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Introduction

A tsunami "harbor wave"; also called a tsunami wave train, and at one time incorrectly referred to as a tidal wave, is a series of water waves caused by the displacement of a large volume of a body of water, usually an ocean, though it can occur in large lakes. Tsunamis are a frequent occurrence in Japan; approximately 195 events have been recorded. Owing to the immense volumes of water and the high energy involved, tsunamis can devastate coastal regions.

Earthquakes, volcanic eruptions and other underwater explosions (including detonations of underwater nuclear devices), landslides and other mass movements, meteorite ocean impacts or similar impact events, and other disturbances above or below water all have the potential to generate a tsunami.

The Greek historian Thucydides was the first to relate tsunami to submarine earthquakes, but the understanding of a tsunami's nature remained slim until the 20th century and is the subject of ongoing research. Many early geological, geographical, and oceanographic texts refer to tsunamis as "seismic sea waves."

Some meteorological conditions, such as deep depressions that cause tropical cyclones, can generate a storm surge, called a meteotsunami, which can raise tides several metres above normal levels. The displacement comes from low atmospheric pressure within the centre of the depression. As these storm surges reach shore, they may resemble (though are not) tsunamis, inundating vast areas of land.

ETYMOLOGY AND HISTORY

The term *tsunami* comes from the Japanese, composed of the two kanji (*tsu*) meaning "harbor" and (*nami*), meaning "wave". (For the plural, one can either follow ordinary English practice and add an *s*, or use an invariable plural as in the Japanese.)

Tsunami are sometimes referred to as tidal waves. In recent years, this term has fallen out of favor, especially in the scientific community, because tsunami actually have nothing to do with tides. The once-popular term derives from their most common appearance, which is that of an extraordinarily high tidal bore. Tsunami and tides both produce waves of water that move inland, but in the case of tsunami the inland movement of water is much greater and lasts for a longer period, giving the impression of an incredibly high tide. Although the meanings of "tidal" include "resembling" or "having the form or character of" the tides, and the term *tsunami* is no more accurate because tsunami are not limited to harbours, use of the term *tidal wave* is discouraged by geologists and oceanographers.

There are only a few other languages that have an equivalent native word. In the Tamil language, the word is *aazhi peralai*. In the Acehnese language, it is *ië beuna* or *alôn buluëk* (Depending on the dialect. Note that in the fellow Austronesian language of Tagalog, a major language in the Philippines, *alon* means "wave".) On Simeulue island, off the western coast of Sumatra in Indonesia, in the Defayan language the word is *smong*, while in the Sigulai language it is *emong*.

As early as 426 B.C. the Greek historian Thucydides inquired in his book *History of the Peloponnesian War* about the causes of tsunami, and was the first to argue that ocean earthquakes must be the cause.

The cause, in my opinion, of this phenomenon must be sought in the earthquake. At the point where its shock has been the most violent the sea is driven back, and suddenly recoiling with redoubled force, causes the inundation. Without an earthquake I do not see how such an accident could happen.

The Roman historian Ammianus Marcellinus (*Res Gestae* 26.10.15-19) described the typical sequence of a tsunami, including an incipient earthquake, the sudden retreat of the sea and a following gigantic wave, after the 365 A.D. tsunami devastated Alexandria.

While Japan may have the longest recorded history of tsunamis, the sheer destruction caused by the 2004 earthquake and tsunami event mark it as the most devastating of its kind in modern times, killing around 230,000 people. The Sumatran region is not unused to tsunamis either, with earthquakes of varying magnitudes regularly occurring off the coast of the island.

GENERATION MECHANISMS

The principal generation mechanism (or cause) of a tsunami is the displacement of a substantial volume of water or perturbation of the sea. This displacement of water is usually attributed to either earthquakes, landslides, volcanic eruptions, or more rarely by meteorites and nuclear tests. The waves formed in this way are then sustained by gravity. Tides do not play any part in the generation of tsunamis.

Tsunami generated by seismicity

Tsunami can be generated when the sea floor abruptly deforms and vertically displaces the overlying water. Tectonic earthquakes are a particular kind of earthquake that are associated with the Earth's crustal deformation; when these earthquakes occur beneath the sea, the water above the deformed area is displaced from its equilibrium position. More specifically, a tsunami can be generated when thrust faults associated with convergent or destructive plate boundaries move abruptly, resulting in water displacement, owing to the vertical component of movement involved. Movement on normal faults will also cause displacement of the seabed, but the size of the largest of such events is normally too small to give rise to a significant tsunami.

Tsunamis have a small amplitude (wave height) offshore, and a very long wavelength (often hundreds of kilometers long, whereas normal ocean waves have a wavelength of only 30 or 40 metres), which is why they generally pass unnoticed at sea, forming only a slight swell usually about 300 millimetres (12 in) above the normal sea surface. They grow in height when they reach shallower water, in a wave shoaling process described below. A tsunami can occur in any tidal state and even at low tide can still inundate coastal areas.

On April 1, 1946, a magnitude-7.8 (Richter Scale) earthquake occurred near the Aleutian Islands, Alaska. It generated a tsunami which inundated Hilo on the island of Hawai'i with a 14 metres (46 ft) high surge. The area where the earthquake occurred is where the Pacific Ocean floor is subducting (or being pushed downwards) under Alaska.

Examples of tsunami originating at locations away from convergent boundaries include Storegga about 8,000 years ago, Grand Banks 1929, Papua New Guinea 1998 (Tappin, 2001). The Grand Banks and Papua New Guinea tsunamis came from earthquakes which destabilized sediments, causing them to flow into the ocean and generate a tsunami. They dissipated before traveling transoceanic distances.

The cause of the Storegga sediment failure is unknown. Possibilities include an overloading of the sediments, an earthquake or a release of gas hydrates (methane etc.)

The 1960 Valdivia earthquake (M_w 9.5) (19:11 hrs UTC), 1964 Alaska earthquake (M_w 9.2), 2004 Indian Ocean earthquake (M_w 9.2) (00:58:53 UTC) and 2011 Tôhoku earthquake (M_w9.0) are recent examples of powerful megathrust earthquakes that generated tsunamis (known as teletsunamis) that can cross entire oceans. Smaller (M_w 4.2) earthquakes in Japan can trigger tsunamis (called local and regional tsunamis) that can only devastate nearby coasts, but can do so in only a few minutes.

In the 1950s, it was discovered that larger tsunamis than had previously been believed possible could be caused by giant landslides. These phenomena rapidly displace large water volumes, as energy from falling debris or expansion transfers to the water at a rate faster than the water can absorb. Their existence was confirmed in 1958, when a giant landslide in Lituya Bay, Alaska, caused the highest wave ever recorded, which had a height of 524 metres (over 1700 feet). The wave didn't travel far, as it struck land almost immediately. Two people fishing in the bay were killed, but another boat amazingly managed to ride the wave. Scientists named these waves megatsunami. Scientists discovered that extremely large landslides from volcanic island collapses can generate megatsunamis that can cross oceans.

Characteristics

Tsunamis cause damage by two mechanisms: the smashing force of a wall of water travelling at high speed, and the destructive power of a large volume of water draining off the land and carrying all with it, even if the wave did not look large.

While everyday wind waves have a wavelength (from crest to crest) of about 100 metres (330 ft) and a height of roughly 2 metres (6.6 ft), a tsunami in the deep ocean has a wavelength of about 200 kilometres (120 mi). Such a wave travels at well over 800 kilometres per hour (500 mph), but owing to the enormous wavelength the wave oscillation at any given point takes 20 or 30 minutes to complete a cycle and has an amplitude of only about 1 metre (3.3 ft). This makes tsunamis difficult to detect over deep water. Ships rarely notice their passage.

As the tsunami approaches the coast and the waters become shallow, wave shoaling compresses the wave and its velocity slows below 80 kilometres per hour (50 mph). Its wavelength diminishes to less than 20 kilometres (12 mi) and its amplitude grows enormously. Since the wave still has the same very long period, the tsunami may take minutes to reach full height. Except for the very largest tsunamis, the approaching wave does not break, but rather appears like a fast-moving tidal bore. Open bays and coastlines adjacent to very deep water may shape the tsunami further into a step-like wave with a steep-breaking front.

When the tsunami's wave peak reaches the shore, the resulting temporary rise in sea level is termed *run up*. Run up is measured in metres above a reference sea level. A large tsunami may feature multiple waves arriving over a period of hours, with significant time between the wave crests. The first wave to reach the shore may not have the highest run up.

About 80% of tsunamis occur in the Pacific Ocean, but they are possible wherever there are large bodies of water, including lakes. They are caused by earthquakes, landslides, volcanic explosions, and bolides.

Drawback

If the first part of a tsunami to reach land is a trough—called a drawback—rather than a wave crest, the water along the shoreline recedes dramatically, exposing normally submerged areas.

A drawback occurs because the water propagates outwards with the trough of the wave at its front. Drawback begins before the wave arrives at an interval equal to half of the wave's period. Drawback can exceed hundreds of metres, and people unaware of the danger sometimes remain near the shore to satisfy their curiosity or to collect fish from the exposed seabed.

SCALES OF INTENSITY AND MAGNITUDE

As with earthquakes, several attempts have been made to set up scales of tsunami intensity or magnitude to allow comparison between different events.

Intensity scales

The first scales used routinely to measure the intensity of tsunami were the *Sieberg-Ambraseys scale*, used in the Mediterranean Sea and the *Imamura-Iida intensity scale*, used in the Pacific Ocean. The latter scale was modified by Soloviev, who calculated the Tsunami intensity *I* according to the formula.

$$I = \frac{1}{2} + \log_2 H_{av}$$

where H_{av} is the average wave height along the nearest coast. This scale, known as the *Soloviev-Imamura tsunami intensity scale*, is used in the global tsunami catalogues compiled by the NGDC/ NOAA and the Novosibirsk Tsunami Laboratory as the main parameter for the size of the tsunami.

Magnitude scales

The first scale that genuinely calculated a magnitude for a tsunami, rather than an intensity at a particular location was the ML scale proposed by Murty & Loomis based on the potential energy. Difficulties in calculating the potential energy of the tsunami mean that this scale is rarely used. Abe introduced the *tsunami* *magnitude scale* M_t, calculated from,

$$M_t = a \log h + b \log R = D$$

where h is the maximum tsunami-wave amplitude (in m) measured by a tide gauge at a distance R from the epicenter, a, b & D are constants used to make the M_t scale match as closely as possible with the moment magnitude scale.

Warnings and predictions

Drawbacks can serve as a brief warning. People who observe drawback (many survivors report an accompanying sucking sound), can survive only if they immediately run for high ground or seek the upper floors of nearby buildings. In 2004, ten-year old Tilly Smith of Surrey, England, was on Maikhao beach in Phuket, Thailand with her parents and sister, and having learned about tsunamis recently in school, told her family that a tsunami might be imminent. Her parents warned others minutes before the wave arrived, saving dozens of lives. She credited her geography teacher, Andrew Kearney.

In the 2004 Indian Ocean tsunami drawback was not reported on the African coast or any other eastern coasts it reached. This was because the wave moved downwards on the eastern side of the fault line and upwards on the western side. The western pulse hit coastal Africa and other western areas.

A tsunami cannot be precisely predicted, even if the magnitude and location of an earthquake is known. Geologists, oceanographers, and seismologists analyse each earthquake and based on many factors may or may not issue a tsunami warning. However, there are some warning signs of an impending tsunami, and automated systems can provide warnings immediately after an earthquake in time to save lives. One of the most successful systems uses bottom pressure sensors that are attached to buoys. The sensors constantly monitor the pressure of the overlying water column. This is deduced through the calculation:

$$P = \rho g h$$

where

P = the overlying pressure in newtons per metre square,

ñ = the density of the seawater= 1.1 x 10^3 kg/m^3,

g = the acceleration due to gravity= 9.8 m/s^2 and

h = the height of the water column in metres.

Hence for a water column of 5,000 m depth the overlying pressure is equal to

$$P = \rho g h = \left(1.1 \times 10^3 \ \frac{\mathrm{kg}}{\mathrm{m}^3}\right)\left(9.8 \ \frac{\mathrm{m}}{\mathrm{s}^2}\right)\left(5.0 \times 10^3 \ \mathrm{m}\right) = 5.4{\times}10^7 \ \frac{\mathrm{N}}{\mathrm{m}^2} = 54 \ \mathrm{MPa}$$

or about 5500 tonnes-force per square metre.

Regions with a high tsunami risk typically use tsunami warning systems to warn the population before the wave reaches land. On the west coast of the United States, which is prone to Pacific Ocean tsunami, warning signs indicate evacuation routes. In Japan, the community is well-educated about earthquakes and tsunamis, and along the Japanese shorelines the tsunami warning signs are reminders of the natural hazards together with a network of warning sirens, typically at the top of the cliff of surroundings hills.

The Pacific Tsunami Warning System is based in Honolulu, Hawaii. It monitors Pacific Ocean seismic activity. A sufficiently large earthquake magnitude and other information triggers a tsunami warning. While the subduction zones around the Pacific are seismically active, not all earthquakes generate tsunami. Computers assist in analysing the tsunami risk of every earthquake that occurs in the Pacific Ocean and the adjoining land masses.

As a direct result of the Indian Ocean tsunami, a re-appraisal of the tsunami threat for all coastal areas is being undertaken by national governments and the United Nations Disaster Mitigation Committee. A tsunami warning system is being installed in the Indian Ocean.

Computer models can predict tsunami arrival, usually within minutes of the arrival time. Bottom pressure sensors relay information in real time. Based on these pressure readings and other seismic information and the seafloor's shape (bathymetry) and coastal topography, the models estimate the amplitude and surge height of the approaching tsunami. All Pacific Rim countries collaborate in the Tsunami Warning System and most regularly practice evacuation and other procedures. In Japan, such preparation is mandatory for government, local authorities, emergency services and the population.

Some zoologists hypothesise that some animal species have an ability to sense subsonic Rayleigh waves from an earthquake or a tsunami.

If correct, monitoring their behavior could provide advance warning of earthquakes, tsunami etc. However, the evidence is controversial and is not widely accepted. There are unsubstantiated claims about the Lisbon quake that some animals escaped to higher ground, while many other animals in the same areas drowned.

The phenomenon was also noted by media sources in Sri Lanka in the 2004 Indian Ocean earthquake. It is possible that certain animals (e.g., elephants) may have heard the sounds of the tsunami as it approached the coast. The elephants' reaction was to move away from the approaching noise. By contrast, some humans went to the shore to investigate and many drowned as a result.

MITIGATION

In some tsunami-prone countries earthquake engineering measures have been taken to reduce the damage caused onshore. Japan, where tsunami science and response measures first began following a disaster in 1896, has produced ever-more elaborate countermeasures and response plans.

That country has built many tsunami walls of up to 4.5 metres (15 ft) to protect populated coastal areas. Other localities have built floodgates and channels to redirect the water from incoming tsunami. However, their effectiveness has been questioned, as tsunami often overtop the barriers.

For instance, the Okushiri, Hokkaidô tsunami which struck Okushiri Island of Hokkaidô within two to five minutes of the earthquake on July 12, 1993 created waves as much as 30 metres (100 ft) tall—as high as a 10-story building. The port town of Aonae was completely surrounded by a tsunami wall, but the waves washed right over the wall and destroyed all the woodframed structures in the area. The wall may have succeeded in slowing down and moderating the height of the tsunami, but it did not prevent major destruction and loss of life.

As a weapon

There have been studies and at least one attempt to create tsunami waves as a weapon. In World War II, the New Zealand Military Forces initiated Project Seal, which attempted to create small tsunamis with explosives in the area of today's Shakespear Regional Park; the attempt failed.

2

History of Tsunami

This chapter lists notable historic tsunamis, which are sorted by the date and location that the tsunami occurred, the earthquake that generated it, or both.

Because of seismic and volcanic activity at tectonic plate boundaries along the Pacific Ring of Fire, tsunamis occur most frequently in the Pacific Ocean, but are worldwide natural phenomena. They are possible wherever large bodies of water are found, including inland lakes, where they can be caused by landslides and glacier calving. Very small tsunamis, non-destructive and undetectable without specialized equipment, occur frequently as a result of minor earthquakes and other events.

As early as 426 BC, the Greek historian Thucydides inquired in his book *History of the Peloponnesian War* (3.89.1-6) about the causes of tsunamis. He argued rightly that it could only be explained as a consequence of ocean earthquakes, and could see no other possible causes for the phenomenon.

Crete and the Argolid and other locations were destroyed by a tsunami caused by the eruption of Thira, which destroyed Minoan civilization on Crete and related cultures in the Cyclades and in areas facing the eruption on the Greek mainland such as the Argolid.

During the Persian siege of the sea town Potidaea, Greece, in 479 BC, the Greek historian Herodotus reports how the Persian attackers who tried to exploit an unusual retreat of the water were suddenly surprised by "a great flood-tide, higher, as the people of the place say, than any one of the many that had been before". Herodotus attributes the cause of the sudden flood to the wrath of Poseidon.

BEFORE 1000 AD

H"6100 BC: Norwegian Sea

The Storegga Slides occurred 100 km north-west of the Møre coast in the Norwegian Sea, causing a very large tsunami in the North Atlantic Ocean.

This collapse involved an estimated 290 km length of coastal shelf, with a total volume of 3,500 km^3 of debris. Based on carbon dating of plant material recovered from sediment deposited by the tsunami, the latest incident occurred around 6100 BC. In Scotland, traces of the subsequent tsunami have been recorded, with deposited sediment being discovered in Montrose Basin, the Firth of Forth, up to 80 km inland and 4 metres above current normal tide levels.

H"1600 BC: Santorini, Greece

The volcanic eruption on Santorini, Greece is assumed to have caused severe damage to cities around it, most notably the Minoan civilization on Crete. A tsunami is assumed to be the factor that caused the most damage.

426 BC: Maliakos Gulf, Greece

In the summer of 426 BC, a tsunami hit hard the Maliakos bay in Eastern Greece. The Greek historian Thucydides (3.89.1-6) described how the tsunami and a series of earthquakes intervened with the events of the raging Peloponnesian War (431-404 BC) and correlated for the first time in the history of natural science quakes and waves in terms of cause and effect.

373 BC: Helike, Greece

An earthquake and a tsunami destroyed the prosperous Greek city Helike, lying 2 km away from the sea. The fate of the city, which remained permanently submerged, was often commented upon by ancient writers and may have inspired the contemporary Plato to the myth of Atlantis.

365 AD: Alexandria, Eastern Mediterranean

In the morning of July 21, 365 AD, an earthquake of great magnitude caused a huge tsunami more than 100 feet high. It devastated Alexandria and the eastern shores of the Mediterranean, killing thousands and hurling ships nearly two miles inland. The Roman historian Ammianus Marcellinus (*Res Gestae* 26.10.15-19) describes in his vivid account the typical sequence of the tsunami including an incipient earthquake, the sudden retreat of the sea and a following gigantic wave:

Slightly after daybreak, and heralded by a thick succession of fiercely shaken thunderbolts, the solidity of the whole earth was made to shake and shudder, and the sea was driven away, its waves were rolled back, and it disappeared, so that the abyss of the depths was uncovered and many-shaped varieties of sea-creatures were seen stuck in the slime; the great wastes of those valleys and mountains, which the very creation had dismissed beneath the vast whirlpools, at that moment, as it was given to be believed, looked up at the sun's rays. Many ships, then, were stranded as if on dry land, and people wandered at will about the paltry remains of the waters to collect fish and the like in their hands; then the roaring sea as if insulted by its repulse rises back in turn, and through the teeming shoals dashed itself violently on islands and extensive tracts of the mainland, and flattened innumerable buildings in towns or wherever they were found.

Thus in the raging conflict of the elements, the face of the earth was changed to reveal wondrous sights. For the mass of waters returning when least expected killed many thousands by drowning, and with the tides whipped up to a height as they rushed back, some ships, after the anger of the watery element had grown old, were seen to have sunk, and the bodies of people killed in shipwrecks lay there, faces up or down. Other huge ships, thrust out by the mad blasts, perched on the roofs of houses, as happened at Alexandria, and others were hurled nearly two miles from the shore, like the Laconian vessel near the town of Methone which I saw when I passed by, yawning apart from long decay.

The tsunami in 365 AD was so devastating that the anniversary of the disaster was still commemorated annually at the end of the

6th century in Alexandria as a "day of horror." Researchers at the University of Cambridge recently carbon dated corals on the coast of Crete which were lifted 10 metres and clear of the water in one massive push.

This indicates that the tsunami of 365 AD was generated by an earthquake in a steep fault in the Hellenic trench near Crete. The scientists estimate that such a large uplift is only likely to occur once in 5,000 years, however the other segments of the fault could slip on a similar scale - and could happen every 800 years or so.

It is unsure whether "one of the contiguous patches might slip in the future."

684 AD: Hakuho, Japan

Japan is the nation with the most recorded tsunamis in the world. The number of tsunamis in Japan totals 195 over a 1,313 year period (thru 1997), averaging one event every 6.73 years, the highest rate of occurrence in the world.

The Great Hakuho Earthquake was the first recorded tsunami in Japan. It hit in Japan on November 29, 684. It occurred off the shore of the Kii Peninsula, Nankaido, Shikoku, Kii, and Awaji region. It has been estimated to be a magnitude 8.4 It was followed by a huge tsunami, but no estimates on how many deaths.

869 AD: Sendai, Japan

The Sendai region was struck by a major tsunami that caused flooding extending 4 km inland from the coast. The town of Tagajô was destroyed, with an estimated 1,000 casualties.

887 AD: Ninna Nankai, Japan

On August 26 of the Ninna era, there was a strong shock in the Kyoto region, causing great destruction and some victims. At the same time, there was a strong earthquake in Osaka, Shiga, Gifu, and Nagano prefectures. A tsunami flooded the coastal locality, and some people died. The coast of Osaka and primarily Osaka Bay suffered especially heavily from the tsunami. The tsunami was also observed on the coast of Hyuga-Nada.

1000–1700

1293: Kamakura, Japan

Magnitude 7.1 Quake and tsunami hit Kamakura, Japan's *de facto* capital, killing 23,000 after resulting fires.

1303: Eastern Mediterranean

A team from Southern Cross University in Lismore, New South Wales, Australia, has found geological evidence of five tsunamis that have hit Greece over the past 2000 years. "Most were small and local, but in 1303 a larger one hit Crete, Rhodes, Alexandria and Acre in Palestine."

1361: Shôhei Nankai, Japan

On Aug 3 of the Shôhei era, a 8.4 Nankaido quake and tsunami hit, with 660 deaths, 1700 houses destroyed. There was a strong earthquake in Tokushima, Osaka, Wakayama, and Nara Prefectures and on Awaji Island. A tsunami was observed on the coast of Tokushima and Kochi Prefectures, in Kii Strait and in Osaka Bay.Yunomine Hot Spring (Wakayama Prefecture) stopped. Yukiminato, Awa completely destroyed by tsunami and more than 1,700 houses washed away. 60 persons drowned at Awa.

1498: Meiô Nankai, Japan

Sep 20 7.5 Quake and tsunami hit in the Meiô era. Port in Wakayama damaged by tsunami of several meters in height.30-40 thousand deaths estimated. The building around great Buddha of Kamakura (altitude 7m) was swept away by the tsunami.

1541: Nueva Cadiz, Venezuela

In 1528, Cristóbal Guerra founded the city "La Villa de la Nueva Cádiz" in the island of Cubagua, the first Spanish settlement in Venezuela, and one of the first ones in the Americas. Nueva Cádiz, which reached a population between 1000 and 1500, was destroyed in an earthquake followed by tsunami in 1541. The ruins were declared a National Monument of Venezuela in 1979.

1605: Keichô Nankaido, Japan

On Feb 3 of the Keichô era, a 8.1 Quake and tsunami hit 700 houses (41%) at Hiro, Wakayama Prefecture washed away. 3,600 drowned in Shishikui area. Awa, wave height 6-7m. 350 at Kannoura 60 at Sakihama drowned, wave height 5–6 m and 8–10 m, respectively. Total more than 5,000 drowned. An enormous tsunami with a maximum known rise of water of 30 m was observed on the coast from the Boso Peninsula to the eastern part of Kyushu Island. The eastern part of the Boso Peninsula, the coast of Tokyo Bay, the coast of the prefectures of Kanagawa and Shizouka, and the southeastern coast of Kochi Prefecture suffered especially heavily.

1607: Bristol Channel, Great Britain

On 30 January 1607, approximately 2,000 or more people were drowned, houses and villages swept away and an estimated 200 square miles (518 km2) was inundated. Until the 1990s, it was undisputed that the flooding was caused by a storm surge aggravated by other factors, but recent research indicates a tsunami. The probable cause is postulated as a submarine earthquake off the Irish coast.

1698: Seikaido-Nankaido, Japan

On December 22, 1698, a large tsunami struck Seikaido-Nankaido, Japan.

1700S

1700: Vancouver Island, Canada

On January 26, 1700, the Cascadia earthquake, one of the largest earthquakes on record (estimated MW 9 magnitude), ruptured the Cascadia subduction zone (CSZ) offshore from Vancouver Island to northern California, and caused a massive tsunami across the Pacific Northwest logged in Japan and oral traditions of the indigenous peoples of the Pacific Northwest.

1707: Hôei, Japan

On October 28, 1707, during the Hôei era, an 8.4 earthquake and tsunami 25.7-meter-high struck at the Kochi Prefecture. More than 29,000 houses in total wrecked and washed away and about 30,000 deaths. In Tosa, 11,170 houses washed away and 18,441 people drowned. About 700 drowned and 603 houses washed away in Osaka. 20 m high at Tanezaki, Tosa, 6.58 at Muroto. Hot springs at Yunomine, Sanji, Ryujin, Seto-Kanayana (Kii) and Dogo (Iyo,145 days) stopped.

1741: W. Hokkaido, Japan

On 29 August 1741 the western side of Hokkaido was hit by a tsunami associated with the eruption of the volcano on Oshima island. The cause of the tsunami is thought to have been a large landslide, partly submarine, triggered by the eruption. 1,467 people were killed on Hokkaido and another 8 in Aomori Prefecture.

1755: Lisbon, Portugal

Tens of thousands of Portuguese people who survived the Great Lisbon Earthquake on November 1, 1755 were killed by a tsunami which followed 40 minutes later.

Many townspeople fled to the waterfront, believing the area safe from fires and from falling debris from aftershocks. When at the waterfront, they saw that the sea was rapidly receding, revealing a sea floor littered with lost cargo and forgotten shipwrecks. The tsunami struck with a maximum height of 15 metres (49 ft), and went far inland.

The earthquake, tsunami, and many fires killed between 60,000 and 100,000 in Lisbon alone, making it one of the deadliest natural disasters in recorded history. Historical records of explorations by Vasco da Gama and other early navigators were lost, and countless buildings were destroyed (including most examples of Portugal's Manueline architecture).

Europeans of the 18th century struggled to understand the disaster within religious and rational belief systems. Philosophers of the Enlightenment, notably Voltaire, wrote about the event. The philosophical concept of the sublime, as described by philosopher Immanuel Kant in the *Observations on the Feeling of the Beautiful and Sublime*, took inspiration in part from attempts to comprehend the enormity of the Lisbon quake and tsunami.

The tsunami took just over 4 hours to travel over 1,000 miles (1,600 km) to Cornwall in the United Kingdom. An account by

Arnold Boscowitz claimed "great loss of life." It also hit Galway in Ireland, and caused some serious damage to the Spanish Arch section of the city wall.

1771: Yaeyama Islands, Okinawa, Japan

An undersea earthquake of estimated magnitude 7.4 occurred near Yaeyama Islands in Okinawa, Japan on 4 April 1771 at about 8 A.M.. The earthquake is not believed to have directly resulted in any deaths, but a resulting tsunami is thought to have killed about 12,000 people, (9313 on the Yaeyama Islands and 2548 on Miyako Islands according to one source). Estimates of the highest seawater runup on Ishigaki Island, range between 30 meters and 85.4 meters. The tsunami put an abrupt stop to population growth on the islands, and was followed by malaria epidemics and crop failures which decreased the population further. It was to be another 148 years before population returned to its pre-tsunami level.

1792: Mount Unzen, Nagasaki Prefecture, Kyûshû, Japan

Tsunamis were the main cause of death for Japan's worst-ever volcanic disaster, due to an eruption of Mount Unzen in Nagasaki Prefecture, Kyûshû, Japan. It began towards the end of 1791 as a series of earthquakes on the western flank of Mount Unzen which gradually moved towards *Fugen-daké*, one of Mount Unzen's peaks. In February 1792, *Fugen-daké* started to erupt, triggering a lava flow which continued for two months. Meanwhile, the earthquakes continued, shifting nearer to the city of Shimabara. On the night of 21 May, two large earthquakes were followed by a collapse of the eastern flank of Mount Unzen's Mayuyama dome, causing an avalanche which swept through Shimabara and into Ariake Bay, triggering a tsunami. It is not known to this day whether the collapse occurred as a result of an eruption of the dome or as a result of the earthquakes. The tsunami struck Higo Province on the other side of Ariake Bay before bouncing back and hitting Shimabara again. Out of an estimated total of 15,000 fatalities, around 5,000 is thought to have been killed by the landslide, around 5,000 by the tsunami across the bay in Higo Province, and a further 5,000 by the tsunami returning to strike Shimabara. The waves reached a height of 330 ft, classing this tsunami as a small megatsunami.

1800S

1833: Sumatra, Indonesia

On 25 November 1833, a massive earthquake estimated to have been between 8.8-9.2 on the moment magnitude scale, struck Sumatra in Indonesia. The coast of Sumatra near the quake's epicentre was hardest hit by the resulting tsunami.

1854: Nankai, Tokai, and Kyushu Japan

The Ansei Quake which hit the south coast of Japan, was actually set of 3 quakes, two magnitude 8.4 quakes and a 7.4 quake all in 3 days.

- The first on Nov 4, 1854 near what is today Aichi Prefecture and Shizuoka Prefecture with tsunami.
- It was followed by another 8.4 the next day in Wakayama Prefecture, Earthquake generated a maximum wave of 28 meters at Kochi, Japan, and the earthquake that tsunami killed 3,000 people. The tsunami washed 15,000 homes away. The number of homes destroyed directly by the earthquake was 2,598; 1,443 people died.
- The third was a 7.4 quake on Nov 7, 1854 in Ehime Prefecture and Oita Prefecture.

The total result was 80,000-100,000 deaths.

1855: Edo, Japan

The following year, the 1855 Great Ansei Edo Quake hit (Tokyo region), killing 4,500 to 10,000 people. Popular stories of the time blamed the quakes and tsunamis on giant catfish called Namazu thrashing about. The Japanese era name was changed to bring good luck after 4 menacing quake/tsunamis in 2 years.

1868: Hawaiian Islands

On April 2, 1868, a local earthquake with a magnitude estimated between 7.5 and 8.0 rocked the southeast coast of the Big Island of Hawai»i. It triggered a landslide on the slopes of the Mauna Loa volcano, five miles north of Pahala, killing 31 people. A tsunami then claimed 46 additional lives. The villages of Punaluu, Ninole, Kawaa, Honuapo, and Keauhou Landing were severely damaged and the village of »Âpua was destroyed. According to one account, the tsunami “rolled in over the tops of the coconut trees, probably 60 feet high .... inland a distance of a quarter of a mile in some places, taking out to sea when it returned, houses, men, women, and almost everything movable.” This was reported in the 1988 edition of Walter C. Dudley’s book “Tsunami!”

1868: Arica, Chile

On August 16, 1868, an earthquake with a magnitude estimated at 8.5 struck the oceanic trench currently known as the Peru-Chile Trench. A resulting tsunami struck the port of Arica, then part of Peru, killing an estimated 25,000 in Arica and 70,000 in all. Three military vessels anchored at Arica, the US warship *Wateree* and the storeship *Fredonia*, and the Peruvian warship *America*, were swept up by the tsunami.

1883: Krakatoa, Sunda Strait, Indonesia

The island volcano of Krakatoa in Indonesia exploded with devastating fury on August 26–27, 1883, blowing its underground magma chamber partly empty so that much overlying land and seabed collapsed into it. A series of large tsunami waves was generated from the collapse, some reaching a height of over 40 meters above sea level. Tsunami waves were observed throughout the Indian Ocean, the Pacific Ocean, and even as far away as the American West Coast, and South America. On the facing coasts of Java and Sumatra the sea flood went many miles inland and caused such vast loss of life that one area was never resettled but reverted to the jungle and is now the Ujung Kulon nature reserve.

1896: Meiji Sanriku, Japan

On 15 June 1896, at around 19:36 local time, a large undersea earthquake off the Sanriku coast of northeastern Honshû, Japan, triggered tsunami waves which struck the coast about half an hour later. Although the earthquake itself is not thought to have resulted in any fatalities, the waves, which reached a height of 100 feet, killed approximately 27,000 people. In 2005 the same general area was hit by the 2005 Sanriku Japan Earthquake, but with no major tsunami.

1900–1950

1908: Messina, Italy

The 1908 Messina earthquake in Italy, triggered a large tsunami that took more than 70,000 lives.

1923: Kanto, Japan

The Great Kanto Earthquake, which occurred in eastern Japan on 1 September 1923, and devastated Tokyo, Yokohama and the surrounding areas, caused tsunamis which struck the Shonan coast, Boso Peninsula, Izu Islands and the east coast of Izu Peninsula, within minutes in some cases. In Atami, waves reaching 12 meters were recorded. Examples of tsunami damage include about 100 people killed along Yuigahama beach in Kamakura and an estimated 50 people on the Enoshima causeway. However, tsunamis only accounted for a small proportion of the final death toll of over 100,000, most of whom were killed in fire.

1929: Newfoundland

On November 18, 1929, an earthquake of magnitude 7.2 occurred beneath the Laurentian Slope on the Grand Banks. The quake was felt throughout the Atlantic Provinces of Canada and as far west as Ottawa and as far south as Claymont, Delaware. The resulting tsunami measured over 7 meters in height and took about 2½ hours to reach the Burin Peninsula on the south coast of Newfoundland, where 28 people lost their lives in various communities. It also snapped telegraph lines laid under the Atlantic.

