Course outline

• Introduction to science of earthquakes
• Earthquake measurement
  o Richter scale
  o Moment Magnitude Scale (MMS)
• Seismic waves
  o Surface waves
  o Body waves
    • “P” (“primary”)
    • “S” (“secondary”)
• Earthquakes and plate tectonics
• Earthquakes and tsunamis
• History of major earthquakes: 1964 to 2011
  • “Japan's Killer Quake” (PBS 2011)
Introduction

An earthquake happens when two blocks of the earth suddenly slip past one another, releasing tremendous energy built up over centuries.

The area where they slip is called the “fault” or “fault plane”.
Introduction

Earthquakes occurred December 16, 1811 on the New Madrid Fault Plane, a seismic zone now known to be capable of creating major earthquakes. ¹

These earthquakes were the most powerful to hit the eastern U.S. in recorded history.
Introduction

The New Madrid earthquakes reversed the flow of the Mississippi River.

FEMA warns that an earthquake today in the New Madrid Seismic Zone could result in catastrophic economic losses.
Introduction

Fig. 1: Areas impacted by New Madrid earthquakes (USGS)
Introduction

On August 23, 2011, a 5.8 magnitude earthquake damaged and closed the Washington Monument.

Fig. 2: Repairs on Washington Monument (CNN)
Introduction

The location where earthquakes start is the “hypocenter”. The “epicenter” is on the surface, directly above the “hypocenter”.

Fig. 3: Origin of Earthquakes (USGS)
Introduction

An earthquake may have "foreshocks". These are smaller earthquakes that occur in the same place as the "mainshock".
Introduction

But scientists can not determine that a “foreshock” is an earthquake until the larger “mainshock” earthquake occurs. “Aftershocks” may continue for years.
Causes of earthquakes

The Earth has 4 major layers: ²

1. Crust
2. Mantle
3. Outer core
4. Inner core

Fig. 4: Schematic of layers (USGS)
Causes of earthquakes

Crust: The crust is the outermost layer of the Earth:

- Thinnest beneath oceans
- Thickest beneath mountain ranges
Causes of earthquakes

**Mantle**: The layer below the crust is the mantle. The mantle has more Iron and Magnesium than the crust, making it more dense.

The uppermost part of the mantle is called the Lithosphere, the zone where earthquakes occur.
Causes of earthquakes

Core: The core of the Earth is made up of two layers:

1. Liquid outer layer
2. Solid inner core.

The solid inner core is 5 times denser than the surface, and its diameter is 3,486 km, larger than Mars.
Causes of earthquakes

3 sources of heat are found in the core:

1. Latent heat, remaining from when Earth was formed
2. Frictional heating, caused by denser core material sinking to the center
3. Heat from the decay of radioactive elements, such as Thorium
Causes of earthquakes

The temperature at the center of the Earth has not been directly measured. The center of the earth is some 4,000 miles deep, but the deepest depth drilled to make direct measurements of temperature has been about 6 miles.
Causes of earthquakes

The Earth's core temperature ranges from 7,000 to 12,000°F.

The temperatures are based upon the behavior of Iron at pressure in the core, more than 3,000,000 atmospheres.

This massive thermal energy is the Earth’s engine that causes earthquakes.
Causes of earthquakes

The surface of the Earth is made up of pieces of a puzzle covering the surface. The pieces move slowly, sliding past and bumping into each other.
Plate tectonics demonstrated that the Earth's rigid outer layer, crust, and mantle was not a single piece, but was broken up into 12 “plates”.
Plate tectonics

Fig. 5: Tectonic plates of the world (USGS)
Plate tectonics

The edges of the plates are called the “plate boundaries”.

The term “tectonics” comes from the Latin “tectonicus”, “building”. ⁵
Plate tectonics

Fig. 6: Tectonic plate activity of Earth (NASA)
Plate tectonics

The plate boundaries are made up of many faults, where most of the earthquakes occur.

Since the edges of the plates are rough, they get stuck while the rest of the plate keeps moving.
Plate tectonics

While the edges of the plates are stuck, the rest continues to move.

Seismic energy that would normally dissipate and cause the plates to slide is stored up.
Plate tectonics

The force of the moving plates can build, overcoming the friction of the jagged edges of the fault.

When one of the faults “unsticks”, the stored up energy is released, creating an earthquake.
Magnitude vs. Intensity

Magnitude:

• Amount of energy released at the source
  o One magnitude for each earthquake.

Intensity:

• Site-specific severity and damage
  o Many intensities for each earthquake.
Earthquakes are recorded by "seismographs", creating "seismograms".

Fig. 7: Seismograph (USGS)
Methodology to measure earthquakes

The seismograph has a base and a heavy weight that hangs free.

