 7. But, as data continued to flood into the observatories the numbers started to climb in quick succession. The initial magnitude estimate was revised in quick succession to 7.5, 7.7, 8.0, 8.5 and then to 9.0. The scientists were incredulous because in the entire history of Japan there has not been an earthquake greater than magnitude 8.4. It was becoming clear that this event was so big that it could affect the entire Pacific Basin.

About one hundred seconds after the fault line slipped, the destructive S-waves reached Tokyo. With barely 60 seconds of warning, Tokyo began to shake violently. The shaking that gripped the city went on and on for an unprecedented full five minutes. Normally one would expect the shaking from a strong earthquake to last for a few seconds to may be a full minute at the most. As time ticked on there was a grand realization that the earthquake was indeed a great one. Had it not been for the city's very effective seismic resistant design of its buildings and infrastructure, the entire city could have been flattened. The following figure is a graphic representation of the propagation of the P- and S-waves from the epicenter towards the East Coast of Japan and in the direction of Tokyo.

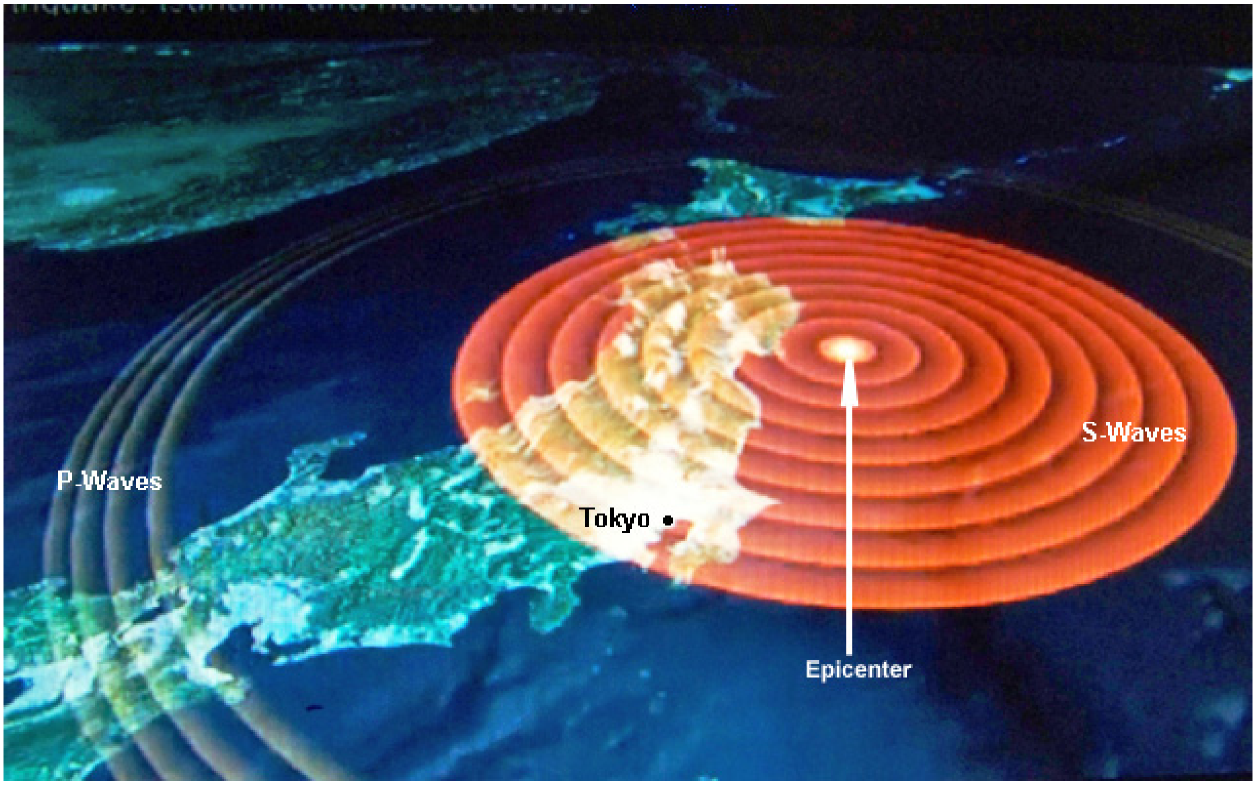

Figure 12: Diagrammatic representation of the propagation of P-waves and S-waves from the epicenter of the earthquake towards the East Coast of Japan and in the direction of Tokyo.

The elevation of Tokyo, the most densely populated metropolis in the world, is only a few feet above sea level. People in Tokyo were readily able to observe cracks opening and stretching through the ground as they developed. Loosely packed and water logged sediments near the surface began to lose their cohesion and behave like a dense liquid bubbling to the surface. This process of liquefaction threatened the structural stability of buildings and the foundations of several roads and highways which were also compromised and damaged. For comparative purposes this earthquake is estimated to have been over 1,000 times more powerful than the devastating Haiti earthquake that flattened the capital city of Port of Prince on January 12, 2010.

Tsunami Initiation

At that point in time, everyone in Japan knew that this catastrophe was far from over. In fact, the earthquake was about to unleash another overwhelming destructive force. As mentioned earlier, the edge of the Eurasian continental plate, east of Japan, started to spring back from its forced buckling under the push of the Pacific Plate. The following figure is a diagrammatic representation of the Pacific Plate thrusting under the leading edge of the Eurasian Plate at the bottom of the Pacific Ocean, East of Japan, just before the occurrence of the earthquake (see Figure 3 and 5).