1933: Showa Sanriku, Japan

On March 3, 1933, the Sanriku coast of northeastern Honshû, Japan which had already suffered a devastating tsunami in 1896 (see above) was again stuck by tsunami waves as a result of an offshore magnitude 8.1 earthquake. The quake destroyed about 5,000 homes and killed 3,068 people, the vast majority as a result of tsunami waves. Especially hard hit was the coastal village of Taro (now part of Miyako city) in Iwate Prefecture, which lost 42% of its total population and 98% of its buildings. Taro is now protected by an enormous tsunami wall, currently 10 meters in height and over 2 kilometers long. The original wall, constructed in 1958, saved Taro from destruction of the 1960 Chilean tsunami (see below). However it failed to protect Taro from the 2011 Tôhoku earthquake and tsunami which inundated the village with 12-15 meters of water.

1944: Tonankai, Japan

A magnitude 8.0 earthquake on 7 December 1944, about 20 km off the Shima Peninsula in Japan, which struck the Pacific coast of central Japan, mainly Mie, Aichi, and Shizuoka Prefectures. News of the event was downplayed by the authorities in order to protect wartime morale, and as a result the full extent of the damage is not known, but the quake is estimated to have killed 1223 people, the tsunami being the leading cause of the fatalities.

1946: Nankaidô, Japan

The Nankai earthquake on 21 December 1946 had a magnitude of 8.4 and hit at 4:19 [local time]. There was a catastrophic earthquake on the southwest of Japan in the Nankai Trough. It was felt almost everywhere in the central and western parts of the country. The tsunami that washed away 1451 houses and caused 1500 deaths in Japan. It was observed on tide gauges in California, Hawaii, and Peru.

The Nankai megathrust earthquakes are periodic earthquakes occurring off the southern coast of Kii Peninsula and Shikoku, Japan every 100 to 150 years. Particularly hard hit were the coastal towns of Kushimoto and Kainan on the Kii Peninsula. The quake led to more than 1400 deaths, tsunami being the leading cause. measuring 8.4.

1946: Aleutian Islands

On April 1, 1946, the Aleutian Islands tsunami killed 159 people on Hawaii and five in Alaska (the lighthouse keepers at the Scotch Cap Light in the Aleutians).

It resulted in the creation of a tsunami warning system known as the Pacific Tsunami Warning Center (PTWC), established in 1949 for Oceania countries. The tsunami is known as the April Fools Day Tsunami in Hawaii due to people thinking the warnings were an April Fools prank.

1950–2000

1952: Severo-Kurilsk, Kuril Islands, USSR

1952 Severo-Kurilsk Tsunami was a major tsunami that hit Severo-Kurilsk, Kuril Islands, Sakhalin Oblast, Russian SFSR, USSR, which occurred on 5 November 1952 at about 5 a.m. It led to the destruction of many settlements in Sakhalin Oblast and Kamchatka Oblast, while the main impact struck the town of Severo-Kurilsk. The tsunami was generated by a major earthquake in the Pacific Ocean, 130 km from the shore of Kamchatka, with an estimated magnitude of 8.5. There were three waves about 15-18 m high. After the earthquake the majority of the Severo-Kurilsk citizens fled to the surrounding hills, where they escaped the first wave. However, most of them returned to the town and were killed by the second wave. The third wave was minor. According to the authorities, out of a population of 6,000 people, 2,336 died.

The remaining survivors were evacuated to continental Russia. The settlement was then rebuilt in another location.

The November 5, 1952 tsunami killed 2,336 on the Kuril Islands, USSR.

1958: Lituya Bay, Alaska, USA

The 1958 Lituya Bay megatsunami occurred on July 9, 1958, in Lituya Bay, Alaska, reaching a height of 524 meters (1,720 feet), 143 meters (470 feet) taller than the roof of the Empire State Building. This was the highest recorded megatsunami, which is defined as a wave reaching more than 100 meters (328 feet) in the deep ocean.

Lituya Bay

Lituya Bay is a fjord located on the Fairweather Fault in the northeastern part of the Gulf of Alaska. It is a T-shaped bay with a width of two miles (3 km) and a length of seven miles. Lituya Bay is an ice-scoured tidal inlet with a maximum depth of 220 m (722 ft). The narrow entrance of the bay has a depth of only 10 m (33 ft). The two arms that create the top of the T-shape of the bay are the Gilbert and Crillon inlets and are a part of a trench on the Fairweather Fault. In the past 150 years Lituya Bay has had five megatsunamis. The last event, before the 1958 megatsunami, occurred on October 27, 1936. This wave reached a height of 150m (492 feet), and was caused by another giant landslide from the mountains.

Inlets

Near the crest of the Fairweather Mountains sit the Lituya and the North Crillon glaciers. They are each about 12 miles (19 km) long and one mile (1.6 km) wide with an elevation of 4000 ft (1,220m). The retreats of these glaciers form the present *T* shape of the bay, the Gilbert and Crillon inlets.

Earthquake

The major earthquake that struck on the Fairweather Fault had a Richter scale reading of 7.9, and some sources have reported it to be as much as 8.3. The epicenter of the quake was at latitude 58.6N., longitude 137.1W. near the Fairweather Range, 7.5 miles (12.1 km) east of the surface trace of the Fairweather fault, and 13 miles (21 km) southeast of Lituya Bay. This earthquake had been the strongest in over 50 years for this region. (The Cape Yakataga earthquake, with a reading of 8.2 on the Richter scale, occurred on September 4, 1899.) The shock was felt in southeastern Alaska cities over an area of 400,000 square miles (1,000,000 km^2), as far south as Seattle, Washington, and as far east as Whitehorse, Y.T., Canada.

Landslide

The earthquake caused a subaerial rock fall in the Gilbert Inlet. This landslide caused 30 million cubic meters of rock to fall into the bay, creating the megatsunami.

Sudden glacial lake drainage

After the earthquake there was an observation made on the subglacial lake, located northwest of the bend in the Lituya Glacier at the head of Lituya Bay. This subglacial lake had dropped 100 ft (30 m). So this proposes another possible cause to the production of the giant 1,720 ft (520 m) wave. It is possible that a good amount of water drained from the glacial lake through a glacial tunnel flowing directly in front of the glacier, though neither the rate of drainage nor the volume of water drained could produce a wave run-off to be 1,720 ft. After all, even if a large enough drainage were to take place in front of the Gilbert Glacier, the run-off would have been projected to be on the opposite side in Crillon inlet. After these considerations glacial drainage was not the mechanism that caused the giant wave.

EYEWITNESS ACCOUNT

At 22:15 PST on July 9, 1958, which is still daylight at that time of year, an earthquake with a magnitude of 7.9 struck the Lituya Bay area. The tide was ebbing at about plus 1.5 m and the weather was clear. Anchored in Anchorage Cove, near the west side of the entrance of the bay, Bill and Vivian Swanson were on their boat fishing when the earthquake hit.:

With the first jolt, I tumbled out of the bunk and looked toward the head of the bay where all the noise was coming from. The mountains were shaking something awful, with slide of rock and snow, but what I noticed mostly was the glacier, the north glacier, the one they call Lituya Glacier. I know you can't ordinarily see that glacier from where I was anchored. People shake their heads when I tell them I saw it that night. I can't help it if they don't believe me. I know the glacier is hidden by the point when you're in Anchorage Cove, but I know what I saw that night, too. The glacier had risen in the air and moved forward so it was in sight. It must have risen several hundred feet. I don't mean it was just hanging in the air. It seems to be solid, but it was jumping and shaking like crazy. Big chunks of ice were falling off the face of it and down into the water. That was six miles away and they still looked like big chunks. They came off the glacier like a big load of rocks spilling out of a dump truck. That went on for a little while—its hard to tell just how long—and then suddenly the glacier dropped back out of sight and there was a big wall of water going over the point. The wave started for us right after that and I was too busy to tell what else was happening up there.

Based on this description, it is possible that the quake had caused the entire glacier (or a large portion of it) to slide over the cliff. What the fisherman may have seen, therefore, could have been that section breaking off and falling into the bay. This might account for the vast displacement of water, while leaving little or no evidence once the ice melted. The height of the wave was accurately measured at 1,720 feet (520 m), based on the elevation extent of the damage caused to the foliage up the headlands around the bay.

1960: Valdivia, Chile

The 1960 Valdivia earthquake or Great Chilean earthquake (Spanish: *Gran terremoto de Chile/Valdivia*) of 22 May 1960 is to date the most powerful earthquake ever recorded on Earth, rating 9.5 on the moment magnitude scale. It occurred in the afternoon (19:11 GMT, 14:11 local time) and its resulting tsunami affected southern Chile, Hawaii, Japan, the Philippines, eastern New Zealand, southeast Australia, and the Aleutian Islands in Alaska.

The initial epicenter was near Cañete (see map) some 900 km (435 miles) south of Santiago, with Temuco being the closest large city, while Valdivia was the most affected city. It caused localised tsunamis that severely battered the Chilean coast, with waves up to 25 metres (82 ft). The main tsunami raced across the Pacific Ocean and devastated Hilo, Hawaii. Waves as high as 10.7 metres (35 ft) were recorded 10,000 kilometres (6,000 miles) from the epicenter, and as far away as Japan and the Philippines.

The death toll (and rate) and monetary losses arising from such a widespread disaster are not obvious. Various estimates of the total number of fatalities from the earthquake and tsunamis have been published, with the USGS citing studies with figures of 2,231; 3,000; or 5,700 killed, and another source uses an estimate of 6,000 dead. Different sources have estimated the monetary cost ranged from 400 million to 800 million US dollars (or 2.9 to 5.8 billion in 2011 dollars, adjusted for inflation).

EARTHQUAKE DEVELOPMENT

The Great Chilean Earthquake came after a smaller earthquake in Arauco Province at 06:02 on 21 May 1960. Telecommunications to southern Chile were cut off and President Jorge Alessandri cancelled the traditional ceremony of the Battle of Iquique memorial holiday to oversee the emergency assistance efforts. The government was just beginning to organize help to the affected region when the second earthquake occurred at 14:55 UTC on 22 May in Valdivia. The second earthquake affected all of Chile between Talca and Chiloé Island, more than 400,000 square kilometers (154,440.9 sq mi). Coastal villages, such as Toltén, disappeared. At Corral, the main port of Valdivia, the water level rose 4 m (13 ft) before it began to recede. At 16:20 UTC, an 8 m (26 ft) wave struck the Chilean coast, mainly between Concepción and Chiloe. Ten minutes later another wave measuring 10 m (33 ft) was reported.

Hundreds of people were already reported dead by the time the tsunami struck. One ship, *Canelos*, starting at the mouth of Valdivia River sank after being moved 1.5 km (1 mi) backward and forward in the river; its mast is still visible from the road to Niebla.

A number of Spanish-colonial fortifications were completely destroyed. Soil subsidence also destroyed buildings, deepened local rivers, and created wetlands in places like the Río Cruces and Chorocomayo, a new aquatic park north of the city. Extensive areas of the city were flooded. The electricity and water systems of Valdivia were totally destroyed. Witnesses reported underground water flowing up through the soil. Despite the heavy rains of 21 May, the city was without a water supply. The river turned brown with sediment from landslides and was full of floating debris, including entire houses. The lack of potable water became a serious problem in one of Chile's rainiest regions.

The earthquake did not strike all the territory with the same strength; measured with the Mercalli scale tectonically depressed areas suffered heavier damage. The two most affected areas were Valdivia and Puerto Octay near the northwest corner Llanquihue Lake. The overall picture of damage showed that Puerto Octay was the center of a north-south elliptical area in the Central Valley where the intensity was at its highest if not counting the Valdivia Basin. East of Puerto Octay in a hotel in Todos los Santos Lake piles of plates were reported to have remained in place.

Two days after the earthquake Cordón Caulle, a volcanic vent close to Puyehue volcano, erupted. Other volcanoes may also have erupted, but none were recorded due to the lack of communication in Chile at the time. The relatively low death toll in Chile (estimated at 6,000) is explained in part by the low population density and by buildings being built taking into account that the region is very active geologically. Other possible reasons include a high number of wooden houses and that coastal towns also tended to be located on higher ground, following a pre-Hispanic tradition.

Tectonic interpretation

The earthquake was a megathrust earthquake resulting from the release of mechanical stress between the subducting Nazca Plate and the South American Plate, on the Peru-Chile Trench. The focus was relatively shallow at 33 km, considering that earthquakes in northern Chile and Argentina may reach depths of 70 km. Subduction zones are known to produce the strongest earthquakes on earth as their particular structure allows more stress to build up before energy is released. Geophysicists consider it a matter of time before this earthquake will be surpassed in magnitude by another. The earthquake's rupture zone was 800 km long, stretching from Talca (35° S) to Chiloé Archipelago (43° S). The rupture velocity has been estimated as 3.5 km per second. On 27 February 2010 at 03:34 local time an 8.8 magnitude earthquake occurred just to the north (off the coast of the Maule region of Chile, between Concepción and Santiago). This quake was reported to be centered approximately 22 miles (35.4 km) deep and several miles off shore.

NATURAL DISASTERS TRIGGERED

Landslides

The earthquake triggered numerous landslides, mainly in the steep glacial valley of the southern Andes. Within the Andes most landslides occurred on forested mountain slopes around the Liquiñe-Ofqui Fault. Some of these areas remain sparsely vegetated while others have naturally developed more or less pure strands of Nothofagus dombeyi. These landslides did not cause many fatalities nor significant economical losses because most of the areas were uninhabited with only minor roads. One landslide did however cause destruction and alarm following its blockage of the outflow of Riñihue Lake (see Riñihuazo). Landslides in the mountains around Golgol River caused it to dam up and then burst creating a flood down to Puyehue Lake. These landslides destroyed also parts of the international Route 215-CH that connects to Bariloche in Argentina trough Cardenal Antonio Samoré Pass.

Sub-aqueous landslides are known to have occurred in Puyehue and Todos los Santos Lake as well as in Reloncaví Fjord.

Tsunami

Earthquake-induced tsunamis affected southern Chile, Hawaii, Japan, the Philippines, eastern New Zealand, south east Australia and the Aleutian Islands. Some localised tsunamis severely battered the Chilean coast, with waves up to 25 metres (82 ft). The main tsunami crossed the Pacific Ocean at a speed of several hundred km/h and devastated Hilo, Hawaii, killing 61 people, allegedly due to their failure to heed warning sirens. Hilo's position in the bay caused a cumulative bounce of tsunami waves far more destructive to Hilo than to other more exposed areas of Hawaii. In Japan, the tsunami arrived about 22 hours after the earthquake and 142 people were killed. Tsunami waves as high as 10.7 metres (35 ft) were recorded 10,000 kilometres (6,000 miles) from the epicentre, several as far away as Japan and the Philippines.

Riñihuazo flood

During the Great Chilean Earthquake, several landslides west of Tralcán Mountain blocked the outflow of Riñihue Lake (39°452 003 S 72°302 003 Wÿþ / ÿþ39.75°S 72.5°Wÿþ / -39.75; -72.5). Riñihue Lake is the lowest of the Seven Lakes chain and receives a constant inflow from the Enco River. The blocked San Pedro River, which drains the lake, passes through several towns and the city of Valdivia before finally reaching Corral Bay.

Because the San Pedro River was blocked, the water level of Riñihue Lake started to rise quickly. Each meter the water level rose was equivalent to 20 million cubic meters, which meant that 4,800 million cubic meters of water would release into the San Pedro River (easily overpowering its flow capacity of 400 cubic meters (14,126 cubic feet) if it rose above the final, 24-meter-high dam. This potential disaster would have violently flooded all the settlements along the course of the river in less than five hours, and had more dire consequences if the dam suddenly broke.

About 100,000 people lived in the affected zone. Plans were made to evacuate Valdivia, and many people left. To avoid the destruction of the city, several military units and hundreds of workers from ENDESA, CORFO, and MOP started an effort, called the Riñihuazo, to control the lake. Twenty-seven bulldozers were put into service, but they had severe difficulties moving in the mud near the dams, so dykes had to be constructed with shovels. The work was not restricted to the lake; drainages from other parts of the Seven Lakes were also dammed to minimize the flow into Riñihue Lake. These dams were removed later, with the exception of Calafquén Lake, which still retains its dam.

By 23 June, the main dam had been lowered from 24 m (79 ft) to 15 m (49 ft), allowing 3,000 million cubic meters of water to leave the lake gradually, but still with considerable destructive power. The team was led by ENDESA engineer Raúl Sáez.

Cordón Caulle eruption

On 24 May, 38 hours after the main shock of the 1960 Valdivia earthquake, Cordón Caulle began a rhyodacitic fissure eruption. Being located between two sparsely populated and isolated Andean valleys, the eruption had few eyewitnesses and received little attention by local media, preoccupied with the huge damages and losses caused by the earthquake. The eruption fed a 5.5 km long and N135° trending fissure where 21 individual vents have been found. These vents produced an output of about 0.25 km^3 DRE both in form of lava flows and tephra. The eruption ended on 22 July.

CONSEQUENCES AND RESPONSE

Urban impact in Valdivia

It has been estimated that about 40% of the houses in Valdivia were destroyed, leaving 20,000 people homeless. The most affected structures were those built of concrete, which in some cases collapsed completely due to lack of earthquake engineering. Traditional wooden houses fared better and were in many places left uninhabitable but without collapse. Houses built upon tectonically elevated areas suffered considerably less damage compared to those on the lowlands. Many city blocks with destroyed buildings in the city center remained empty until the 1990s and 2000s, with some of them still being used as parking lots. Some of these blocks had before the earthquake modern concrete buildings built after the great fire of 1909. In terms of urban development Valdivia suffered the loss of the minor but significant Cau-Cau bridge, a bridge that has not been rebuilt. The other bridges suffered only minor damage. Land subsidence in Corral Bay improved navigability as shoal banks produced earlier by sediments from Madre de Dios and other nearby gold mines sunk and compacted.

The earthquake and the degradation to a provincial capital are seen in retrospect as the culmination of a long period of economic decline that began with shifts in trade routes due to the expansion of railroads in southern Chile and the opening of the Panama Canal in 1911. Industrial activity in Valdivia, dominated by Germans, declined further due to human and capital migration after the earthquake. Facilities of several industries, such as the Anwandter brewery and the Rudloff shoe factory, were destroyed and activity eliminated.

In 1974 Valdivia lost its capital status to Puerto Montt when the military government of Chile reorganized the country's administrative divisions. Valdivia had previously been a first level administrative center within Chile since the 16th century. It regained its status in 2007 with the creation of the Los Ríos Region.

Creation of emergency committee

After the 1960 Valdivia earthquake a committee was formed to solve problems caused by the earthquake. However this committee was not dissolved afterward and in 1974 it became ONEMI (Spanish acronym for National Emergency and Information Office) when it acquired by law independent status as a governmental office.

Human sacrifice

In the coastal village Collileufu, Lafkenches carried out a ritual human sacrifice during the days following the main earthquake. Collileufu, located in the Budi Lake area, south of Puerto Saavedra, was by 1960 highly isolated and inhabitants there spoke mainly Mapudungun. The community had gathered in Cerro La Mesa, while the lowlands were struck by successive tsunamis. Juana Namuncura Añen, a local machi, demanded the sacrifice of the grandson of Juan Painecur, a neighbor, in order to calm the earth and the ocean.

The victim, 5 year old José Luis Painecur, had his arms and legs removed by Juan Pañán and Juan José Painecur (the victim's grandfather), and was stuck into the sand of the beach like a stake. The waters of the Pacific Ocean then carried the body out to sea. The sacrifice came to be known after a boy in the commune of Nueva Imperial denounced to local leaders the theft of two horses that were allegedly eaten during the sacrifice ritual.

The 2 men were charged with the crime of murder and confessed, but later recanted. They were released after 2 years. A judge ruled that those involved had "acted without free will, driven by an irresistible natural force of ancestral tradition." The story was mentioned in a *Time* magazine article, although with little detail.

PREVIOUS AND LATER EARTHQUAKES

There is evidence that a similar landslide and earthquake occurred in 1575. This earthquake was of similar strength and also caused a Riñihuazo. According to Mariño de Lobera, corregidor of Valdivia in 1575, a landslide blocked the outflow of the lagoon of Renigua and several months later caused a flood. Mariño de Lobera states that while the flood killed many Indians, Spanish settlers waited on high ground until after the dam burst.

The 2010 Chile earthquake may be related or consequential to the 1960 tremor.

In popular culture

A 1969 episode of the U.S. television series *Hawaii Five-O* titled "Forty Feet High and it Kills!" referenced the tsunami that devastated Hilo in 1960.

Chilean novelist Isabel Allende included the 1960 Valdivia earthquake in *The House of the Spirits* (1982) and *The Stories of Eva Luna* (1989).

1963: Vajont Dam, Monte Toc, Italy

The Vajont Dam (or Vaiont Dam) is a disused dam, completed in 1959 in the valley of the Vajont river under Monte Toc, 100 km north of Venice, Italy. A 1963 landslide caused the overtopping of the dam and around 2,000 deaths.

One of the tallest dams in the world, it is 262 metres (860 ft) high, 27 metres (89 ft) thick at the base and 3.4 metres (11 ft) at the top. Its 1963 over-topping was caused when the designers ignored the geological instability of Monte Toc on the southern side of the basin.

Warning signs and negative appraisals during the early stages of filling were disregarded, and the attempt to complete the filling led to a landslide which created a wave that brought massive flooding and destruction to the Piave valley below, wiping out several villages completely.

On 12 February 2008, while launching the International Year of Planet Earth, UNESCO cited the Vajont Dam tragedy as one of five “cautionary tales”, caused by “the failure of engineers and geologists.”

CONSTRUCTION

The dam was built by SADE (*Società Adriatica di Elettricità*, English: *Adriatic Energy Corporation*), the electricity supply and distribution monopolist in North-Eastern Italy. The owner, Giuseppe Volpi di Misurata, had been Mussolini’s Minister of Finances for several years. The ‘tallest dam in the world’, across the Vajont gorge, was conceived in the 1920s to meet the growing demands for industrialization, but not until the confusion after Mussolini’s fall during World War II was the project authorized on 15 October 1943.

The dam and basin were intended to be at the centre of a complex system of water management in which water would have been channeled from nearby valleys and artificial basins located at higher levels. Tens of kilometres of concrete pipes and pipe-bridges across valleys were planned. Due to the 1963 disaster and to smaller scale landslides in other basins in the zone, the system was never actually operated.

In the 1950s SADE's monopoly was confirmed by post-Fascist governments and it purchased the land despite opposition by the communities of Erto and Casso in the valley, which was overcome with government and police support. SADE stated that the geology of the gorge had been studied, including analysis of ancient landslides, and that the mountain was believed to be sufficiently stable.

Construction work started in 1957, but by 1959 shifts and fractures were noticed while building a new road on the side of Monte Toc. This led to new studies in which three different experts separately told SADE that the entire side of Monte Toc was unstable and would likely collapse into the basin if the filling were completed. All three were ignored by SADE. This has been attributed to the need to meet deadlines for public funding, and to activate the plant before the soon-to-be-approved nationalization of electricity production, so maximizing compensation from the State. In October 1959 construction was completed and in February 1960 SADE was authorised to start filling the basin.

EARLY SIGNS OF DISASTER

Throughout the summer of 1960, minor landslides and earth movements were noticed; however instead of heeding these warning signs, the Italian government chose to sue the handful of journalists reporting the problems for "undermining the social order."

On 4 November 1960, with the level of the basin at about 190 meters of the planned 262, a landslide of about 800,000 cubic meters collapsed into the lake. SADE stopped the filling, lowered the level by about 50 metres and started to build an artificial gallery in the basin in front of Monte Toc, to keep the basin usable even when the expected further landslides divided it into two parts.

In October 1961, after the completion of the gallery, SADE restarted the filling under controlled monitoring. In April and May 1962, with the basin at 215 meters, the people of Erto e Casso reported five earthquakes of 'grade five' on the Mercalli scale, though SADE downplayed their importance. SADE was then authorized to complete the filling up to the maximum level.

In July 1962, SADE's own engineers reported the results of model-based experiments on the effects of further landslides into the lake, which predicted a devastating disaster if they happened when the basin was full. The management ignored these results as well.

In November 1962, SADE was taken into the public ownership of ENEL.

In March 1963, the dam was transferred to the newly constituted public company for electricity, ENEL, but the management remained the same. In the following summer, with the basin almost completely filled, slides, shakes and movements of the ground were continuously reported by the scared population. On 15 September the entire side of the mountain moved down by 22 centimetres. On 26 September, ENEL decided to slowly empty the basin down to the level of 240 meters, but in early October the collapse of the mountain looked unavoidable - one day it moved almost one meter. There is no known record of any warning or displacement order being issued to the populace.

LANDSLIDE AND WAVE

On 9 October 1963 at approximately 10:35pm, the combination of 'drawing-down the reservoir' and heavy rains triggered a landslide of about 260 million cubic meters of forest, earth, and rock, which fell into the reservoir at up to 110 km per hour (68 mph). The resulting displacement of water caused 50 million cubic meters of water to over-top the dam in a 250-meter high wave. Despite this, the dam's structure was largely undamaged — the top metre or so of masonry was washed away, but the basic structure remained intact.

The flooding in the Piave valley destroyed the villages of Longarone, Pirago, Rivalta, Villanova and Faè, killing around 2000 people and turning the land below into a flat plain of mud. Many small villages in the territory of Erto e Casso and the village of Codissago, near Castellavazzo, were largely wrecked. Estimates of the dead range from 1900 to 2500 people, and about 350 families lost all members. Most of the survivors had lost relatives and friends along with their homes and belongings.

The villages near the landslide also suffered damage from the air displacement caused by the impact.

Causes and responsibilities

Immediately after the disaster, the government (who now owned the dam), politicians and public authorities insisted on attributing the tragedy to an unexpected and unavoidable natural event.

The debate in the newspapers was heavily influenced by politics. The left-wing paper L'Unità was the first to denounce the actions of the management and government, as it had previously carried a number of articles by Tina Merlin addressing the behaviour of the SADE management in the Vajont project and other businesses. Indro Montanelli, the most influential Italian journalist and a vocal anti-communist, attacked L'Unità and denied any human factor: L'Unità and PCI were dubbed "jackals, speculating on pain and on the dead" in many articles by the Domenica del Corriere and in a poster of a national campaign paid by Democrazia Cristiana (DC). The catastrophe was attributed only to natural causes and God's will.

The DC campaign accused PCI of sending agitprops into the refugee communities, in form of relief personnel: most of them were partisans from Emilia Romagna who fought on Mount Toc in the Second World War and often had friends in the stricken area.

DC, the party of prime minister Giovanni Leone, accused the PCI of 'political profiteering' from the tragedy. Leone promised to bring justice to the people killed in the disaster. A few months after he lost the premiership he became the head of SADE's team of lawyers who significantly reduced compensation for survivors and avoided payment to at least 600 victims.

The DC's newspaper, La Discussione, stated that the disaster was a "mysterious act of God's love", in an article that was strongly criticized by L'Unità.

Apart from journalistic attacks and the attempted cover-up from news sources aligned with the government, there had been proven flaws in the geological assessments and disregard of warnings about the likelihood of a disaster by SADE, ENEL and the government.

The trial was moved by the judges of the preliminary trial to L'Aquila, near Rome, thus preventing public participation, and resulted in mild punishments for a few of the SADE and ENEL engineers. One SADE engineer (Mario Pancini) committed suicide in 1968. The government never sued SADE for damage compensation.

Subsequent engineering analysis has focused on the cause of the landslide, and there remains ongoing debate about the contribution of rainfall, dam level changes and earthquakes as triggers of the landslide, as well as differing views about whether it was an old landslide that slipped further or a completely new one.

There were a number of problems with the choice of site for the dam and reservoir: The canyon was steep sided, the river had undercut its banks, the limestone and clay-stone rocks that made up the walls of the canyon were inter-bedded with the slippery clay-like Lias and Dogger Jurassic period horizons and the Cretaceous period Malm horizon, all of which were inclined towards the axis of the canyon. In addition, the limestone layers contained many solution caverns which only became more saturated due to rains in September.

Prior to the landslide that caused the over-topping flood, the creep of the regolith had been 0.4 inches per week. During September this creep reached 10.0 inches per day until finally, the day before the landslide, the creep was measured at 40.0 inches (1 metre).

Reconstruction

Most of the survivors were moved into a newly built village, Vajont, 50 kilometres south east on the river Tagliamento plain. Those who insisted on returning to their mountain life in Erto e Casso were strongly discouraged. Longarone and other villages in the Piave valley were rebuilt with modern houses and factories.

The government used the disaster to promote the industrialization of the North-East of Italy. Survivors were entitled to ‘business start-up’ loans, public subsidies and ten years tax exemption, all of which they could ‘sell-on’ to major companies from the Venice region. These concessions were then converted into millions of euro for plants elsewhere. Among the corporations were Zanussi (now owned by Electrolux), Ceramica Dolomite (now owned by American Standard), Confezioni SanRemo, and SAVIC (now owned by Italcementi).

Compensation measures did not clearly differentiate between victims and people who lived nearby, thus much of the compensation went to people who had suffered little damage, creating a negative public image.

A pumping station was installed in the dam basin to keep the lake at a constant level, and the bypass gallery was lengthened beyond the dam to let the water flow down to the Piave valley. The dam wall is still in place and maintained, but there are no plans to exploit it. The dry basin, filled with landslip, has been open to visitors since 2002.

In the media

After the initial world-wide reporting the tragedy became regarded as part of the ‘price of economic growth’ in the 1950s and 1960s.

Interest was rejuvenated by a 1997 television program by Marco Paolini and Gabriele Vacis, “Il racconto del Vajont”.

A 2001 movie “Vajont, La diga del disonore” (“Vajont, the dam of dishonour”) or “La folie des hommes” (in France), starred Michel Serrault and Daniel Auteuil.

It was studied in the 2008 documentary series *Disasters of the Century*.

Images at Italian Wiki

- Aerial view of the ‘Valley-Vajont’ shortly after the disaster of 9 October 1963. Only available on Italian Wikipedia due to Copyright restrictions. The image shows the landslide of 260 million cubic meters of rock and mud that has detached from Mount Toc, then filled and overflowed the reservoir. The ‘over-top’ rock flow on the right side shows the origin of the minor damage to the top 2 meters of concrete that is still visible in 2009.

- The 'bell tower' at Longarone shortly after the disaster of 9 October 1963. Only available on Italian Wikipedia due to Copyright restrictions. The Bell Tower that remained standing after the passage of the 'wave of death'. The Church at the base was completely swept away with the entire village.

The Vajont Dam was completed in 1961 under Monte Toc, 100 km north of Venice, Italy. At 262 metres, it was one of the highest dams in the world. On October 9, 1963 an enormous landslide of about 260 million cubic metres of forest, earth, and rock, fell into the reservoir at up to 110 km per hour (68 mph). The resulting displacement of water caused 50 million cubic metres of water to overtop the dam in a 250-metre high megatsunami wave. The flooding destroyed the villages of Longarone, Pirago, Rivalta, Villanova and Faè, killing 1,450 people. Almost 2,000 people (some sources report 1,909) perished in total.

1964: Niigata, Japan (°e_o0W—)

The 1964 Niigata earthquake in Japan killed 28 people, and liquefacted whole apartment buildings. A subsequent tsunami destroyed the port of Niigata city. ja:°e_o0W.

1964: Alaska, USA

The 1964 Alaska earthquake, also known as the Great Alaskan Earthquake, the Portage Earthquake and the Good Friday Earthquake, was a megathrust earthquake that began at 5:36 P.M. AST on Good Friday, March 27, 1964. Across south-central Alaska, ground fissures, collapsing buildings, and tsunamis resulting from the earthquake caused about 131 deaths.

Lasting nearly four minutes, it was the most powerful recorded earthquake in U.S. and North American history, and the second most powerful ever measured by seismograph. It had a magnitude of 9.2, at the time making it the second largest earthquake in recorded history.

The powerful earthquake produced earthquake liquefaction in the region. Ground fissures and failures caused major structural damage in several communities, much damage to property and several landslides.

Anchorage sustained great destruction or damage to many inadequately engineered houses, buildings, and infrastructure (paved streets, sidewalks, water and sewer mains, electrical systems, and other man-made equipment), particularly in the several landslide zones along Knik Arm. Two hundred miles southwest, some areas near Kodiak were permanently raised by 30 feet (9.1 m). Southeast of Anchorage, areas around the head of Turnagain Arm near Girdwood and Portage dropped as much as 8 feet (2.4 m), requiring reconstruction and fill to raise the Seward Highway above the new high tide mark.

In Prince William Sound, Port Valdez suffered a massive underwater landslide, resulting in the deaths of 30 people between the collapse of the Valdez city harbor and docks, and inside the ship that was docked there at the time. Nearby, a 27-foot (8.2 m) tsunami destroyed the village of Chenega, killing 23 of the 68 people who lived there; survivors out-ran the wave, climbing to high ground. Post-quake tsunamis severely affected Whittier, Seward, Kodiak, and other Alaskan communities, as well as people and property in British Columbia, Oregon, and California. Tsunamis also caused damage in Hawaii and Japan. Evidence of motion directly related to the earthquake was reported from all over the earth.

Geology

At 5:36 p.m. Alaska Standard Time (3:36 a.m. March 28, 1964 UTC), a fault between the Pacific and North American plates ruptured near College Fjord in Prince William Sound. The epicenter of the earthquake was 61°032 N 147°292 Wÿþ / ÿþ61.05°N 147.48°Wÿþ / 61.05; -147.48, 12.4 mi (20 km) north of Prince William Sound, 78 miles (125 km) east of Anchorage and 40 miles (64 km) west of Valdez. The focus occurred at a depth of approximately 15.5 mi (25 km). Ocean floor shifts created large tsunamis (up to 220 feet (67 m) in height), which resulted in many of the deaths and much of the property damage. Large rockslides were also caused, resulting in great property damage. Vertical displacement of up to 38 feet (11.5 m) occurred, affecting an area of 100,000 miles^2 (250,000 km^2) within Alaska.

Studies of ground motion have led to a peak ground acceleration estimate of 0.14 - 0.18 *g*.

Type of fault

The Alaska Earthquake was a subduction zone earthquake (megathrust earthquake), caused by an oceanic plate sinking under a continental plate. The fault responsible was the Aleutian Megathrust. It was a reverse fault caused by a compressional force. This caused much of the uneven ground.