When an earthquake causes the ground to shake, the base of the seismograph shakes, but the weight does not.
Methodology to measure earthquakes

The size of an earthquake depends on the size of the fault and the amount of slip on the fault.

However, it is difficult to measure because movement may occur deep beneath the Earth’s surface.
Metholodology to measure earthquakes

A short “wiggly” line indicates a small earthquake, and a long “wiggly” line indicates a large earthquake.

• The length of the “wiggle” depends on the size of the fault.
• The size of the “wiggle” depends on the amount of slip.
Metholodology to measure earthquakes

Fig 8: Seismogram (USGS)
Modern seismic stations produce a three-component seismogram that measures:

1. Vertical motion;
2. East to West motion; and
3. North to South motion.
Metholodology to measure earthquakes

Fig. 9: Three component Seismogram (USGS)
The Richter scale was developed in 1935 at Caltech by American seismologist Dr. Charles Richter to quantify the magnitude of earthquakes.

Fig. 10: Charles Richter (circa 1920)
The 1994 Northridge earthquake in the Los Angeles area was measured at 6.9 on the Richter scale.

The earthquake killed 57 people and caused $20 billion in damages.

It was caused by a 3-meter slip on a blind-thrust fault 12 km long, 15 km wide, and 10 km deep.
Richter scale

Richter used seismometers at Caltech to measure ground vibration. However, he did not include site-specific properties of the fault.
Richter's scale was modeled on the magnitude scale used by astronomers, which quantifies the amount of light emitted by stars, luminosity.  

A star's luminosity is based upon its brightness, corrected for the magnification and distance from Earth.
Richter scale

Seismic magnitude is not a measure of the physical size of the fault.

It is the amount of vibration emitted. ⁷
Richter defined an earthquake 100 kilometers (km) away that caused a 1-mm amplitude signal as a magnitude 3. This became known as “3 on the Richter scale”.

Magnitude is measured by the logarithm of the amplitude of waves.
Richter scale

An earthquake at 100 km distance that produced a 10-mm amplitude was designated magnitude 4.

An earthquake at 100 km distance that produced a 100-mm amplitude was designated magnitude 5.
But a single number cannot adequately characterize earthquakes.

Earthquakes with the same magnitude can differ in directions and amplitude.
Moment Magnitude Scale (MMS)

The MMS was developed after the 1960 Chilean earthquake, the most powerful ever recorded, measured at 9.5 on the Richter scale. 

The Richter scale could not accurately measure the magnitude or size of an earthquake this powerful.
Seismologists now use the MMS to determine the magnitude, or strength, of an earthquake.

The earthquake that hit Japan in 2011 was measured at 9.0 on the MMS. ⁹
Moment Magnitude Scale (MMS)

The MMS measures the total energy of an earthquake, called the “seismic moment”.

January 24, 2013
Earthquake science
Seismic moment

The seismic moment of an earthquake is based on 3 factors:

1. The distance a rock slides along a fault surface after it breaks, the “fault slip”;

2. The amount of fault surface broken by the earthquake; and

3. The rigidity of the rocks near the fault.
Earthquakes with a magnitude beyond 7.0 emit most of their energy at lower frequencies.

The amplitudes of these waves do not represent all of the energy released.
Momential Magnitude Scale (MMS)

To measure all of the energy produced by a large earthquake, seismologists sometimes have to wait weeks to analyze all vibrations of the Earth.
Moment Magnitude Scale (MMS)

The Richter scale is not related to the physical properties of the fault zone.

The MMS can be correlated to the distance and area a fault has slipped, and the strength of the soil.
Moment tensor

The "moment tensor" for an earthquake can be determined using seismic data in the MMS.

The "moment tensor" is a three-dimensional plot of a fault’s orientation and the direction and the distance it slipped. ¹¹
Fig.11: 3 x 3 array of the seismic moment tensor: mathematical representation of seismic source
New faults were discovered in the large earthquakes in Japan using MMS. MMS connects earthquake size to the fault movements. This provides data describing where and why large earthquakes happen.
Seismic waves

Energy radiates outward from the fault in all directions in “seismic waves” like ripples on a pond.

Seismic waves shake the Earth as they move through it.

When the waves reach the surface, they shake the ground.
There are several kinds of seismic waves that move in different ways.

The two main types of waves are: 12

1. Surface waves
2. Body waves
Seismic waves

Surface waves have a lower frequency than body waves, and are easily distinguished on a seismometer.

Surface waves are responsible for most of the damage and destruction associated with earthquakes. ¹³
One surface wave is called a "Love wave", named after British mathematician A.E.H. Love, who developed the model in 1911. "Love waves" have transverse, horizontal motion, and are perpendicular to propagation. ¹⁴
Seismic waves

Fig. 12: Love wave
(Purdue University)
Seismic waves

The other surface wave is the “Rayleigh wave”, named for Lord Rayleigh.