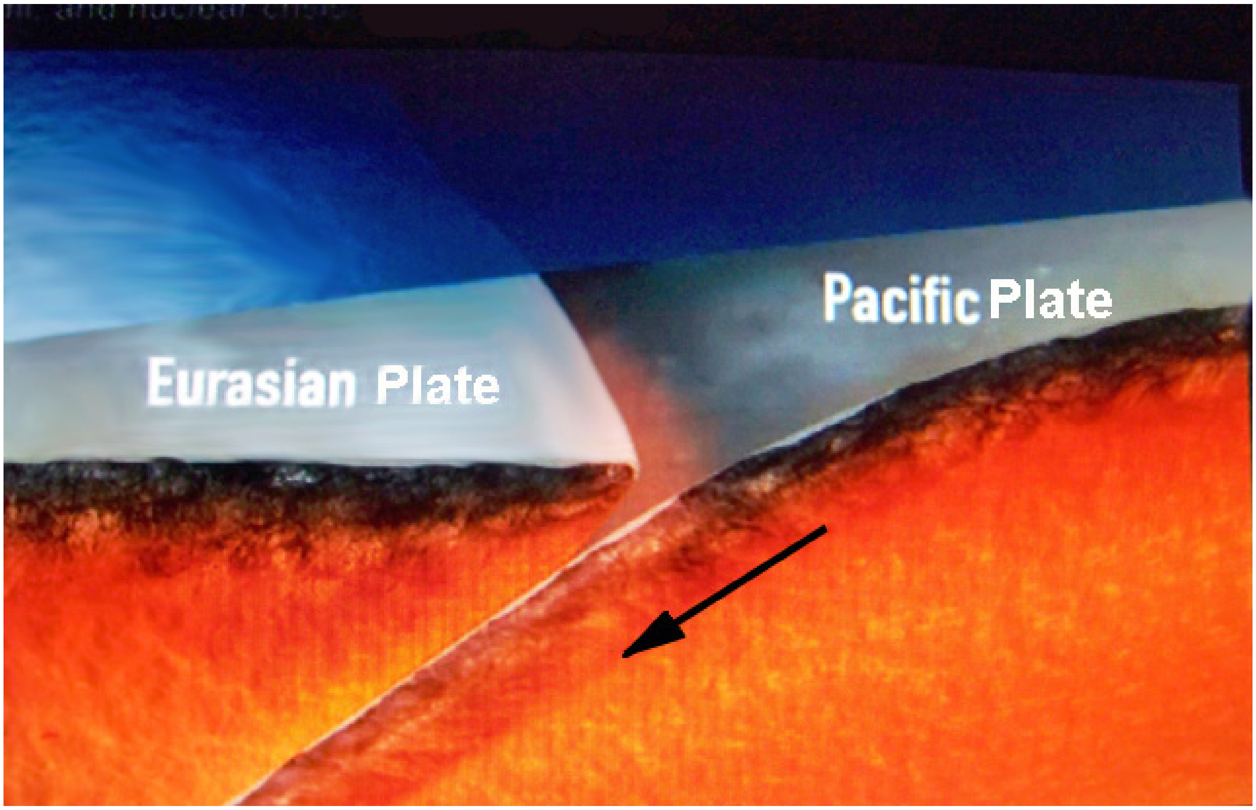

Figure 13: Diagrammatic representation of the Pacific Plate thrusting under the Eurasian Plate. The yellowish-red material beneath the Plates represents the hot and viscous upper mantle of the earth.

As the leading edge of the continental Eurasian plate sprung back from its buckled position, its upward motion pushed a 4-mile deep mass of oceanic water upward. When this initial dome of water collapsed back on itself, immense waves formed and began to race in all directions across the ocean. The following figure captures this moment in time.

Figure 14: Diagrammatic representation of the initiation of a tsunami at the epicenter of a great earthquake following the collapse of the initial dome of water that formed by the springing back of the Eurasian Plate.

In the open ocean the tsunami waves are on the order of 3 to 6 feet in height (about one to two meters). However, in this case the initial waves were amplified to a sheer wall of water about 7 meters in height. This wave amplification phenomenon was caught real time by a Global Positioning System (GPS) buoy located several miles offshore of Northeast Japan, in the direction of the epicenter. The following picture shows the type of GPS buoy deployed off the Eastern Coast of Japan.

Figure 15: Type of GPS buoy deployed in the ocean off the Eastern Coast of Japan to record real time changes in sea level.

As recorded by the buoy sensors, a startling phenomenon that had never been witnessed before started to occur. After the sea level had risen the initial 2 meters, quite suddenly the sea level rose again radically and quickly reaching a height of 7 meters. This sudden rise took the shape of a huge steep wall of water in the deep ocean. This kind of rapid transformation had never been observed before. The next two diagrams show the data recorded by the buoy sensors that recorded the passing of the initial tsunami waves.