DEATH TOLL, DAMAGE AND CASUALTIES

Various sources indicate that about 131 people died as a result of the earthquake: nine during the earthquake itself, 106 from subsequent tsunamis in Alaska and 16 from tsunamis in Oregon and California. Property damage was estimated at over $310 million ($2.12 billion in current U.S. dollars).

Anchorage area

Most damage occurred in Anchorage, 75 mi (120 km) northwest of the epicenter. Nine people were killed, the only deaths directly attributed to the earthquake. Anchorage was not hit by tsunamis, but downtown Anchorage was heavily damaged, and parts of the city built on sandy bluffs overlying “Bootlegger Cove clay” near Cook Inlet, most notably the Turnagain neighborhood, suffered landslide damage. The Government Hill school suffered from the Government Hill landslide leaving it in two jagged, broken pieces. Land overlooking the Ship Creek valley near the Alaska Railroad yards also slid, destroying many acres of buildings and city blocks in downtown Anchorage. Most other areas of the city were only moderately damaged. The 60-foot concrete control tower at Anchorage International Airport was not engineered to withstand earthquake activity and collapsed, killing one employee.

The house at 918 W. 10th Avenue suffered damage peripherally, but one block away the recently completed and still unoccupied Four Seasons Building on Ninth Avenue collapsed completely with one whole wing sticking up out of the rubble like a seesaw.

The hamlets of Girdwood and Portage, located 30 and 40 mi (60 km) southeast of central Anchorage on the Turnagain Arm, were destroyed by subsidence and subsequent tidal action. Girdwood was relocated inland and Portage was abandoned. About 20 miles (32 km) of the Seward Highway sank below the high-water mark of Turnagain Arm; the highway and its bridges were raised and rebuilt in 1964-66.

Elsewhere in Alaska

Most coastal towns in the Prince William Sound, Kenai Peninsula, and Kodiak Island areas, especially the major ports of Seward, Whittier and Kodiak were heavily damaged by a combination of seismic activity, subsidence, post-quake tsunamis and/or earthquake-caused fires. Valdez was not totally destroyed, but after three years, the town relocated to higher ground 7 km (4 mi) west of its original site.

Some Alaska Native villages, including Chenega and Afognak, were destroyed or damaged. The earthquake caused the Cold-War era ballistic missile detection radar of Clear Air Force Station to go offline for six minutes, the only unscheduled interruption in its operational history. Near Cordova, the Million Dollar Bridge crossing the Copper River also collapsed. The community of Girdwood was also confined to the southern side of the Seward Highway when water rushed into Turnagain Arm arm and flooded or destroyed any buildings left standing to the north of the highway. Interestingly, only the ground immediately along the highway and that on the north side of the road dropped, prompting geologists to speculate that Girdwood may rest upon an ancient cliff face, now covered by countless thousands of years of sediment and glacial deposits.

Canada

A 4.5 ft (1.4 m) wave reached Prince Rupert, British Columbia, just south of the Alaska Panhandle, about three hours after the quake. The tsunami then reached Tofino, on the exposed west coast of Vancouver Island, and traveled up a fjord to hit Port Alberni twice, washing away 55 homes and damaging 375 others. The towns of Hot Springs Cove, Zeballos, and Amai also saw damage. The damage in British Columbia was estimated at $10 million Canadian ($65 million in 2006 Canadian dollars, or $56 million in 2006 U.S. dollars).

Elsewhere

Twelve people were killed by the tsunami in or near Crescent City, California, while four children were killed on the Oregon coast at Beverly Beach State Park. Other towns along the U.S. Pacific Northwest and Hawaii were damaged. Minor damage to boats reached as far south as Los Angeles.

As the entire planet vibrated as a result of the quake, minor effects were felt worldwide. Several fishing boats were sunk in Louisiana, and water sloshed in wells in Africa.

AFTERSHOCKS

Over 10,000 aftershocks were recorded following the main shock. In the first day alone, eleven major aftershocks were recorded with a magnitude greater than 6.0. Nine more occurred over the next three weeks. It was not until more than a year later that the aftershocks were no longer noticed.

1976: Moro Gulf, Mindanao, Philippines

On August 16, 1976 at 12:11 A.M., a devastating earthquake of 7.9 hit the island of Mindanao, Philippines. It created a tsunami that devastated more than 700 km of coastline bordering Moro Gulf in the North Celebes Sea. An estimated number of victims for this tragedy left 5,000 dead, 2,200 missing or presumed dead, more than 9,500 injured and a total of 93,500 people were left homeless. It devastated the cities of Cotabato, Pagadian, and Zamboanga, and the and provinces of Basilan, Lanao del Norte, Lanao del Sur, Maguindanao, Sultan Kudarat, Sulu, and Zamboanga del Sur.

1979: Tumaco, Colombia

A magnitude 7.9 earthquake occurred on December 12, 1979 at 7:59:4.3 UTC along the Pacific coast of Colombia and Ecuador. The earthquake and the resulting tsunami caused the destruction of at least six fishing villages and the death of hundreds of people in the Colombian Department of Nariño. The earthquake was felt in Bogotá, Cali, Popayán, Buenaventura, and several other cities and towns in Colombia and in Guayaquil, Esmeraldas, Quito, and other parts of Ecuador.

When the tsunami hit the coast, it caused huge destruction in the city of Tumaco, as well as in the small towns of El Charco, San Juan, Mosquera, and Salahonda on the Pacific coast of Colombia. The total number of victims of this tragedy was 259 dead, 798 wounded and 95 missing or presumed dead.

1980: Spirit Lake, Washington, USA

Spirit Lake is a lake north of Mount St. Helens in Washington State. The lake was a popular tourist destination for many years until the 1980 eruption of Mount St. Helens. With the eruption and resulting megatsunami, thousands of trees were torn from the surrounding hillside after lake water was displaced 800 feet up the hillside. Lahar and pyroclastic flow deposits from the eruption then blocked the North Fork Toutle River valley at its outlet, raising the surface elevation of the lake by over 200 ft (60 m). The newly raised lake, once it reappeared, was also 10 percent smaller and much shallower.

After the eruption, Spirit Lake contained highly toxic water with volcanic gases seeping up from the lake bed. A month after the eruption, the bacteria-carrying water was devoid of oxygen. Scientists predicted that the lake would not recover quickly, but the reemergence of phytoplankton starting in 1983 began to restore oxygen levels. Amphibians such as frogs and salamanders recolonized the lake, and fish (reintroduced by fishermen) thrived.

However, the logs that were deposited in the lake during the Mount St. Helens eruption still remain and cover a large portion of the surface water. The rasping of logs together has deposited tree bark in the bottom of the lake.

The bare logs sink upright to the bottom of the lake due to the higher density of the root end, and land on layers of volcanic ash sediment. The high mineral content of the water rapidly petrifies the logs in upright position as transplanted stumps. Spirit Lake is the first location where this process was observed; the process was predicted by scientists shortly before the 1980 eruption. Even though the lake was devastated by Mount St. Helens, it has rebounded significantly and is on the way to recovery.

Before the eruption of Mount St. Helens, there were four camps on the shore of Spirit Lake: a Boy Scout camp, a Girl Scout camp, a YMCA camp, and another for the general public. There were also a number of lodges catering to visitors, including Spirit Lake Lodge and Mt. St. Helens Lodge; the latter was inhabited by Harry R. Truman, who became one of the volcano's victims.

1983: Sea of Japan

On May 26, 1983 at 11:59:57 local time, a magnitude-7.7 earthquake occurred in the Sea of Japan, about 100 km west of the coast of Noshiro in Akita Prefecture, Japan. Out of the 107 fatalities, all but four were killed by the resulting tsunami, which struck communities along the coast, especially Aomori and Akita Prefectures and the east coast of Noto Peninsula. Footage of the tsunami hitting the fishing harbor of Wajima on Noto Peninsula was broadcast on TV. The waves exceeded 10 meters in some areas. Three of the fatalities were along the east coast of South Korea (whether North Korea was affected is not known). The tsunami also hit Okushiri Island, the site of a more deadly tsunami 10 years later.

1993: Okushiri, Hokkaido, Japan

The 1980 eruption of Mount St. Helens, a stratovolcano located in Washington state, in the United States, was a major volcanic eruption. The eruption (which was a VEI 5 event) was the only significant one to occur in the contiguous 48 U.S. states since the 1915 eruption of Lassen Peak in California.

The eruption was preceded by a two-month series of earthquakes and steam-venting episodes, caused by an injection of magma at shallow depth below the volcano that created a huge bulge and a fracture system on Mount St. Helens' north slope.

USGS scientists convinced the authorities to close Mount St. Helens to the general public and to maintain the closure in spite of pressure to re-open it; their work saved thousands of lives.

An earthquake at 8:32:17 a.m. PDT (UTC-7) on Sunday, May 18, 1980, caused the entire weakened north face to slide away, suddenly exposing the partly molten, gas- and steam-rich rock in the volcano to lower pressure. The rock responded by exploding a hot mix of lava and pulverized older rock toward Spirit Lake so fast that it overtook the avalanching north face.

An eruption column rose 80,000 feet (24,400 m) into the atmosphere and deposited ash in 11 U.S. states. At the same time, snow, ice and several entire glaciers on the volcano melted, forming a series of large lahars (volcanic mudslides) that reached as far as the Columbia River, nearly fifty miles (eighty kilometers) to the southwest. Less severe outbursts continued into the next day only to be followed by other large but not as destructive eruptions later in 1980.

Fifty-seven people (including innkeeper Harry R. Truman and geologist David A. Johnston) and thousands of animals were killed. Hundreds of square miles were reduced to wasteland, causing over a billion U.S. dollars in damage ($2.74 billion in 2007 dollars), and Mount St. Helens was left with a crater on its north side. At the time of the eruption, the summit of the volcano was owned by the Burlington Northern Railroad, but afterward the land passed to the United States Forest Service. The area was later preserved, as it was, in the Mount St. Helens National Volcanic Monument.

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2004: Indian Ocean

The 2004 Indian Ocean earthquake was an undersea megathrust earthquake that occurred at 00:58:53 UTC on Sunday, December 26, 2004, with an epicentre off the west coast of Sumatra, Indonesia. The quake itself is known by the scientific community as the Sumatra-Andaman earthquake. The resulting tsunami is given various names, including the 2004 Indian Ocean tsunami, South Asian Tsunami, Indonesian Tsunami, and Boxing Day Tsunami.

The earthquake was caused by subduction and triggered a series of devastating tsunamis along the coasts of most landmasses bordering the Indian Ocean, killing over 230,000 people in fourteen countries, and inundating coastal communities with waves up to 30 meters (100 feet) high. It was one of the deadliest natural disasters in recorded history. Indonesia was the hardest hit, followed by Sri Lanka, India, and Thailand.

With a magnitude of between 9.1 and 9.3, it is the third largest earthquake ever recorded on a seismograph. This earthquake had the longest duration of faulting ever observed, between 8.3 and 10 minutes. It caused the entire planet to vibrate as much as 1 centimetre (0.4 inches) and triggered other earthquakes as far away as Alaska. Its hypocenter was between Simeulue and mainland Indonesia.

The plight of the many affected people and countries prompted a worldwide humanitarian response. In all, the worldwide community donated more than $14 billion (2004 U.S. dollars) in humanitarian aid.

EARTHQUAKE CHARACTERISTICS

The earthquake was initially documented as moment magnitude 8.8. In February 2005 scientists revised the estimate of the magnitude to 9.0. Although the Pacific Tsunami Warning Center has accepted these new numbers, the United States Geological Survey has so far not changed its estimate of 9.1. The most recent studies in 2006 have obtained a magnitude of M_w 9.1–9.3. Dr. Hiroo Kanamori of the California Institute of Technology believes that M_w 9.2 is a good representative value for the size of this great earthquake.

The hypocentre of the main earthquake was approximately 160 km (100 mi), in the Indian Ocean just north of Simeulue island, off the western coast of northern Sumatra, at a depth of 30 km (19 mi) below mean sea level (initially reported as 10 km (6.2 mi)). The northern section of the Sunda megathrust, which had been assumed dormant, ruptured; the rupture having a length of 1,300 km (810 mi). The earthquake (followed by the tsunami) was felt simultaneously as far away as Bangladesh, India, Malaysia, Myanmar, Thailand, Singapore and the Maldives. Splay faults, or secondary "pop up faults", caused long, narrow parts of the sea floor to pop up in seconds. This quickly elevated the height and increased the speed of waves, causing the complete destruction of the nearby Indonesian town of Lhoknga.

Indonesia lies between the Pacific Ring of Fire along the north-eastern islands adjacent to and including New Guinea and the Alpide belt along the south and west from Sumatra, Java, Bali, Flores, and Timor.

Great earthquakes such as the Sumatra-Andaman event, which are invariably associated with megathrust events in subduction zones, have seismic moments that can account for a significant fraction of the global earthquake moment across century-scale time periods. The Sumatra-Andaman earthquake was the largest earthquake since 1964, and the second largest since the Kamchatka earthquake of October 16, 1737.

Of all the seismic moment released by earthquakes in the 100 years from 1906 through 2005, roughly one-eighth was due to the Sumatra-Andaman event. This quake, together with the Good

Friday Earthquake (Alaska, 1964) and the Great Chilean Earthquake (1960), account for almost half of the total moment. The much smaller but still catastrophic 1906 San Francisco earthquake is included in the diagram below for perspective. M_w denotes the magnitude of an earthquake on the moment magnitude scale.

Since 1900 the only earthquakes recorded with a greater magnitude were the 1960 Great Chilean Earthquake (magnitude 9.5) and the 1964 Good Friday Earthquake in Prince William Sound (9.2). The only other recorded earthquakes of magnitude 9.0 or greater were off Kamchatka, Russia, on November 4, 1952 (magnitude 9.0) and Tôhoku, Japan (magnitude 9.0) on March 11, 2011. Each of these megathrust earthquakes also spawned tsunamis in the Pacific Ocean. However, the death toll from these was significantly lower, primarily because of the lower population density along the coasts near affected areas and the much greater distances to more populated coasts and also due to the superior infrastructure and warning systems in MEDCs (More Economically Developed Countries) such as Japan.

Other very large megathrust earthquakes occurred in 1868 (Peru, Nazca Plate and South American Plate); 1827 (Colombia, Nazca Plate and South American Plate); 1812 (Venezuela, Caribbean Plate and South American Plate) and 1700 (western North America, Juan de Fuca Plate and North American Plate). All of them are believed to be greater than magnitude 9, but no accurate measurements were available at the time.

Tectonic plates

The megathrust earthquake was unusually large in geographical and geological extent. An estimated 1,600 kilometres (1,000 mi) of fault surface slipped (or ruptured) about 15 metres (50 ft) along the subduction zone where the India Plate slides (or subducts) under the overriding Burma Plate. The slip did not happen instantaneously but took place in two phases over a period of several minutes:

- Seismographic and acoustic data indicate that the first phase involved a rupture about 400 kilometres (250 mi) long and 100 kilometres (60 mi) wide, located 30 kilometres (19 mi) beneath the sea bed—the largest rupture ever known to have been caused by an earthquake. The rupture proceeded at a speed of about 2.8 kilometres per second (1.7 miles per second) (10,000 km/h or 6,200 mph), beginning off the coast of Aceh and proceeding north-westerly over a period of about 100 seconds.

- A pause of about another 100 seconds took place before the rupture continued northwards towards the Andaman and Nicobar Islands. However, the northern rupture occurred more slowly than in the south, at about 2.1 km/s (1.3 mi/s) (7,500 km/h or 4,700 mph), continuing north for another five minutes to a plate boundary where the fault type changes from subduction to strike-slip (the two plates slide past one another in opposite directions). This reduced the speed of the water displacement and so reducing the size of the tsunami that hit the northern part of the Indian Ocean.

The India Plate is part of the great Indo-Australian Plate, which underlies the Indian Ocean and Bay of Bengal, and is drifting north-east at an average of 6 centimetres per year (2.4 inches per year). The India Plate meets the Burma Plate (which is considered a portion of the great Eurasian Plate) at the Sunda Trench. At this point the India Plate subducts beneath the Burma Plate, which carries the Nicobar Islands, the Andaman Islands, and northern Sumatra. The India Plate sinks deeper and deeper beneath the Burma Plate until the increasing temperature and pressure drive volatiles out of the subducting plate. These volatiles rise into the overlying plate causing partial melting and the formation of magma. The rising magma intrudes into the crust above and exits the Earth's crust through volcanoes in the form of a volcanic arc. The volcanic activity that results as the Indo-Australian Plate subducts the Eurasian Plate has created the Sunda Arc.

As well as the sideways movement between the plates, the sea floor is estimated to have risen by several metres, displacing an estimated 30 cubic kilometres (7.2 cu mi) of water and triggering devastating tsunami waves. The waves did not originate from a point source, as was inaccurately depicted in some illustrations of their paths of travel, but rather radiated outwards along the entire 1,600-kilometre (1,000 mi) length of the rupture (acting as a line source). This greatly increased the geographical area over which the waves were observed, reaching as far as Mexico, Chile, and the Arctic. The raising of the sea floor significantly reduced the capacity of the Indian Ocean, producing a permanent rise in the global sea level by an estimated 0.1 millimetres (0.004 in).

Aftershocks and other earthquakes

Numerous aftershocks were reported off the Andaman Islands, the Nicobar Islands and the region of the original epicentre in the hours and days that followed. The largest aftershock, which originated off the coast of the Sumatran island of Nias, registered a magnitude of 8.7, prompting debate among seismologists as to whether it should be classified as an aftershock of the December 2004 quake or as a “triggered earthquake” (which typically differs from an aftershock in that it is not located along the same fault line and may be as large or larger than the earthquake which triggered it). This earthquake was so large that it produced its own aftershocks (some registering a magnitude of as great as 6.1) and presently ranks as the 7th largest earthquake on record since 1900. Other aftershocks of up to magnitude 6.6 continued to shake the region daily for up to three or four months. As well as continuing aftershocks, the energy released by the original earthquake continued to make its presence felt well after the event. A week after the earthquake, its reverberations could still be measured, providing valuable scientific data about the Earth’s interior.

The 2004 Indian Ocean earthquake came just three days after a magnitude 8.1 earthquake in an uninhabited region west of New Zealand’s sub-Antarctic Auckland Islands, and north of Australia’s Macquarie Island. This is unusual, since earthquakes of magnitude 8 or more occur only about once per year on average. Some seismologists have speculated about a connection between these two earthquakes, saying that the former one might have been a catalyst to the Indian Ocean earthquake, as the two earthquakes happened on opposite sides of the Indo-Australian Plate. However, the U.S. Geological Survey sees no evidence of a causal relationship in this incident. Coincidentally, the earthquake struck almost exactly one year (to the hour) after a 6.6 magnitude earthquake killed an estimated 30,000 people in the city of Bam in Iran on December 26, 2003.

Some scientists confirm that the December earthquake had activated Leuser Mountain, a volcano in Aceh province along the same range of peaks as Mount Talang, while the 2005 Sumatran earthquake had sparked activity in Lake Toba, an ancient crater in Sumatra. Geologists say that the eruption of Mount Talang in April 2005 is connected to the December earthquake.

Energy released

The energy released on the Earth's surface only (M_E, which is the *seismic potential for damage*) by the 2004 Indian Ocean earthquake and tsunami was estimated at 1.1×10^{17} joules, or 26.3 megatons of TNT. This energy is equivalent to over 1502 times that of the Hiroshima atomic bomb, but less than that of Tsar Bomba, the largest nuclear weapon ever detonated. However, this is but a tiny fraction of the total work done M_W (and thus energy) by this quake, 4.0×10^{22} joules (4.0×10^{29} ergs), the vast majority underground. This equates to 4.0×10^{22} J, over 363,000 times more than its M_E. This is a truly enormous figure, equivalent to 9,560 gigatons of TNT equivalent (550 million times that of Hiroshima), or about 370 years of energy use in the United States at 2005 levels of 1.08×10^{20} J.

The only recorded earthquakes with a larger M_W were the 1960 Chilean and 1964 Alaskan quakes, with 2.5×10^{23} joules (250 ZJ) and 7.5×10^{22} joules (75 ZJ) respectively.

The earthquake generated a seismic oscillation of the Earth's surface of up to 20–30 cm (8–12 in), equivalent to the effect of the tidal forces caused by the Sun and Moon. The shock waves of the earthquake were felt across the planet; as far away as the U.S. state of Oklahoma, where vertical movements of 3 mm (0.12 in) were recorded. By February 2005, the earthquake's effects were still detectable as a 20 µm (0.02 mm; 0.0008 in) complex harmonic oscillation of the Earth's surface, which gradually diminished and merged with the incessant free oscillation of the Earth more than 4 months after the earthquake.

Because of its enormous energy release and shallow rupture depth, the earthquake generated remarkable seismic ground motions around the globe, particularly due to huge Rayleigh (surface) elastic waves that exceeded 1 cm (0.4 in) in vertical amplitude everywhere on Earth. The record section plot below displays vertical displacements of the Earth's surface recorded by seismometers from the IRIS/USGS Global Seismographic Network plotted with respect to time (since the earthquake initiation) on the horizontal axis, and vertical displacements of the Earth on the vertical axis (note the 1 cm scale bar at the bottom for scale). The seismograms are arranged vertically by distance from the epicenter in degrees. The earliest, lower amplitude, signal is that of the compressional (P) wave, which takes about 22 minutes to reach the other side of the planet (the antipode; in this case near Ecuador). The largest amplitude signals are seismic surface waves that reach the antipode after about 100 minutes. The surface waves can be clearly seen to reinforce near the antipode (with the closest seismic stations in Ecuador), and to subsequently encircle the planet to return to the epicentral region after about 200 minutes. A major aftershock (magnitude 7.1) can be seen at the closest stations starting just after the 200 minute mark. This aftershock would be considered a major earthquake under ordinary circumstances, but is dwarfed by the mainshock.

The shift of mass and the massive release of energy very slightly altered the Earth's rotation. The exact amount is not yet known, but theoretical models suggest the earthquake shortened the length of a day by 2.68 microseconds, due to a decrease in the oblateness of the Earth. It also caused the Earth to minutely "wobble" on its axis by up to 2.5 cm (1 in) in the direction of 145° east longitude, or perhaps by up to 5 or 6 cm (2.0 or 2.4 in). However, because of tidal effects of the Moon, the length of a day increases at an average of 15 µs per year, so any rotational change due to the earthquake will be lost quickly. Similarly, the natural Chandler wobble of the Earth, which in some cases can be up to 15 m (50 ft), will eventually offset the minor wobble produced by the earthquake.

More spectacularly, there was 10 m (33 ft) movement laterally and 4–5 m (13–16 ft) vertically along the fault line. Early speculation was that some of the smaller islands south-west of Sumatra, which is on the Burma Plate (the southern regions are on the Sunda Plate), might have moved south-west by up to 36 m (120 ft), but more accurate data released more than a month after the earthquake found the movement to be about 20 cm (8 in). Since movement was vertical as well as lateral, some coastal areas may have been moved to below sea level. The Andaman and Nicobar Islands appear to have shifted south-west by around 1.25 m (4 ft 1 in) and to have sunk by 1 m (3 ft 3 in).

In February 2005, the Royal Navy vessel HMS *Scott* surveyed the seabed around the earthquake zone, which varies in depth between 1,000 and 5,000 m (550 and 2,700 fathoms; 3,300 and 16,000 ft). The survey, conducted using a high-resolution, multi-beam sonar system, revealed that the earthquake had made a huge impact on the topography of the seabed. 1,500-metre-high (5,000 ft) thrust ridges created by previous geologic activity along the fault had collapsed, generating landslides several kilometers wide. One such landslide consisted of a single block of rock some 100 m high and 2 km long (300 ft by 1.25 mi). The momentum of the water displaced by tectonic uplift had also dragged massive slabs of rock, each weighing millions of tons, as far as 10 km (6 mi) across the seabed. An oceanic trench several kilometres wide was exposed in the earthquake zone.

The TOPEX/Poseidon and Jason 1 satellites happened to pass over the tsunami as it was crossing the ocean. These satellites carry radars that measure precisely the height of the water surface; anomalies of the order of 50 cm (20 in) were measured. Measurements from these satellites may prove invaluable for the understanding of the earthquake and tsunami. Unlike data from tide gauges installed on shores, measurements obtained in the middle of the ocean can be used for computing the parameters of the source earthquake without having to compensate for the complex ways in which close proximity to the coast changes the size and shape of a wave.

TSUNAMI CHARACTERISTICS

The sudden vertical rise of the seabed by several metres during the earthquake displaced massive volumes of water, resulting in a tsunami that struck the coasts of the Indian Ocean. A tsunami which causes damage far away from its source is sometimes called a teletsunami and is much more likely to be produced by vertical motion of the seabed than by horizontal motion.

The tsunami, like all others, behaved very differently in deep water than in shallow water. In deep ocean water, tsunami waves form only a small hump, barely noticeable and harmless, which generally travels at a very high speed of 500 to 1,000 km/h (310 to 620 mph); in shallow water near coastlines, a tsunami slows down to only tens of kilometres per hour, but in doing so forms large destructive waves. Scientists investigating the damage in Aceh found evidence that the wave reached a height of 24 metres (80 ft) when coming ashore along large stretches of the coastline, rising to 30 metres (100 ft) in some areas when travelling inland.

Radar satellites recorded the heights of tsunami waves in deep water: at two hours after the earthquake, the maximum height was 60 centimetres (2 ft). These are the first such observations ever made. Unfortunately these observations could not be used to provide a warning, since the satellites were not built for that purpose and the data took hours to analyze.

According to Tad Murty, vice-president of the Tsunami Society, the total energy of the tsunami waves was equivalent to about five megatons of TNT (20 petajoules). This is more than twice the total explosive energy used during all of World War II (including the two atomic bombs), but still a couple of orders of magnitude less than the energy released in the earthquake itself. In many places the waves reached as far as 2 km (1 mi) inland.

Because the 1,600 km (1,000 mi) fault affected by the earthquake was in a nearly north-south orientation, the greatest strength of the tsunami waves was in an east-west direction. Bangladesh, which lies at the northern end of the Bay of Bengal, had very few casualties despite being a low-lying country relatively near the epicenter. It also benefited from the fact that the earthquake proceeded more slowly in the northern rupture zone, greatly reducing the energy of the water displacements in that region.

Coasts that have a landmass between them and the tsunami's location of origin are usually safe; however, tsunami waves can sometimes diffract around such landmasses. Thus, the Indian state of Kerala was hit by the tsunami despite being on the western coast of India, and the western coast of Sri Lanka also suffered substantial impacts. Also distance alone was no guarantee of safety; Somalia was hit harder than Bangladesh despite being much farther away.

Because of the distances involved, the tsunami took anywhere from fifteen minutes to seven hours (for Somalia) to reach the various coastlines. The northern regions of the Indonesian island of Sumatra were hit very quickly, while Sri Lanka and the east coast of India were hit roughly 90 minutes to two hours later. Thailand was also struck about two hours later despite being closer to the epicentre, because the tsunami travelled more slowly in the shallow Andaman Sea off its western coast.

The tsunami was noticed as far as Struisbaai in South Africa, some 8,500 km (5,300 mi) away, where a 1.5 m (5 ft) high tide surged on shore about 16 hours after the earthquake. It took a relatively long time to reach this spot at the southernmost point of Africa, probably because of the broad continental shelf off South Africa and because the tsunami would have followed the South African coast from east to west. The tsunami also reached Antarctica, where tidal gauges at Japan's Showa Base recorded oscillations of up to a metre (3 ft 3 in), with disturbances lasting a couple of days.

Some of the tsunami's energy escaped into the Pacific Ocean, where it produced small but measurable tsunamis along the western coasts of North and South America, typically around 20 to 40 cm (7.9 to 16 in). At Manzanillo, Mexico, a 2.6 m (8 ft 6 in) crest-to-trough tsunami was measured. As well, the tsunami was large enough to be detected in Vancouver, British Columbia, Canada. This puzzled many scientists, as the tsunamis measured in some parts of South America were larger than those measured in some parts of the Indian Ocean. It has been theorized that the tsunamis were focused and directed at long ranges by the mid-ocean ridges which run along the margins of the continental plates.

Signs and warnings

Despite a lag of up to several hours between the earthquake and the impact of the tsunami, nearly all of the victims were taken completely by surprise. There were no tsunami warning systems in the Indian Ocean to detect tsunamis or to warn the general populace living around the ocean. Tsunami detection is not easy because while a tsunami is in deep water it has little height and a network of sensors is needed to detect it. Setting up the communications infrastructure to issue timely warnings is an even bigger problem, particularly in a relatively poor part of the world.

Tsunamis are much more frequent in the Pacific Ocean because of earthquakes in the "Ring of Fire", and an effective tsunami warning system has long been in place there. Although the extreme western edge of the Ring of Fire extends into the Indian Ocean (the point where this earthquake struck), no warning system exists in that ocean. Tsunamis there are relatively rare despite earthquakes being relatively frequent in Indonesia. The last major tsunami was caused by the Krakatoa eruption of 1883. It should be noted that not every earthquake produces large tsunamis; on March 28, 2005, a magnitude 8.7 earthquake hit roughly the same area of the Indian Ocean but did not result in a major tsunami.

In the aftermath of the disaster, there is now an awareness of the need for a tsunami warning system for the Indian Ocean. The United Nations started working on an Indian Ocean Tsunami Warning System and by 2005 had the initial steps in place. Some have even proposed creating a unified global tsunami warning system, to include the Atlantic Ocean and Caribbean.

The first warning sign of a possible tsunami is the earthquake itself. However, tsunami can strike thousands of kilometres away where the earthquake is only felt weakly or not at all. Also, in the minutes preceding a tsunami strike, the sea often recedes temporarily from the coast. Around the Indian Ocean, this rare sight reportedly induced people, especially children, to visit the coast to investigate and collect stranded fish on as much as 2.5 km (1.6 mi) of exposed beach, with fatal results. However, not all tsunami causes this "disappearing sea" effect. In some cases, there are no warning signs at all: the sea will suddenly swell without retreating, surprising many people and giving them little time to flee. One of the few coastal areas to evacuate ahead of the tsunami was on the Indonesian island of Simeulue, very close to the epicentre. Island folklore recounted an earthquake and tsunami in 1907, and the islanders fled to inland hills after the initial shaking yet before the tsunami struck.

On Maikhao beach in northern Phuket, Thailand, a 10-year-old British tourist named Tilly Smith had studied tsunami in geography at school and recognised the warning signs of the receding ocean and frothing bubbles. She and her parents warned others on the beach, which was evacuated safely. John Chroston, a biology teacher from Scotland, also recognised the signs at Kamala Bay north of Phuket, taking a busload of vacationers and locals to safety on higher ground.

Anthropologists had initially expected the aboriginal population of the Andaman Islands to be badly affected by the tsunami and even feared the already depopulated Onge tribe could have been wiped out. Of the six native tribes only the Nicobarese, who had converted to Christianity and taken up agriculture in place of their previous hunter-gatherer lifestyle, and mainland settlers suffered significant losses. Many of the aboriginal tribes evacuated and suffered fewer casualties.

Phases and wave form

A tsunami can arrive at a coastline in one of two ways. In the first form, a negative wave, a trough precedes the actual arrival of the crest or "wave" itself. Here, the more common and better recognized warning sign of an impending tsunami strike is a rapidly receding sea followed by a sudden onrushing body of water traveling inland at high speed.

The second form in which a tsunami arrives is the positive wave or crest first. In this case, the warning signs are much more vague if any. The sea will usually start rising immediately, slowly at first without the receding phase, like an on-coming high tide. However, instead of stopping at tidal level, the sea will keep rising faster and faster until the crest of the tsunami passes and continues moving inland. The second form of tsunami waves are usually more dangerous, since they can arrive without easily identifiable warning, giving residents less time to prepare and outrun the tsunami. These two types of tsunamis are usually generated simultaneously (in opposing direction of travel) by a megathrust earthquake similar to the 2004 Indian Ocean earthquake.

Retreat-rise cycle (negative wave)

The tsunami was a succession of several waves, occurring in retreat and rise cycles with a period of over 30 minutes between each peak. The third wave was the most powerful and reached highest, occurring about an hour and a half after the first wave.

Rise-retreat-rise cycle (positive wave)

If the crest of a tsunami arrives first, there won't be any recession. The sea level will increase rapidly to inundate everything in the path of the tsunami. This appears to be the case in countries such as Sri Lanka and India that lies to the west of the Andaman-Sumatra fault where the tsunami originates.

DEATH TOLL AND CASUALTIES

According to the U.S. Geological Survey a total of 227,898 people died (see table below for details). Measured in lives lost, this is one of the ten worst earthquakes in recorded history, as well as the single worst tsunami in history. Indonesia was the worst affected area, with most death toll estimates at around 170,000. However, another report by health minister Fadilah Supari has estimated the death total to be as high as 220,000 in Indonesia alone, giving a total of 280,000 casualties.

The tsunami caused serious damage and deaths as far as the east coast of Africa, with the farthest recorded death due to the tsunami occurring at Rooi Els in South Africa, 8,000 km (4,971 mi) away from the epicentre. In total, eight people in South Africa died due to abnormally high sea levels and waves.

Relief agencies report that one-third of the dead appear to be children. This is a result of the high proportion of children in the populations of many of the affected regions and because children were the least able to resist being overcome by the surging waters. Oxfam went on to report that as many as four times more women than men were killed in some regions because they were waiting on the beach for the fishermen to return and looking after their children in the houses.

In an addition to the large number of local residents, up to 9,000 foreign tourists (mostly Europeans) enjoying the peak holiday travel season were among the dead or missing, especially people from the Nordic countries. The European nation hardest hit may have been Sweden, whose death toll was 543.

States of emergency were declared in Sri Lanka, Indonesia, and the Maldives. The United Nations estimated at the outset that the relief operation would be the costliest in human history. Then UN Secretary-General Kofi Annan stated that reconstruction would probably take between five and ten years. Governments and non-governmental organisations feared that the final death toll might double as a result of diseases, prompting a massive humanitarian response. In the end, this fear did not materialise.

For purposes of establishing timelines of local events, the time zones of affected areas are: UTC+3: (Kenya, Madagascar, Somalia, Tanzania); UTC+4: (Mauritius, Réunion, Seychelles); UTC+5: (Maldives); UTC+5:30: (India, Sri Lanka); UTC+6: (Bangladesh); UTC+6:30: (Cocos Islands, Myanmar); UTC+7: (Indonesia (western), Thailand); UTC+7: (Malaysia, Singapore). Since the earthquake occurred at 00:58:53 UTC, add the above offsets to find the local time of the earthquake.