“Rayleigh waves” have a transverse horizontal motion, perpendicular to the direction of propagation, and produce most of the shaking. ¹⁵
Seismic waves

Fig. 13: Rayleigh wave
(Purdue University)
Body waves

Seismograms use body waves to determine location of earthquakes.

There are two types of body waves:

- "P" waves ("primary")
- "S" waves ("secondary")
“P” waves

Fig 14: “P” waves
(Purdue University)
“S” waves

Fig 15: “S” waves
(Purdue University)
“P” and “S” waves shake the ground in different ways.

“P” waves are faster than “S” waves.

“P” waves are heard as a rumble if they refract out of the rock surface.
“P” waves

“P” waves are compressional, primary, and longitudinal.

“P” waves have alternating compressions, or “pushes”, and dilations, or “pulls”, in the same direction as the wave, and are perpendicular to the wavefront. ¹⁶
“P” waves

“P” waves travel fastest and are the first to be detected on a seismogram. “P” waves are used to provide emergency response of earthquakes.

“P” waves are smaller and have higher frequency than the “S” waves.
“S” waves exhibit shear, secondary, and transverse properties.

“S” waves have alternating transverse motions that are perpendicular to the direction of propagation. 17
“S” waves

“S” waves do not travel through fluids, so they do not propagate in the Earth’s core, primarily liquid iron, in water, or molten rock, magma.\textsuperscript{18}
Scientists use “triangulation” to determine exactly where the earthquake is/was. It takes three seismographs to locate an earthquake.
Fig. 16: Triangulation used to locate earthquake (USGS)
Surface waves: Because of low frequency, long duration, and large amplitude, surface waves are more destructive than body waves.  \(^{19}\)

Fig. 17: Surface waves lift and drop the ground (USGS)
Body waves: Soil particles move in compressive “P” waves or shearing “S” waves. The arrows show the direction of waves.

Fig. 18: “P” and “S” body waves
Summary

Fig. 19: Body waves compared to surface waves
Summary

“P” waves:

• Compressive waves
  o Travel through solids and liquids

“S” waves:

• Shear waves
  o Travel through solids only
Summary

• “P” wave is greatest on the vertical component seismogram.

• “S” wave is greatest on the horizontal component seismograms.
Continental drift and plate tectonics

Continental drift was first proposed in 1596 by Dutch map maker Abraham Ortelius in "Thesaurus Geographicus".\(^2\)
In 1912, geologist Dr. Alfred Wegener noticed that all of the continents seemed to fit together like the pieces of a giant puzzle. He thought continents were once joined together in a single landmass that broke up and drifted apart.
Continental drift and plate tectonics

Wegener called the supercontinent “Pangea”, meaning "all lands".

“Pangea” is derived from Greek words “Pan”, meaning "entire," and “Gaia”, meaning "Earth."

Pangea became part of the “Continental Drift Theory”.
Continental drift and plate tectonics

Fig. 20: Continental drift (USGS)
Continental drift and plate tectonics

But Wegener was unable to find solid evidence to support his theory.

In 1929 scientist Dr. Arthur Holmes supported Wegener's theory of Continental drift. 23
Continental drift and plate tectonics

Holmes said that the molten mantle beneath the Earth's crust experiences thermal convection, using the sources of heat in the core.

He said convection currents in the mantle cause upwelling under the crust, forcing the mantle to move and break.
New technologies developed to explore the ocean floor produced 4 major discoveries supporting Continental drift:

1. Youth of the ocean floor;
2. Reversals of magnetic fields;
3. Seafloor-spreading; and
4. Undersea mountain ranges.
Scientists had believed that the oceans had existed for at least 4 billion years. Therefore the sediment layer should have been very thick. But in 1947, seismologists found relatively young sedimentary rock on the ocean floor.²⁴
Reversals of magnetic fields

In the 1950s, scientists began to measure variations in the magnetic field on the ocean floor with magnetometers, developed and used during World War II to detect submarines. ²⁵
Reversals of magnetic fields

The ocean floor contains “Basalt”, a volcanic rock that contains high concentrations of Iron and magnetite. Basalt had previously distorted compass readings. 26

The word “Basalt" comes from “basaltes”, Latin for "very hard stone".
Reversals of magnetic fields

Fig. 21: Magnetic striping and polar reversals on sea floor (USGS)
Reversals of magnetic fields

The ocean floor has a zebra-like pattern. This is "magnetic striping", created by Continental drift.²⁷
Seafloor spreading

Seafloor spreading occurs at mid-ocean ridges, where new oceanic crust is formed through convection, and then gradually moves away from the ridge.