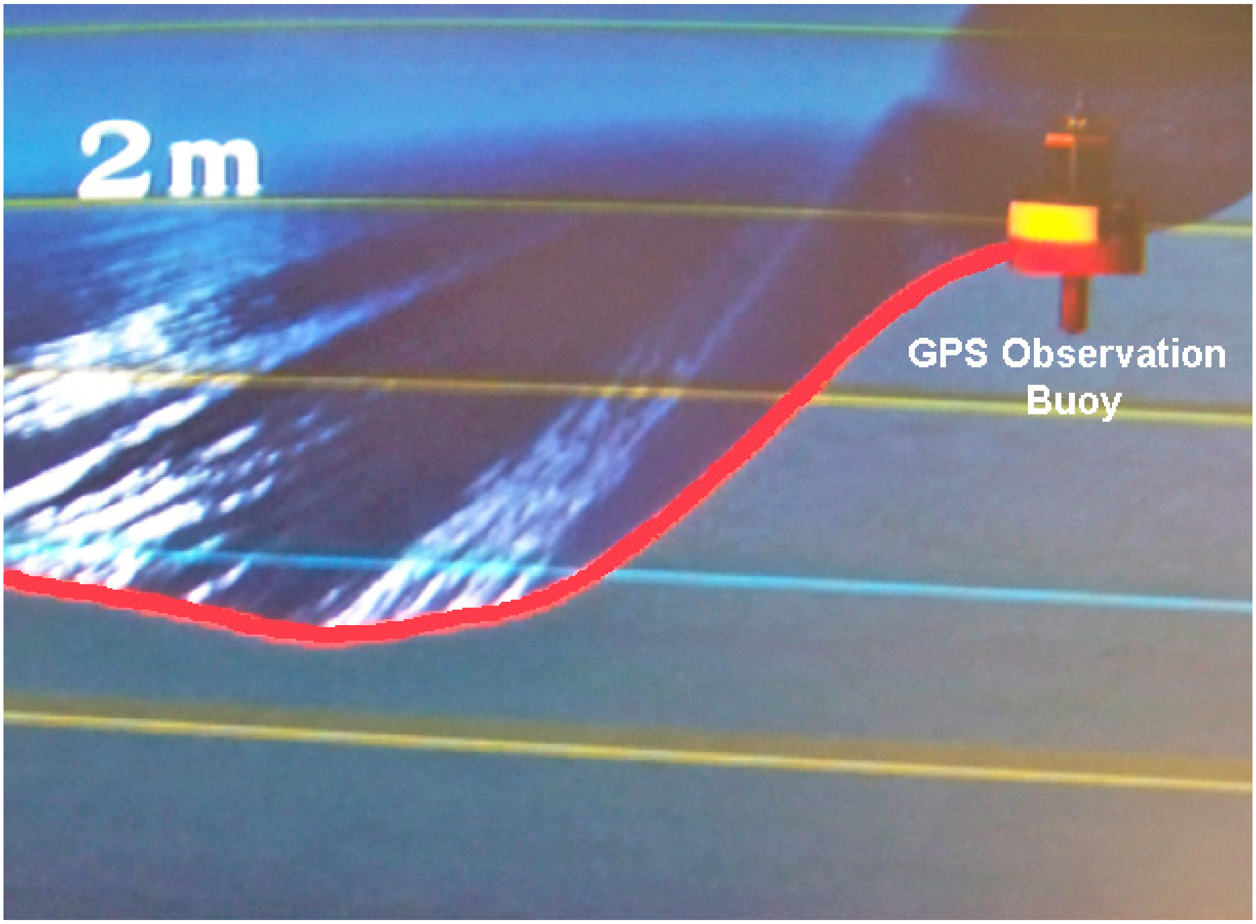

Figure 16: Initial rise of the tsunami wave to a height of 2 meters as recorded by the sensors on the GPS buoy.

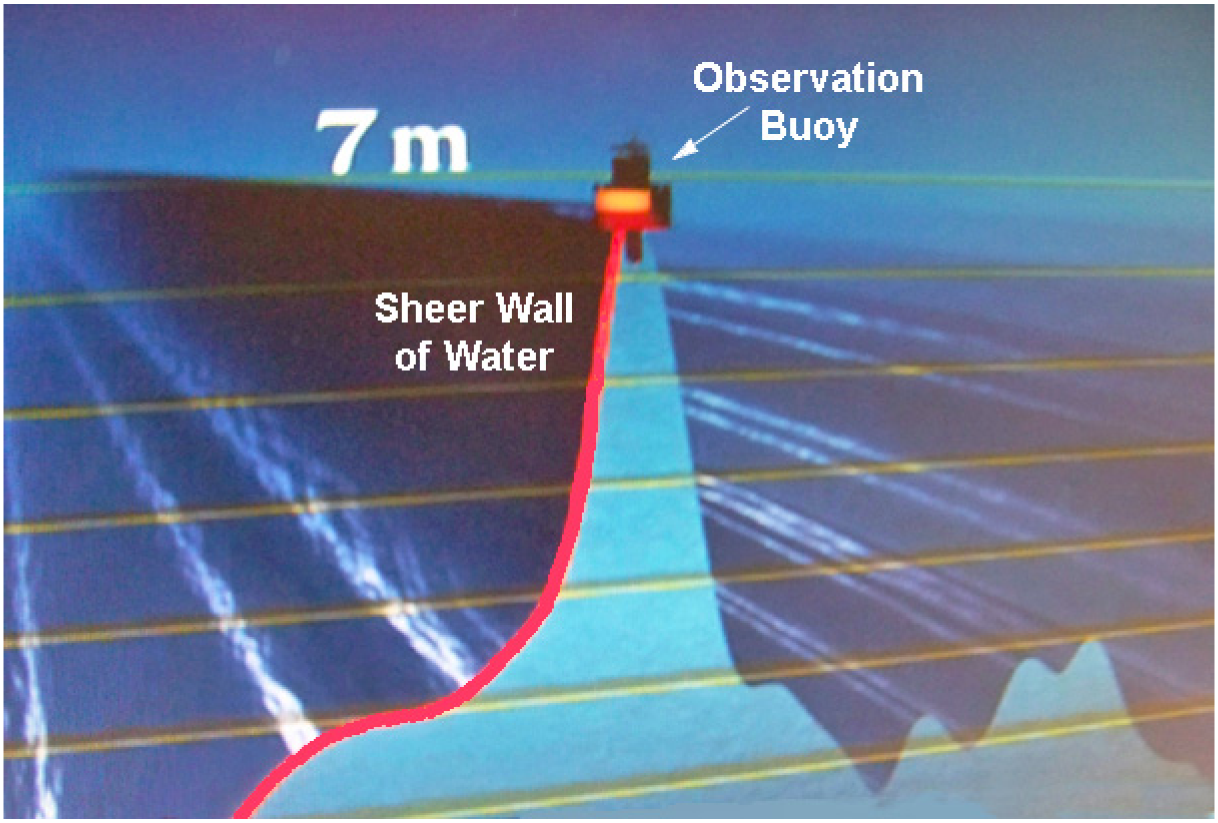

Figure 17: Sudden sea level rise to a height of 7 meters in Open Ocean as recorded by the sensors located on the GPS observation buoy.

The following graph shows the timeline of the initial tsunami wave development in the open ocean following the occurrence of the great earthquake which was triggered by the sudden dislocation of the section of the tectonic plate boundary shown in red on Figure 5.