COUNTRIES AFFECTED

The earthquake and resulting tsunami affected many countries in Southeast Asia and beyond, including Indonesia, Sri Lanka, India, Thailand, the Maldives, Somalia, Myanmar, Malaysia, Seychelles and others. Many other countries, especially Australia and those in Europe, had large numbers of citizens traveling in the region on holiday. Both Sweden and Germany lost over 500 citizens each in the disaster.

Event in historical context

This earthquake was the biggest in the Indian Ocean in some 700 years, or since around A.D. 1400. In 2008, a team of scientists working on Phra Thong, a barrier island along the hard-hit west coast of Thailand, reported evidence of at least three previous major tsunamis in the preceding 2,800 years, the most recent from about 550 to 700 years ago. A second team found similar evidence of previous tsunamis during the last 1,200 years in Aceh, a province at the northern tip of Sumatra. Radiocarbon dating of bark fragments in soil below the second sand layer led the scientists to estimate that the most recent predecessor to the 2004 tsunami probably occurred between A.D. 1300 and 1450.

This earthquake was the third most powerful earthquake recorded since 1900, and the confirmed death toll is just under 200,000 due to the ensuing tsunami. The deadliest earthquakes since 1900 were the Tangshan, China earthquake of 1976, in which at least 255,000 were killed; the earthquake of 1927 in Xining, Qinghai, China (200,000); the Great Kanto earthquake which struck Tokyo in 1923 (143,000); and the Gansu, China, earthquake of 1920 (200,000). The deadliest known earthquake in history occurred in 1556 in Shaanxi, China, with an estimated death toll of 830,000, though figures from this time period may not be reliable.

The 2004 tsunami is the deadliest in recorded history. Prior to 2004, the deadliest recorded tsunami in the Pacific Ocean was in 1782, when 40,000 people were killed by a tsunami in the South China Sea. The tsunami created by the 1883 eruption of Krakatoa is thought to have resulted in 36,000 deaths. The most deadly tsunami between 1900 and 2004 occurred in 1908 in Messina, Italy, on the Mediterranean Sea, where the earthquake and tsunami killed 70,000. The most deadly tsunami in the Atlantic Ocean resulted from the 1755 Lisbon earthquake, which, combined with the toll from the actual earthquake and resulting fires, killed over 100,000.

The 2004 earthquake and tsunami combined have been described as the deadliest natural disaster since either the 1976 Tangshan earthquake or the 1970 Bhola cyclone, or could conceivably exceed both of these. Because of uncertainty over death tolls, it might never be known for sure which of these natural disasters was the deadliest.

POSSIBLE HUMAN COMPONENT IN MAGNITUDE OF DAMAGE

A town near the coast of Sumatra lies in ruin on January 2, 2005. This picture was taken by a United States military helicopter crew from the USS *Abraham Lincoln* that was conducting humanitarian operations. In an opinion piece in the Wall Street Journal, published five days after the tsunami, a journalist, Andrew Browne, argued that the human destruction of coral reefs may have played a role in exacerbating the destruction caused by the tsunami.

Many countries across Asia, including Indonesia, Sri Lanka and Bangladesh, have put forth efforts to destroy the coral surrounding their beaches, and instead make way for shrimp farms and other economic choices. On the Surin Island chain of Thailand's coast, Browne argued, people may have been saved as the tsunami rushed against the coral reefs, lessening its impact. However, there were many fewer people on these islands, which helps explain the lower death toll. Many reefs areas around the Indian Ocean have been exploded with dynamite because they are considered impediments to shipping, an important part of the South Asian economy. Similarly, Browne argued that the removal of coastal mangrove trees may have intensified the effect of the tsunami in some locations. He argued that these trees, which lined the coast but were removed to make way for coastal residences, might have lessened the force of the tsunami, in certain areas. Another factor, Browne argued, is the removal of coastal sand dunes.

Humanitarian, economic and environmental impact

A great deal of humanitarian aid was needed because of widespread damage of the infrastructure, shortages of food and water, and economic damage. Epidemics were of special concern due to the high population density and tropical climate of the affected areas. The main concern of humanitarian and government agencies was to provide sanitation facilities and fresh drinking water to contain the spread of diseases such as cholera, diphtheria, dysentery, typhoid and hepatitis A and B.

There was also a great concern that the death toll could increase as disease and hunger spread. However, because of the initial quick response, this was minimized.

In the days following the tsunami, significant effort was spent in burying bodies hurriedly for fear of disease. However, the public health risks may have been exaggerated, and therefore this may not have been the best way to allocate resources. The World Food Programme provided food aid to more than 1.3 million people affected by the tsunami.

Nations all over the world provided over US$14 billion in aid for damaged regions, with the governments of Australia pledging US$819.9 million (including a US$760.6-million aid package for Indonesia), Germany offering US$660 million, Japan offering US$500 million, Canada offering US$343 million, Norway and the Netherlands offering both US$183 million, the United States offering US$35 million initially (increased to US$350 million), and the World Bank offering US$250 million. Also Italy offered US$95 million, increased later to US$113 million of which US$42 million was donated by the population using the SMS system According to USAID, the US has pledged additional funds in long-term U.S. support to help the tsunami victims rebuild their lives. On February 9, 2005, President Bush asked Congress to increase the U.S. commitment to a total of $950 million. Officials estimated that billions of dollars would be needed. Bush also asked his father, former President George H. W. Bush, and former President Bill Clinton to lead a U.S. effort to provide private aid to the tsunami victims.

In mid-March the Asian Development Bank reported that over US$4 billion in aid promised by governments was behind schedule. Sri Lanka reported that it had received no foreign government aid, while foreign individuals had been generous. Many charities were given considerable donations from the public. For example, in the UK the public donated roughly £330,000,000 sterling (nearly US$600,000,000). This considerably outweighed the donation by the government and came to an average of about £5.50 (US$10) donated by every citizen.

In August 2006, fifteen local aid staff working on post-tsunami rebuilding were found executed in northeast Sri Lanka after heavy fighting, the main umbrella body for aid agencies in the country said. There had been reports and rumors that the local aid workers had been killed.

Economic impact

The impact on coastal fishing communities and the people living there, some of the poorest in the region, has been devastating with high losses of income earners as well as boats and fishing gear. In Sri Lanka artisanal fishery, where the use of fish baskets, fishing traps, and spears are commonly used, is an important source of fish for local markets; industrial fishery is the major economic activity, providing direct employment to about 250,000 people. In recent years the fishery industry has emerged as a dynamic export-oriented sector, generating substantial foreign exchange earnings. Preliminary estimates indicate that 66% of the fishing fleet and industrial infrastructure in coastal regions have been destroyed by the wave surges, which will have adverse economic effects both at local and national levels.

The tsunami created demand for fiberglass reinforced plastic catamarans in boatyards of Tamil Nadu.

But some economists believe that damage to the affected national economies will be minor because losses in the tourism and fishing industries are a relatively small percentage of the GDP. However, others caution that damage to infrastructure is an overriding factor. In some areas drinking water supplies and farm fields may have been contaminated for years by salt water from the ocean.

Both the earthquake and the tsunami may have affected shipping in the Malacca Straits by changing the depth of the seabed and by disturbing navigational buoys and old shipwrecks. Compiling new navigational charts may take months or years.

Countries in the region appealed to tourists to return, pointing out that most tourist infrastructure is undamaged. However, tourists were reluctant to do so for psychological reasons. Even beach resorts in parts of Thailand which were completely untouched by the tsunami were hit by cancellations.

Environmental impact

Beyond the heavy toll on human lives, the Indian Ocean earthquake has caused an enormous environmental impact that will affect the region for many years to come. It has been reported that severe damage has been inflicted on ecosystems such as mangroves, coral reefs, forests, coastal wetlands, vegetation, sand dunes and rock formations, animal and plant biodiversity and groundwater. In addition, the spread of solid and liquid waste and industrial chemicals, water pollution and the destruction of sewage collectors and treatment plants threaten the environment even further, in untold ways. The environmental impact will take a long time and significant resources to assess.

According to specialists, the main effect is being caused by poisoning of the freshwater supplies and the soil by saltwater infiltration and deposit of a salt layer over arable land. It has been reported that in the Maldives, 16 to 17 coral reef atolls that were overcome by sea waves are totally without fresh water and could be rendered uninhabitable for decades. Uncountable wells that served communities were invaded by sea, sand and earth; and aquifers were invaded through porous rock. Salted-over soil becomes sterile, and it is difficult and costly to restore for agriculture. It also causes the death of plants and important soil micro-organisms. Thousands of rice, mango and banana plantations in Sri Lanka were destroyed almost entirely and will take years to recover. On the island's east coast, the tsunami contaminated wells on which many villagers relied for drinking water. The Colombo-based International Water Management Institute monitored the effects of saltwater and concluded that the wells recovered to pre-tsunami drinking water quality one and a half years after the event. IWMI developed protocols for cleaning wells contaminated by saltwater; these were subsequently officially endorsed by the World Health Organization as part of its series of Emergency Guidelines.

The United Nations Environment Programme (UNEP) is working with governments of the region in order to determine the severity of the ecological impact and how to address it. UNEP has decided to earmark a US$1,000,000 emergency fund and to establish a Task Force to respond to requests for technical assistance from countries affected by the tsunami. In response to a request from the Maldivian Government, the Australian Government sent ecological experts to help restore marine environments and coral reefs—the lifeblood of Maldivian tourism. Much of the ecological expertise has been rendered from work with the Great Barrier Reef, in Australia's northeastern waters.

Other effects

Many health professionals and aid workers have reported widespread psychological trauma associated with the tsunami. Traditional beliefs in many of the affected regions state that a relative of the family must bury the body of the dead, and in many cases, no body remained to be buried.

The hardest hit area, Aceh, is considered to be a religiously conservative Islamic society and has had no tourism nor any Western presence in recent years due to armed conflict between the Indonesian military and Acehnese separatists. Some believe that the tsunami was divine punishment for lay Muslims shirking their daily prayers and/or following a materialistic lifestyle. Others have said that Allah was angry that there were Muslims killing other Muslims in an ongoing conflict. Women in Aceh required a special approach from foreign aid agencies, and continue to have unique needs.

The widespread devastation caused by the tsunami led the main rebel group GAM to declare a cease-fire on December 28, 2004, followed by the Indonesian government, and the two groups resumed long-stalled peace talks, which resulted in a peace agreement signed August 15, 2005. The agreement explicitly cites the tsunami as a justification.

The extensive international media coverage of the tsunami, and the role of mass media and journalists in reconstruction, were discussed by editors of newspapers and broadcast media in tsunami-affected areas, in special video-conferences set up by the Asia Pacific Journalism Centre.

The December 26, 2004 Asian Tsunami left both the people and government of India in a state of heightened alert. On December 30, 2004, four days after the tsunami, the Portland, Oregon-based company Terra Research notified the India government that its sensors indicated there was a possibility of 7.9 to 8.1 magnitude tectonic shift in the next 12 hours between Sumatra and New Zealand. In response, the India Home Affairs minister announced that a fresh onslaught of deadly tidal waves were likely along the India southern coast and Andaman and Nicobar Islands, even as there was no sign of turbulences in the region. The announcement generated panic in the Indian Ocean region and caused thousands to flee their homes, which resulted in jammed roads. The announcement was a false alarm and the Home Affairs minister withdrew their announcement. On further investigation, the India government learned that the consulting company Terra Research was run from the home of a self-described earthquake forecaster who had no telephone listing and maintained a website where he sold copies of his detection system. Three days after the announcement, Indian National Congress president Sonia Gandhi called Science & Technology minister Kapil Sibal to express her concern about Sibal's December 30 public warning being "hogwash".

Another result of the tsunami, respective toward Indian culture, was the water that washed away centuries of sand from some of the ruins of a 1,200-year-old lost city at Mahabalipuram on the south coast of India. The site, containing such notable structures as a half-buried granite lion near a 7th century Mahablipuram temple and a relic depicting an elephant, is part of what archaeologists believe to be an ancient port city that was swallowed by the sea hundreds of years ago.

The tsunami had a severe humanitarian and political impact in Sweden. The hardest hit country outside Asia, 543 Swedish tourists, mainly in Thailand, died. With no single incident having killed more Swedish people since the battle of Poltava in 1709, the cabinet of Göran Persson was heavily criticized for lack of action.

Apung 1, a 2600 ton ship, was flung some 2-3 km inland by the tsunami, and has become a popular tourist attraction in Banda Aceh.

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2006: South of Java Island

The July 2006 Java earthquake was a magnitude 7.7 earthquake off the southwestern coast of Java, Indonesia. It occurred on July 17, 2006, at 08:24 UTC (15:24 local time).

The U.S. Geological Survey placed the epicentre of the quake at 9°172 423 S 107°202 493 Eÿþ / ÿþ9.295°S 107.347°Eÿþ / -9.295; 107.347, and its hypocentre at a depth of 48.6 km below the seabed. This is 225 km (140 miles) NE of Christmas Island, 240 km (150 miles) SSW of Tasikmalaya, Indonesia, and 358 km (222 miles) S of Jakarta, the capital and largest city of Indonesia.

Cause

According to the U.S. Geological Survey "The earthquake occurred as a result of thrust-faulting on the boundary between the Australia plate and the Sunda Plate.

On this part of their mutual boundary, the Australia plate moves north-northeast with respect to the Sunda plate at about 59 mm/year. The Australia plate thrusts beneath the Sunda plate at the Java Trench, south of Java, and is subducted to progressively greater depths beneath Java and north of Java. The earthquake occurred on the shallow part of the plate boundary, about 50 km north of the Java trench."

ESTIMATED CASUALTIES

The Ministry of Health (MOH) reports that approximately 668 people died, 65 are missing and 9,299 are in-treatment because of the disaster.

At least three non-Indonesian nationals were among the dead, including travellers from the Netherlands, Pakistan and Sweden. The Swedish foreign ministry reported that two Swedish children on holiday in the region were missing the first day; they were later found at safe ground higher up in the community.

Aftershocks

The USGS recorded at least 22 aftershocks south of Java ranging between magnitude 4.6 and 6.1. The two largest aftershocks measured 6.0 and 6.1 M_w.

TSUNAMI

The July 2006 Java earthquake caused a three-meter-high tsunami which destroyed houses on the south coast of Java, killing at least 668 people and leaving at least 65 missing.

The tsunami smashed into a 110-mile stretch of Java's coastline that was unaffected by the devastating 2004 Indian Ocean tsunami. Waves more than 6 feet high reached 200 yards inland in some places, destroying scores of houses, restaurants and hotels. Cars, motorbikes and boats were left mangled amid fishing nets, furniture and other debris.

The tsunami struck the southern Indonesian coastal villages of Cipatujah and Pangandaran on the coast southeast of Bandung and Garut. There is reportedly extensive damage at the West Java beach resort of Pangandaran. Thousands of people at the resort fled to higher ground.

Localised tsunami

Following the earthquake, the Indonesian Meteorological and Geophysics Agency stated that "There is the possibility of a local tsunami that could affect coasts located usually no more than 100 kilometres from the earthquake epicentre", indicating the improbability of a large-scale tsunami, like the one that affected Indonesia and other areas following the 2004 Indian Ocean earthquake on December 26, 2004. Despite this, India still issued a tsunami warning for the Andaman Islands archipelago region, which is located in the Bay of Bengal. This archipelago suffered severe damage in the December 26, 2004 tsunami. A warning was also issued for Christmas Island, however police reports from the island say that no damage was caused. A mere 60 cm tsunami was recorded at the Bureau of Meteorology's tide gauge on the island. A warning was also issued for the Kimberley region of Western Australia.

Warning

The Pacific Tsunami Warning Center in Hawaii issued a Tsunami bulletin 12 minutes after the earthquake alerting Indonesia (Java) and Australia (Christmas Island) to a possible local tsunami affecting coasts within a 100 km radius from the quake epicentre. The bulletin gave an estimated tsunami impact time for Indonesia of 09:00 UTC, an advanced warning of 24 minutes. It suggested that based on historical data, the risk of a destructive widespread tsunami was non-existent. The second bulletin issued two and a half hours later confirmed the occurrence of local tsunami by the news media and the reiteration that a more widespread tsunami was non-existent.

Kusmayanto Kadiman, the State Minister for Research and Technology confirmed that Indonesian officials had received bulletins from both the Pacific Tsunami Warning Center in Hawaii and the Japan Meteorological Agency twenty minutes before the first tsunami wave struck. However, Kadiman indicated that the government did not publicise the bulletins because they did not want to cause unnecessary alarm. According to an AP report, he had stated the bulletins were received 45 minutes before the tsunami hit. He later stated that warnings were issued seven minutes before incident via text messaging but that it was not enough time to alert local communities.

Edi Prihantoro, an official at Indonesia's Ministry of Research and Technology that oversees a national warning project, said the southern Java area had no system to warn people of coming waves.

As part of a five-year project to install tsunami buoys around the archipelago, Indonesia deployed two such devices off the island of Sumatra last year. However, when asked how many of the deployed devices were operational, Prihantoro replied: " None." He continued, "We need at least 22 buoys to cover all of Indonesia.

We have received two from Germany and they were deployed months ago. However, both of them are damaged now." Both devices have since been decommissioned and one of them is awaiting repairs.

Evacuation

At least 23,000 people did eventually evacuate the coast, either afraid that more tsunami were coming or because their homes had been destroyed.

2006: Kuril Islands

The 2006 Kuril Islands earthquake was an 8.3 magnitude earthquake that hit the Kuril Islands at 11:14 UTC (8:14pm JST) on November 15, 2006. A small tsunami hit the Japanese northern coast, with a larger wave following earlier small ones, due to reflection.

The tsunami crossed the Pacific and did damage in the harbor at Crescent City, CA, USA. This earthquake was the largest earthquake having occurred in the central Kuril Islands since the earthquake in 1915 with an estimated magnitude of about 8. Post-tsunami surveys indicate that the local tsunami in the central Kuril Islands reached runup of 15 meters or more.

At about 11:45 UTC, tsunami warnings were issued in Japan for the north coasts of Hokkaidô and Honshû, and a number of towns in this area were hurriedly evacuated. Tsunami warnings, advisories and watches were also issued for the coastal areas of Alaska, Hawaii, parts of British Columbia, Washington, Oregon, and California. JMA initially estimated tsunami waves to be as tall as 2 metres when it hit the Japanese northern and eastern coasts, but it turned out to be merely 40 centimetres when it reached Hanasaki Ko, Nemuro, Nemuro, Hokkaidô at 9:29 pm local time. The tsunami also hit the rest of Hokkaidô and Tôhoku Region.

The tallest wave recorded in Japan was at Tsubota (jW0u), Miyakejima (N…[ö\) in the Izu Shotô of the Tokyo To, at 84 centimetres. Tsunami also hit as far as Anami in Kagoshima Prefecture and Naha in Okinawa Prefecture, and reached the Hawaiian and California coasts. A 176-centimetre wave in the Crescent City, California harbor caused an estimated $10 million in damage to the docks there. The United States authorities had issued warnings for the Russian Far East, Japan, Wake Island and Midway Atoll.

The nearfield tsunami struck islands with no current inhabitants. However, geologists and archaeologists had visited these islands the previous summer, and returned in the summers of 2007 and 2008. Because there were two central Kurils tsunamis in the winter of 2006-2007 (see 2007 Kuril Islands earthquake), the specific effects of each tsunami are difficult to determine; evidence is that the 2006 tsunami was the larger on all islands in the Kurils except Matua and parts of Rasshua.

2007: Solomon Islands

The 2007 Solomon Islands earthquake took place on 2 April 2007, near the island of Gizo, in the Solomon Islands. Its magnitude was calculated by the United States Geological Survey (USGS) as being at 8.1 on the moment magnitude scale. The tsunami that followed the earthquake killed 52 people.

According to the USGS, the earthquake was recorded around 7:39:56 a.m. local time (UTC+11). The focus was 10 km (6 mi) deep and 40 km (25 mi) South South-East of Gizo township on New Georgia Islands in Western Province. There were numerous aftershocks, the largest of which had a magnitude of 6.2.

EFFECTS

At least fifty-two people were reported to have been killed and sixty reported missing when a tsunami triggered by the earthquake struck the Solomon Islands, wiping out thirteen or more villages. Thousands were left homeless, and damages are estimated in millions. In South Choiseul, waves 10 meters high swept away villages, gardens and a hospital. About 900 homes were destroyed.

The tsunami reached Papua New Guinea, with a family of five reportedly missing from a remote island in Milne Bay Province, which was in the tsunami's path.

Aid workers reported that an outbreak of diarrhea emerged among the survivors. However, the UN reported that the outbreak and other diseases were under control as of April 12. On April 18, a measles outbreak was reported and an immunization program was underway.

The island of Ranongga in the New Georgia Group was lifted three meters by the earthquake, causing its beaches to shift outwards of up to 70 meters. Large coral reefs in the area are now largely above the surface and local fishermen are worried that the fishing grounds have been destroyed. However, Australian scientists said the exposure of the reefs are a normal part of island building and that careful wildlife management can preserve the reefs that remain.

RESPONSE

Warnings

A tsunami warning was issued for the South Pacific Ocean, and advisories issued for Japan and Hawaii. The Australian Bureau of Meteorology issued a warning for Australia's eastern coast, from Queensland's Barrier Reef to Tasmania, and beaches along the coast were closed, while many evacuated to higher ground. However, as the epicenter was close to the Solomon Islands, the tsunami hit before the Hawaiian Pacific Tsunami Warning Center released the warning.

High-magnitude ocean waves propagate at high speeds close to 25 meters per second, which meant that they traversed the 55-kilometer distance from the epicenter to Gavo in less than 20 minutes. Fortunately, the S-waves from the earthquake shook the ground and alerted the population, allowing many to flee to high ground before the wave struck.

From Honiara, one of the first warnings came from the People First Network's Simbo email station, situated close to the epicentre. PFnet's Technical Advisor David Leeming relates that 20 minutes after the earthquake, Simbo came on the (HF) radio and announced the arrival of a huge wave that had washed away several houses and come inland about 200m. This information was passed on by telephone to the Hawaii-based NOAA Pacific Tsunami Warning Centre who then upgraded their warning to an "expanding regional alert". This was achieved before the 35-minute arrival time of the wave for the capital Honiara, which in the event proved non-destructive. The PFnet email station operators had been trained in disaster response by Manager Randall Biliki (late), who had previous worked as Director of the Solomon Islands National Disaster offices for nine years. All stations were equipped with UN-standard assessment forms installed on the email station laptops using Microsoft Access. Information was received from several email stations reporting on damages, needs and assessment information for several days after the tsunami, notably from badly affected Korovou in Shortland Islands.

Aid response

Australia committed to contribute an initial 3 million AUD in emergency aid, later increased to 5.7 million as of June 2007. New Zealand gave 950,000 NZD during the initial relief period, and committed 7.5 million NZD over two years to reconstruction, as of July 2007. The United States contributed US$250,000 in aid. Taiwan contributed US$214,000 and shipment of 1,000 kg of rice. France has also airlifted supplies via New Caledonia.

The United Nations established a field hospital in Gizo, with a total of eight planned for the entire country, and also established three camps for internally displaced persons. Australian and Canadian medical teams have also been deployed across the islands. Papua New Guinea, itself affected by the tsunami, has contributed US$340,000 and a light plane that can better access smaller, more remote airstrips. UNICEF issued an appeal for US$500,000 for both the Solomon Islands and Papua New Guinea. Separately, the Red Cross has issued an appeal for US$800,000. The remoteness of some villages meant that aid did not reach them until several days after the tsunami occurred. However, the Associated Press reported on April 6 that Gizo's airport had reopened, easing the delivery of supplies. A Taiwanese fishing boat ran aground on coral reefs while delivering supplies, but it was successfully evacuated by a United States Navy helicopter. The boat's crew managed to free the vessel from the rocks a few days later.

Aftermath

Francis Billy Hilly, the MP for Simbo Island where 11 people died, said on April 8 that those who had previously resisted resettlement away from the island's active volcano were reconsidering their options. The national government may also relocate islanders away from low-lying areas pending a review of long-term rehabilitation and disaster preparedness plans. The Australian government announced that a network of five tsunami warning buoys will be deployed along its Pacific coast, with two buoys stationed in the Papua New Guinea/Solomon Islands area.

TECTONIC SUMMARY

The earthquake occurred along the boundary of the Pacific plate with, respectively, the Australia, Woodlark, and Solomon Sea plates. The latter three plates converge to the east-northeast or northeast against the Pacific plate with velocities of 90–105 millimetres/year. Along much of the plate boundary between the Pacific plate and the Australia/Woodlark/Solomon Sea plates, relative plate-motion is accomplished principally by subduction of the Australia/Woodlark/Solomon Sea plates beneath the Pacific plate. The April 2 earthquake's location and focal mechanism are consistent with the earthquake having occurred as underthrusting of the Australia/Woodlark/Solomon Sea plate beneath the Pacific plate, as part of the broader northeast-directed subduction process.

The Solomon Islands arc as a whole experiences a very high level of earthquake activity, and many shocks of magnitude 7 and larger have been recorded since the early decades of the twentieth century. The April 2 earthquake, however, nucleated in a 250 kilometre-long segment of the arc that had produced no shocks of magnitude 7 or larger since the early 20th century.

5

2011: Pacific Coast of Japan

The 2011 Tôhoku earthquake and tsunami (, *Higashi Nihon Daishinsai*?, literally "Eastern Japan Great Earthquake Disaster "[fn 1]), officially named the Great East Japan Earthquake, was caused by a 9.0-magnitude undersea megathrust earthquake off the coast of Japan that occurred at 14:46 JST (05:46 UTC) on Friday, 11 March 2011. The epicenter was approximately 72 km (45 mi) east of the Oshika Peninsula of Tôhoku, with the hypocenter at an underwater depth of approximately 32 km (19.9 mi). On 1 April 2011, the Japanese government named the disaster resulting from the earthquake and tsunami the "Great Eastern Japan Earthquake" (, *Higashi Nihon Daishinsai*).

The earthquake triggered extremely destructive tsunami waves of up to 37.9 meters (124 ft) that struck Japan minutes after the quake, in some cases traveling up to 10 km (6 mi) inland, with smaller waves reaching many other countries after several hours. Tsunami warnings were issued and evacuations ordered along Japan's Pacific coast and at least 20 other countries, including the entire Pacific coast of the Americas.

The Japanese National Police Agency has confirmed 13,439 deaths, 4,900 injured, and 14,867 people missing across eighteen prefectures, as well as over 125,000 buildings damaged or destroyed. The earthquake and tsunami caused extensive and severe structural damage in Japan, including heavy damage to roads and railways as well as fires in many areas, and a dam collapse. Around 4.4 million households in northeastern Japan were left without electricity and 1.5 million without water. Many electrical generators were taken down, and at least three nuclear reactors suffered explosions due to hydrogen gas that had built up within their outer containment buildings after cooling system failure. On 18 March, Yukiya Amano—the head of the International Atomic Energy Agency—described the crisis as "extremely serious." Residents within a 20 km (12 mi) radius of the Fukushima I Nuclear Power Plant and a 10 km (6 mi) radius of the Fukushima II Nuclear Power Plant were evacuated. In addition, the U.S. recommended that its citizens evacuate up to 80 km (50 mi) of the plant.

Estimates of the Tôhoku earthquake's magnitude make it the most powerful known earthquake to have hit Japan, and one of the five most powerful earthquakes in the world overall since modern record-keeping began in 1900. Japanese Prime Minister Naoto Kan said, "In the 65 years after the end of World War II, this is the toughest and the most difficult crisis for Japan." The earthquake moved Honshu 2.4 m (7.9 ft) east and shifted the Earth on its axis by almost 10 cm (3.9 in). Early estimates placed insured losses from the earthquake alone at US$14.5 to $34.6 billion. The Bank of Japan offered ¥15 trillion (US$183 billion) to the banking system on 14 March in an effort to normalize market conditions. On 21 March, the World Bank estimated damage between US$122 billion and $235 billion. Japan's government said the cost of the earthquake and tsunami that devastated the northeast could reach $309 billion, making it the world's most expensive natural disaster on record.

Earthquake

The 9.0-magnitude (M_W) undersea megathrust earthquake occurred on 11 March 2011 at 14:46 JST (05:46 UTC) in the western Pacific Ocean at a relatively shallow depth of 32 km (19.9 mi), with its epicenter approximately 72 km (45 mi) east of the Oshika Peninsula of Tôhoku, Japan, lasting approximately six minutes. The nearest major city to the quake was Sendai, on the main island of Honshu, 130 km (81 mi) away. The quake occurred 373 km (232 mi) from Tokyo. The main earthquake was preceded by a number of large foreshocks, and hundreds of aftershocks were reported. The first major foreshock was a 7.2 M_W event on 9 March, approximately 40 km (25 mi) from the location of the 11 March quake, with another three on the same day in excess of 6.0 M_W. Following the quake, a 7.0 M_W aftershock was reported at 15:06 JST, followed by a 7.4 at 15:15 JST and a 7.2 at 15:26 JST. Over eight hundred aftershocks of magnitude 4.5 or greater have occurred since the initial quake. United States Geological Survey (USGS) director Marcia McNutt explained that aftershocks follow Omori's Law, might continue for years, and will taper off in time.

One minute before the earthquake was felt in Tokyo, the Earthquake Early Warning system, which includes more than 1,000 seismometers in Japan, sent out warnings of impending strong shaking to millions. The early warning is believed by the Japan Meteorological Agency (JMA) to have saved many lives.

Initially reported as 7.9 M_W by the USGS, the magnitude was quickly upgraded to 8.8, then again to 8.9, and then finally to 9.0.

Geology

This earthquake occurred where the Pacific Plate is subducting under the plate beneath northern Honshu; which plate is a matter of debate amongst scientists. The Pacific plate, which moves at a rate of 8 to 9 cm (3.1 to 3.5 in) per year, dips under Honshu's underlying plate releasing large amounts of energy. This motion pulls the upper plate down until the stress builds up enough to cause a seismic event. The break caused the sea floor to rise by several meters. A quake of this magnitude usually has a rupture length of at least 480 km (300 mi) and generally requires a long, relatively straight fault surface. Because the plate boundary and subduction zone in the area of the rupture is not very straight, it is unusual for the magnitude of an earthquake to exceed 8.5; the magnitude of this earthquake was a surprise to some seismologists. The hypocentral region of this earthquake extended from offshore Iwate Prefecture to offshore Ibaraki Prefecture. The Japanese Meteorological Agency said that the earthquake may have ruptured the fault zone from Iwate to Ibaraki with a length of 500 km (310 mi) and a width of 200 km (120 mi). Analysis showed that this earthquake consisted of a set of three events. The earthquake may have had a mechanism similar to that of another large earthquake in 869 with an estimated surface wave magnitude (M_s) of 8.6, which also created a large tsunami. Other major earthquakes with tsunamis struck the Sanriku Coast region in 1896 and in 1933.

The strong ground motion registered at the maximum of 7 on the Japan Meteorological Agency seismic intensity scale in Kurihara, Miyagi Prefecture. Three other prefectures—Fukushima, Ibaraki and Tochigi—recorded an upper 6 on the JMA scale. Seismic stations in Iwate, Gunma, Saitama and Chiba Prefecture measured a lower 6, recording an upper 5 in Tokyo.

Energy

This earthquake released a surface energy (M_e) of $1.9 \pm 0.5 \times 10^{17}$ joules, dissipated as shaking and tsunamic energy, which is nearly double that of the 9.1-magnitude 2004 Indian Ocean earthquake and tsunami that killed 230,000 people. "If we could only harness the [surface] energy from this earthquake, it would power [a] city the size of Los Angeles for an entire year," McNutt said in an interview. The total energy released, also known as the seismic moment (M_0), was more than 200,000 times the surface energy and was calculated by the USGS at 3.9×10^{22} joules, slightly less than the 2004 Indian Ocean quake. This is equivalent to 9,320 gigatons of TNT, or approximately 600 million times the energy of the Hiroshima bomb.

Japan's National Research Institute for Earth Science and Disaster Prevention (NIED) calculated a peak ground acceleration of 2.99 *g* (29.33 m/s^2).[fn 2] The largest individual recording in Japan was 2.7g, in the Miyagi Prefecture, 75 km from the epicentre; the highest reading in the Tokyo metropolitan area was 0.16g.

Geophysical impacts

The quake moved portions of northeast Japan by as much as 2.4 m (7.9 ft) closer to North America, making portions of Japan's landmass wider than before. Portions of Japan closest to the epicenter experienced the largest shifts. A 400 km (250 mi) stretch of coastline dropped vertically by 0.6 m (2.0 ft), allowing the tsunami to travel farther and faster onto land. One early estimate suggested that the Pacific plate may have moved westwards by up to 20 m (66 ft),and another early estimate put the amount of slippage at as much as 40 m (130 ft). On 6 April the Japanese coast guard said that the quake shifted the seabed near the epicenter 24 meters (79 ft.) and elevated the seabed off the coast of Miyagi prefecture by 3 meters.

The earthquake shifted the Earth's axis by 25 cm (9.8 in). This deviation led to a number of small planetary changes, including the length of a day and the tilt of the Earth. The speed of the Earth's rotation increased, shortening the day by 1.8 microseconds due to the redistribution of Earth's mass. The axial shift was caused by the redistribution of mass on the Earth's surface, which changed the planet's moment of inertia. Because of conservation of angular momentum, such changes of inertia result in small changes to the Earth's rate of rotation. These are expected changes for an earthquake of this magnitude.

Soil liquefaction was evident in areas of reclaimed land around Tokyo, particularly in Urayasu, Chiba City, Funabashi, Narashino (all in Chiba Prefecture) and in the Koto, Edogawa, Minato, Chûô, and Ôta Wards of Tokyo. Approximately 30 homes or buildings were destroyed and 1,046 other buildings were damaged to varying degrees. Nearby Haneda Airport, built mostly on reclaimed land, was not damaged. Odaiba also experienced liquefaction, but damage was minimal.