Fig. 23: Seafloor spreading (National Geographic)
Underwater mountain ranges

In 1855, U.S. Navy Lt. Matthew Maury found underwater mountains in the central Atlantic, later known as "Middle Ground". 28

This was later confirmed by ships laying the trans-Atlantic cable.
Mariana trench

While thousands have climbed Mount Everest, the highest point on Earth, only two people have reached the deepest point on Earth, the Mariana Trench, seven miles beneath the surface in the Pacific Ocean, in the Challenger Deep. One was director James Cameron.
Mariana trench

Fig. 24: Mariana trench
(National Geographic)
Fig. 25: The Mariana trench is deeper than Mount Everest is tall.
There are 3 primary types of tectonic plate boundaries:

1. Divergent (constructive)
2. Convergent (destructive)
3. Transform (conventional)
Tectonic plate boundaries

Energy released along plate borders creates earthquakes:

• Plates with divergent boundaries "diverge", or pull apart.

• Plates with convergent boundaries "converge", or come together.

• Plates with transform boundaries move laterally.
Convergent boundaries

Fig. 26: Red lines on the map indicate “convergent boundaries”: (Oregon State University)
Convergent boundaries

Fig. 27: Oceanic-continental convergence ("asthenosphere": from Greek "asthenēs" or "weak")
Divergent boundaries

In a mid-ocean ridge, two plates move in opposite directions.

The Mid-Atlantic Ridge is a "divergent plate" boundary. ³₀

Fig. 28: Divergent boundary (USGS)
Transform boundary

Two plates slide past each other in the crust, moving slowly as a conveyor belt until one suddenly slips, as in 1906 in San Francisco.

The San Andreas fault is a transform boundary.

Fig. 29: San Andreas Fault (USGS)
Speed of movement of plates

- The Arctic Ridge has the slowest rate, less than 2.5 cm/yr
- The East Pacific Rise in the South Pacific has the fastest rate, more than 15 cm/yr
- The San Andreas Fault Zone moves 56 mm/yr, the rate fingernails grow.
Mid-Ocean Ridges

The Earth produces new crust where two plates that diverge or spread in what are known as mid-ocean ridges. Mid-ocean ridges are the longest continually running mountain range in the world, about 40,000 miles long. \(^{31}\)
Mid-Ocean Ridges

Fig. 30: Rising magma in Mid-Ocean Ridges
(Geological Sciences and Marine Sciences Institute, UCSB)
The Mid-Atlantic ridge is spreading apart, making the Atlantic Ocean wider.

As the two plates move, the mantle melts, making new magma.
Mid-Ocean Ridges

The bottom of the Atlantic Ocean has some of the "youngest" crust.

Iceland in the North Atlantic is still being formed at the Mid-Atlantic ridge.
Iceland and Mid-Ocean Ridge

Iceland straddles the Mid-Atlantic Ridge, split by the North American and Eurasian Plates.

Fig. 31: Iceland and Mid Ocean Ridge (USGS)
Earthquakes and Volcanism

In April 2010, ash plumes from one of Iceland’s many volcanoes covered Europe, turning it into no-fly zones.

Volcanoes have affected global climate, emitting ash that blocks the sun from large areas around the world.
Subduction Zones

When the less dense, lighter continental plate overrides the oceanic plate, a subduction zone forms.

Because the oceanic plate is driven down, a deep trench forms.
Subduction Zones

As the oceanic plate descends, it melts, and causes the mantle to melt.

Liquid rock, called magma, rises to the surface because it is less dense.

If the magma reaches the surface, a volcano forms.
Subduction Zones

Fig. 32: Accumulation of magma
(Geological Sciences and Marine Sciences Institute, UCSB)
Subduction Zones

The Atlantic Ocean is getting larger: the Western Hemisphere is moving away from Europe and Asia.

The Pacific Ocean is becoming smaller: the North American and South American plates move toward Asia and Australia.
Subduction Zones

Fig. 33: Descending plates
(Geological Sciences and Marine Sciences Institute, UCSB)
Subduction Zones

Fig. 34: Movement of magma in subduction zone (Geological Sciences and Marine Sciences Institute, UCSB)
Subduction Zones

The Pacific Ocean region is a subduction Zone, and has more earthquakes and volcanic activity than any other area of the world.

Because of all the volcanoes, this region is known as "The Ring of Fire" and the "Islands of Fire". 32
Pacific Ring of Fire

Fig. 35: Pacific Ring of Fire (USGS)
Islands of Fire

Fig. 36: Islands of Fire (USGS)
Three basic fault types

1. Normal: block drops down
2. Strike-slip: block slides horizontally
3. Reverse: block moves upward

Fig. 37: Three Fault types
Earthquakes and tsunamis

A “tsunami” is a series of waves caused by the displacement of a large volume of a body of water.