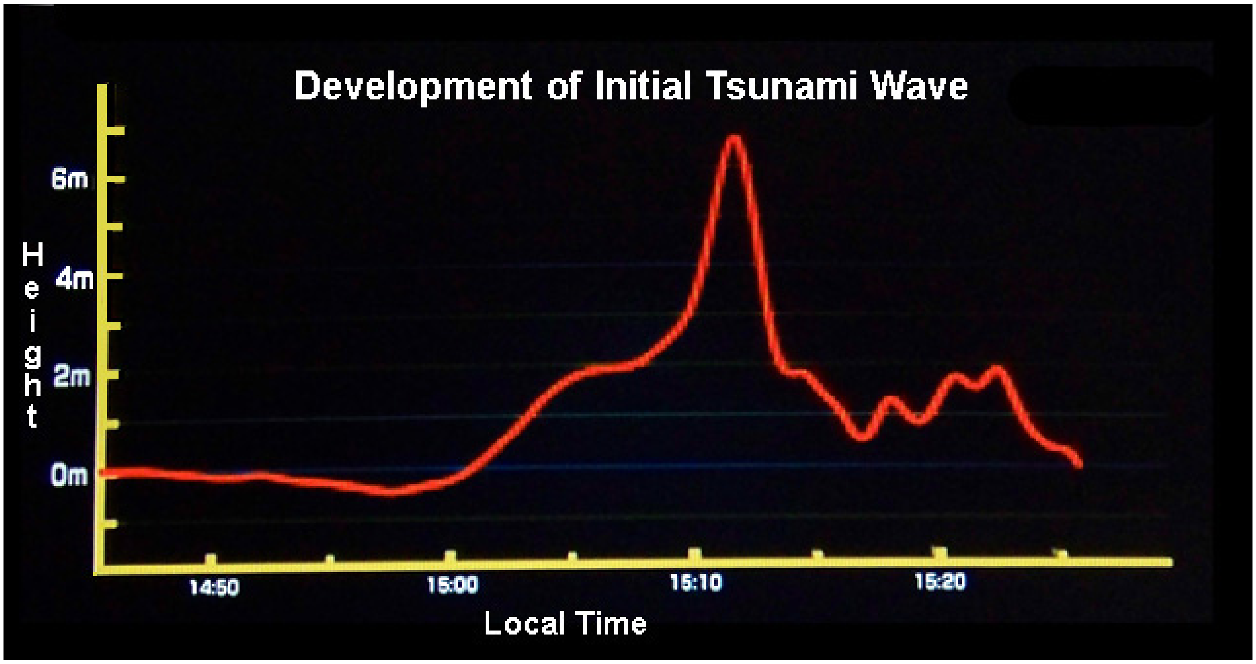

Figure 18: Graph showing the timeline of the initial tsunami wave that developed in the open ocean following the occurrence of the Great Japan Tohoku-oki Earthquake.

Why did the tsunami take the shape of a sheer wall of water 7 meters in height soon after its initial development? Professor Yushi Hirohito of Tohoku University offered a new hypothesis to explain this phenomenon. In the years that preceded the earthquake he had used underwater vessels and other means of geophysical investigations to survey the ocean floor along the coast of the northern Tohoku region. His surveys showed that sediments had accumulated in the area where the oceanic plate submerges beneath the Eurasian continental plate. He thus confirmed that there is a hard layer of sediments several kilometers thick above the plates’ junction. The following figure shows this wedge of sediments.

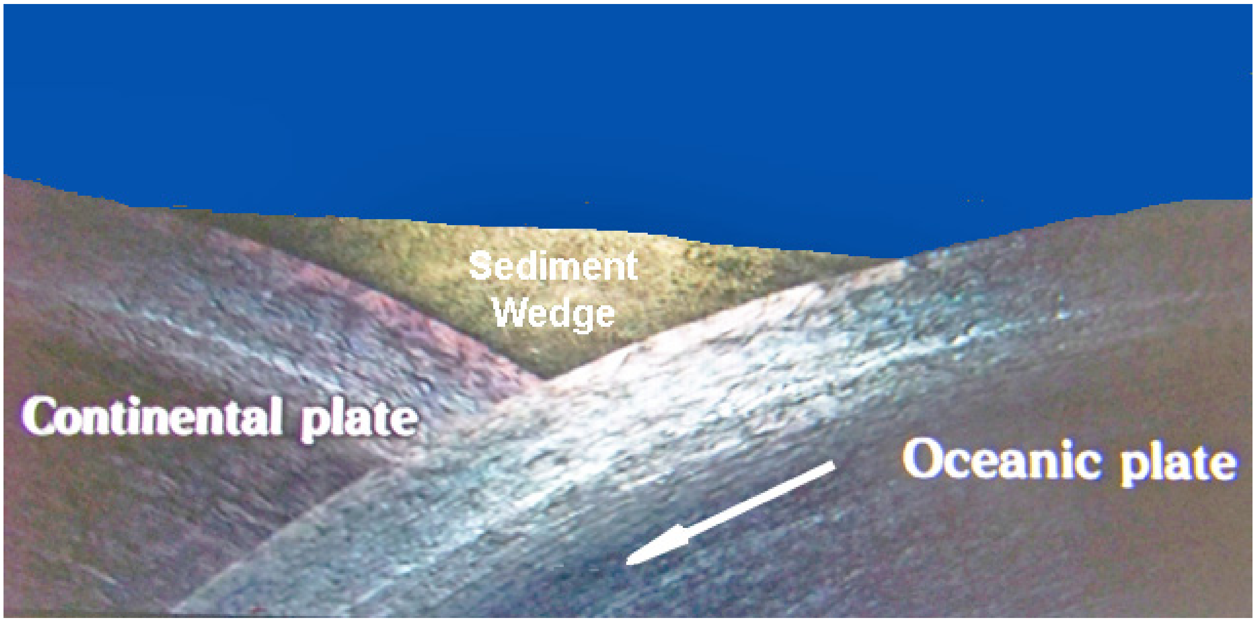

Figure 19: Sediment wedge resting above the junction between the oceanic and continental plates.

The internal structure of the sediment wedge has also been clarified by Professor Hirohito. Many faults, called splay faults, have been mapped extending from the region of the plate borders into these sedimentary strata. Professor Hirohito postulated that the initial snapping and rebound of the continental plate created the 2 meter high initial tsunami wave. The energy of the plate movement was then transmitted into the sedimentary strata causing a large vertical movement in the sediment wedge. As a result the sea level above the sedimentary strata rose abruptly to a 7 meter high sheer wall of water, thus greatly amplifying the initial 2 meter swell. The following diagram shows how this amplification occurred.