Shinmoedake, a volcano in Kyushu, erupted two days after the earthquake. The volcano had previously erupted in January 2011; it is not known if the later eruption was linked to the earthquake. In Antarctica, the seismic waves from the earthquake were reported to have caused the Whillans Ice Stream to slip by about 0.5 m (1.6 ft).

Aftershocks

Japan experienced over 900 aftershocks since the earthquake with about 60 being over 6.0 M and three over 7.0 M. A 7.7 M and a 7.9 M quake occurred on March 11 and the third one on 7 April 7 2011, with a disputed magnitude. Its epicenter was underwater, 66 km (41 mi) off the coast of Sendai. The Japan Meteorological Agency assigned a magnitude of 7.4, while the U.S. Geological Survey lowered it to 7.1. At least four people were killed, and electricity was cut off across much of northern Japan including the loss of external power to Higashidori Nuclear Power Plant and Rokkasho Reprocessing Plant. A 7.0 aftershock on 11 April 2011 killed four more people and seriously injured three others.

The earthquake which was caused by 5 to 8 meters upthrust on 180-km wide seabed at 60 km offshore from the east coast of Tôhoku resulted in a major tsunami which brought destruction along the Pacific coastline of Japan's northern islands and resulted in the loss of thousands of lives and devastated entire towns. The tsunami propagated across the Pacific, and warnings were issued and evacuations carried out. In many countries bordering the Pacific, including the entire Pacific coast of North and South America from Alaska to Chile; however, while the tsunami was felt in many of these places, it caused only relatively minor effects. Chile's section of Pacific coast is one of the furthest from Japan, at about 17,000 km (11,000 mi) away, but still was struck by tsunami waves 2 m (6.6 ft) high. A wave height of 37.9 meters (124 ft) was estimated at Tarô, Iwate.

Japan

The tsunami warning issued by the Japan Meteorological Agency was the most serious on its warning scale; it rated as a "major tsunami", being at least 3 m (9.8 ft) high. The actual height predicted varied, the greatest being for Miyagi at 10 m (33 ft) high. The tsunami inundated a total area of approximately 470 km² in Japan.

The earthquake took place at 14:46 JST around 67 km (42 mi) from the nearest point on Japan's coastline, and initial estimates indicated the tsunami would have taken 10 to 30 minutes to reach the areas first affected, and then areas further north and south based on the geography of the coastline. Just over an hour after the earthquake at 15:55 JST, a tsunami was observed flooding Sendai Airport, which is located near the coast of Miyagi Prefecture, with waves sweeping away cars and planes and flooding various buildings as they traveled inland. The impact of the tsunami in and around Sendai Airport was filmed by an NHK News helicopter, showing a number of vehicles on local roads trying to escape the approaching wave and being engulfed by it. A 4 m high tsunami hit Iwate Prefecture. Wakabayashi Ward in Sendai was also particularly hard hit. At least 101 designated tsunami evacuation sites were hit by the wave.

Like the 2004 Indian Ocean earthquake and tsunami, the damage by surging water, though much more localized, was far more deadly and destructive than the actual quake. There were reports of entire towns destroyed from tsunami-hit areas in Japan, including 9,500 missing in Minamisanriku; one thousand bodies had been recovered in the town by 14 March 2011.

Among several factors causing the high death toll from the tsunami, one was the unexpectedly large size of the water surge. The tsunami walls at several of the affected cities were based on much smaller tsunami heights. Also, many people caught in the tsunami thought that they were located on high enough ground to be safe.

Kuji and Ôfunato were almost entirely destroyed Also destroyed was Rikuzentakata, where the tsunami was reportedly three stories high. Other cities reportedly destroyed or heavily damaged by the tsunami include Kamaishi, Miyako, Ôtsuchi, and Yamada (in Iwate Prefecture), Namie, Sôma and Minamisôma (in Fukushima Prefecture) and Shichigahama, Higashimatsushima, Onagawa, Natori, Ishinomaki, and Kesennuma (in Miyagi Prefecture). The most severe effects of the tsunami were felt along a 670-km (420 mi)-long stretch of coastline from Erimo in the north to Ôarai in the south, with most of the destruction in that area occurring in the hour following the earthquake. Near Ôarai, people captured images of a huge whirlpool that had been generated by the tsunami. The tsunami washed away the sole bridge to Miyatojima, Miyagi, isolating the island's 900 residents. A two meter high tsunami hit Chiba Prefecture about 2 1/2 hours after the quake, causing heavy damage to cities such as Asahi.

On 13 March 2011, the Japan Meteorological Agency (JMA) published details of tsunami observations recorded around the coastline of Japan following the earthquake. These observations included tsunami maximum readings of over 3 m (9.8 ft) at the following locations and times on 11 March 2011, following the earthquake at 14:46 JST:

- 15:12 JST – Iwate Kamaishi-oki – 6.8 m (22 ft)

- 15:15 JST – Ôfunato – 3.2 m (10 ft) or higher
- 15:20 JST – Ishinomaki-shi Ayukawa – 3.3 m (11 ft) or higher
- 15:21 JST – Miyako – 4.0 m (13.1 ft) or higher
- 15:21 JST – Kamaishi – 4.1 m (13 ft) or higher
- 15:44 JST – Erimo-cho Shoya – 3.5 m (11 ft)
- 15:50 JST – Sôma – 7.3 m (24 ft) or higher
- 16:52 JST – Ôarai – 4.2 m (14 ft)

These readings were obtained from recording stations maintained by the JMA around the coastline of Japan. Many areas were also affected by waves of 1 to 3 meters (3.3 to 9.8 ft) in height, and the JMA bulletin also included the caveat that *"At some parts of the coasts, tsunamis may be higher than those observed at the observation sites."* The timing of the earliest recorded tsunami maximum readings ranged from 15:12 to 15:21, between 26 and 35 minutes after the earthquake had struck. The bulletin also included initial tsunami observation details, as well as more detailed maps for the coastlines affected by the tsunami waves.

On 23 March 2011, Port and Airport Research Institute reported tsunami height by visiting the port sites or by telemetry from offshore as follows:

- Port of Hachinohe – 5–6 m (16–19 ft)
- Port of Hachinohe area – 8–9 m (26–29 ft)
- Port of Kuji – 8–9 m (26–29 ft)
- Mooring GPS wave height meter at offshore of central Iwate (Miyako) – 6 m (20 ft)
- Port of Kamaishi – 7–9 m (23–30 ft)
- Mooring GPS wave height meter at offshore of southern Iwate (Kamaishi) – 6.5 m (22 ft)
- Port of Ôfunato – 9.5 m (31 ft)
- Run up height, port of Ôfunato area – 24 m (79 ft)
- Mooring GPS wave height meter at offshore of northern Miyagi – 5.6 m (18 ft)
- Fishery port of Onagawa – 15 m (50 ft)

- Port of Ishinomaki – 5 m (16 ft)
- Mooring GPS wave height meter at offshore of central Miyagi – could not measure
- Shiogama section of Shiogama-Sendai port – 4 m (13 ft)
- Sendai section of Shiogama-Sendai port – 8 m (26 ft)
- Sendai Airport area – 12 m (39 ft)

A joint research team from Yokohama National University and the University of Tokyo also reported that the tsunami at Ryôri Bay funato was about 30 m high. They found fishing equipment scattered on the high cliff above the bay. At Tarô, Iwate, a University of Tokyo researcher reported an estimated tsunami height of 37.9 m (124 ft) reached the slope of a mountain some 200 m (660 ft) away from the coastline. This height is deemed the second record in Japan historically, as of reporting date, that follows 38.2 m (125 ft) of 1896 Meiji-Sanriku earthquake.

Elsewhere across the Pacific

Shortly after the earthquake, the Pacific Tsunami Warning Center (PTWC) in Hawaii issued tsunami watches and warnings for locations in the Pacific. At 07:30 UTC, PTWC issued a widespread tsunami warning covering the entire Pacific Ocean. Russia evacuated 11,000 residents from coastal areas of the Kuril Islands. The United States West Coast and Alaska Tsunami Warning Center issued a tsunami warning for the coastal areas of most of California, all of Oregon, and the western part of Alaska, and a tsunami advisory covering the Pacific coastlines of most of Alaska, and all of Washington and British Columbia, Canada. In California and Oregon, up to 2.4 m (8 ft) high tsunami surges hit some areas, damaging docks and harbors and causing over US$10 million of damage. Surges of up to 1 m (3.3 ft) hit Vancouver Island in Canada prompting some evacuations, and causing boats to be banned from the waters surrounding the island for 12 hours following the wave strike, leaving many island residents in the area without means of getting to work.

In the Philippines, waves up to 0.5 m (1.6 ft) high hit the eastern seaboard of the country. Some houses along the coast in Jayapura, Indonesia were destroyed. Authorities in Wewak, East

Sepik, Papua New Guinea evacuated 100 patients from the city's Boram Hospital before it was hit by the waves, causing an estimated US$4 million in damages. Hawaii estimated damage to public infrastructure alone at US$3 million, with damage to private properties, including resort hotels such as Four Seasons Resort Hualalai, estimated at tens of millions of dollars. It was reported that a 1.5 m (5 ft) high wave completely submerged Midway Atoll's reef inlets and Spit Island, killing more than 110,000 nesting seabirds at the Midway Atoll National Wildlife Refuge. Some other South Pacific countries, including Tonga and New Zealand, and U.S. territories American Samoa and Guam, experienced larger-than-normal waves, but did not report any major damage. However in Guam some roads were closed off and people were evacuated from low-lying areas.

Along the Pacific Coast of Mexico and South America, tsunami surges were reported, but in most places caused little or no damage. Peru reported a wave of 1.5 m (5 ft) and more than 300 homes damaged. The surge in Chile was large enough to damage more than 200 houses, with waves of up to 3 m (9.8 ft). In the Galapagos Islands, 260 families received assistance following a 3 m (9.8 ft) surge which arrived 20 hours after the earthquake, after the tsunami warning had been lifted. There was a great deal of damage to buildings on the islands and one man was injured but there were no reported fatalities.

CASUALTIES

The National Police Agency has confirmed 13,439 deaths, 4,900 injured, and 14,867 people missing across eighteen prefectures. Prefectural officials and the Kyodo News Agency, quoting local officials, said that 9,500 people from Minamisanriku in Miyagi Prefecture—about a half of the town's population—were unaccounted for. NHK has reported that the death toll in Iwate Prefecture alone may reach 10,000. On 14 March, Kyodo News Agency reported that some 2,000 bodies were found on two shores in Miyagi Prefecture. As of 12 April 2011, *Yomiuri Shimbun* reported that 282 people had died from post-earthquake-related factors, such as exposure to cold and wet weather, communicable disease and infection, unsanitary conditions, or inability to receive adequate medical care for pre-existing conditions. Save the Children reports that as many as 100,000 children were uprooted from their homes, some of whom were separated from their families because the earthquake occurred during the school day. As of 10 April 2011, Japan's Ministry of Health, Labour and Welfare stated that it was aware of at least 82 children who had been orphaned by the disaster.

The Japanese Foreign Ministry has confirmed the deaths of nineteen foreigners. Among them are two English teachers from the United States affiliated with the Japan Exchange and Teaching Program; a Canadian missionary in Shiogama; and citizens of China, North and South Korea, Taiwan, Pakistan and the Philippines.

It was reported that four passenger trains containing an unknown number of passengers disappeared in a coastal area during the tsunami. One of the trains, on the Senseki Line, was found derailed in the morning; all passengers were rescued by a police helicopter. *Der Spiegel* later reported that five missing trains in Miyagi Prefecture had been found with all passengers safe, although this information could not be confirmed locally.

By 9:30 UTC on 11 March, Google Person Finder, which was previously used in the Haitian, Chilean, and Christchurch, New Zealand earthquakes, was collecting information about survivors and their locations. The Next of Kin Registry (NOKR) is assisting the Japanese government in locating next of kin for those missing or deceased.

Japanese funerals are normally elaborate Buddhist ceremonies, which entail cremation. The thousands of bodies, however, exceed the capacity of available crematoriums and morgues, many of them damaged, and there are shortages of both kerosene—each cremation requires 50 liters—and dry ice for preservation. The single crematorium in Higashimatsushima, for example, can only handle four bodies a day, although hundreds have been found there and hundreds of people are still missing. Governments and the military have thus been forced to bury many bodies in hastily dug mass graves with rudimentary or no rites, although relatives of the deceased have been promised that cremation will occur later. The tsunami is reported to have caused several deaths outside of Japan. One man was killed in Jayapura, Papua, Indonesia after being swept out to sea. At the mouth of the Klamath River, south of Crescent City, California, a man who is said to have been attempting to photograph the oncoming tsunami was swept out to sea. His body was found on April 2 along Ocean Beach in Fort Stevens State Park.

DAMAGE AND EFFECTS

The degree and extent of damage caused by the earthquake and resulting tsunami were enormous, with most of the damage being caused by the tsunami. Video footage of the towns worst affected shows little more than piles of rubble, with almost no parts of any structures left standing. Estimates of the cost of the damage range well into the tens of billions of US dollars; before-and-after satellite photographs of devastated regions show immense damage to many regions. Although Japan has invested the equivalent of billions of dollars on anti-tsunami seawalls which line at least 40% of its 34,751 km (21,593 mi) coastline and stand up to 12 m (39 ft) high, the tsunami simply washed over the top of some seawalls, collapsing some in the process.

Japan's National Police Agency said on 3 April 2011, that 190,000 buildings were destroyed or damaged by the quake and tsunami. Of those, 45,700 were destroyed. The damaged buildings included 29,500 structures in Miyagi Prefecture, 12,500 in Iwate Prefecture and 2,400 in Fukushima Prefecture. The earthquake and tsunami created an estimated 25 million tons of rubble and debris in Japan.

Nuclear power plants

The Fukushima I, Fukushima II, Onagawa Nuclear Power Plant and Tôkai nuclear power stations, consisting of a total eleven reactors, were automatically shut down following the earthquake. Higashidôri, also on the northeast coast, was already shut down for a periodic inspection. Cooling is needed to remove decay heat after a reactor has been shut down, and to maintain spent fuel pools. The backup cooling process is powered by emergency diesel generators at the plants and at Rokkasho nuclear reprocessing plant. At Fukushima I and II tsunami waves overtopped seawalls and destroyed diesel backup power systems, leading to severe problems at Fukushima I, including two large explosions and radioactive leakage. Over 200,000 people were evacuated.

The April 7 aftershock caused the loss of external power to Rokkasho Reprocessing Plant and Higashidori Nuclear Power Plant but backup generators were functional. Onagawa Nuclear Power Plant lost 3 of 4 external power lines and lost cooling function for as much as 80 minutes. A spill of a couple liters of radioactive water occurred at Onagawa.

Europe's Energy Commissioner Guenther Oettinger addressed the European Parliament on 15 March, explaining that the nuclear disaster an "apocalypse". As the nuclear crisis entered a second month, experts recognized that Fukushima is not the worst nuclear accident ever but it is the most complicated.

Fukushima I and II Nuclear Power Plants

Main articles: Fukushima I nuclear accidents, Timeline of the Fukushima I nuclear accidents, and Timeline of the Fukushima II nuclear accidents.

Japan declared a state of emergency following the failure of the cooling system at the Fukushima I Nuclear Power Plant, resulting in the evacuation of nearby residents. Officials from the Japanese Nuclear and Industrial Safety Agency reported that radiation levels inside the plant were up to 1,000 times normal levels, and that radiation levels outside the plant were up to 8 times normal levels. Later, a state of emergency was also declared at the Fukushima II nuclear power plant about 11 km (7 mi) south. This brought the total number of problematic reactors to six.

It was reported that radioactive iodine was detected in the tap water in Fukushima, Toshigi, Gunma, Tokyo, Chiba, Saitama, and Niigata, and radioactive cesium in the tap water in Fukushima, Tochigi and Gunma. Radioactive cesium, iodine, and stronium were also detected in the soil in some places in Fukushima. There may be a need to replace the contaminated soil. Food products were also found contaminated by radioactive matter in several places in Japan. On April 5, 2011, the government of the Ibaraki

Prefecture banned the fishing of sand lance after discovering that this species was contaminated by radioactive cesium above legal limits.

Onagawa Nuclear Power Plant

A fire occurred in the turbine section of the Onagawa Nuclear Power Plant following the earthquake. The blaze was in a building housing the turbine, which is sited separately from the plant's reactor, and was soon extinguished. The plant was shut down as a precaution.

On 13 March the lowest-level state of emergency was declared regarding the Onagawa plant as radioactivity readings temporarily exceeded allowed levels in the area of the plant. Tohoku Electric Power Co. stated this may have been due to radiation from the Fukushima I nuclear accidents but was not from the Onagawa plant itself.

As a result of the April 7 aftershock, Onagawa Nuclear Power Plant lost 3 of 4 external power lines and lost cooling function for as much as 80 minutes. A spill of a couple liters of radioactive water occurred at Onagawa.

Tôkai Nuclear Power Plant

The number 2 reactor at Tôkai Nuclear Power Plant was shut down automatically. On 14 March it was reported that a cooling system pump for this reactor had stopped working; however, the Japan Atomic Power Company stated that there was a second operational pump sustaining the cooling systems, but that two of three diesel generators used to power the cooling system were out of order.

Ports

All of Japan's ports were briefly closed after the earthquake, though the ones in Tokyo and southwards soon re-opened. Fifteen ports were located in the disaster zone. The north-eastern ports of Hachinohe, Sendai, Ishinomaki and Onahama were destroyed, while Chiba port (which serves the hydrocarbon industry) and Japan's ninth-largest container port at Kashima were also affected though less severely. The ports at Hitachinaka, Hitachi, Soma, Shiogama, Kesennuma, Ofunato, Kamashi and Miyako were also damaged and closed to ships. All 15 ports reopened to limited ship traffic by 29 March 2011.

The Port of Tokyo suffered slight damage; the effects of the quake included visible smoke rising from a building in the port with parts of the port areas being flooded, including soil liquefaction in Tokyo Disneyland's carpark.

Dam failure

The Fujinuma irrigation dam in Sukagawa ruptured, causing flooding and washing away homes. Eight people were missing and four bodies were discovered by the morning. Reportedly, some locals had attempted to repair leaks in the dam before it completely failed. On 12 March, 252 dams were inspected and it was discovered that six embankment dams had shallow cracks on their crests. The reservoir at one concrete gravity dam suffered a small non-serious slope failure. All damaged dams are functioning with no problems. Four dams within the quake area were unreachable. When the roads clear, experts will be dispatched to conduct further investigations.

Water

In the immediate aftermath of the calamity, at least 1.5 million households were reported to have lost access to water supplies. By 21 March 2011, this number fell to 1.04 million.

Electricity

According to Tôhoku Electric Power (TEP), around 4.4 million households in northeastern Japan were left without electricity. Several nuclear and conventional power plants went offline after the earthquake, reducing TEPCO's total capacity by 21 GW. Rolling blackouts began on 14 March due to power shortages caused by the earthquake. The Tokyo Electric Power Company (TEPCO), which normally provides approximately 40 GW of electricity, announced that it can currently provide only about 30 GW. This is because 40% of the electricity used in the greater Tokyo area is now supplied by reactors in the Niigata and Fukushima prefectures. The reactors at the Fukushima Dai-ichi and Fukushima

Dai-ni plants were automatically taken offline when the first earthquake occurred and have sustained major damage related to the earthquake and subsequent tsunami. Rolling blackouts of three hours are expected to last until the end of April and will affect the Tokyo, Kanagawa, Eastern Shizuoka, Yamanashi, Chiba, Ibaraki, Saitama, Tochigi, and Gunma prefectures. Voluntary reduced electricity use by consumers in the Kanto area helped reduce the predicted frequency and duration of the blackouts. By 21 March 2011, the number of households in the north without electricity fell to 242,927.

Tôhoku Electric Power cannot currently provide the Kanto region with additional power, because TEP's power plants were also damaged in the earthquake. Kansai Electric Power Company (Kepco) cannot share electricity, because its system operates at 60 hertz, whereas TEPCO and TEP operate their systems at 50 hertz; this is due to early industrial and infrastructure development in the 1880s that left Japan without a unified national power grid. Two substations, one in Shizuoka Prefecture and one in Nagano Prefecture, can convert between frequencies and transfer electricity from Kansai to Kanto and Tôhoku, but their capacity to do so is limited to 1 GW. With the damage to so many power plants, it could be years before electricity productions levels in eastern Japan return to pre-quake levels.

In effort to help alleviate the shortage, three steel manufacturers in the Kanto region are contributing electricity produced by their in-house conventional power stations to TEPCO for distribution to the general public. Sumitomo Metal Industries can produce up to 500 MW, JFE Steel 400 MW, and Nippon Steel 500 MW of electric power.

Oil, gas and coal

A 220,000-barrel-per-day oil refinery of Cosmo Oil Company was set on fire by the quake at Ichihara, Chiba Prefecture, to the east of Tokyo, while others halted production due to safety checks and power loss. In Sendai, a 145,000-barrel-per-day refinery owned by the largest refiner in Japan, JX Nippon Oil & Energy, was also set ablaze by the quake. Workers were evacuated, but tsunami warnings hindered efforts to extinguish the fire until 14 March, when officials planned to do so. An analyst estimates that consumption of various types of oil may increase by as much as 300,000 barrels per day (as well as LNG), as back-up power plants burning fossil fuels try to compensate for the loss of 11 GW of Japan's nuclear power capacity.

The city-owned plant for importing liquefied natural gas in Sendai was severely damaged, and supplies were halted for at least a month.

Transport

Japan's transport network suffered severe disruptions. Many sections of Tôhoku Expressway serving northern Japan were damaged. The expressway did not reopen to general public use until 24 March 2011. All railway services were suspended in Tokyo, with an estimated 20,000 people stranded at major stations across the city. In the hours after the earthquake, some train services were resumed. Most Tokyo area train lines resumed full service by the next day-12 March. Twenty thousand stranded visitors spent the night of 11–12 March inside Tokyo Disneyland.

A tsunami wave flooded Sendai Airport at 15:55 JST, about 1 hour after the initial quake, causing severe damage. Narita and Haneda Airport both briefly suspended operations after the quake, but suffered little damage and reopened within 24 hours. Eleven airliners bound for Narita were diverted to nearby Yokota Air Base.

Various train services around Japan were also canceled, with JR East suspending all services for the rest of the day. Four trains on coastal lines were reported as being out of contact with operators; one, a four-car train on the Senseki Line, was found to have derailed, and its occupants were rescued shortly after 8 am the next morning. Sixty-two of 70 JR East train lines suffered damage to some degree; in the worst-hit areas, 23 stations on 7 lines were washed away, with damage or loss of track in 680 locations and the 30-km radius around the Fukushima I nuclear plant unable to be assessed.

There were no derailments of Shinkansen bullet train services in and out of Tokyo, but their services were also suspended. The

Tôkaidô Shinkansen resumed limited service late in the day and was back to its normal schedule by the next day, while the Jôetsu and Nagano Shinkansen resumed services late on 12 March. The Tôhoku Shinkansen line was worst hit, with JR East estimating that 1,100 sections of the line, varying from collapsed station roofs to bent power pylons, will need repairs. Services on the Tôhoku Shinkansen partially resumed only in Kantô area on 15 March, with one round-trip service per hour between Tokyo and Nasu-Shiobara, and Tôhoku area service partially resumed on 22 March between Morioka and Shin-Aomori. Services on Akita Shinkansen resumed with limited numbers of trains on 18 March. Services on Yamagata Shinkansen resumed with limited numbers of trains on 31 March.

Minami-Kesennuma Station on the Kesennuma Line was obliterated save for its platform; anecdotal evidence suggests severe damage to the line as well as other coastal lines (including the Ishinomaki Line and Senseki Line).

The rolling blackouts brought on by the crises at the nuclear power plants in Fukushima had a profound effect on the rail networks around Tokyo starting on 14 March. Major railways began running trains at 10–20 minute intervals, rather than the usual 3–5 minute intervals, operating some lines only at rush hour and completely shutting down others; notably, the Tokaido Main Line, Yokosuka Line, Sobu Main Line and Chûô-Sôbu Line were all stopped for the day. This led to near-paralysis within the capital, with long lines at train stations and many people unable to come to work or get home. Railway operators gradually increased capacity over the next few days, until running at approximately 80% capacity by 17 March and relieving the worst of the passenger congestion.

Telecommunications

Cellular and landline phone service suffered major disruptions in the affected area. On the day of the quake, American broadcaster NPR was unable to reach anyone in Sendai with working phone or Internet. Internet services were largely unaffected in areas where basic infrastructure remained, despite the earthquake having damaged portions of several undersea cable systems landing in the affected regions; these systems were able to reroute around affected segments onto redundant links. Within Japan, only a few websites were initially unreachable. Several Wi-Fi hotspot providers have reacted to the quake by providing free access to their networks, and some American telecommunications and VoIP companies such as AT&T, Sprint, Verizon and VoIP companies such as netTALK and Vonage have offered free calls to (and in some cases, from) Japan for a limited time.

Space center

JAXA (Japan Aerospace Exploration Agency) evacuated the Tsukuba Space Center in Tsukuba, Ibaraki. The Center, which houses a control room for part of the International Space Station, has been shut down, with some damage reported. The Tsukuba control center resumed full operations for the space station's Kibo laboratory and the HTV cargo craft on March 21.

AFTERMATH

The aftermath of the earthquake and tsunami included both a humanitarian crisis and a major economic impact. The tsunami resulted in over 300,000 refugees in the Tôhoku region, and shortages of food, water, shelter, medicine and fuel for survivors. In response the Japanese government mobilized the Self-Defence Forces, whilst many countries sent search and rescue teams to help search for survivors. Aid organizations both in Japan and worldwide also responded, with the Japanese Red Cross reporting $1 billion in donations. The economic impact included both immediate problems, with industrial production suspended in many factories, and the longer term issue of the cost of rebuilding which has been estimated at ¥10 trillion ($122 billion). *(This is a summary only – see main article for supporting references.)*

MEDIA COVERAGE

Japan's national public broadcaster, NHK, and Japan Satellite Television suspended their usual programming to provide ongoing coverage of the situation. Various other nationwide Japanese TV networks also broadcast uninterrupted coverage of the disaster. Ustream Asia broadcast live feeds of NHK, Tokyo Broadcasting System, Fuji TV, TV Asahi, TV Kanagawa, and CNN on the Internet starting on 12 March 2011. YokosoNews, an Internet webcast in Japan, dedicated its broadcast to the latest news gathered from Japanese news stations, translating them in real time to English.

NHK has been noted for its calmness, in comparison to foreign television news such as CNN and Fox News Channel, whose coverage has contained factual errors and raised alarm among foreign residents of Japan. The same critics note that the Japanese news media has been at times overly cautious to avoid panic and reliant on confusing statements by experts and officials.

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Scientific and Research Response

A large amount of data was collected that provides "the possibility to model in great detail what happened during the rupture of an earthquake." The effect of this data is expected to be felt across other disciplines as well, and this disaster "would provide unprecedented information about how buildings hold up under long periods of shaking – and thus how to build them better. We had very little information about that before now".

Seismologists had anticipated that the "big one" would strike the same place as the 1923 Great Kantô earthquake—in the Sagami Trough, southwest of Tokyo. Since 1976, when Katsuhiko Ishibashi said a large earthquake in the Suruga Trough was forthcoming, the government tracked plate movements, in preparation for the so-called Tokai earthquake. Occurring 373 km (232 mi) northeast of Tokyo, the Tôhoku earthquake came as a surprise to seismologists, since the Japan Trench was known for creating large quakes, but was not expected to generate quakes above an 8.0 magnitude.

HIGHEST OR TALLEST

Megatsunami (also known as *iminami* or "purification wave") is an informal term to describe a tsunami that has initial wave heights that are much larger than normal tsunamis. Unlike usual tsunamis, which originate from tectonic activity and the raising or lowering of the sea floor, known megatsunamis have originated from large scale landslides or impact events.

Concept

A megatsunami is meant to refer to a tsunami with an initial wave amplitude (wave height) measured in several tens, hundreds, or possibly thousands of meters.

Normal tsunamis generated at sea have a small wave height offshore, and a very long wavelength (often hundreds of kilometers long). They generally pass unnoticed at sea, forming only a slight swell usually of the order of 30 cm (12 in) above the normal sea surface. When they reach land the wave height increases dramatically as the base of the wave pushes the water column above it upwards.

Megatsunamis can be caused by giant landslides and asteroid impacts. Underwater earthquakes or volcanic eruptions do not normally generate such large tsunamis, but landslides next to bodies of water resulting from earthquakes do, since they cause a massive amount of displacement.

History of the hypothesis

Geologists searching for oil in Alaska in 1953 observed that in Lituya Bay, mature tree growth did not extend to the shoreline as it did in many other bays in the region. Rather, there was a band of younger trees closer to the shore. Forestry workers, glaciologists, and geographers call the boundary between these bands a trim line. Trees just above the trim line showed severe scarring on their seaward side, whilst those from below the trim line did not. The scientists hypothesized that there had been an unusually large wave or waves in the deep inlet. Because this is a recently deglaciated fjord with steep slopes and crossed by a major fault, one possibility was a landslide-generated tsunami.

On 9 July 1958, an earthquake of magnitude 7.7 (on the Richter scale), caused 90 million tonnes of rock and ice to drop into the deep water at the head of Lituya Bay. The block fell almost vertically and hit the water with sufficient force to create a wave approximately 524 metres (1,719 ft). Howard Ulrich and his son, Howard Jr., were in the bay in their fishing boat when they saw the wave. They both survived and reported that the wave carried their boat "over the trees" on one of the initial waves which washed them back into the bay, though the larger wave did not harm them a great lot. A similar tsunami out at sea could come tens of kilometers inland.

This event and evidence of a potentially similar past event at the same location inspired the term *megatsunami*.

List of megatsunami

Prehistoric:

- The asteroid which created the Chicxulub crater in Yucatan approximately 65 million years BP would have generated some of the largest megatsunami in Earth's history.
- A series of megatsunami were generated by the bolide impact that created the Chesapeake Bay impact crater, about 35.5 million years BP.
- At Seton Portage, British Columbia, Canada, a freshwater megatsunami may have occurred approximately 10,000 BP. A huge block of the Cayoosh Range suddenly slid northwards into what had been a large lake spanning the area from Lillooet, British Columbia to near Birken, in the Gates Valley or Pemberton Pass to the southwest. The event has not been studied in detail, but the proto-lake (freshwater fjord) may have been at least as deep as the two present-day halves, Seton and Anderson Lakes, on either side of the Portage, suggesting that the surge generated by the giant landslide in the narrow mountain confines of the fjord valley may have been comparable in scale to Lituya Bay. Another more recent landslide on the south shore of Anderson Lake dropped a large portion of high mountainside down a debris chute, creating a rockwall "fan" which *must* have made a megatsunami-type wave, though not as large as the main one at the Portage.
- Approximately 8,000 BP, a massive volcanic landslide off of Mt. Etna, Sicily caused a megatsunami which devastated the eastern Mediterranean coastline on three continents.
- In the Norwegian Sea, the Storegga Slide caused a megatsunami approximately 7,000 years BP.

- Approximately 4,000 BC, a landslide on Réunion island, to the east of Madagascar, may have caused a megatsunami.
- The recently discovered undersea Burckle Crater located at the bottom of the Indian Ocean would have caused a megatsunami at the time of impact estimated to be c. 3000–2800 BC. It is unknown whether the Burckle Crater is connected to the Fenambosy Chevron which provides evidence of another megatsunami.
- Evidence for large landslides has been found in the form of extensive underwater debris aprons around many volcanic ocean islands which are composed of the material which has slid into the ocean. The island of Molokai had a catastrophic collapse over a million years ago; this underwater landslide likely caused large tsunamis. In recent years, five such debris aprons have been located around the Hawaiian Islands. The Canary Islands have at least 14 such debris aprons associated with the archipelago.

MODERN

1792: Mount Unzen, Japan

In 1792, Mount Unzen in Japan erupted, causing part of the volcano to collapse into the sea. The landslide caused a megatsunami that reached 100 meters (328 ft) high and killed 15,000 people in the local fishing villages.

1958: Lituya Bay, Alaska, USA

On 9 July 1958, a giant landslide at the head of Lituya Bay in Alaska, caused by an earthquake, generated a wave with an initial amplitude of 524 meters (1,719 ft). This is the highest wave ever recorded, and surged over the headland opposite, stripping trees and soil down to bedrock, and surged along the fjord which forms Lituya Bay, destroying a fishing boat anchored there and killing two people. Howard Ulrich and his son managed to ride the wave in their boat, and both survived.

1963: Vajont Dam, Italy

On 9 October 1963, a landslide above Vajont Dam in Italy produced a 250 m (820 ft) surge that overtopped the dam and destroyed the villages of Longarone, Pirago, Rivalta, Villanova and Faè, killing nearly 2,000 people.

1980: Spirit Lake, Washington, USA

On May 18, 1980, the upper 460 meters of Mount St. Helens failed and detached in a massive landslide. This released the pressure on the magma trapped beneath the summit bulge which exploded as a lateral blast, which then released the over-pressure on the magma chamber and resulted in a plinian eruption.

One lobe of the avalanche surged onto Spirit Lake, causing a megatsunami which pushed the lake waters in a series of surges, which reached a maximum height of 260 metres above the pre-eruption water level (~975 m asl). Above the upper limit of the tsunami, trees lie where they were knocked down by the pyroclastic surge; below the limit, the fallen trees and the surge deposits were removed by the megatsunami and deposited in Spirit Lake.

POTENTIAL FUTURE MEGATSUNAMI

Experts interviewed by the BBC think that a massive landslide on a volcanic ocean island is the most likely future cause of a megatsunami. The size and power of a wave generated by such means could produce devastating effects, travelling across oceans and inundating up to 25 kilometres (16 mi) inland from the coast.

British Columbia

Some geologists consider an unstable rock face at Mount Breakenridge, above the north end of the giant fresh-water fjord of Harrison Lake in the Fraser Valley of southwestern British Columbia, Canada, to be unstable enough to collapse into the lake, generating a megatsunami that might destroy the town of Harrison Hot Springs (located at its south end).