The word “tsunami” is derived from the Japanese word for “harbor wave”.$^{34}$
Earthquakes and tsunamis

Tsunamis were originally referred to as "tidal waves" or "seismic sea waves". Tsunamis are unrelated to tides.
Earthquakes and tsunamis

When earthquakes occur beneath the sea, water can be displaced.

Waves are formed as the displaced water attempts to regain equilibrium.

When large areas of the sea floor elevate or subside, a tsunami can form.
Earthquakes and tsunamis

Large vertical movements of the crust can occur at plate boundaries.

Denser oceanic plates slip under continental plates as subduction, which can generate tsunamis.
Earthquakes and tsunamis

Tsunamis move as shallow waves at a speed equal to the square root of the product of the acceleration of gravity and the depth of the water.

In the Pacific Ocean, the typical water depth is about 4000 meters.
Earthquakes and tsunamis

The velocity of a tsunami is calculated by $\sqrt{g \times d}$, where:

- $g =$ gravity (9.8 m/s$^2$); and if
- $d =$ depth (4,000 m), then

Velocity = $4,000 \text{ m} \times 9.8 \text{ m/s}^2$; 
$39,200 \text{ (m/s)}^2$; or
$713 \text{ km/hr}$ or $443 \text{ mph}$
Earthquakes and tsunamis

The rate that a wave loses its energy is inversely related to wave length.

Therefore, as shallow waves, tsunamis not only move at high speed, they can also travel great distances with limited energy losses.
Earthquakes and tsunamis

Fig. 38: Wind-generated wave

Wind waves come and go without flooding higher areas.

Water flows in a circle.
Earthquakes and tsunamis

Tsunamis run quickly over the land as a wall of water.

Fig. 39: Tsunami wave
Earthquakes and tsunamis

Fig. 40: Plate subduction and tsunami
Soil liquefaction

Liquefaction occurs when the strength of a soil is affected by an earthquake. Liquefaction has been responsible for tremendous amounts of damage in earthquakes around the world.
Soil liquefaction

Liquefaction occurs in saturated soils in which the space between particles is saturated with water.
Soil liquefaction

Fig. 41: Liquefaction
Soil liquefaction

The porewater pressure becomes so high that soil particles lose contact with each other.

The soil behaves more like a liquid than a solid; hence the term, "liquefaction".
1964 – Alaska

As a part of the Pacific Ring of Fire, the southern coast area of Alaska experiences many earthquakes.

On Good Friday, March 27, 1964, a magnitude 9.2 earthquake struck Prince William Sound and caused severe damage from liquefaction.
1964 – Alaska

Fig. 42: Liquefaction on Alaskan coast – 1964
(NBC News)
1964 – Alaska

It was the second largest earthquake ever recorded, lasted for over 3 minutes, and was felt over 500,000 square miles.

A subsequent tsunami caused 5 deaths hours after the earthquake.
1995 – Kobe

The 1995 Kobe earthquake was the most devastating earthquakes to hit Japan until 2011, killing more than 5,500 and injuring over 26,000.

Strong ground motion and collapsed the Hanshin Expressway, and soil liquefaction caused damage to port and wharf facilities.
1995 – Kobe

Fig. 43: Liquefaction damage in Kobe (NBC News)
The Indian Ocean earthquake had a MMS of 9.0, causing a series of lethal tsunamis on December 26, 2004.

The tsunamis killed approximately 230,000 people, making it the deadliest tsunami as well as one of the deadliest natural disasters in recorded history.
2004 - Indian Ocean earthquake

It was the third largest earthquake in recorded history.

The initial surge was measured at a height of approximately 33 meters, making it the largest earthquake-generated tsunami in recorded history.
2004 - Indian Ocean earthquake

The tsunamis killed people in Indonesia, Thailand, Malaysia, Bangladesh, India, Sri Lanka, the Maldives, and in Somalia and Kenya in East Africa.
2004 - Indian Ocean earthquake

Fig. 44: Coastlines impacted by 2004 Tsunami (NOAA)
Fig. 45: The earthquakes caused the seafloor to uplift 5-meters, causing deadly tsunamis
2004 - Indian Ocean earthquake

Unlike in the Pacific Ocean, there was no organized tsunami alert service covering the Indian Ocean.

This was due to the absence of major tsunamis since the Krakatoa eruption in 1883, which killed 36,000 people.
2010 - Haiti earthquake

On January 12, 2010 Port-au-Prince was hit by the deadliest earthquake in a century, killing 230,000 people.