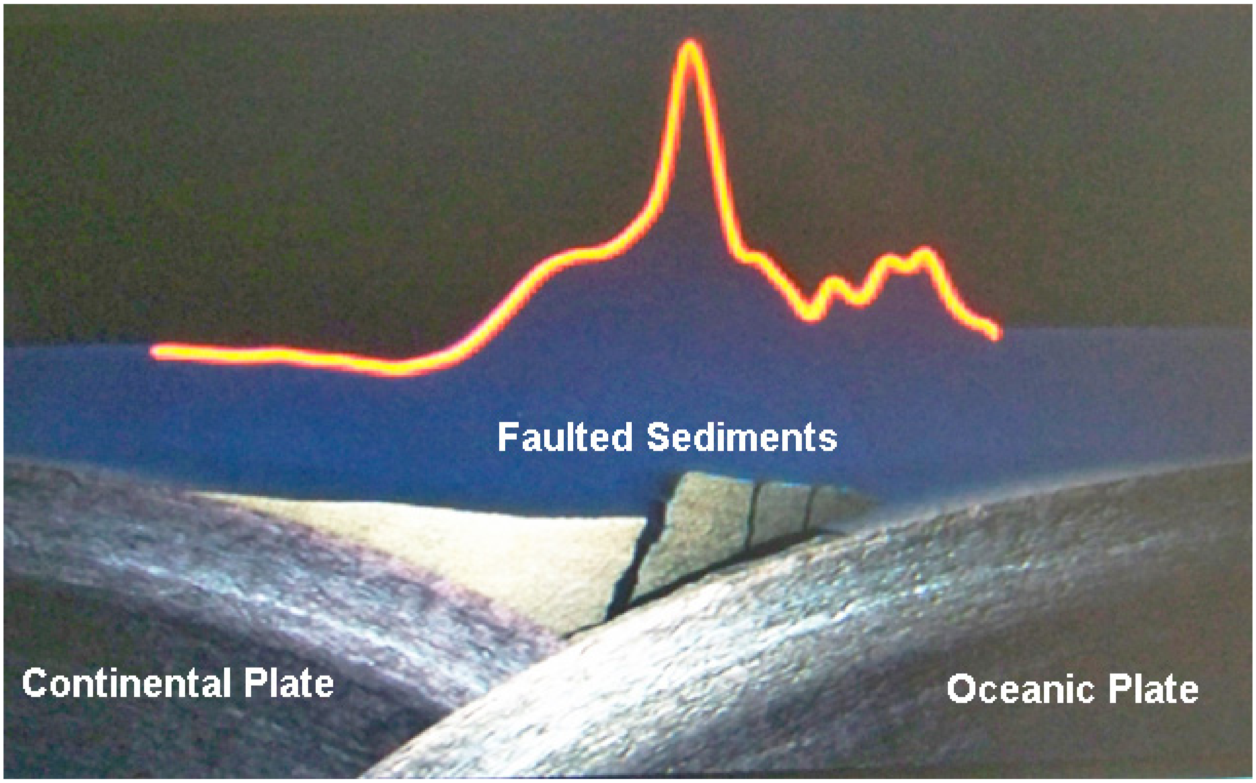

Figure 20: Graph of the sequence of sea level changes that occurred after the snapping and rebound of the continental plate and following the propagation of faulting into the wedge of sediments above the junction of the two plates.

Tsunami Propagation

Once they formed, the tsunami waves travelled at a blistering speed towards the Japanese shore and, in the opposite direction, across the Pacific Ocean. In the open ocean the waves travel at the speed of a jet aircraft, or over 500 miles per hour. The waves took only minutes to reach the exposed east coast of Japan. The propagation of tsunami waves in open water is explained in course G-207 titled: "Tsunamis: Basic Principles". The following figure shows the point in time at which the first tsunami waves hit the Northeastern Coast of Japan.

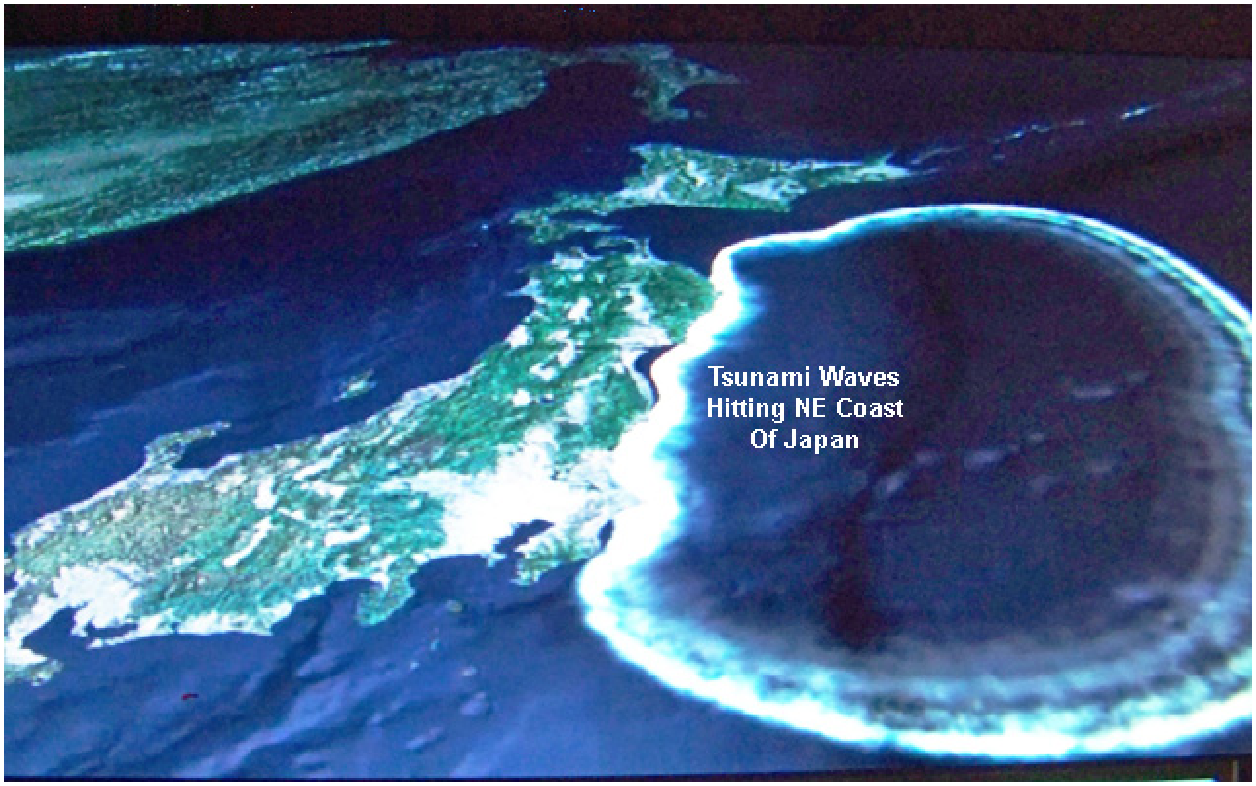

Figure 21: Diagrammatic representation of the tsunami as it reached the Northeastern Coast of Japan.

On the opposite side of the epicenter the tsunami waves raced across the open Pacific Ocean. Countries across the Pacific Rim watched nervously, and the Hawaii Tsunami Warning Center was in full alert at this point. This was the biggest tsunami wave to cross the Pacific in over 40 years. Fortunately time was on the side of the population of the Hawaiian Islands and an evacuation order was issued to all coastal communities there and everyone was instructed to reach the safety of higher ground. The following figure shows the travel times of the tsunami waves to various locations across the Pacific Ocean.