Canary Islands

Geologists S. Day and S. Ward consider that a megatsunami could be generated during a future eruption involving the Cumbre Vieja on the volcanic ocean island of La Palma, in the Canary Islands. In 1949, the Cumbre Vieja volcano erupted at its Duraznero, Hoyo Negro and San Juan vents. During this eruption, an earthquake with an epicentre near the village of Jedy occurred. The following day Rubio Bonelli, a local geologist, visited the summit area and discovered that a fissure about 2.5 kilometers (2 mi) long had opened on the eastern side of the summit. As a result, the western half of the Cumbre Vieja (which is the volcanically active arm of a triple-armed rift) had slipped about 2 meters (7 ft) downwards and 1 meters (3 ft) westwards towards the Atlantic Ocean.

The Cumbre Vieja volcano is currently in a dormant stage, but will almost certainly erupt again in the future. Day and Ward hypothesize that if such an eruption causes the western flank to fail, a megatsunami will be generated.

La Palma is currently the most volcanically active island in the Canary Islands Archipelago. It is likely that several eruptions would be required before failure would occur on Cumbre Vieja. However, the western half of the volcano has an approximate volume of 500 cubic kilometres (120 cu mi) and an estimated mass of 1,500,000,000,000 metric tons (1.7×10^{12} short tons) If it were to catastrophically slide into the ocean, it could generate a wave with an initial height of about 1,000 metres (3,300 ft) at the island, and a likely height of around 50 metres (164 ft) at the Caribbean and the Eastern North American seaboard when it runs ashore eight or more hours later. Tens of millions of lives would be lost as New York, Boston, Baltimore, Washington, D.C., Miami, Havana, and many other cities near the Atlantic coast are leveled. The likelihood of this happening is a matter of vigorous debate.

The last Cumbre Vieja eruption occurred in 1971 at the southern end of the sub-aerial section without any movement. The section affected by the 1949 eruption is currently stationary and does not appear to have moved since the initial rupture.

Geologists and volcanologists also disagree about whether an eruption on the Cumbre Vieja would cause a single large gravitational landslide or a series of smaller landslides.

Hawaii

Prehistoric sedimentary deposits on the Kohala Volcano, Lanai and Molokai controversially indicates that landslides from the flank of the Kilauea and Mauna Loa volcanoes in Hawaii may have triggered past megatsunamis, most recently at 120,000 BP. A future tsunami event is also possible, with the tsunami potentially reaching up to about 1 kilometre (3,300 ft) in height. According to a documentary called National Geographic's Ultimate Disaster: Tsunami, if a big landslide occurred at Mauna Loa, a 30 metres (98 ft) tsunami would take only thirty minutes to reach Honolulu, Hawaii. There, hundreds of thousands of people would be killed as the tsunami leveled Honolulu and traveled 25 kilometres (16 mi) inland.

- The tallest tsunami ever recorded so far is the 1958 Lituya Bay megatsunami, which had a record height of 524 m (1742 ft).
- The only other *recent* megatsunamis are the 1980 Spirit Lake megatsunami, which measured 260 m (780 ft) tall and the 1963 Vajont Dam megatsunami which had an initial height of 250 m (750 ft).

Deadliest

The deadliest tsunami in recorded history was the 2004 Asian tsunami, which killed almost 230,000 people in eleven countries across the Indian Ocean.

OTHER HISTORIC TSUNAMIS

Other tsunamis that have occurred include the following:

- ca. 500 BC: Poompuhar, Tamil Nadu, India, Maldives.
- 1541: a tsunami struck the earliest European settlement in Brazil, São Vicente. There is no record of deaths or injuries, but the town was almost completely destroyed.

North America and the Caribbean:

- 1690 - Nevis
- 14 November 1840 - Great Swell on the Delaware River
- 18 November 1867 - Virgin Islands
- 17 November 1872 - Maine
- 11 October 1918 - Puerto Rico
- 9 January 1926 - Maine

- 4 August 1946 - Dominican Republic
- 18 August 1946 - Dominican Republic
- 15 November 2006 - Crescent City, CA

Possible:

- 35 million years ago - Chesapeake Bay impact crater, Chesapeake Bay
- 9 June 1913 - Longport, NJ
- 6 August 1923 - Rockaway Park, Queens, NY.
- 8 August 1924 - Coney Island, NY.
- 19 August 1931 - Atlantic City, NJ
- 22 June 1932 - Cuyutlán, Colima, Mexico
- 19 May 1964 - Northeast USA
- 4 July 1992 - Daytona Beach, FL

Source: NOAA National Weather Service Forecast Office.

Europe

- 6100 BC - Storegga Slide, Norway - The Storegga slide generated a huge tsunami that washed through the North Atlantic Ocean, hitting Norway, Iceland and the east coast of Scotland, where it reached a height of 21 metres, and even washed over some of the Shetland Islands.
- 11 January 1683 - An earthquake in Italy triggered a tsunami that killed more than 1000 people.
- 6 February 1783 - An offshore earthquake in Southern Italy caused a tsunami that killed around 1500 people.
- 20 September 1867 - An earthquake in Greece caused a tsunami that killed 12 people.
- 11 September 1930 - 2 people were killed by a tsunami in Italy, caused by an undersea earthquake measuring 7.7 on the Richter Scale.
- 9 July 1956 - An earthquake in Greece generated a tsunami that drowned 4 people.
- 28 February 1969 - A submarine earthquake measuring 7.3 on the Richter Scale, with its epicentre of the coast of

Portugal, caused a tsunami that hit Northern Portugal, parts of Spain, and Morocco. No lives were lost.

- 16 October 1979 - 23 people died when the coast of Nice, France, was hit by a tsunami, caused by an undersea landslide. The sea suddenly receded from the shore and returned in two huge waves, hitting a 36-mile-long coastal stretch. Hundreds of boats were overturned, and 11 people working in a shipyard were drowned.
- 13 December 1990 - 6 people died when an undersea earthquake in Italy caused a tsunami.
- 17 August 1999 - The 1999 Ýzmit earthquake in Northwest Turkey triggered a 2 metre high tsunami in the Sea of Marmara.

Possible

The 1607 Bristol Channel floods, which were traditionally believed to be a massive storm surge, could possibly have been a tsunami, caused by an earthquake or landslide off the coast of Southern Ireland. There is some evidence suggesting it was a tsunami, but not enough to confirm. It was the deadliest natural disaster in the history of the United Kingdom, and killed around 2000 people from Somerset to Cardiff.

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Technological Information of Tsunami

A tsunami (seismic sea wave, tidal wave) is a series of waves most commonly caused by an earthquake beneath the sea floor or by a large undersea landslide. In the open ocean, tsunami waves travel at speeds of up to 600 miles per hour but are too small to be observed. As the waves enter shallow water, they slow down and may rise to several feet or, in rare cases, tens of feet. Tsunamis can cause great loss of life and property damage where they come ashore. The first wave is almost never the largest; successive waves may be spaced tens of minutes apart and continue arriving for many hours. Since 1812, the California coast has had 14 tsunamis with wave heights higher than three feet; six of these were destructive. The Channel Islands were hit by a damaging tsunami in the early 1800s. The worst tsunami resulted from the 1964 Alaskan earthquake and caused 12 deaths and at least $17 million in damage to northern California. The April 25, 1992 Cape Mendocino earthquake produced a one-foot tsunami that reached Humboldt Bay in about 20 minutes after the shaking. Although not damaging, this tsunami demonstrated that a wave could reach our coastline quickly. Two general types of tsunamis could affect the coastal areas of California:

Local-source tsunami: If a large tsunami-genic earthquake occurs at or near the California coast, the first waves may reach coastal communities within minutes after the ground shaking stops. There is no time for authorities to issue a warning. Mitigation requires an understanding of areas at risk, areas of safety, evacuation routes and a trained public that understands the need to immediately move inland or to higher ground.

Though infrequent, California has experienced local tsunamis in the past, and paleotsunami evidence shows major tsunami impact in the recent geologic past. Risk is considered high along the north coast of California, from Crescent City to Cape Mendocino; moderate south of Cape Mendocino to north of Monterey; high south of Monterey to Palos Verdes; and moderate south of Palos Verdes to San Diego (see Historic California Tsunamis in Appendix 2.) Large local tsunamis may impact the entire California coastline. Waves from an earthquake at the Cascadia Subduction Zone could reach southern California in less than 2 hours.

Distant-source tsunami: Very large earthquakes in other areas of the Pacific Rim may also cause tsunamis which could impact California's coast. The first waves would reach our coastline many hours after the earthquake occurred. Tsunami Warning Centers are responsible for alerting local officials, who may order evacuation. Effective mitigation requires an understanding of the tsunami warning system, local areas at risk, and evacuation planning.

USE OF MODEL INUNDATION MAPS

California coastal communities need to know the areas where damage is possible from a tsunami in order to prepare for and reduce losses. Local decision makers need to understand their risk in order to make informed planning decisions. The major steps in using the model inundation maps to develop a tsunami vulnerability analysis are:

- Transfer information from the model tsunami inundation maps to jurisdiction based maps.
- Analyze and confirm the inundation projections by field surveys and detailed topographic review.
- Develop map overlays for the following:
  - — Critical facilities (police, fire, city hall, public works facilities, airports, major supply warehouses).

- — Special needs facilities (schools, public assembly, hospitals, convalescent homes).
- — Special needs populations (e.g. non-English speakers, physically disabled, elderly, children).
- — Transportation lifelines.
- — Hazardous materials sites and facilities.
- — Population demographics.

- Identify boundaries of Tsunami Evacuation Zone with well-known landmarks, such as streets, railroad or freeway rights-of-way, parks, etc.
- Identify refuge areas within the Tsunami Evacuation Zone and their shelter capacity for evacuated population.
- Survey proposed evacuation routes to determine post earthquake function of bridges, adjacent buildings, and expected safety of adjacent land uses (avoid hazardous buildings and HazMat sites).
- Locate evacuation routes and alternates.

LIMITATIONS AND USE OF INUNDATION PROJECTIONS

Ideally, tsunami response and evacuation planning should be based on reliable models of projected inundation at a given location and estimates of the probability of occurrence of earthquakes and tsunamis based on known as well as recurrence intervals. Unfortunately, both factors are limited by our knowledge of the tsunami history of the Pacific coast of California.

Three factors affect the accuracy of inundation projections: the quality of the mathematical model of tsunami wave propagation, the detail of data on topography and bathymetry (underwater topography), and the assumptions made about the origins and mechanism of tsunami generation.

The mathematical models now being used by NOAA and the State of California for projecting tsunami inundation are based on a consensus in the scientific community about the propagation of waves from deep ocean to shallow coastal conditions. Furthermore, the models have been calibrated against actual recent tsunamis in Japan. A more important factor in the accuracy of inundation projections is the detail in the topographical and bathymetrical data. A lack of detail in mapping offshore bathymetry, or even seasonal changes in beach conditions, can have a significant impact on model output.

Identifying the origin or mechanism of "tsunami genesis" poses additional problems for inundation modeling. Tsunami waves generated from near-source or near-shore earthquakes, or underwater landslides, may vary in impact from those generated by distant subduction zone earthquakes. In order to avoid the conflict over tsunami origin, inundation projections are based on worst-case scenarios. Since the inundation projections are intended for emergency and evacuation planning, flooding is based on the highest projection of inundation regardless of the tsunami origin. As such, projections are not an assessment of the probability of reaching the projected height (probabilistic hazard assessment) but only a planning tool.

Inundation projections and resulting planning maps are to be used for emergency planning purposes only. They are not based on a specific earthquake and tsunami. Areas actually inundated by a specific tsunami can vary from those predicted. The inundation maps are not a prediction of the performance, in an earthquake or tsunami, of any structure within or outside of the projected inundation area.

DEVELOPMENT OF TSUNAMI PLANS

Information gathered during the transfer of the model inundation maps to local map overlays will be the basis for identifying both high priority responses and the steps to reduce potential dangers. The estimates can also be used to determine where damage is likely to occur, which areas and segments of the population are at the greatest risk, and to develop an evacuation route with a traffic control plan. A tsunami plan can identify what can be done to improve public safety and indicate where a community may need resources after a tsunami.

The development of a Tsunami Plan requires a multi-disciplinary approach and should involve local specialists (emergency responders, planners, engineers, utilities, and community based organizations). The city or county administrative officer should appoint a Tsunami Plan Working Group and designate a chairperson, usually the emergency services manager. The Tsunami Plan Working Group should include representatives from the following agencies:

- Law Enforcement
- Emergency Management
- Public Works
- Land Use Planning
- Social Services
- Fire Suppression
- American Red Cross
- Transportation providers
- Non-governmental and Community Based Organizations
- Warning Coordination Meteorologist from the regional NWS office
- Education Community

The Work Group will determine the best way to accomplish the planning process, develop an overall work program, and set a time schedule for completion *(See Tsunami Plan Checklist and Sample San Mateo County Plan in Appendix 3).*

One of the most critical elements of a Tsunami Plan is the Evacuation and Traffic Control Plan. Local governments are responsible for developing evacuation plans for possible implementation in response to a near or distant-source event. A distant-source tsunami event may allow several hours to evacuate. A near-source tsunami may require immediate self-evacuation through areas damaged by the earthquake and at some risk of aftershocks.

Each jurisdiction should analyze how much time an evacuation would require and build that into the decision-making procedure. While developing its plan, each jurisdiction should decide how best to handle the occurrence of both earthquakes and tsunamis. Evacuation plans should also take into account the special needs of evacuees, including the medically fragile, mobility impaired, deaf, blind, and those who speak no English or English as a second language.

EVACUATION PLANS

Elements to consider in developing an evacuation plan are:

- Locate optimum evacuation routes. The primary objective is to move up and inland, away from the coast.
- Develop an evacuation route traffic control plan. This should be tasked to the public safety agencies. Public safety agencies should use their auxiliaries and volunteers to staff traffic control points.
- Identify refuge areas with the capacity to shelter the evacuated population. Select landmarks, school facilities, or other well-known public facilities.
- Develop simplified maps depicting tsunami evacuation zones, evacuation routes, and refuge areas.
- Develop notification and evacuation procedures with public safety agencies and distribute to field personnel.
- Disseminate maps and procedures to public. Ensure maps and procedures are posted in assembly facilities and areas, schools, special facilities, included in telephone books, etc.

After the plan has been completed, it is essential to develop education, training, and exercise programs for city and county employees as well as for the residents in the community. *(See sample Evacuation Checklist in Appendix 3).*

Public Education Programs and Training

A sustained public outreach program is needed to gain the long-term grassroots support of coastal populations and to institutionalize tsunami preparedness and mitigation. Such a program should encourage consistent information between local government and the community at risk. Innovative approaches should be encouraged at many different levels. Training is a crucial component for a successful tsunami response program. Local jurisdictions may want to develop a comprehensive program, based upon a training needs assessment. One of the most important means of educating the public is through tsunami education in the public schools. There are several areas that local jurisdictions may want to consider when developing a "Tsunami Training and Awareness Program":

- Existing employee orientation and training programs and staff briefings.
- First Responder training and exercise programs.
- Incorporating tsunami education into existing earthquake programs in the public schools.
- “Tsunami Awareness Programs” for the public, including the special needs populations.

Questions to consider when evaluating existing employee training programs:

- What training already exists?
- What additional areas of training will be needed?
- How can these elements best be incorporated into current training programs?

Questions to consider regarding tsunami awareness programs:

- What training is needed to reach the various population types (e.g. elderly, business, transient, tourist, etc.)?
- How can training be delivered to best reach the community?
- How can tsunami education be incorporated into existing earthquake or all hazard mitigation programs?
- Does the awareness training for personnel and volunteers include a quick orientation?

Questions to consider regarding First Responder training programs:

- What First Responder training already exists that can be used by the local jurisdiction?
- Where does the First Responder training fit with other training elements?
- Does the jurisdiction need to develop First Responder training?
- Does the jurisdiction need assistance in developing its training?

Questions to consider when looking at employee training:

- What training needs to be implemented for dispatch centers?

- What training is needed for fire and rescue?
- What training is needed for EMS? HazMat?
- What training is needed for law enforcement?

Exercises

Communities can benefit by developing and implementing an exercise program to test the training received on the tsunami response plan. Important considerations are:

- How can development of a separate exercise program for tsunami improve the communities' ability to respond to a tsunami?
- Who should develop, conduct, and maintain the new tsunami response exercise program?
- Does the jurisdiction have the resources to conduct such exercises?
- In what creative ways can funding be found for an exercise program?

TSUNAMI WARNING SYSTEM

The West Coast and Alaska Tsunami Warning Center in Alaska (WC/ATWC) and the Pacific Tsunami Warning Center (PTWC) in Hawaii monitor potential tsunamis. A regional Tsunami Warning or Watch is issued based on earthquake location and magnitude. When an earthquake of 7.5 or larger occurs within the Pacific basin, the warning centers issue warnings and watches. Areas within a 3-hour tsunami travel time of the epicenter will be placed in a Tsunami Warning status, and areas within a 3-6 hour tsunami travel time will be placed in a Tsunami Watch status.

Tsunami estimated time of arrival will be disseminated for the tide stations within the Tsunami Warning and Watch areas. Additional bulletins are issued by the warning centers at hourly intervals until the advisories are either canceled or the existence of a damaging tsunami is confirmed. The information is transmitted to the Governor's Office of Emergency Services Warning Control Center and local emergency managers (See Appendix 4 for explanation of Tsunami Warning and Watch and sample messages).

When the California State Warning Center (CSWC) receives the information from WC/ATWC via NAWAS and/or California Law Enforcement Teletype System (CLETS), the WC/ATWC will announce what areas the message is for, whether it is an Information Bulletin, a Tsunami Watch, or a Tsunami Warning. The Warning Center does not undertake any threat analysis. All information received is passed directly to the Operational Areas via CLETS, California Alert and Warning System (CALWAS) and Emergency Alert System (EAS). Once the information has been sent out the following actions are taken:

Verification is made with the printed copy received via National Weather Service (NWS) satellite. The information is re-transmitted via CLETS to all sheriff's offices (SO) of coastal counties and most local police departments (PD). Turn-around time from NWS to CLETS and out is a matter of a few seconds.

NOTE: If the bulletin is only informational and a tsunami has not been generated, or is not expected, then no further action is taken by the CSWC.

The CSWC immediately polls all SOs of the 19 coastal counties and the CHP dispatch to verify that they received the bulletin via CALWAS. If not, then it is repeated to those counties that need the information. All 19 coastal counties' SOs are advised to check CLETS for the hard copy and to advise if not received.

Verbal notification is then made to the OES Executive & Regional Duty Officers (EDO,RDO) and the following agencies:

— California Division of Mines and Geology

— Utilities such as Pacific Bell, San Onofre and Diablo Canyon nuclear plants and the California Utilities Emergency Association (CUEA)

— Department of Water Resources

— FEMA Region IX

— California National Guard

— Department of Fish and Game, Oil Spill PR

— Department of Parks and Recreation

— State Lands Commission

— American Red Cross
— Department of Health Services Duty Officer
— Department of Toxic Substances Control Duty Officer
— US Fish and Wildlife Service
— Emergency Medical Services Authority
— Federal Aviation Administration
— Any other notifications as requested by OES Duty Officers

"All Clears" are issued two hours after the last damaging wave. However, if there is no confirmation of a wave within two hours, the "all clear" is the responsibility of the local government regardless of whether a tsunami has been generated. This requires that the local government is able to observe the waves from a safe distance/height.

A word of caution: Tidal gauges are not a reliable source of information if a damaging tsunami has occurred.

As part of their tsunami plans, Operational Areas should develop procedures for disseminating the information to local jurisdictions and special districts. Local governments should work with the appropriate Operational Area or region to develop the elements of their notification system.

APPENDICES

Appendix 1 : Acronyms and Terminology

Acronyms

ARB	Air Resources Board
CALTRANS	California Department of Transportation (DOT in State Agency Tables)
CALOSHA	California Occupational Safety and Health Administration
CALWAS	California Alert and Warning System
CCC	California Conservation Corps
CDC	California Department of Corrections
CDF	California Department of Forestry and Fire Protection

CDFA	California Department of Food and Agriculture
CHP	California Highway Patrol
CLETS	California Law Enforcement Teletype System
CNG	California National Guard
CSWC	California State Warning Center
CYA	California Youth Authority
DFG	California Department of Fish and Game
DHS	California Department of Health Services
DIR	California Department of Industrial Relations
DMAT	Disaster Medical Assistance Team
DOD	United States Department of Defense
DOE	United States Department of Energy
DOE	United States Department of Education
DOJ	California Department of Justice
	United States Department of Justice
DOT	United States Department of Transportation
DPR	California Department of Pesticide Regulation
DTSC	California Department of Toxic Substances Control
DWR	California Department of Water Resources
EAS	Emergency Alert System
EMSA	California Emergency Medical Services Authority
EOC	Emergency Operations Center
EOPT	Emergency Operations Planning & Training (an OES Division)
ETA	Estimated time of arrival
FEMA	Federal Emergency Management Agency
FOSC	Federal On Scene Coordinator
FRERP	Federal Radiological Emergency Response Plan
FRP	Federal Response Plan
FTB	California Franchise Tax Board
HHS	United States Department of Health and Human Services

HMICP	Hazardous Materials Incident Contingency Plan
ICG/ITSU	The International Coordination Group for the Tsunami Warning System in the Pacific
ITIC	International Tsunami Information Center
LFA	Lead Federal Agency
MLLW	Mean Lower Low Water
NAWAS	National Alert and Warning System
NCP	National Oil and Hazardous Substances Pollution Contingency Plan
NEHRP	National Earthquake Hazard Reduction Program
NEST	Nuclear Emergency Support Team
NOAA	National Oceanic and Atmospheric Administration
NRT	National Response Team
NTHMG	National Tsunami Hazard Mitigation Program
NWS	National Weather Service
OA	Operational Area
OEHHA	California Office of Environmental Health Hazard Assessment
OES	California Office of Emergency Services
PTWC	Pacific Tsunami Warning Center
REOC	Regional Emergency Operations Center (OES)
SEMS	Standardized Emergency Management System
SEP	State Emergency Plan
SSWWS	Seismic Sea Wave Warning System
SOC	State Operations Center
SWRCB	California State Water Resources Control Board
THRUST	Tsunami Hazard Reduction Using System Technology
TIME	Tsunami Inundation Mapping Effort
TWC	Tsunami Warning Center
USNSN	United States National Seismic Network
UTC	Universal Coordinated Time

WC/ATWC	West Coast/Alaska Tsunami Warning Center
WCM	Warning Coordination Meteorologist
WMD/NBC	Weapons of Mass Destruction/Nuclear, Biological, Chemical
USCG	United States Coast Guard
US EPA	United States Environmental Protection Agency

Terminology

Amplitude: The rise above or drop below the ambient water level as read on a tide gauge.

Arrival Time: Time of arrival, usually of the first wave of the tsunami, at a particular location.

Bathymetry: The measurement of the depths of oceans, seas, etc.

Bore: Traveling wave with an abrupt vertical front or wall of water. Under certain conditions, the leading edge of a tsunami wave may form a bore as it approaches and runs onshore. A bore may also be formed when a tsunami wave enters a river channel, and may travel upstream penetrating to a greater distance inland than the general inundation.

CREST: Consolidated Reporting of Earthquakes and Tsunamis. A project funded through the Tsunami Hazard Mitigation Federal/State Working Group to upgrade regional seismic networks in Alaska, Washington, Oregon, California, and Hawaii and to provide real-time seismic information from these networks and the United States National Seismic Network to the tsunami warning centers.

ETA: Estimated Time of Arrival. Computed arrival time of the first tsunami wave at coastal communities after a specific earthquake has occurred.

First Motion: Initial motion of the first wave. A rise in the water level is denoted by R, a fall by F.

Free Field Offshore Profile: A profile of the wave measured far enough offshore so that it is unaffected by interference from harbor and shoreline effects.

Harbor Resonance: The continued reflection and interference of waves from the edge of a harbor or narrow bay. This interference can cause amplification of the wave heights and extend the duration of wave activity from a tsunami.

Horizontal Inundation Distance: The distance that a tsunami wave penetrates onto the shore. Measured horizontally from the mean sea level position of the water's edge, it is usually measured as the maximum distance for a particular segment of the coast.

Inundation: The depth, relative to a stated reference level, to which a particular location is covered by water.

Inundation area: An area that is flooded with water.

Inundation Line (limit): The inland limit of wetting, measured horizontally from the edge of the coast, defined by mean sea level.

Leading-Depression Wave: Initial tsunami wave is a trough, causing a draw down of water level.

Leading-Positive Wave: Initial tsunami wave is a crest, causing a rise in water level. Also called a leading-elevation wave.

Local/Regional Tsunami: Source of the tsunami is within 1000 km of the area of interest. Local or near-field tsunami has a very short travel time (30 minutes or less), mid-field or regional tsunami waves have travel times on the order of 30 minutes to 2 hours.

Note: "Local" tsunami is sometimes used to refer to a tsunami of landslide origin.

Maremoto: Spanish term for tsunami

Marigram: Tide gauge recording showing wave height as a function of time.

Marigraph: The instrument which records wave height.

MLLW: Mean Lower Low Water. The average low tide water elevation often used as a reference to measure run-up.

Ms: Surface Wave Magnitude. Magnitude of an earthquake as measured from the amplitude of seismic surface waves. Often referred to by the media as "Richter" magnitude.

Mw: Moment Magnitude. Magnitude based on the size and characteristics of the fault rupture, and determined from long-period seismic waves. It is a better measure of earthquake size than surface wave magnitude, especially for very large earthquakes. Calibrated to agree on average with surface wave magnitudes for earthquakes less than magnitude 7.5.

Normal Earthquake: An earthquake caused by slip along a sloping fault where the rock above the fault moves downward relative to the rock below.

Period: The length of time between two successive peaks or troughs. May vary due to complex interference of waves. Tsunami periods generally range from 5 to 60 minutes.

Run-up: Maximum height of the water onshore observed above a reference sea level. Usually measured at the horizontal inundation limit.

Seiche: An oscillating wave (also referred to as a seismic seawave) in a partially or fully enclosed body of water. May be initiated by long period seismic waves, wind and water waves, or a tsunami.

Strike-Slip Earthquake: An earthquake caused by horizontal slip along a fault.

Teletsunami: Source of the tsunami is more than 1000 km away from area of interest. Also called a distant-source or far-field tsunami. Travel time is greater than 2 hours.

Thrust Earthquake: Earthquake caused by slip along a gently sloping fault where the rock above the fault is pushed upward relative to the rock below. The most common type of earthquake source of damaging tsunamis.

Tidal Wave: Common term for tsunami used in older literature, historical descriptions, and popular accounts. Tides, caused by the gravitational attractions of the sun and moon, may increase or decrease the impact of a tsunami, but have nothing to do with their generation or propagation. However, most tsunamis (initially) give the appearance of a fast-rising or fast-ebbing tide as they approach shore, and only rarely appear as a near-vertical wall of water.

Travel Time: Time (usually measured in hours and tenths of hours) that it took the tsunami to travel from the source to a particular location.

Tsunami: A Japanese term derived from the characters "tsu" meaning harbor and "nami" meaning wave. Now generally accepted by the international scientific community to describe a series of traveling waves in water produced by the displacement of the sea floor associated with submarine earthquakes, volcanic eruptions, or landslides.

Tsunami Earthquake: A tsunamigenic earthquake which produces a much larger tsunami than expected for its magnitude.

Tsunamigenic Earthquake: Any earthquake which produces a measurable tsunami.

Tsunami Magnitude: A number that characterizes the strength of a tsunami based on the tsunami wave amplitudes. Several different tsunami magnitude determination methods have been proposed.

TSUNAMI BACKGROUND INFORMATION

What is a Tsunami? What Causes It?

A tsunami is a system of gravity waves formed in the sea by a large-scale disturbance of sea level over a short duration of time. A tsunami can be generated by submarine volcanic eruptions, displacement of submarine sediments, coastal landslides into a bay or harbor, meteor impact, or by vertical displacement of the earth's crust along a subduction zone/fault. The latter is by far the most frequent cause of tsunamis and, for all practical purposes, the primary cause of tsunamis capable of propagation across an ocean basin. The rupture of the earth's crust also generates a major earthquake, which can be detected and measured by seismic instrumentation throughout the world. However, because not all major coastal or near-coastal earthquakes produce tsunamis, there is no operational method to determine whether a tsunami has been generated by an earthquake except to note the epicenter of the earthquake and then detect the arrival of the characteristic waves at a network of tide stations.

In the deep and open ocean, tsunamis travel at speeds of 500 to 1,000 kilometers per hour (300 to 600 miles per hour). The distance between successive crests can be as much as 500 to 650 kilometers (300 to 400 miles). However, the successive tsunami waves in the deep sea have such great length and so little height they are not visually recognizable from a surface vessel. In the open ocean, the height of the waves may be no more than 30 to 60 centimeters (1 or 2 feet), and the passing waves produce only a gentle rise and fall of the sea surface. During the April 1946 tsunami impact in Hawaii, ships standing off the coast observed tremendous waves breaking on shore but did not detect any change in sea level at their offshore locations.

Upon reaching shallower water, the speed of the advancing wave diminishes, its wavelength decreases, and its height may increase greatly, owing to the piling up of water. The configuration of the coastline, shape of the ocean floor, and character of the advancing waves all play important roles in the destruction wrought by tsunamis along any coast, whether near the generating area or thousands of kilometers from it. Consequently, detection of a relatively small tsunami at any locality warrants immediate reporting to spread the alarm to all coastal localities of approaching potentially dangerous waves.

The force and destructive effects of tsunamis should not be underestimated. At some places, the advancing turbulent front is the most destructive part of the wave. However, where the rise is quiet, the outflow of water to the sea between crests may be rapid and destructive, sweeping all before it and undermining roads, buildings, and other infrastructure with its swift currents. During withdrawals of the sea, ships can be thrown against breakwaters, wharves, and other craft, or washed ashore and left grounded.

In the shallow waters of bays and harbors, tsunamis can initiate a seiche, a seismic seawave in an enclosed body of water. If the tsunami period is influenced by the close proximity of a bay or harbor, the seiche is amplified with each succeeding wave. Under these circumstances, maximum wave activity is often observed much later than the arrival of the first wave.

A tsunami is not one wave, but a series of waves. The elapsed time between successive wave crests at a given point is usually 10 to 45 minutes. Oscillations of destructive proportions may continue for several hours, and several days may pass before the sea returns to its normal state. Frequently, the second or third wave is the most destructive. In the 1964 Cresent City tsunami, most of the deaths were caused by the debris-carrying second wave.

Tsunami Categories

A tsunami can be categorized as local, regional, or Pacific-wide. Those terms describe the potential destruction relative to the tsunami source area.

Local (near-source) tsunamis occur soon after the generating event and allow little time for warning and evacuations. Their impact may be large, but in a limited area. For example, in 1958, waves from a local tsunami in Lituya, Alaska ran up 485 meters, but destruction was focused on a small area.

Regional (intermediate) tsunamis are by far the most common. Destruction may be limited because the energy released was not sufficient to generate a destructive Pacific-wide tsunami, or because the source area limited the destructive potential of the tsunami. These events can occur within 15 minutes to 2 hours after the generating event. Areas affected by the tsunamis may not have felt the generating event.

Pacific-wide (distant source) tsunamis are much less frequent, but have a far greater destructive potential. The waves are not only larger initially, but they subject distant coastal areas to their destructive impact as they cross the Pacific basin. For example, the Chilean tsunami of May 22, 1960, spread death and destruction across the Pacific from Chile to Hawaii, Japan, and the Philippines. These events may have long lead times (up to 6 hours), but the breadth of the destruction is wide.

Tsunamis in California

Since 1812, 14 tsunamis with wave heights higher than three feet have struck the California coast. Six of these waves were destructive. The Santa Barbara Channel Islands were hit by a tsunami in the early 1800's. The worst tsunami in recent history resulted from a 1964 Alaskan earthquake and that caused 12 deaths and at least $17 million in damage in northern California. The 1992 Cape Mendocino earthquake produced a 0.5 meter tsunami that reached Humboldt Bay about 15 minutes after the shaking. Although not damaging, this tsunami demonstrated that locally generated tsunamis can reach our coastline quickly.

The 1992 Cape Mendocino tsunami triggered more comprehensive analysis of historic tsunami events in California. Research findings now support the belief that the risk from locally generated (nearshore) tsunamis is 1) high along the coast from Crescent City to Cape Mendocino, 2) moderate south of Cape Mendocino to north of Monterey, 3) high south of Monterey to Palos Verdes, and 4) moderate south of Palos Verdes to San Diego.

Paleoseismic evidence suggests that large earthquakes capable of producing local tsunamis recur every two or three hundred years along the Cascadia Subduction Zone (see Figure # 1). Large earthquake-generated tsunami events in Southern California are believed to have similar return periods. In the Cascadia Subduction Zone, a locally generated tsunami may reach the shore in minutes or tens of minutes.

The Tsunami Threat to Northern California

The tsunami hazard on the north coast of California affects a predominantly rural area, with populations concentrated in low-lying coastal communities near the estuaries of large rivers. About 20,000 people live or work in areas of potential inundation, and an even greater number of tourists and visitors travel through potential inundation areas each year. The economy is resource and tourist-based. The area suffers from chronically higher unemployment than other parts of the state. The largest industrial centers are located along low-lying coastal sand pits and near harbors. These areas are particularly vulnerable to both tsunami flooding and strong shaking damage. Populated areas are isolated from each other and from regional urban centers. Roads, communication links, and critical lifelines connecting populated areas are extremely vulnerable to disruption from strong shaking, tsunami inundation, and other likely effects of a large Cascadia earthquake.

The Cape Mendocino region and the coastal and offshore areas of Humboldt and Del Norte Counties are among the most seismically active areas in the United States. Since 1980, there have been five earthquakes close to magnitude 7, and an additional six of magnitude 6 or larger. This contrasts significantly with the rest of the Pacific Northwest, where large or damaging earthquakes have been relatively infrequent in recent historical times.

The April 25, 1992 earthquake, with a moment magnitude of 7.1, was located onshore from the town of Petrolia at a depth of about 11km. The location and orientation of rupture strongly suggested a Cascadia Subduction Zone origin. This earthquake also produced many of the effects expected from a larger Cascadia Subduction Zone event: coastal uplift, strong ground shaking, and a locally generated tsunami that was detected at coastal tide gauges within 15 minutes of the earthquake. The tsunami, although not damaging, raised the concerns of agencies responsible for disaster planning and response.