Haiti lies directly above a network of faults, where the Caribbean plate meets the North American plate.
2010 - Haiti earthquake

Fig. 46: Intensity map of 2010 Haiti earthquake (USGS pager alert)
Satellite-based GPS measurements can reveal subtle movements of the Earth.

Port-au-Prince was tracked for over a decade as the ground south of the city moved east, and the ground north of the city moved west.
2010 - Haiti earthquake

The last earthquake on the Haiti fault had occurred 250 years ago.

As the plates crept past each other, they distorted and stretched, building up enormous stress.

Then on January 12 the land suddenly shifted 30 centimeters to the east.
But only 50 of the 300 kilometers of the fault released its energy during the 2010 earthquake.

The rest of the fault remains under stress, and the area remains at risk.
On March 11, 2011, a magnitude 9.0 earthquake occurred off the coast of northeast Japan.

This earthquake caused a tsunami, which struck Japan as well as other areas around the Pacific Ocean.
2011 – Japan earthquake, tsunami, and nuclear release

Fig. 47: Propagation of waves from the tsunami around the globe (NOAA)
2011 – Japan earthquake, tsunami, and nuclear release

An Earthquake Early Warning was issued 8.6 seconds after detection of the first P-wave at the nearest seismic station.

Fig. 48: Map of intensities (Japan Meteorological Agency)
2011 – Japan earthquake, tsunami, and nuclear release

Fig. 49: Observed tsunamis (Japan Meteorological Agency)
The Japan National Police Agency reported over 20,000 persons killed and over 8,000 missing after the earthquake and tsunami.

The 2011 Tohoku Earthquake Tsunami Joint Survey Group reported tsunamis crests at Sendai up 20 meters.
The Fukushima Daiichi nuclear disaster caused a series of nuclear meltdowns and releases of radioactive materials, caused by the earthquake and subsequent tsunamis. It was the largest nuclear disaster since Chernobyl in 1986.
2011 - Fukushima Daiichi nuclear meltdown after tsunami

Fig. 50: Four damaged reactor buildings (New York Times 2011)
After the earthquake, the remaining reactors shut down automatically, and emergency generators came online to control electronics and coolant systems. However, the tsunami quickly flooded the low-lying rooms in which the emergency generators operated.
At this point, only prompt flooding of the reactors with seawater could have cooled the reactors quickly enough to prevent meltdown.

However, salt water flooding was delayed because it would ruin the costly reactors permanently.
2011 - Fukushima Daiichi nuclear meltdown after tsunami

Flooding with seawater began only after the government ordered TEPCO.

Tokyo firefighters laid 800 feet of hose from the ocean to the facility, but it was too late to prevent meltdowns.
Because of the intense heat, Zirconium metal cladding surrounding the fuel rods vaporized, stripping Hydrogen out of the steam.

As firefighters struggled to cool the reactors, several explosions occurred when the temperature reached 1200°C.
2011 - Fukushima Daiichi nuclear meltdown after tsunami

Fig. 51: Meltdowns caused Hydrogen explosions (New York Times 2011)
A Hydrogen explosion on March 11 ripped the roof off of the secondary containment vessel of reactor No. 1.

Another Hydrogen explosion occurred March 14 in reactor No. 3.
Ancient stone markers in Japan

Modern sea walls failed to protect coastal towns and TEPCO’s nuclear power plants from the 2011 tsunami. But in hamlets in Japan, centuries-old tablets warned of previous tsunamis.
Ancient stone markers in Japan

Fig. 52: Stone slabs offer tsunami warnings in Japan
Ancient stone markers in Japan

This stone slab reads: ³⁶

• “High dwellings are the peace and harmony of our descendants.

• Remember the calamity of the great tsunamis.

• Do not build any homes below this point.”
Hundreds of stone markers are on the Japanese coastline, some more than 600 years old. Collectively they form a crude warning system for Japan, vulnerable to earthquakes and tsunamis with its coasts along major fault lines.
Ancient stone markers in Japan

However, few villages heeded these old warnings, and did not build their houses on high ground.

The stones and other warnings were disregarded as coastal towns grew after World War II.
Ancient stone markers in Japan

Even communities that had moved to high ground eventually relocated to the coast to be nearer to their boats.

These historic stones were around Fukushima, warning of the danger of a major earthquake and tsunami.
Ancient stone markers in Japan

But TEPCO built their nuclear power facilities at Fukushima, far lower than these ancient stone markers.

Ironically, Fukushima means “fortunate island” in Japanese.^[37]
2012 – Task Force investigating Fukushima Daiichi

The task force said TEPCO failed to follow international standards and recommendations that could have mitigated the impact of the incident. The task force said TEPCO treated crisis management drills as a formality.
The task force also said TEPCO employees lacked crisis management skills and equipment needed to respond to a crisis of this magnitude.
Japan lacked an independent nuclear regulatory system.