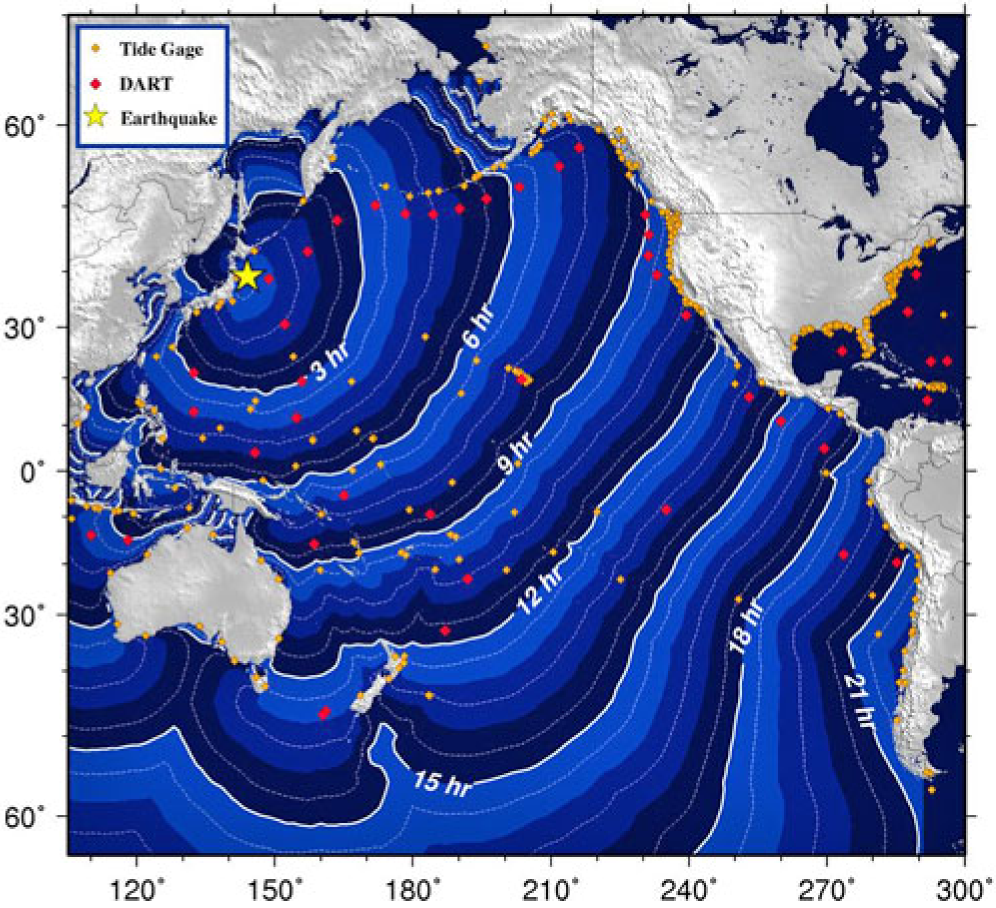

Figure 22: Tsunami travel times across the Pacific Ocean. The red dots are the stations of a monitoring network operated by NOAA for Deep-ocean Assessment and Reporting of Tsunamis (DART). The orange dots are tide gages.

The waves hit Hawaii at the exact time predicted by the forecasters. For more than an hour the tsunami waves kept hitting the beaches and surged inland demolishing houses and pulling cars and boats back out to sea. Damage was estimated in the tens of millions of dollars, but unlike Japan, no one lost his/her life. Hawaii early warning system gave citizens ample time to move to high ground, away from the coast. Although tsunamis are simply unstoppable, they can be followed and tracked accurately over long distances.

Leaving Hawaii, the tsunami waves continued to race towards the US, their power diminishing with every passing mile. Ten hours later and more than 5,000 miles from the epicenter of the earthquake the tsunami finally hit the coast of California. The waves still created havoc along the coast at Crescent City. One person even lost his life by rushing towards the beach to take pictures, instead of seeking the safety of higher ground. The tsunami finally dissipated over 21 hours later, after reaching the West Coast of South America (Figure 22).

Near Shore Amplification of Tsunami Waves

As the waves approached the coast of Japan, the shallower seafloor slowed down the front of the waves. But, the still fast moving rear of the waves continued to race forward and soon caught up with the front. The increased pressure pushed the sea water up into a rising swell. In other words, the tsunami swelled up as the sea floor got shallower. Near the coast the swell became a breaking wave and the wall of water, which in some cases reached a height of over 30 feet, raced forward and crashed onto the shore. The following figure is a diagrammatic representation of this phenomenon.

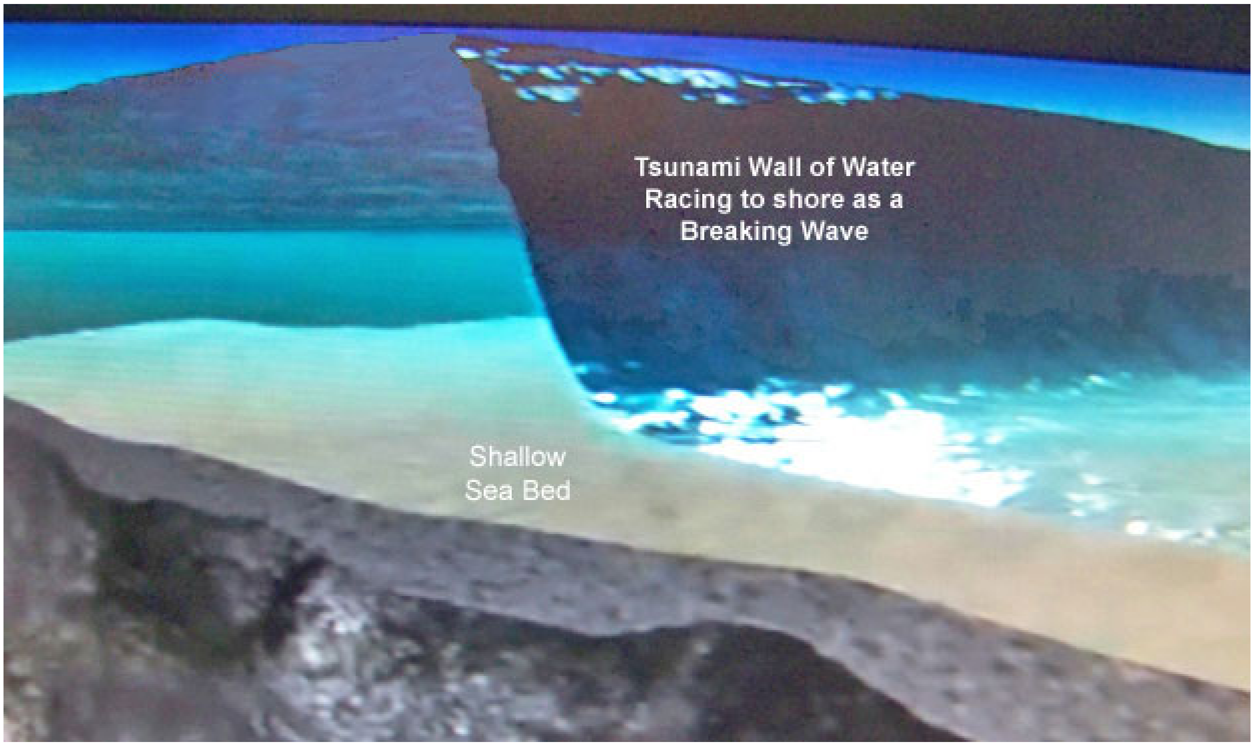

Figure 23: Diagrammatic representation of a tsunami wave breaking onto the shore. The amplification of the wave front is brought about by the shallowness of the sea floor.