The Tsunami Threat to Southern California

There is concern that a Cascadia event may have significant impacts on Southern California, similar to those experienced in Crescent City after the 1964 Alaskan earthquake, since the distance between Cascadia and Southern California is about the same as the distance from Alaska to Eureka. Indeed, tide gauges in Santa Barbara detected the tsunami generated by the April 25, 1992 Cape Mendocino earthquake. While not damaging, this event indicates that the southern California coastline is vulnerable to Cascadia events. Several poorly documented local tsunamis caused some damage to southern California communities in the 1800s. Historic records suggest that three tsunamis produced flooding in the Santa Barbara area during this period.

In addition, the Working Group on California Earthquake Probabilities of the Southern California Earthquake Center (SCEC) has identified the Palos Verdes, Santa Cruz Island, and Santa Rosa Island faults as active and potentially tsunamigenic. The displacement between the North American and Pacific plate is accommodated in part by the movements along strike-slip faults, some of which are in the offshore borderland. Strike-slip faults were not believed capable of generating damaging tsunamis before the 1994 Mindoro, Philippines event when a strike-slip onshore fault generated a tsunami large enough to move a 6,000-ton barge one mile inland. There is also suggestive evidence of episodes of vertical displacement capable of conventional tsunami generation associated with the offshore extension in the Palos Verdes fault.

The impacts of an earthquake on the Palos Verdes fault, and the resulting tsunami, may affect the Ports of Los Angeles and Long Beach, like the 1964 Alaska quake affected Anchorage. The resulting damage would be far larger than the $17 million in damage seen in 1964 in Crescent City. Recent field surveys and modeling (1992-1996) by Professor Costas Synolakis have projected a 4 meter (13 ft.) tsunami that would cause extensive damage and flooding along flat coastlines such as those in Santa Monica Bay or in Orange and San Diego Counties. Communities that are sandwiched between the ocean and other bodies of water — such as wetlands, river inlets, or salinas — are at very high risk due to the possible overland flow and simultaneous tsunami attacks from multiple directions.

The densification of land use in Southern California and the continued development in areas exposed to coastal and riverine inundations have increased the risk of property damage and loss of life from future tsunamis. Even in locales where the tsunami hazard may be small, the land use development in areas subject to inundation and ground subsidence increases the overall risk. The rapid arrival of waves from a local event and the long duration of tsunami wave action intensify the risk from near-shore events. Future tsunamis may cause economic losses in coastal communities dependent on marine and harbor commerce. Losses to the tourist industry and harbor facilities in the Ports of Los Angeles, Long Beach, and San Diego could be very high, even for small events. Additional risk is posed by the potential release of toxic pollutants due to the failure of marine oil-transfer facilities and terminals.

Near-Source Tsunami Detection

At present, detection of near-source tsunamis is possible only where the shore can be observed. The first visible indication of an approaching tsunami is often a recession of water caused by the trough preceding an advancing wave. Any withdrawal of the sea, therefore, should be considered a warning of an approaching wave. On the other hand, a rise in water level may be the first event. Tide-gauge records of the Chilean tsunami of May 22,1960, generally showed a rise in water level as the first indication of this tsunami.

Near-Source Tsunami Warnings

There is agreement within the tsunami and emergency response communities that technology alone, automated warnings that can take up to 15 to 20 minutes to issue, cannot protect coastal inhabitants located in the immediate area of a near-source tsunami. When a large subduction zone earthquake occurs nearby, the first tsunami waves may reach coastal communities within minutes of the event. Local populations at risk should be able to recognize the signs of impending tsunami hazards, such as strong, prolonged ground shaking, and seek higher ground immediately. Communities should be informed, or determine themselves, which areas are likely to be flooded. Development, publication and distribution of inundation maps that define the inundation area, and designation of evacuation routes that indicate safe regions in which to assemble evacuees, can accomplish this. An effort to project potential inundation areas for selected communities in the state is underway.

Planners, emergency responders, and residents should try to assess and project the impacts of a very large local earthquake. At-risk regions need near-real-time determination of earthquake source information to assess the nature of the hazard in order to optimize emergency response. Local decision makers need to understand their risk and be provided with mitigation tools in order to make informed planning decisions.

The Pacific-Wide Tsunami Warning System

The West Coast & Alaska Tsunami Warning Center (WC/ATWC) in Alaska, and the Pacific Tsunami Warning Center (PTWC) in Hawaii monitor potential tsunamis. A Regional Tsunami Warning/Watch is issued based on earthquake location and magnitude, generally exceeding M7.5 (M7.0 for the Aleutians). Areas within a 3-hour tsunami travel-time zone of the epicenter will be placed in a Tsunami Warning status. Areas within a 3-6 hour travel-time zone will be placed in a Tsunami Watch status.

Tsunami ETAs will be disseminated for the tide stations within the Tsunami Warning and Watch areas. Agencies contacted then evaluate the probability of a tsunami reaching their area and decide on appropriate action.

Local Government Evacuation Plans

Local governments are responsible for developing evacuation plans for possible implementation in response to near or distant-source events. A distant-source tsunami event may allow several hours to evacuate. Each jurisdiction should analyze how much time a thorough evacuation would require and build that into its decision-making procedures. For instance, if it would take three hours to evacuate a densely populated area, an evacuation decision must be made when the first probable tsunami wave arrival time is a little more than three hours away.

A near-source tsunami may require immediate self-evacuation through areas damaged by the earthquake and at high risk of aftershocks. Evacuation plans should take into account potential earthquake damage when planning routes to use for evacuation. When developing a plan, each jurisdiction should decide how best to handle the occurrence of both an earthquake and a tsunami. Evacuation plans should take into consideration the special needs of the evacuees. Some of the special needs groups include the injured, the medically fragile, the aged, infants and young children, the handicapped, and non-English speakers or those who speak English as a second language. Care, shelter, communication, and transportation should be available at evacuee staging areas.

8

Tsunami Planning

TSUNAMI SAMPLE PLANNING TEMPLATE

Management

Management may want to focus on several areas during the planning process, including organizational structure; coordination of various disciplines; inclusion of non-profit organizations or private businesses in the possible response organization; public information concerns; safety and security; and information sharing among the key players. In addition, management may also want to be involved in threat analysis plans and procedures development.

Organizational Structure

Local government should consider the organizational structure required for a tsunami threat or actual event. In developing the organization, agencies may want to address the following questions:

- How should organizational and planning issues be addressed? Through multi-agency tsunami planning committee (TPCs)? Through regional as well as local efforts? Much of the success of future tsunami response efforts will depend upon establishing close working relationships among the key players at various government levels.
- What organization is already in place to deal with tsunamis?
- How will they interface with their state and federal counterparts?
- What levels of government need to be represented?

- What are the procedures for liaison to OES? Others?
- What organizational elements need to be represented? For example, the unified command?
- How will the transition from tsunami watch/warning to tsunami response be accomplished—if necessary?

Coordination of Disciplines

A tsunami event will require multi-agency, multi-discipline coordination at all levels, including first responders. Questions to consider:

- How do local jurisdictions plan to coordinate medical, health, fire and rescue, public works, law and coroner?
- What are the issues associated with discipline coordination? In the EOC environment? In the field?
- What communication systems and protocols need to be in place?
- How will vulnerable population issues be addressed?
- How will education and childcare facilities be addressed?
- How will animal care issues be addressed?

Non-Profits and Private Businesses

Non-profit organizations and businesses may become involved in a tsunami threat or event, either as potential victims or as possible support organizations.

- What non-profit organizations need to be involved in tsunami response planning?
- How do local jurisdictions include them in tsunami response?
- Are there businesses that need to be involved in tsunami response planning? Would they be potential victims? Could they provide support to emergency operations?

Public Information

All Public Information personnel should review current plans and/or protocols to ensure the area(s) listed below are addressed.

As we have seen in California during our natural disasters, public information plays a crucial role in managing an event. Some questions to consider are:

- What system(s) are available to alert the public?
- What protocols need to be established by local government?
- How does local government ensure support and cooperation with the media on a potentially sensitive subject?
- What protective actions need to occur for government response personnel to the public?
- How do local governments and the media address bilingual and multicultural concerns?
- What public information organizations need to be established? Media centers?

Safety and Security

All Safety and Security personnel should review current plans and/or protocols to ensure the area(s) listed below are addressed. Staff safety and operational security will be key concerns during a tsunami threat or actual event. Questions to consider:

- What actions do local governments need to take to protect their staff?
- What actions need to be taken to ensure operational security?
- What agencies have responsibility for perimeter security?

Information Dissemination

Information dissemination and sharing will be crucial during a tsunami threat or actual event. How an event unfolds will be determined to a great extent by “information” and how it is processed. Questions to consider:

- What protocols need to be established about sharing threat information? How will various disciplines share information across discipline lines (e.g.: law enforcement to medical).
- What components of the local response organization need to have information?

- What information elements need to be shared? And with what agencies, organizations, businesses, volunteer organizations, the media, and so on?
- Do agencies need to have "alert levels" or "readiness conditions" – even those that do not normally use these terms?

Operations

This section addresses concerns that may surface during tsunami response planning for branches normally associated with Operations.

Fire Department

All Fire and Rescue personnel should review current plans and/or protocols to ensure the areas listed below are addressed. Tsunami inundations are not a single wave event; several waves may inundate the coast over several hours. The first wave may be followed by larger, more destructive waves that go farther inland and carry debris.

- Are fire and rescue response personnel staged outside of the potential tsunami run up area until an all clear is given?
- Do existing procedures need to be modified to accommodate a tsunami scenario?
- Do first responder personnel need to receive any special instructions in the face of a potential tsunami threat?
- What time-critical refresher training needs to occur in anticipation of an event? (For example, refresher training on chemical agent identification.)
- What additional technical support teams will be required for a tsunami situation?
- Which fire and rescue functions need to be co-located with other disciplines for coordination purposes?
- Will the Fire and Rescue Branch need to request mutual aid to deal with the consequences of a tsunami event?
- Will Fire and Rescue Branch require extensive logistical support for their operations?

- How will fire and rescue personnel deal with the potential that they may become secondary tsunami casualties upon response to an event?
- How will fire and rescue personnel expand their operations beyond the normal day-to-day emergency response? What will be required to do this?
- How will the environmental needs be addressed?
- Have fire and rescue personnel prepared for an incident?
- Are decontamination procedures in place for fire and rescue personnel?

Hazardous Materials

All Hazardous Materials/Radiological personnel should review current plans and/or protocols to ensure the areas listed below are addressed. Tsunamis often involve many waves; several waves may inundate the coast over several hours. The first wave may be followed by larger, more destructive waves that go farther inland and carry debris.

- Are hazardous materials response personnel staged outside of the potential tsunami run up area until an all clear is given?
- Do existing procedures need to be modified to accommodate a tsunami scenario?
- Do first responder personnel need to receive any special instructions in the face of a potential tsunami threat?
- What time-critical refresher training needs to occur in anticipation of an event? (For example, refresher training on chemical agent identification.)
- What additional technical support teams will be required for a tsunami situation?
- Which hazardous materials or radiological functions need to be co-located with other disciplines for coordination purposes?
- Will the HazMat or Radiological Branch need to request mutual aid to deal with the consequences of a tsunami event?

- Will HazMat or Radiological Branch require extensive logistical support for their operations?
- How will HazMat or Radiological team personnel deal with the potential that they may become secondary tsunami casualties upon response to an event?
- How will HazMat expand their operations beyond the normal day-to-day emergency response? What will be required to do this?
- How will the environmental needs be addressed?
- Have radiological personnel prepared for an incident?
- Are decontamination procedures in place for radiological personnel?

Law Enforcement

All law enforcement personnel should review current plans and/or protocols to ensure the areas listed below are addressed. Several tsunami waves may inundate the coast over a number of hours. The first wave may be followed by larger, more destructive waves that go farther inland and carry debris.

- Are law enforcement personnel staged outside of the potential tsunami run up area until an all clear is given?
- Do existing procedures need to be modified to accommodate a tsunami scenario?
- Do first responder personnel need to receive any special instructions in the face of a potential tsunami threat?
- What time-critical refresher training needs to occur in anticipation of an event? (For example, refresher training on evacuations.)
- What additional technical support teams will be required for a tsunami situation?
- Which law enforcement functions need to be co-located with other disciplines for coordination purposes?
- Will the law enforcement branch need to request mutual aid to deal with the consequences of a tsunami event?
- What additional logistical support will law enforcement require for operations?

- How will law enforcement expand their operations beyond the normal day-to-day emergency response? What will be required to do this?
- Are law enforcement personnel prepared to perform/direct mass evacuations and spontaneous evacuations?

Coroner

Generally, all of the standard mass fatality concerns would apply for coroner operations during a tsunami response. Tsunami inundations are not a single wave event; several waves may inundate the coast over several hours. The first wave may be followed by larger, more destructive waves that go farther inland and carry debris.

- Are coroner personnel staged outside of the potential inundation area?
- Do existing procedures need to be modified to accommodate a tsunami scenario?
- Do existing procedures address and deal with decontamination in the presence of hazardous materials? One area to be addressed is decontamination of the deceased prior to leaving the scene to prevent contamination of facilities. This requires setting up a specific decontamination procedure prior to transportation to the incident morgue or central morgue facility. It may also be necessary to establish a temporary morgue for any work with contaminated deceased.
- Are there provisions in place for securing of personal effects? They may be needed to assist in identification or at least in the “believed to “be (BTB) identification. They must be secured for release to the family if appropriate.
- Are there provisions for the recovery and identification of the deceased? This is usually the highest priority of the family. It may, however, conflict with the other issues of a tsunami response. Recovery of bodies may be delayed, for instance, due to continued tsunami risks. Coroner staff should not enter the inundation zone until the “all clear” is issued.

- Do procedures address the issues of identification of large numbers of tsunami casualties, when there may be decontamination and dismemberment issues?
- Do procedures include the establishment of a Family Assistance Center? Mass fatalities management usually includes such centers. The centers facilitate information flow. Family members may need to be available for interviews, identification notifications, and remains disposition.
- Do coroner personnel need to receive any special instructions in the face of a potential tsunami threat?
- What time-critical refresher training needs to occur in anticipation of an event?
- What additional technical support teams will be required for a tsunami situation?
- Which coroner functions need to be co-located with other disciplines for coordination purposes?
- Will the Law Enforcement Branch need to request mutual aid to deal with the consequences of a tsunami event?
- What additional logistical support will be required for coroner operations?
- How will operations be expanded beyond the normal day-to-day emergency response? What will be required to do this?

Medical and Health

All medical and health personnel should review current plans and/or protocols to ensure the areas listed below are addressed.

Tsunami waves may inundate the coast over several hours. The first wave may be followed by larger, more destructive waves that go farther inland and carry debris.

- Are medical personnel staged outside of the potential tsunami run-up area until an all clear is given.
- Do existing procedures need to be modified to accommodate a tsunami scenario?

- Do first responder personnel need to receive any special instructions in the face of a potential tsunami threat?
- What time-critical refresher training needs to occur in anticipation of an event (refresher training on chemical agent identification, biological hazards, or decontamination procedures, for example)?
- What additional technical support teams will be required for a tsunami situation?
- Which medical or health functions need to be co-located with other disciplines for coordination purposes? For example, there are instances in which medical and hazardous material personnel may need to conduct joint activities.
- Will the medical and health branches need to request mutual aid to deal with the consequences of a tsunami event? What will be the source of this aid?
- Will the medical and health branches need to establish significant logistical support for operations?
- How will medical and health personnel deal with the possibility that they may become secondary tsunami victims upon response to an event?
- How will medical and health expand their operations beyond the normal day-to-day emergency response? What will be required to do this?
- Should medical and health personnel establish contacts in the private sector prior to an incident for quicker access to supplies and personnel?
- Are decontamination procedures in place for medical personnel?
- If the event is a Mass Casualty Incident (MCI), how will medical personnel address the need for the possible massive amounts of mutual aid required?

MENTAL HEALTH

"Medical" also includes mental health support, which will focus on support to victims of a tsunami and support to response personnel, including EOC staff. Mental health planners should consider the same sort of questions that other elements of the medical and health community address. In addition, plans should incorporate the following areas:

Staff Background and Training

- Does your mental health staff have the requisite training in disasters, tsunamis, and dealing with trauma?
- Do they have an understanding of governmental response roles?
- Are they able to function as part of a multi-disciplinary team?

Crisis Management

- Public information: What role should mental health practitioners play as part of public information? What effect does public information have upon the mental health of the victims and responders?
- Support services: How can the mental health community provide crisis counseling, screening, diagnosis, and treatment for those in need of such services?
- Stress Management: How can mental health personnel support stress management programs within the EOC and other locations?
- Follow-up: What mental health follow-up programs need to be developed as a result of a threat or event?
- Integration and support: How do mental health activities integrate with and support other medical/health activities?
- Resources: What mental health resources are available within the community? Will additional mental health resources be required? How can non-medical support personnel, such as religious staff or social services personnel, be integrated into the process?
- Psychological aspects: How can mental health professionals address the psychological aspects of response activities such as: body recovery, identification, family notification, and transportation of the injured?

Care & Shelter

All care and shelter personnel should review current plans and/or protocols to ensure the areas listed below are addressed.

- Do existing procedures need to be modified to accommodate a tsunami scenario?
- What special instructions do care and shelter personnel need to receive regarding a potential tsunami threat?
- What time-critical refresher training needs to occur in anticipation of an event (for example, refresher training on facility security procedures or mental health concerns during a tsunami event)?
- What level of facility security will be required for care and shelter operations during a tsunami situation?
- At what levels of the emergency response organization should there be care and shelter representation? Field level incident command post? City EOC? OA EOC?
- Will the care and shelter branch need to request mutual aid to deal with the consequences of a tsunami event? If so, what will be the source of this aid?
- Will the care and shelter branch need to establish significant logistical support for its operations? How will this connect to other logistical support, such as medical?
- How will care and shelter personnel handle mass evacuations and spontaneous evacuations? How will local law enforcement and fire personnel address this situation?

PUBLIC WORKS AND UTILITIES

All Public Works personnel should review current plans and/or protocols to ensure the areas listed below are addressed. This branch may include public works, local state agency representation, and private concerns.

It may include representatives from professional organizations. Tsunami inundations are not a single wave event; several waves may inundate the coast over several hours. The first wave may be followed by larger, more destructive waves that go farther inland and carry debris.

- Are public works and private and public agency personnel staged outside of the potential tsunami run up area until an all clear is given?
- How will building inspectors and other professionals be included in the process?
- All Utilities personnel should review current plans and/or protocols to ensure the areas listed below are addressed.
- The Utilities branch may be composed of both public and private utilities organizations in the areas of potable water, wastewater and sewage treatment, gas, and electricity. The branch may, of necessity, coordinate extensively with the construction and engineering branch.
- What are the vulnerabilities for utilities?
- Do existing utilities procedures need to be modified to accommodate a tsunami scenario? If so, how should they be modified?
- Do utilities field personnel need to receive any special instructions in the face of a potential tsunami threat?
- What time-critical refresher training needs to occur in anticipation of an event?
- At what levels of the emergency response organization should there be utilities representation? Field level incident command post? City EOC? OA EOC?
- What additional utility technical support teams will be required for a tsunami situation?
- Which utilities components need to be co-located with other disciplines for coordination purposes? There are, For example, instances when utilities personnel may need to conduct joint activities with fire and rescue personnel.
- Will the utilities branch need to request mutual aid to deal with the consequences of a tsunami event? If so, what will be the source of this aid?
- Will the utilities branch need to establish significant logistical support for operations?
- How will utilities expand their operations to accommodate the emergency response?

PLANNING AND INTELLIGENCE

There are at least two main areas to consider:

1) Threat analysis.
2) Identification of gaps and shortfalls in plans and procedures.

Threat Analysis

Threat analysis can include human factors (deaths, injuries, sheltering needs, etc.), lifelines and infrastructure (utilities, roads, bridges, etc.), and critical facilities (police and fire stations, schools, hospitals, etc).

Other possible areas to examine would be facilities such as transportation hubs and industrial facilities with hazardous materials that are in the tsunami run-up zone. The Certified Unified Program Agency (CUPA), for example, will be registering the facilities that are exposed to the tsunami threat.

Identification of Planning Gaps

After reviewing the items contained in this Planning Template section, answer the following questions:

- What needs to be done?
- What are the action items?
- Who needs to do them?
- What are the timelines?
- Does the local jurisdiction need an entirely new plan to address tsunami issues or can existing plans and procedures be modified?

LOGISTICS

As part of the planning process for the tsunami response, local government will probably identify support requirements (supplies, services, equipment, facilities, etc.). Resources databases will also need to be identified, developed, and maintained. Logistics planners will probably want to identify critical support operations, such as computer operations, that must remain intact and functional during an event.

Support Requirements

The following questions should be considered when identifying support requirements:

- What assets do local jurisdictions have to deal with the tsunami threat?
- What do they think they might need to overcome shortfalls?
- Do local jurisdictions know how to access/request resources from other sources?

RESOURCES DATA BASES

Development and use of the appropriate databases will be essential to the response effort. Some questions to consider:

- What resource databases exist? How does the local government access them?
- What inundation maps exist?
- What resources do they need to manage and how?
- Does the jurisdiction need to develop a tsunami specific resources database? What should be in this database? Should its accessibility be restricted in some way?

FINANCE AND ADMINISTRATION

Issues, which may need to be addressed, include continuity of operations, such as payroll processing, and tracking the costs of an event.

Continuity of Operations

- What systems do local jurisdictions have for personnel tracking and payroll operations?
- What are the staff recall procedures?
- Will there need to be a set of recall procedures specific to tsunami response?

Cost Tracking

Like any other emergency response, local jurisdictions will want to track costs associated with a tsunami response. Is there anything unique to tsunami response that will impact cost tracking procedures?

TRAINING AND EXERCISES

Training and exercises are a crucial component for a successful tsunami response program. There are several areas which local jurisdictions may want to consider:

- Development of a "Tsunami Response Training Program"
- Existing training programs
- Tsunami Awareness Programs
- First Responder Training Exercise Program

Tsunami Response Training

The local jurisdiction may want to develop a comprehensive program, based upon its training needs assessment. The program would include maintenance of training records.

Key questions to consider:

- What are our training needs?
- Can we identify our training needs?
- What do we need to do to meet our training needs?

Tsunami Awareness Programs

Questions to consider regarding tsunami awareness programs:

- Does the local jurisdiction need to develop and conduct a tsunami awareness program?
- Who should get the awareness training?
- Does the awareness training include a quick orientation module that personnel can take in anticipation of a potential threat?

First Responder Training

Questions to consider:

- What First Responder Training already exists that can be used by the local jurisdiction?
- Where does the first responder training fit with other training elements?
- Does the jurisdiction need to develop first responder training?

- Does the jurisdiction need assistance in developing its training?
- What training needs to be implemented for dispatch centers? For fire and rescue? For EMS? For HazMat? For law enforcement?

Exercises

What is the current exercise program? Can it be modified to accommodate tsunami concerns?

- Does the jurisdiction need to develop a separate exercise program for tsunami?
- Who should develop, conduct, and maintain the new tsunami response exercise program?
- Does the jurisdiction have the resources to conduct such exercises?
- What about funding for the program?

APPENDIX 4 SAMPLE SAN MATEO COUNTY PLAN

SAMPLE SAN MATEO COUNTY PLAN

The phenomenon called "Tsunami" is a series of ocean waves of extremely long length generated by earthquakes, volcanic eruptions, or massive undersea landslides.

As a tsunami crosses the deep ocean its length from crest to crest may be a hundred miles and its height from trough to crest only a few feet. Tsunamis may reach speeds of 600 miles per hour in deep water.

When the tsunami enters shallow coastal waters, its speed decreases and the wave height increases. This creates the large wave that becomes a threat to life and property. Following the arrival of the first wave, subsequent waves may increase in height and arrive minutes to hours later.

Background

Although there are no known recorded deaths from tsunami action in San Mateo County, it is probable that wave impact occurred in 1946, 1960, and 1964. In 1946 an earthquake in the Aleutian

Islands generated a tsunami that caused one death in Santa Clara County. The resultant tsunami from the Alaskan earthquake of 1964 caused eleven deaths in Crescent City just south of the Oregon border. The USGS has produced a tsunami inundation area map based on a 20-foot run-up along coastal areas and the Golden Gate. Such a run-up is estimated to occur an average of once every 200 years. The areas of the county that would be most heavily damaged by a tsunami are those along the Northern San Mateo Pacific Coast; Sharp Park State Beach, Rockaway Beach, and the Linda Mar area. The degree of damage experienced by these areas would depend on the local sea bottom and coastal topography as well as the incoming direction of the tsunami.

Purpose

The overall purpose of this plan is to protect life and property of the citizens of San Mateo County. Specific purposes of the plan are:

- To establish a county-wide understanding of the special operational concepts, organization, tasks, and coordinated emergency actions of public agencies, utility districts, and other organizations and institutions which would be involved in a tsunami warning response.
- To provide for mobilization and direction of county and various city emergency organizations in support of evacuation and security operations.
- To provide for the rapid deployment of mutual aid.

Activation

This plan becomes effective upon notification of a Tsunami Watch or Warning issued by the National Weather Service, or on order of the Area Coordinator of Emergency Services or County Director of Emergency Services (County Manager). Any city may activate this plan for areas under its incident command authority.

Concept of Operations

Re-entry

In the event of a Tsunami Warning, population in the designated risk areas will be warned and advised to move to temporary mass care facilities. After general warning to the public, the highest priority is alerting and moving institutional populations such as schools, hospitals, and convalescent care facilities.

The public will be warned using the following methods:

- Emergency service units using PA systems
- Providing Leaflets door-to-door (Enclosures 4 and 5)
- Announcements on TCI Cable Company system (Enclosure 6)
- Announcements on Travelers Information Service and Emergency Alert System
- Sounding of sirens (steady blast indicates peacetime emergency)

Each agency assigned Incident Command responsibilities will control operations within its area of responsibility.

SEE COASTSIDE Tsunami CHECKLIST (ENCLOSURE 2) FOR SPECIFIC ACTIONS REQUIRED IN THE EVENT OF A WATCH, WARNING, OR OCCURANCE.

Traffic Control Points to restrict sightseer traffic to the coast will be put into place as required (Enclosure 7). This plan is consistent with the San Mateo Operational Area Multi-Hazard Functional Plan. It contains information about authority, organization, and responsibilities of emergency services.

This plan outlines a broad response concept with attachments showing more detailed information for each risk area.

Agencies and organizations with assigned response tasks should develop specific response procedures and checklists to support this plan.

After an area has been evacuated, police security set up roadblocks, barricades, and/or a system of patrols.

Evacuated areas must remain closed to the public until after the threat of a Tsunami no longer exists. The decision to allow re-entry will be made by the risk area incident commander in consultation with the appropriate EOC. Residents should enter through control points to ensure that safety and sanitary precautions are provided.

ENCLOSURE 2: COASTSIDE TSUNAMI CHECKLIST

— Prepare Tsunami Information Statement to pass to public (Enclosure 6). Cable Television and Emergency Alert Stations will pass information.

— Contact Westar Cable System Emergency Coordinator (*name*) to initiate Tsunami Warning Video and messages on Channels 6, 17 and 28.

— Prepare written warnings for the general public (Enclosure 4 and 5).

— Prepare plans for evacuation of equipment away from inundation areas.

SPECIFIC ACTIONS TO BE TAKEN BY EACH AGENCY UPON NOTIFICATION OF A TSUNAMI WARNING, INDICATING THAT A TSUNAMI HAS BEEN DETECTED, AND THAT WARNING AND EVACUATION OF THREATENED AREAS SHOULD BE INITIATED.

— Complete all items on Tsunami Watch Checklist above.

— Initiate warning and evacuation of threatened areas.

— Confirm Tsunami Warning with American Red Cross. Confirm opening of shelters.

— Move equipment away from threatened areas.

— Maintain contact with the San Mateo Area OES to provide situation updates and coordinate evacuation and road closures.

— Secure evacuated areas. Cordon off evacuated areas. Mark evacuated areas with placards.

— Maintain evacuation for a minimum period of two hours after arrival of last wave or upon ALL CLEAR transmitted by San Mateo Area OES.

SPECIFIC ACTIONS TO BE TAKEN BY EACH AGENCY IF TSUNAMI OCCURS AND DAMAGE RESULTS

— Maintain full evacuation until minimum of two hours after arrival of last wave or upon ALL CLEAR from San Mateo Area OES. Additional waves may occur.

— After a two-hour safety period, secure damaged areas from re-entry by non-residents and property owners, emergency responders, and the press.

— Initiate windshield damage assessment. Compile Coastside Damage Assessment Report for dissemination to San Mateo Area OES.

— Request San Mateo County Public & Environmental Health Departments inspect damaged areas to ensure areas are safe for residents.

— Upon approval by County Health that areas are safe for resident re-entry, allow residents, property owners, responders, the press, and other authorized individuals to enter area.

— Based on damage, consider Declaration of Emergency or Disaster.

— Establish response priorities and mutual aid requirements. Keep San Mateo Area OES up-to-date on events in damaged areas.

ENCLOSURE 3: SAMPLE BRIEFING FORMAT

We have been warned by the National Weather Service that a Tsunami, or seismic sea wave, (may have) (has been) generated in the Pacific and may strike our coast. If a wave was generated, it will arrive here at approximately __________.

Tsunamis have done great damage on the California coast. The most recent one in 1964 killed 12 people in Crescent City. They were not evacuated in time or were allowed to return to the evacuated area too soon. This tsunami also did damage in our area. A 1960 tsunami killed 61 in Hawaii and damaged our coast.

Our responsibility is to warn everyone within the inundation area shown on the map on the back of this briefing sheet, and to insure that special facilities in the risk area are evacuated. Temporary staging areas are being established at the Farallone View Elementary School, LeConte and Kanoff in Montara and Half Moon Bay High School on Lewis Foster Drive in Half Moon Bay. Information will be given to you at these locations as to when or if American Red Cross Shelters will be opened at these locations.

A tsunami is not a single wave, but a series of waves. Keep people out of the risk area until you are advised that re-entry may begin. Waves may be as far apart as one hour and may be as high as twenty feet on this section of coast.

Traffic Control Points may be set up at strategic locations to reduce traffic flow toward the coast. If you are on a Traffic Control Point, you may allow the following people through after warning them of the danger and expected time of arrival:

- residents who have a local address on their driver's license
- boat owners who can give you either a berth or CF number
- commercial trucks enroute to non-affected areas
- emergency services personnel including Red Cross Volunteers enroute to support operations

ENCLOSURE 4: SAMPLE EVACUATION ORDER

We have been warned by the National weather Service that a tsunami, or seismic sea wave (may have been) (has been) generated in the Pacific and may strike our coast. If a wave was generated, it will arrive here at approximately ___________.

Under provisions of the Emergency Services Ordinance of the City of Half Moon Bay, I am ordering all persons in the risk area to evacuate to either Farallone View Elementary School or Half Moon Bay High School. Personnel evacuating from Point Montara, Princeton by the Sea, or El Granada should evacuate to Farallone View Elementary School located at LeConte and Kanoff in Montara. Personnel evacuating from Miramar, Highland Park, and Half Moon Bay should evacuate to Half Moon Bay High School on Lewis Foster Drive. You should be able to return to your homes within six hours. Security patrols will prevent anyone from entering the evacuated areas.

Tsunamis have done great damage on the California coast. The most recent one in 1964 killed 12 people in Crescent City. They were not evacuated in time or returned to the evacuated area before the all-clear signal was given. This tsunami also did damage in our area. A 1960 tsunami killed 61 in Hawaii six hours after a warning had been issued. Only those who ignored the warning were killed.

A tsunami is not a single wave but a series of waves. Stay out of the risk area until you are advised that reentry may begin. Waves may be as far apart as one hour and up to twenty feet high on this part of the coast.

There is no way to determine in advance the size of tsunamis in specific locations. A small tsunami at one beach can be a giant wave a few miles away. Don't let the modest size of one make you lose respect for all.

All tsunamis - like hurricanes - are potentially dangerous even though they may not strike each coastline or do damage when they do strike.

Never go down to the beach to watch for a tsunami. The wave moves much faster than you can run.

Sooner or later, tsunamis visit every coastline in the Pacific. This means that Tsunami Warnings apply to you if you live in any Pacific coastal area.

During this emergency, local police, fire, and emergency services officials are trying to save your life. Give them your fullest cooperation.

ENCLOSURE 5

Nos han advertido que un aguaje (maremoto) ha sido generado en el Oceano Pacifico y amenaza a nuestra costa maritima, segun el servicio federal metereologico. Las olas llegeran aqui aproximadamente a las [TIME OF ARRIVAL].

Se encuentra usted en una area de riesgo de aguaje o inunclacion? Esto significa que el fuerte oleaje podria alcanzar o inundar esta area y se le advierte que para su seguridad abandone immediatamente esta area y proceda a un lugar mas seguro hasta que las autoridades le informen que ha pasado el peligro.

Se avisa a todos los residentes afectados alejarse del area y proceder a: Farallone View Elementary School on LeConte y Kanoff en Montara or Half Moon Bay High on Lewis Drive en Half Moon Bay. Por favor permanezcan en el lugar indicado hasta que las autoridades les informen que pueden volver a sus hogares. Maremotos han hecho muchos daños a la costa de California. En el mas reciente en 1964 perecieron 12 personas en Crescent que no se han evacuado a tiempo o que han vuelto al area evacuada antes que las autoridades han dado la señal. Este maremoto tambien ha hecho daños en nuestra area. En otro maremoto en 1961, 61 personas perecieron en Hawaii 6 horas despues de la advertencia. Solamente perecieron los que han desconocido la advertencia.

Un aguaje no es una sola ola sino una serie de olas con fuerza mayor que ias las comunes. Esten fuera del area de peligro hasta que las autoridades dicen que pueden volver. Las olas a veces se separan hasta una hora, y pueden alcanzar hasta una altura de 20 pies (6 metros).

No se puede prevenir la altura de un maremoto en avance. Un pequeño maremoto en una playa puede ser gigante en pocos kilometros de distancia. No pierden responcto por los maremotos cuando uno es pequeno!

Todos los maremotos pueden ser peligrosos, aun cuando no tocan todas las areas de peligro y no dañan todas las areas que tocan. Nunca se baja hasta la playa para observar un maremoto. Las olas corren mucho mas rapido que nosotros.