The regulator at the time of the accident was part of the industry ministry that promotes nuclear energy.

The U.S. oil industry had a similar relation with regulators before the BP Oil Spill.
Cascading effects of earthquake and tsunami

Fig. 53: Tsunami hits TEPCO
(CBS News)
Cascading effects of earthquake and tsunami

Japan understood the impacts of earthquakes and tsunamis.

Japan spent billions of dollars developing mitigation measures and early warning technologies.
Cascading effects of earthquake and tsunami

Japan conducts routine earthquake and tsunami drills, and uses advanced technology, including 40-foot coastal seawalls and automated flood gates.

But the seawalls became inadequate when the sea floor dropped over 3 feet and moved 10 feet laterally.
Cascading effects of earthquake and tsunami

USGS seismologists said that the earthquake ruptured the sea floor an area 217 miles long and 50 miles wide, moving the Earth's axis 4 inches. 39
Cascading effects of earthquake and tsunami

Fig. 54: Tsunami hits Japan
(NASA Jet Propulsion Laboratory)
Scientists know that the shape of the seafloor determines how tsunami waves build up as they approach coastlines. Seafloor topography determines why some areas get hit worse than others.
Cascading effects of earthquake and tsunami

Since the Japan 2011 tsunami, scientists also now know that seafloor topography affects the strength and height of a tsunami.
Cascading effects of earthquake and tsunami

Scientists suspected that underwater mountains as well as islands deflected tsunami waves in some places, and amplified them in others.

But it was not until three satellites passed over Japan simultaneously in March 2011 that they could confirm it.
Researchers from NASA JPL and Ohio State used satellite-based altimeter data in December 2011 to observe “merging tsunamis”. 40

“Merging tsunamis” are wave fronts that combine to form single waves at double the previous height.
Cascading effects of earthquake and tsunami

Fig. 55: Two tsunamis merged and doubled in height up to 65 feet. (NASA Jet Propulsion Laboratory)
Cascading effects of earthquake and tsunami

The NASA Jason-1 satellite passed over the tsunami on March 11 as the Jason-2 passed over at a slightly different location at almost the same time.

NASA estimated that this was a one in ten million chance to observe this double wave with satellites.
Cascading effects of earthquake and tsunami

Cascading effects from a major disaster can be as severe as the original event.

The estimated economic damages of the layered disasters, earthquake, tsunami and nuclear emergency exceed $300 billion, which would make it the most expensive natural disaster in history.
Summary of causes of unexpected tsunami damage

1. The 3-foot collapse and 10-foot lateral shift of the sea floor caused by the earthquake allowed the tsunami to breach the seawalls.

2. The unique undersea topography caused separate tsunamis to merge, doubling in height and strength.
Fukushima's impact on the future of nuclear energy

Fig. 56: TEPCO Fukushima Daiichi nuclear power plant reactors (CBS News)
Fukushima's impact on the future of nuclear energy

International investigations of TEPCO are directed at the meltdowns, causing explosions that destroyed the secondary containment vessels.

TEPCO executives ignored warnings about the hazards of tsunamis given by Japanese citizens for hundreds of years.
Fukushima's impact on the future of nuclear energy

The siting of Japanese nuclear power plants in locations known to be vulnerable to tsunamis is also being investigated.

Fig. 57: Radiation detectors in Japanese villages (NBC News)
Fukushima's impact on the future of nuclear energy

Public health forecasts are more positive in assessments of cancer risks after the largest release of radioactive material since Chernobyl.

435 reactors operate in 30 countries, generating 14 percent of electricity.
However, the number of new nuclear power stations permitted fell dramatically after the incident at the Fukushima nuclear plant. Germany is phasing out all atomic plants by 2022. Italy and Switzerland have voted to phase out nuclear energy.
Fukushima's impact on the future of nuclear energy

The closest America came to a partial meltdown occurred at the Three Mile Island plant in 1979.

It did not produce any deaths; however, since Three Mile Island few plants were planned or approved.
Fukushima's impact on the future of nuclear energy

A release at the Indian Point nuclear plant, 35 miles north of Times Square, would impact 20,000,000 people.

The “9/11” hijackers flew directly over Indian Point.

Hurricane Sandy had the potential to affect Indian Point.
Fukushima's impact on the future of nuclear energy

Fig. 58: Indian Point nuclear facility on Hudson River (CBS News)
Fukushima's impact on the future of nuclear energy

Nuclear power does not emit “greenhouse gases”.