As it reached the shore, the dynamics of the frontal tsunami wave propelled it far inland destroying everything in its path. There appears to be no clear pattern as to when and where the tsunami waves hit. The height and intensity of the waves also varied drastically from town to town. Part of the answer depended on the varying depths of the seabed at the point of impact. Another critical factor was related to the layout of the land. Cliffs, bays and inlets along the shore helped determine the behavior of the tsunami. In summary it all depended on how the waves were focused and defocused by the geography and topography of the coast line itself.

Sequence of Events

At about 15:00 pm local time, approximately 20 minutes after the earthquake, the first tsunami hit the town of Ofunato with a wave estimated to be 26 feet high bringing to shore with it over 10 billion tons of water. The following figure shows the location of Ofunato, along the Northeastern Coast of Japan.

Figure 24: Location of Ofunato, Sendai and Miyako along the Northeastern Coast of Japan

About 15 minutes later, the tsunami hit Sendai (figure 24, above), located 70 miles southwest of Ofunato. The area around the city is mostly low-lying flat farmland. In such low-lying areas there was nothing to stop the surging water and the wave continued to move inland for over 6 to 7 kilometers until it was stopped by higher ground.

Next the waves slammed into Miyako (Figure 24, above). This area had good tsunami defenses and residents thought they were well prepared. They were protected by 30 feet high sea walls. In addition safety drills were a regular feature of life in this town and everyone knew what to do when the sirens sounded. However, the tsunami waves easily breached the coastal defenses and the high walls proved ineffectual. Data sensors suggested a surprising answer; the earthquake caused the entire shore line to subside which meant that the oncoming tsunami waves were able to easily overtop the defenses. All along the coast this land subsidence put a lot of towns in danger. In one small isolated mountain community, 8 km inland from the coast, the tsunami took a huge surge uphill into a river valley and flooded the town. The result was a stunning new saltwater lake that formed up in the mountains, miles from the sea. The local residents feared that the receding waters would expose dead bodies swept up from the coast by the force of the waves.

In many places boats, cars and trucks were lifted high by the waters and dumped on top of three and four stories buildings, much higher than the recorded height of the waves. This happened because the water got funneled as it travelled through the streets and between the buildings and kept rising up as it pushed materials onto heights of up to 50 feet. The moving wall of debris acted more like a glacier in its scouring strength. The more mass it accumulated the more power it had coming in. In fact, it did not look much like water but rather more like a debris flow which just kept coming in, causing complete destruction. It felt like the entire town was being bulldozed.

Tsunami Effects on the Fukushima Daiichi Site

Having survived the earthquake essentially intact, the Fukushima Daiichi power plant site was now exposed to the onslaught of the tsunami. With the subsidence of the coastline, the 18 foot high defense wall around the plant site proved to be utterly ineffectual and the plant site became instantly vulnerable. The tsunami waves easily smashed over the protecting walls and flooded the diesel generators, which were all located at or below ground level. The placing of the back-up generators, which are used to cool the reactor cores, at low ground elevations proved to be an especially serious and unfortunate design flaw. This singular and unique oversight by itself set Japan on the path to a full blown nuclear crisis.

As the minutes continued to tick on, the nuclear crisis at Fukushima worsened. The emergency batteries were flooded and died and there was no power to activate the pumps to cool the reactors. The temperature within the reactors quickly rose and water levels dropped to dangerous levels in the cooling pools. At the same time pressure began to build up in the reactors. In addition, the extreme heat of the fuel rods began to generate hydrogen gas, and the hydrogen gas exploded, blowing up the roof of the containment building venting radioactivity into the atmosphere. Desperate plant workers injected sea water into the reactors in an effort to cool them down. This was done in spite of the realization that the injection of the salt water would ruin the reactors. The Japanese military joined the effort and used helicopters to scoop water from the ocean to dump on the reactors, but nothing seemed to work. It became quickly evident that it would take a very long time before the situation could be reigned in and stabilized.

The plant had just experienced the worst nuclear disaster since Chernobyl in 1986. A 12-mile exclusion zone was established soon after the tsunami crippled the facility sending three of its reactors into meltdown status, touching off fires and triggering several explosions. It eventually took about eight months to reach an essentially "cold shutdown state," meaning the temperatures at the reactors were deemed to be constant and stable at below the boiling point of water. Even so, a Japanese government panel has estimated that it would eventually take at least 30 years to safely decommission the damaged reactors at Fukushima Daiichi.

One year later, an independent investigation into the accident disclosed that Japan had actually teetered on the edge of an even greater nuclear crisis than the one that actually engulfed the Fukushima Daiichi Plant. Japan's response to the crisis at the time was hindered by a breakdown in communication between the major stake holders: the Prime Minister's office, the Tokyo headquarters of the plant's operator (Tokyo Electric Power, Tepco), and the onsite manager of the stricken plant. The plant Manager argued with top officials in the prime minister's Office that he could get the plant under control if he could keep his staff in place. At the same time he also ignored orders from Tepco's headquarters not to use sea water to cool the overheating reactors. At the same time Tepco's president was calling the prime minister's office arguing that the company should evacuate its entire staff from the stricken plant. Such a step could have been catastrophic and would have allowed the plant to spiral out of control, releasing even larger amounts of radioactive material into the atmosphere. This in turn would have led to the evacuation of other nearby nuclear plants, causing further meltdowns. The prime minister's office was concerned that such a chain reaction of plant meltdowns could eventually lead to the forced evacuation of Tokyo, a metropolis of 30 million people, a disaster of unimaginable proportion.

As it finally turned out, the Japanese people were extremely lucky because the plant manager prevailed in his assessment of the situation and the prime minister was credited with making the right decision by forcing Tepco not to abandon the plant. The gods also helped avoid a worsening scenario by having the winds blow towards the Pacific Ocean instead of towards the land during the four days that immediately followed this great catastrophe.