Antes o despues, maremotos tocan todas las costas pacificas. Eso quiere decir que las advertencias pueden occurir en todas las areas de la costa.

Durante estas emergencia, las autoridades de seguridad publica intentan protegerle. Por favor den su cooperacion completa.

ENCLOSURE 6: WESTAR CABLE WARNING MESSAGE

Westar Cable Company will place Tsunami Warning Messages on Channels 17 and 28 to warn people in the danger zones to evacuate. Additionally, an OES Tsunami Warning Video may be shown on Channel 6. Coordination for a tsunami message will be made through Mr./Ms ________ at Westar Cable. After normal work hours, Mr./Ms__________ can be paged

at__________. Mr. Fischer will confirm the validity of the request for the tsunami tape by contacting County Communications at ________, or the Office of Emergency Services at _____________.

The Following tape message will be played on Westar Cable

Television Channels 17 and 28. "A tsunami, or seismic sea wave, has been generated in the Pacific and may strike our coast. If the wave was generated, it will arrive here at approximately __________. All persons in risk areas (low areas adjacent to the ocean) are ordered to evacuate to safe areas. Staging areas have been established at the Farallone View Elementary School on LeConte and Kanoff in Montara or Half Moon Bay High School on Lewis Drive in Half Moon Bay. You should be able to return to your homes within six hours. Security patrols will prevent anyone from entering the evacuated areas. Additional information is available on the Emergency Alert System. A tsunami information film is being played on Channel 6 and will provide some useful information."

SPECIFIC ACTIONS TO BE TAKEN BY EACH AGENCY UPON NOTIFICATION OF TSUNAMI WATCH INDICATING THAT A TSUNAMI MAY OCCUR.

ALL PREPARATIONS FOR WARNING AND EVACUATION ARE PLACED ON HOLD UNTIL A TSUNAMI WARNING IS RECEIVED.

— *Upon notification of a Tsunami Watch, initiate recall of OES personnel and activate the Area OES office Emergency Operations Center (EOC). The OES office EOC will be used as the initial EOC for short period responses. If time permits, and if directed by the Area Coordinator, or if a tsunami occurs, the full scale EOC will be activated.*

— *Establish and maintain a Tsunami Master Log of all key information, contacts, actions taken, and related information. Information in log should include time of event and point of contact (with phone number).*

— Assemble available information on Tsunami Watch. Sources of Information:

- California State Warning Center
- California Coastal Region OES
- National Weather Service, Redwood City
- Alaska Tsunami Warning Center
- Pacific Tsunami Warning Center

— Senior OES representative determines recommended initial course of action for jurisdictions and agencies.

— Conduct briefings for key personnel at Area OES or city EOCs as appropriate.

- Assign off-duty San Mateo Area OES personnel as follows:

— Area Coordinator and Assistant Area Coordinator to Redwood City.

— Public Information Officer to Redwood City.

— District Administrators (one each) to Pacifica and Half Moon Bay.

— Confirm that coastal communities and key agencies have received Tsunami Watch information and have established procedures for evacuation of endangered areas. Relay to the communities and agencies the recommended initial course of action and Area OES Point of Contact/phone number.

SPECIFIC ACTIONS TO BE TAKEN BY EACH AGENCY IF A TSUNAMI OCCURS AND DAMAGE RESULTS

— Advise jurisdictions to maintain full evacuation until minimum of two hours after arrival of last wave or upon ALL CLEAR. Additional waves may occur.

— Request jurisdictions initiate windshield damage assessment. Compile area wide Damage Assessment Report for dissemination to the Area Director of Emergency Services, OES Coastal Region, and State.

— Prepare for major PIO effort to disseminate information to public about event.

— Request County Public & Environmental Health departments inspect damaged areas to ensure they are safe for residents.

— Based on damage, consider San Mateo County Declaration of Emergency or Disaster.

— Establish response priorities and mutual aid requirements. Keep Coastal Region and State OES up-to-date on events in damaged areas.

— Activation, documentation, communication, and requests for assistance shall be in conformance with SEMS utilizing RIMS.

TSUNAMI PROCEDURE

General

The coastal area and the baylands of San Mateo County are vulnerable to tsunami flooding when earthquakes occur in or around the Pacific Basin. To provide early warning of such waves, the National Warning System (NAWAS) has two major monitoring stations:

— The West Coast/Alaska Tsunami Warning Center (Palmer, Alaska) is responsible for reporting seismic movement along the North American Coast from the Aleutian Islands south through Baja California.

— The Pacific Tsunami Warning Center (Honolulu, Hawaii) is responsible for reporting seismic movement within the rest of the Pacific Ocean and coastal regions.

This plan describes actions to be taken by coastside and county agencies upon notification of a Tsunami Watch or Warning. Fourteen areas with potential flooding problems have been included in this plan. The areas threatened extend from Sharp Park State Beach in the north to Ano Nuevo Point in the south. They include portions of the communities of Pacifica, Montara, Moss Beach, Princeton by the Sea, Miramar, Half Moon Bay, Pescadero, and state beach areas.

ASSUMPTIONS

The plan is based on the following assumptions:

- The tsunami threat in San Mateo county may be caused by a seismic event far from California. A locally generated tsunami is unlikely.
- At least three to four hours warning time will be available to warn the public, evacuate sensitive facilities, establish temporary shelters, and secure the coast area.
- After the arrival of the first wave, waves may continue to arrive at intervals for several hours. Risk areas can be

reopened two hours after the last observed wave, or two hours after the Expected Time of Arrival (ETA) has passed without a wave coming ashore.

- Maximum wave height expected in this area is approximately 20 feet. This can vary considerably from one location to another.
- Withdrawal of the sea may be a precursor to arrival of the wave.
- Intervals between successive major waves may be similar. If the second wave arrives 20 minutes after first, it is likely that a third wave (if there is one) would arrive 20 minutes after the second.
- The first wave may not be the largest. The largest wave usually occurs within the first ten waves.
- Watch is an announcement by the National Weather Service that a seismic event has occurred in the Pacific and may have caused a tsunami.
- Warning is an announcement that a tsunami has been detected. Warning will be given if a wave is detected anywhere in the Pacific basin.

The coordination and response actions by involved agencies and jurisdictions shall be organized under the structure of the Standardized Emergency Management System (SEMS) and Incident Command System (ICS). The inundation map for each tsunami-threatened area shows the maximum potential flood from tsunami action based on the Seismic Safety Element Geotechnical Hazard Synthesis maps of the County General Plan, or more current information. Within the inundation area, special institutions such as schools, hospitals, and nursing homes are identified. Special procedures for warning, evacuation, and care of occupants should be arranged by the local agency with incident command authority.

ALERT SITUATIONS

Dummy

An unscheduled "test" message to determine time required for disseminating messages.

Watch

A Tsunami Watch message is generated in one of two ways based on earthquake location:

- West Coast/Alaska Warning Center detects an earthquake with a magnitude of 6.5 or greater generated along the North American Continent with a possible seismic sea wave with an arrival time of greater than three hours
- Pacific Tsunami Warning Center detects an earthquake of magnitude 6.5 or greater in the Pacific Basin with a possible seismic wave arrival time of greater than four hours

Warning

A Tsunami Warning message is generated in one of two ways based on earthquake location:

- West Coast/Alaska Warning Station detects an earthquake of magnitude 6.5 or greater along the North American Continent that may have generated a seismic sea wave with an arrival time of less than three hours
- Pacific Tsunami Warning Center detects an earthquake of 6.5 magnitude or greater in the Pacific Basin and a tsunami has been generated with an arrival time to be reported

Cancellation

A cancellation message will be sent when all danger of seismic sea wave has passed.

SPECIFIC RESPONSIBILITIES

Area Coordinator and Assistant Area Coordinator

— Collect and interpret tsunami messages (ATTACHMENT A)

— Coordinate and disseminate area-wide response with jurisdictions and agencies

— Ensure watch/warning information is provided to media and public ASAP

— Designate facility for emergency operations for concerned agencies

— Maintain liaison with State OES for rapid access to mutual aid
— Prepare final report or memorandum at cancellation or end of event
— Review supplemental information (ATTACHMENTS)

Public Information Officer

— Maintain liaison with media and prepare news releases (ATTACHMENT B)
— Prepare and send EAS message(s) as required
— Send watch/warning/cancellation messages to appropriate agencies (ATTACHMENTS C, D, E)
— Establish OES public information phone-in line and provide periodic or as required updates to recorded message
— Disseminate OES public information phone number to jurisdictions and news media
— Review supplemental information (ATTACHMENTS)

District Administrators

— Recommend city EOC activation and disaster declaration as required
— Coordinate city EOC operations as directed
— Record damage assessment information
— Review supplemental information (ATTACHMENTS)

HazMat Specialist

— Analyze affected cities for potential HazMat incidents
— Assist with any HazMat mitigation efforts before tsunami arrival
— Respond to HazMat incidents if required
— Assist in city/Area EOC with HazMat response as required
— Review supplemental information (ATTACHMENTS)

ATTACHMENTS

A. Pre-Watch/Watch Message

B. Sample News Release (English and Spanish)

C. Tsunami Watch Message

D. Tsunami Warning Message

E. Tsunami Cancellation Message

F. Agencies Concerned with Tsunamis

G. Incident Command Responsibilities

H. Tsunami Time Curves (and Time-Conversion Table)

I. Tsunami Warning Video Tape Distribution

PRE-WATCH/WATCH MESSAGE

Information regarding seismic movement and the possible generation of seismic sea waves is collected from the Pacific Tsunami Warning Station at Honolulu, Hawaii (HO) and the West Coast/Alaska Warning Station at Palmer, Alaska (AL). The reports contain the following elements:

SAMPLE MESSAGE

1. From Alaska Warning Station
2. To Office of Emergency Services
3. Pacific Coastal Earthquake 081527 GMT
4. Region - Prince William Sound, Alaska
5. 8.4
6. Johnson, Palmer Observatory

Lines 1 - 2 : Self-explanatory

Line 3 : Refers to the arrival time of ground-transmitted seismic waves (NOT tsunami or tidal waves) in Greenwich Mean Time (GMT or "Zulu") at the Palmer Observatory. Convert to local time using ATTACHMENT H. In the Sample Message "08" is the hour; "15" stands for minutes after the hour; and "27" stands for seconds.

Line 4 : Indicates the general location of the earthquake. Sometimes only a general direction or approximate mileage will be given.

Line 5 : Gives the magnitude of the earthquake on the Richter Scale.

Line 6 : Provides the name of employee sending the report.

SAMPLE NEWS RELEASE (ENGLISH)

According to the (West Coast/Alaska-Pacific) Tsunami Warning Center, a severe earthquake has been generated at (location) at (time). The earthquake was measured at (Magnitude) on the Richter Scale. It is (known/not known) at this time (that/if) a tsunami has been generated. If a tsunami has, in fact, been generated, the wave heights cannot be accurately predicted; however, the tsunami waves could cause great damage to coastal cities and communities.

Residents of affected areas are urged to keep tuned to your local Emergency Alert System station (KNBR 680; KGO 810; KCBS 740) for further information. People should stay away from low lying coastal areas until further notice. A tsunami is a series of waves and may be dangerous for several hours after the initial wave arrives at any particular point.

9

Explanation of the Tsunami Watch and Warning System

THE TSUNAMI WARNING SYSTEM IN THE PACIFIC

Tsunami Warning Centers are responsible for gathering information on earthquakes which may generate tsunamis, and alerting state and local officials who may order evacuation. The entire Coast of California is at risk from distant-source tsunamis, such as the Crescent City tsunami of 1964 that originated in Alaska. Planning for these disasters requires local governments to look at their vulnerabilities. Where tsunami inundation projections are available, jurisdictions should develop inundation maps based on topographical features and population density. Where there are no such projections, governments can nonetheless develop evacuation plans.

The agency responsible for issuing information and warnings on possible tsunamis is the National Oceanic and Atmospheric Administration (NOAA), through the Tsunami Warning System. They operate two Tsunami Warning Centers. California receives all information about a potential threat of tsunamis from the West Coast/Alaska Tsunami Warning Center (WC/ATWC) in Palmer, Alaska. Information regarding Pacific-wide tsunamis is also collected by the Pacific Tsunami Warning Center in Ewa Beach, Hawaii. The operational objective of the Tsunami Warning System (TWS) in the Pacific is to detect and locate major earthquakes in the Pacific region, to determine whether they have generated tsunamis, and to provide timely and effective tsunami information and warnings to the population of the Pacific. Information and warnings are expected to minimize the hazards of tsunamis, especially to human life and welfare. To achieve this objective, the TWS continuously monitors the seismic activity and ocean surface level of the Pacific Basin.

OPERATIONAL PROCEDURES

Functioning of the system begins with the detection, by any participating seismic observatory, of an earthquake of sufficient size to trigger an alarm attached to the seismograph at the individual station. Personnel at the station immediately interpret their seismograms and send their readings to PTWC or WC/ATWC. After the earthquake has been located and magnitude determined, a decision is made at the Warning Center concerning further action. If the earthquake is within or near the Pacific Ocean basin and its magnitude is 6.5 or greater, but less than or equal to 7.5 (less than or equal to 7.0 in the Aleutian Islands), then a Tsunami Information Bulletin is issued to the Warning System participants. Tsunami Warning/Watch Bulletins are issued to the dissemination agencies for earthquakes of magnitude greater than 7.5 (greater than 7.0 in the Aleutian Island region), alerting them to the possibility that a tsunami has been generated and providing data that can be relayed to the public so that necessary preliminary precautions can be taken.

If the earthquake appears to be strong enough to cause a tsunami and is located in an area where tsunami generation is possible, PTWC or WC/ATWC will check water level data from automatic tide stations located near the epicenter for evidence of a tsunami. If they show that a tsunami has been generated that poses a threat to the population in part or all of the Pacific, the Tsunami Warning/Watch Bulletin is extended until there is no longer the threat of a destructive tsunami or it is upgraded to a Warning for the whole Pacific. The dissemination agencies then implement predetermined plans to evacuate people from endangered areas. If the tide station data indicate that either a negligible tsunami or no tsunami has been generated, PTWC or WC/ATWC issues a cancellation of its previously disseminated Tsunami Warning/Watch.

DEFINITIONS

Regional Tsunami Warning: A bulletin, usually based only on seismic information, initially issued as a means of providing the earliest possible alert to the population near the epicentral area of an earthquake. It places a restricted area (2- to 3-hour tsunami travel time) in a condition that requires all coastal areas in the region to be prepared for imminent flooding from a tsunami and is usually based only on seismic information without tsunami confirmation. Subsequent warning bulletins, which incrementally expand the warning area, shall be issued at least hourly, or when conditions warrant, until upgraded to a Pacific-wide Warning or canceled.

Pacific-wide Tsunami Warning: A bulletin issued by the PTWC or the WC/ATWC after confirmation has been received that a tsunami has been generated which has caused damage at distances greater than 1000 kilometers from the epicenter and thus poses a threat to any populated area within the Pacific Basin.

Regional Tsunami Watch: A bulletin issued initially using only seismic information to alert all participants within 1 to 3 hours travel time beyond the tsunami warning area. The tsunami watch area will be expanded hourly until it is either canceled or upgraded by issuing a Pacific-wide warning. A Regional Tsunami Watch may be included in the text of the message that disseminates a Regional Tsunami Warning.

Tsunami Information Bulletin: A bulletin issued to advise participants of the occurrence of an earthquake in the Pacific or near-Pacific area with the evaluation that a potentially destructive tsunami was not generated. If the evaluation indicates the possible generation of a non-destructive tsunami, an investigation will be initiated and additional tsunami information bulletins will be issued until the investigation is concluded.

Appropriate Bulletins will generally be issued within 15 minutes of earthquake origin time for earthquakes occurring within a Center's regional Area of Responsibility (AOR) and within 10 minutes of receipt of data necessary to characterize the earthquake for earthquakes occurring outside of a Center's regional AOR. As initial warnings may be issued when tsunamis have not been generated, warnings are limited in geographical extent until rapid confirmation of the existence or nonexistence of a tsunami is obtained.

Pacific-wide Tsunami Warning Bulletin: A message issued to all participants on a Pacific-wide basis after confirmation has been received that a tsunami capable of causing destruction beyond the local area has been generated and poses a threat to the coastal population for the entire Pacific Basin. Each hour updated information will be sent until the Pacific-wide Tsunami Warning is canceled.

Regional Tsunami Warning/Watch Bulletin: A message issued initially using only seismic information to alert all participants of the probability of a tsunami and advise that a tsunami investigation is underway. The area placed in Tsunami Warning status will encompass a 3-hour tsunami travel-time relative to the time of message issuance. Those areas within a 3 to 6-hour tsunami travel-time will be placed in a Watch status. A Tsunami Warning/Watch will be followed hourly by additional bulletins until it is either upgraded to a Pacific-wide Tsunami Warning or is canceled.

Tsunami Message Bulletin: A message issued to advise participants of the occurrence of a major earthquake in the Pacific or near-Pacific area. The message evaluates whether (a) A Pacific-wide tsunami was not generated based on earthquake and historical tsunamis data. This will be the only bulletin issued. No Pacific-wide tsunami warning is in effect; (b) An investigation is underway to determine if a Pacific-wide tsunami has been generated. Additional bulletins will be issued hourly, or sooner, as information becomes available. No Pacific-wide tsunami warning is in effect; or (c) No destructive Pacific-wide tsunami threat exists. However, some areas may experience small sea level changes. This will be the final bulletin issued unless additional information becomes available. No Pacific-wide tsunami warning is in effect.

If the event occurs in the WC/ATWC area of responsibility and exceeds the WC/ATWC Regional Warning threshold, but is less than the PTWC Warning/Watch threshold, an investigation will be initiated by PTWC and additional Tsunami Information Bulletins will be issued until the investigation is concluded.

Tsunami Communication Test Test messages are issued by PTWC at unannounced times on a monthly basis to determine writer-to-reader delays in disseminating tsunami information, to test the operation of the warning system by the evaluation of two-way communications with interactive personnel response, and to keep communication operating personnel familiar with the procedures for handling message traffic pertaining to the TWS.

COMMUNICATIONS REQUIREMENTS AND METHODS

Objective

To ensure the timely and effective operation of the TWS, it is essential to have communication facilities that are capable of rapidly handling all data requests from Tsunami Warning Centers, the dissemination of seismic and tide reports, and the Tsunami Warning/Watch and Information Bulletins. Since such traffic is relatively infrequent, existing communication channels are used with some supplementation where absolutely necessary, instead of establishing a separate communication system that would, to a large extent, duplicate existing channels. Hence, the communication channels under the management and control of the United States Defense Information Systems Agency (DISA), Federal Aviation Administration (FAA), National Weather Service (NWS), Army, Navy, Air Force, Coast Guard, various international agencies, and private companies, as outlined herein, are to be used to handle the message traffic involved between Tsunami Warning Centers, the seismic and tide stations, and the dissemination agencies participating in the warning system.

DISSEMINATION OF TSUNAMI WATCHES AND WARNINGS

Selection of Agency

In order to limit the number of agencies to be contacted in the event of a tsunami, Tsunami Warning/Watch and Information bulletins generally are issued to only one agency in a country, territory, or administrative area. This agency usually is appointed by the central government or administrative head of the area concerned and has fundamental responsibilities for public safety and disaster mitigation. In California, the State Warning Center

(CSWC) is the designated dissemination agency of bulletins issued by the PTWC or the WC/ATWC. In turn, the CSWC forwards the information to the operational areas, the operational areas are responsible for notifying local coastal cities and districts.

FUNCTION AND RESPONSIBILITIES OF DISSEMINATION AGENCY

It is the ultimate responsibility of the dissemination agency, which may or may not be the local government, to evaluate the tsunami information received from PTWC or WC/ATWC and to decide on appropriate action after the receipt of a Tsunami Warning/ Watch and Warning. Responsible agencies should have well-developed emergency plans for all threatened localities. These plans should clearly delineate areas of possible inundation. Evacuation routes should be designated, and safe areas should be marked.

The amount of advance warning necessary to ensure evacuation from danger areas also should be known. Emergency duties and responsibilities should be designated, and all affected officials should be thoroughly familiar with their duties. Tsunami Watch and Warning information may be passed (depending on the time and facilities available) to the coastal population by any or all of the following methods: radio, television, sirens, bells, whistles, warning flags, mobile loud speakers, and personal contact.

All Clear Procedure

At present, WC/ATWC does not have enough data available to enable it to determine when danger has passed in many areas. Local conditions can cause wide variations in tsunami wave action. Consequently, the local agencies and not WC/ATWC should make all-clear determinations. In general, after receipt of a Tsunami Warning, action agencies can assume all-clear status when their area is free from damaging waves for 2 hours, unless additional ETA have been announced by PTWC or WC/ATWC, or local conditions (e.g., particularly strong currents in channels and harbors), warrant continuation of the Tsunami Warning status. If no wave or only insignificant waves occur, action agencies may assume all-clear status 2 hours after the latest ETA announced by

PTWC or WC/ATWC, unless the presence of strong currents in channels and harbors has been noted, which may warrant continuation of the Tsunami Warning.

Operation

WC/ATWC detects, locates, and computes magnitudes for major earthquakes in the entire Pacific Basin region. For events equal to or greater than M6.5, WC/ATWC coordinates epicenter and magnitude with PTWC. Bulletins issued by WC/ATWC and PTWC will contain statements telling of the other center's actions. Only WC/ATWC has the responsibility to issue messages/bulletins to Alaska, British Columbia, Washington, Oregon, and California. This includes warning, watch, advisory and information bulletins. WC/ATWC can provide technical advice to emergency managers within its area of responsibility. Data are provided to PTWC, NEIC, the Japan Meteorological Agency, HMS Russia, and others.

Micro computers provide 24-hour monitoring and analysis of seismic data telemetered to WC/ATWC from throughout North America and Hawaii. Locations and magnitudes are automatically computed in as little as two minutes. Two independent systems provide primary and back up reliability. Information is immediately transmitted via the NWWS and/or the NAWAS to emergency managers on the West Coast, in Alaska, and British Columbia. Tide data is available in real or near real time from throughout the Pacific.

EARTHQUAKES IN THE ALASKA PENINSULA, GULF OF ALASKA, AND UNITED STATES/CANADA WEST COAST (Unimak Pass to the California/Mexico Border)

A warning will be issued for an area within two hours wave travel time from the time of expected bulletin issuance for earthquakes greater than magnitude 7.0. A watch will be in effect for an area within two to three hours wave travel time.

Confirmation of the existence of a tsunami will be sought as rapidly as possible. ATWC will monitor the recorded tsunami effects and issue a cancellation or supplemental bulletin as appropriate. If negative or minor tsunami activity has been noted on the tide gauges nearest the earthquake epicenter 30 minutes after the ETA, the warning status will be canceled. All bulletins will be updated a least hourly.

EARTHQUAKES IN ALASKA'S ALEUTIAN ISLANDS (Attu to Unimak Pass)

A warning will be issued for an area within three hours wave travel time from the time of expected bulletin issuance. for Aleutian earthquakes greater than magnitude 7.0 A watch will be in effect for an area within three to six hours wave travel time.

Confirmation of the existence of a tsunami will be sought as rapidly as possible. WC/ATWC will monitor the recorded tsunami effects and issue a cancellation or supplemental bulletin as appropriate. If negative or minor tsunami activity has been noted on the tide gauges nearest the earthquake epicenter 30 minutes after the ETA, the warning status will be canceled. All bulletins will be updated a least hourly.

EARTHQUAKES IN ALASKA'S BERING SEA

A warning will be issued covering St. Paul and St. George Islands and the Aleutian Islands (Attu to False Pass). for earthquakes greater than magnitude 7.0. There will be no watch area and the warning will not be expanded, even if a significant tsunami is detected.

The WC/ATWC, after coordination with PTWC, will take the following actions for Pacific earthquakes greater than magnitude 7.5.

a. When any part of the WC/ATWC area of responsibility is within six hours tsunami travel time from the epicenter, the Center will issue a tsunami warning covering an area with at least a 3-hour wave travel time from the time of expected bulletin issuance and a tsunami watch extending for an additional three hours travel time.

b. When the epicenter is more than six hours tsunami travel time distant from any part of the WC/ATWC area of responsibility, the Center will issue a tsunami advisory bulletin.

Tide gauges throughout the Pacific will be monitored for confirmation of the existence of the tsunami. WC/ATWC will either issue a cancellation, continue the advisory/watch/warning, or cancel the watch/warning and change to an advisory bulletin if there is no danger to the WC/ATWC area of responsibility but PTWC continues its watch/warning. The appropriate action will be based on the tsunami history and actual wave observations. WC/ATWC will continue to monitor all tsunami effects and keep California, Oregon, Washington, British Columbia, and Alaska advised until all danger is past for any area of the Pacific.

TSUNAMI INFORMATION BULLETINS

WC/ATWC will issue a Tsunami Information Bulletin whenever:

a. An earthquake occurs with a magnitude of 6.5 or greater, but below the watch/warning thresholds of *A.4.*2 through of *A.4.5*, within its area of responsibility.

b. An earthquake occurs with a magnitude equal to 6.5, but less than 7.5, outside its area of responsibility.

10

Unified Command and SEMS: A Guide for State and Local Government

PURPOSE AND SCOPE

This document clarifies how local, state, and federal agencies can successfully manage emergency incidents through the application of unified command at the field level of the Standardized Emergency Management System (SEMS).

SEMS is mandated for state agencies, voluntary for local governments (but necessary for reimbursement of response-related personnel costs), and not required for federal agencies.

GENERAL CONCEPT

The Response

Structure: State and local agencies use the Incident Command System (ICS) as the structure to manage emergency incidents at the field level of SEMS. ICS incorporates the concept of unified command when more than one agency is responsible for the emergency incident. This system allows agencies to exercise their responsibilities without compromising jurisdictional authorities.

There are four elements to consider when applying unified command:

A. Policies, Objectives, Strategies: The responsibility to set joint policies, objectives, and strategies for an incident belongs to the various jurisdictional and agency administrators who set policy and are accountable to their agencies. This activity is done in advance of tactical operations and may be coordinated from a location other than where the field response is taking place.

B. Representatives: The unified command organization consists of the on-scene senior representatives (agency incident commanders) from the various agencies with responsibility for the incident.

C. Resources: Unified command resources are the personnel and equipment supplied by the jurisdictions and agencies that have responsibility for the incident or by cooperating agencies.

D. Operations: Unified command resources stay under the administrative and policy control of their agencies; however, operationally, resources are deployed by a single Operations Sections Chief based on the requirements of the consolidated action plan. Consolidated action plans identify objectives and strategy determinations for the incident made by the unified command. The incident objectives must adequately reflect the needs of all the jurisdictional agencies.

Unified command represents an important element in increasing the effectiveness of response to multi-jurisdictional or multi-agency incidents. As incidents become more complex and involve more agencies, the need for unified command is increased.

INTERAGENCY

Agreements

Agencies that will be partners in a unified command situation should, whenever possible, establish agreements in advance of emergency incidents that identify jurisdictional and functional responsibilities and delineate the elements of the unified command structure. In addition, agencies should take every opportunity to exercise the provisions of these agreements through periodic training and simulation drills.

SEMS Applied—Coordinating Diverse Authorities

A cornerstone of SEMS is the application of ICS in emergency incident management at the field level. Under this system, unified command must be used when emergency incidents involve multiple agencies and/or jurisdictions. The basic precept of unified command is that all agencies with jurisdictional responsibility for the incident will manage an incident by establishing a common set of incident objectives and strategies. This is accomplished without losing or abdicating agency authority, autonomy, responsibility or accountability. Therefore, in order for state and local agencies to be consistent with SEMS, the unified command must include all the individual authorities with response jurisdiction over the incident.

Any process used by the unified command must permit the command team to develop a consolidated action plan that adequately reflects the jurisdictional needs of t©he agencies with responsibility for the incident. Unified command is based on the presumption that all responsible agencies will cooperate in a collective effort to mitigate an incident.

Recommendations For "Best Practices"

When addressing pre-existing mandates within SEMS, the following guidelines should be applied.

1) *SEMS must be viewed as a structural system only, not a pre-emption authority.*

SEMS is an emergency response management structure designed to focus resources and effort in the most efficient fashion. It is an "overlay" to pre-existing mandates in statute and regulation. It does not re-direct or preempt these authorities.

2) *Jurisdictional authorities must not be compromised.*

A basic precept of unified command is that jurisdictional authorities responsible for the incident are never excluded from the command structure. The legal requirements for federal, state, and local agencies must be taken into account when developing a consolidated action plan. Exactly how those jurisdictional authorities function in the unified command is a matter to be determined according to the details of the incident and the parties involved.

3) *Jurisdictional mandates must be applied within SEMS in a flexible manner.*

SEMS is meant to be flexible and applicable to many disciplines involving many agencies. There will almost always be overlapping authorities subject to interpretation.

Federal, state, and local agencies must coordinate with each other in applying and exercising their respective authorities within the unified command. Individual agencies do not exercise jurisdiction or authority that exceeds their legal limits or usurp the authority of another agency—there is no “vote” inside the unified command. It is incumbent upon the agencies involved to cooperate in order to allow for a successful resolution to a complicated emergency response organizational issue. Often, these issues can be dealt with through pre-planning.

4) *Pre-planning and training must be continuous.*

It is essential to the success of efficient emergency management that jurisdictions and functional agencies pre-establish the unified command structure and conduct frequent drills to exercise the system.

5) *Cooperation and consensus must be a priority.*

It is impossible to implement unified command unless the responsible agencies have agreed to participate in the process. Once this has been achieved, incident management goals, objectives and strategies are established through a consensus process.

6) *Establishment of the unified command structure must be expedited.*

Implement unified command promptly when it is needed in a multi-jurisdictional or multi-agency incident. It is essential to begin joint planning as early as possible, especially on those incidents where there may be conflicting priorities based on agency responsibilities.

Initially the participants should: identify statutory authorities for all agencies; determine a clear functional structure for the incident; coordinate initial activities; and open clear communication channels at all levels of the organization. Conversely, individual agencies in the unified command should not exit the response structure until their jurisdictional responsibilities have been resolved and an orderly transition has been orchestrated.

7) *Proper integration into the ICS structure is essential.*

A member of the unified command is very different than an agency representative. The unified command consists of agencies with direct jurisdictional responsibility for the incident. Agency representatives are individuals assigned to an incident from assisting or cooperating agencies. Agency representatives are personnel other than those on direct tactical assignments or those involved in a unified command.

Summary

SEMS provides the structure for managing the response to multi-agency and multi-jurisdiction emergencies in California and facilitates coordination among all responding agencies. Within SEMS, ICS provides a flexible structure at the field level for coordination of response activities which is geared to the needs of a specific incident. Unified command allows agencies that have responsibility for an incident to meet their statutory requirements through a coordinated process involving diverse jurisdictional authorities.

GENERAL AUTHORITIES AND DEFINITIONS

1. Pursuant to Government Code Section 8607(d) all state agencies are required to use the Standardized Emergency Management System (SEMS) to coordinate multiple jurisdiction or multiple agency emergency and disaster operations.
2. Government Code Section 8607(e) requires a local agency to use SEMS in order to be eligible for reimbursement of personnel-related response costs.
3. Under CCR, Title 19, Section 2403 there are five levels of the SEMS organization. The field response level "commands emergency response personnel and resources" to carry out "tactical decisions and activities in direct response to an incident or threat."
4. Under CCR, Title 19, Section 2405 emergency response agencies operating at the field response level shall use the Incident Command System, incorporating the functions, principles and components of ICS.

5. Under CCR, Title 19, Section 2402 emergency response agencies include "any organization responding to an emergency."
6. Pursuant to CCR, Title 19, Section 2407(c), "communications and coordination shall be established between a local government EOC, when activated, and any state or local emergency response agency having jurisdiction at an incident occurring within a local government's boundaries."
7. Pursuant to CCR, Title 19, Section 2407(d), local government is to "use multi-agency or inter-agency coordination to facilitate decisions for overall local government level emergency response activities."
8. Pursuant to Government Code Section 8616, during a state of emergency, "outside aid" to a local government shall be rendered in accordance with approved emergency plans.
9. Pursuant to Government Code Section 8618, unless otherwise expressly provided by the parties, the responsible local official in whose jurisdiction an incident requiring mutual aid has occurred "shall remain in charge at such incident, including the direction of personnel and equipment provided him through mutual aid."
10. CCR, Title 19, Section 2405(a)(3)(C), defines the Unified Command structure as, "...a unified team effort which allows all agencies with responsibility for the incident, either geographical or functional, to manage an incident by establishing a common set of incident objectives and strategies. This is accomplished without losing or abdicating agency authority, autonomy, responsibility, or accountability."
11. The state has broad authority under the Emergency Services Act to address any local need in a declared emergency if the conditions warrant. Government Code Sec. 8614 states:
    (a) Each department, division, bureau, board, commission, officer, and employee of each political subdivision of the state shall render all possible assistance to the Governor and to the Director of the Office of Emergency Services in carrying out the provisions of this chapter.

(b) The emergency power which may be vested in a local public official during a state of war emergency or a state of emergency shall be subject or subordinate to the powers herein vested in the Governor when exercised by the Governor.

(c) Ordinances, orders, and regulations of a political subdivision shall continue in effect during a state of war emergency or a state of emergency except as to any provision suspended or superseded by an order of regulation issued by the Governor.

12. CCR, Title 19, Sec. 2405(a)(3)(D), defines consolidated action plans as ones that, "...identify objectives and strategy determinations made by the Incident Commander for the incident based upon the requirements of the jurisdiction. In the case of a unified command, the incident objectives must adequately reflect the policy and needs of all the jurisdictional agencies. The action plan for the incident covers the tactical and support activities required for the operational period."

13. "Jurisdiction" describes a [legal] authority or responsibility, and can also mean a geographical area, e.g., a city, county, state, federal lands, etc. (SEMS Approved Course of Instruction Field Course, Module 13—Unified Command—August 1995 Instructor Guide.)

14. "Agency" is used to describe organizations which have a legal and functional responsibility at an incident. These may be from the same jurisdiction, other jurisdictions, or represent functional governmental authorities which do not necessarily have a geographical influence. They can also represent industrial and commercial organizations from the private sector. Examples could include the coroners office, the FAA, the XYZ chemical corporation, etc.