The burning of natural gas and other fossil fuels emit significant amounts of Carbon dioxide, a “greenhouse gas”. 
Fukushima's impact on the future of nuclear energy

Studies of ice cores from the last 420,000 years have confirmed the dramatic increase in Carbon dioxide in the atmosphere since the Industrial Revolution. ⁴¹
Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica


The recent completion of drilling at Vostok station in East Antarctica has allowed the extraction of the ice record of atmospheric composition and climate to the past four glacial-interglacial cycles. The core, from which a continuous 360-meter-long record has been obtained, provides a unique time series for the study of climate history. The core is 3.6 km deep, and the ice core contains lying 750,000 years of climate history in a column of ice 360 meters long.

The ice core reveals a climate record that is complementary to that of the marine records from the Southern Ocean, providing a unique opportunity to study the interactions between the atmosphere and the ocean. The core is 3.6 km deep, and the ice core contains lying 750,000 years of climate history in a column of ice 360 meters long.

The core is 3.6 km deep, and the ice core contains lying 750,000 years of climate history in a column of ice 360 meters long.

Fig. 59: Vostok ice core in Antarctica (Nature Vol. 399 1999)
Fukushima's impact on the future of climate change

Fig. 60: Carbon dioxide in atmosphere of Antarctica (Nature Vol. 399 1999)

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Fukushima's impact on the future of climate change

Fig. 61: Variations in Earth’s surface temperature (Nature Vol. 399 1999)
Fukushima's impact on the future of nuclear energy

The risks and threats from nuclear energy become highlighted in singular events such as Fukushima.

But the emission of Carbon dioxide from fossil fuels is pervasive and continuous, with effects appearing indirectly as climate change.
Fukushima's impact on the future of nuclear energy

Scientists confirm increasing sea levels while over 60% of the U.S. population live along vulnerable coasts.

The impacts of earthquakes, the future of energy sources, and their impact upon global warming are complex and interactive, with no simple answers.
Earthquake preparation

The recent tragedies are a reminder that despite almost a half century of research, seismologists are no closer to predicting earthquakes.

The task may be impossible. Without high certainty and accuracy, getting people to take action is difficult.
Earthquake preparation

But you do not always need to predict an earthquake to sound the alarm.

Having extra seconds to respond could save lives.

Earthquakes make this possible by generating their own warning signal.
Earthquake preparation

The warning time is the difference between the P-wave and the S-wave.

In a rupture on the San Andreas fault, the P-wave would come across the San Francisco Bay at about 7 km/second.
Earthquake preparation

The Hayward fault runs parallel to the San Andreas fault on the other side of the San Francisco Bay.

The location for ShakeAlert, the Earthquake Early Warning (EEW) system is Berkeley. ⁴²
Earthquake preparation

ShakeAlert used on the California coast detects the P-wave. 

ShakeAlert issues a warning before the much slower S-wave does the damage.
Earthquake preparation

Fig. 62: Seismic stations used by ShakeAlert (CalTech)
Earthquake preparation

400 seismometers are connected in a huge network across California buried beneath the soil.

They sound the alarm the moment a P-wave is detected.

These stations samples the ground 100 times per second.
Earthquake preparation

P-wave warning systems currently operate in high earthquake-risk countries like Japan.

When P-waves are detected in Japan, trains automatically halt, gas mains seal themselves, and schools, businesses and homes are alerted.
Earthquake preparation

But there are limits.

If a quake is hundreds of miles away, up to two minutes warning is provided.

But the closer the earthquake is, the less warning is possible.

P-wave warning systems help, but they are not the answer.
Many scientists now believe the real answer to the earthquake threat lies in engineering, not geology.

In the January 2010 quake, the vast majority of Haitians who died were killed by collapsing buildings.
Earthquake preparation

Residents along the Cascadia fault in the Pacific Northwest face the same Fate as the Japanese.

The residents of Cannon Beach have a unique plan to keep their heads above water with a new City Hall.
Earthquake preparation

The design is from FEMA, a “Tsunami Vertical Evacuation Refuge”, a survival platform from “Vertical Evacuation from Tsunamis: A Guide for Community Officials” published in June 2009.  

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Earthquake preparation

Fig. 63: FEMA National Earthquake Hazard Reduction Program and NOAA National Tsunami Hazard Mitigation Program
Earthquake preparation

Over the last quarter century, seismologists have made huge strides in understanding how and why earthquakes happen and calculating where, if not when, they will strike.
The disasters of 2010 and 2011 prove that prediction remains difficult for seismology, but knowledge developed by engineers can make us safer.
Surviving an earthquake depends upon advanced preparation.

Until seismologists can predict earthquakes, communities must be ready for the unexpected, because the next quake could strike at any time.
Earthquake preparation

“Japan's Killer Quake”

Japan’s earthquake, tsunami, and nuclear crisis.


FRONTLINE: “Inside Japan's Nuclear Meltdown”

The role of the Tokyo Fire Department after the Fukushima nuclear disaster

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