How Can You Protect Against a Tsunami?

According to the official toll it is the tsunami and not the earthquake that is linked to the over 15,000 deaths and the over 4,000 missing. The high number of the missing is because the dead are counted only when a body is recovered and identified. The missing by now can be assumed to have died as well, bringing the total toll to around 20,000 casualties.

Pneumatic breakwater systems, made of pylons buried in the seafloor, that are capable to telescope upward to variable heights when air is pumped in have been tested at several locations in harbors along the northeast Coast of Japan. It is estimated that, when fully deployed, such pylons could reduce the height of waves by one half. However, the use of breakwaters and sea walls to reduce the impact of tsunamis within a bay are just part of a solution. After all it is not possible to build a sea wall all around Japan. A more effective strategy would be to protect the population by enlisting their cooperation and providing them with easily accessible elevated structures within the most vulnerable areas.

The topic of vertical evacuation is currently being studied at the University of Oregon. A model of Seaside, Oregon, population 6,400, was created in the wave laboratory. The researchers then watched what happened when artificial tsunami waves came in and engulfed the town. The ensuing computer analyses revealed that if everyone followed the current strategy of going up to the hills in the back of the town an estimated 1,700 people, or about 27% of the population, would perish because they will be unable to reach the high ground in time. But, if a strategy to evacuate the population to strategically placed tsunami hardened high towers within the vulnerable zone was adopted, the predicted casualties dropped dramatically to 200, or about 3% of the population. The obvious conclusion reached, therefore, was to re-write a tsunami building code for Oregon that would embrace the concept of vertical evacuation in the hazard zone as its central tenet. This could be accomplished by either:

- Retrofitting tall old buildings that would have to withstand a great earthquake from a subduction zone offshore and the frontal onslaught of a tsunami, or

- By building new structures that are specifically designed for vertical evacuation, or

- By modifying the plans for appropriate tall buildings that are already planned for construction.

Ten miles south of Seaside, the inhabitants of the town of Cannon Beach wanted to do just that. They decided that the New City Hall building they were planning to construct will have to double-up as a tsunami evacuation structure. This new earthquake proof and tsunami hardened building is planned to have a wide staircase to assist the local population reach the wide open roof terrace. The following Figure is an artistic rendition of this building.

Figure 25: Artistic rendition of the planned Cannon Beach City Hall on the West Coast of Oregon, engineered to double up as a vertical evacuation building.

In Japan several types of vertical evacuation structures have already been constructed in the tsunami hazard zones along the East Coast. The Japanese have invested a lot of time and money to ensure that these tall structures are capable to withstand the shaking from major earthquakes and the onslaught of tsunamis. The following figure shows two examples of these types of engineered structures.

Figure 26: Pictures of Vertical Evacuation Structures in Tsunami Hazard zones in Japan.

Finally, the coastal population of Japan should learn to heed the warnings etched in stone that are left by their ancestors all over the vulnerable areas. Most of the warnings just read: **"Do not build your homes below this point"**. This simple and straightforward admonition should now be taken more seriously than ever before.

APPENDIX
Velocity of Body Waves

Laboratory experiments using different types of rocks and artificially produced seismic waves show that the velocity of **P** waves depends on the elastic properties and density of the material through which they pass. The elastic properties of the material are represented by the bulk modulus (K) and the modulus of rigidity (G).

The bulk modulus is an index of how much the volume of the rock changes under the pressure exerted by the wave. Rigidity is a measure of how much a rock deforms when a wave passes through it. The following equation is used to calculate the velocity of **P** waves:

V = Square Root of (K + 4/3G) / D

K = Bulk Modulus, **G** = Modulus of Rigidity (also known as Shear Modulus), and
D = Density

The velocity of **S** waves relates only to the modulus of rigidity and density, and can be calculated using the following equation:

V = Square Root of G/D

Although the equations presented above seem to indicate that velocity is inversely proportional to density, the changes in bulk modulus and modulus of rigidity, in the case of P-waves, and of the modulus of rigidity, in the case of S-waves, are sufficiently large to counter balance the density relationship. For practical purposes it is therefore expedient to consider that seismic velocity increases with rock density.

Velocity of Surface Waves

Rayleigh waves propagate along the surface of the earth with amplitudes that decrease exponentially with depth. The velocity of a Rayleigh wave is approximately 0.9 times that of **S** waves.

Since the velocity of seismic waves increases with depth, another type of surface wave, known as Love wave, will also propagate along the surface slightly more slowly than the Rayleigh waves.

Glossary of Terms and Acronyms used in this Course

Aftershock: A tremor that follows a larger earthquake, or main shock, that originates at or near the focus of the larger earthquake. Generally major earthquakes are usually followed by many aftershocks, which gradually decrease in frequency and magnitude with time. Depending on the size of the main event, aftershocks may last from days to several months.

Amplitude: Half the distance between the crest of a wave or ripple and the adjacent trough.

Epicenter: The point on the earth's surface that is directly above the focus, or point of origin of the earthquake.

Fault: A fracture that separates two blocks of the earth's crust that have slipped with respect to each other parallel to the fracture.

Focus/Hypocenter: The initial rupture point of an earthquake at some depth within the earth.

Magnitude Scale: A measure of the strength of an earthquake as determined by seismographic information. C. F. Richter was the first to define the method to determine the magnitude (see course "G-175-Earthquakes: Basic Principles" for more detailed information).

Plate (Tectonic): A rigid segment of the earth's crust that moves with respect to other adjoining plates. Seismic activity usually occurs along and marks the boundary between two such plates.

Seismograph/Seismometer: An instrument that detects magnifies and records the vibrations of the earth during the occurrence of earthquakes.

Seismogram: The permanent record of an earthquake as recorded by instruments called seismographs/seismometers.

Trench (Oceanic): A narrow and elongate deep depression in the ocean floor oriented parallel to an adjacent continental margin. A trench may be thousands of kilometers long and usually marks the boundary between two rigid plates of the earth's crust. It is along such boundaries that one plate descends into the interior of the earth underneath the other plate.

Tsunami: A gravitational sea wave produced by any large scale, short-duration disturbance of the ocean floor. Although caused primarily by shallow submarine earthquakes, large submarine earth movement or volcanic eruption may also cause it. It is characterized by great speed of propagation, long wavelength, long period, low amplitude on the open sea, and may pile up to heights exceeding 50 feet on entering shallow water along an exposed coast.