Chapter 8
part 2
Earthquakes and the Earth’s Interior

A Violent Pulse: Earthquakes

What is an Earthquake?

• “Earth shaking caused by a rapid release of energy.”
  – Energy buildup due to tectonic stresses.
  – Cause rocks to break.
  – Energy moves outward as an expanding sphere of waves.
  – This waveform energy can be measured around the globe.
• Earthquakes destroy buildings and kill people.
  – 3.5 million deaths in the last 2000 years.
• Earthquakes are common.

Seismicity

• Seismicity (‘quake or shake) cause by...
  – Motion along a newly formed crustal fracture (or, fault).
  – Motion on an existing fault.
  – A sudden change in mineral structure.
  – Inflation of a magma chamber.
  – Volcanic eruption.
  – Giant landslides.
  – Meteorite impacts.
  – Nuclear detonations

Faults and Earthquakes

• Most earthquakes occur along faults.
  – Faults are breaks or fractures in the crust...
  – Across which motion has occurred.
• Over geologic time, faulting produces much change.
• The amount of movement is termed displacement.
  • Displacement is also called...
    – Offset, or
    – Slip
  • Markers may reveal the amount of offset.

Earthquake Concepts

• Focus (or Hypocenter) - The place within Earth where earthquake waves originate.
  – Usually occurs on a fault surface.
  – Earthquake waves expand outward from the hypocenter.
• Epicenter – Land surface above the focus hypocenter.
Faults and Fault Motion

- Faults are like planar breaks in blocks of crust.
- Most faults slope (although some are vertical).
- On a sloping fault, crustal blocks are classified as:
  - Footwall (block below the fault).
  - Hanging wall (block above the fault).
- Miners on a fault would:
  - Stand on the footwall.
  - Bump their heads on the hanging wall.

Fault Types

- Fault type based on relative block motion.
  - Normal fault
    - Hanging wall moves down.
    - Result from extension (stretching).
  - Reverse fault
    - Hanging wall moves up.
    - Result from compression (squeezing).
  - Thrust fault
    - Special kind of reverse fault.
    - Fault surface is at a low-angle.
  - Strike-slip fault
    - Blocks slide past one another.
    - No vertical block motion.

Faults and Fault Motion

- Faults are commonplace in the crust.
  - Active faults – On-going stresses produce motion.
  - Inactive faults – Motion occurred in the geologic past.
  - Displacement can be visible.
    - Fault trace – A surface tear.
    - Fault scarp – A small cliff.
  - Blind faults are invisible.

Fault Initiation (elastic rebound theory)

- Tectonic forces add stress to unbroken rocks.
- The rock deforms slightly (elastic strain).
- Continued stress cause more stress & cracks.
- Eventually, cracks grow to the point of failure.
- Elastic strain transforms into brittle deformation (rebounds), releasing earthquake energy.

Fault Motion

- Faults move in jumps (rebounds).
- Once motion starts, it quickly stops due to friction.
- Eventually, strain will build up again causing failure.
- This behavior is termed stick – slip behavior.
  - Stick – Friction prevents motion.
  - Slip – Friction briefly overwhelmed by motion.

Fault Motion

- When rocks break, stored elastic strain is released.
- This energy radiates outward from the hypocenter.
- The energy, as waves, generates vibrations.
- The vibrations cause motion, as when a bell is rung.
- Large earthquakes are often:
  - preceded by foreshocks, and...
    - Smaller quakes.
    - May signal larger event.
  - followed by aftershocks.
    - Smaller quakes.
    - Indicate readjustment.
Amount of Displacement

- Displacement scale varies.
  - Large events may rip large fault segments.
    - 100s of kilometers long
    - 10s of kilometers deep
  - Smaller events may result in more localized effects.
- Displacement maxima near focus / epicenter.
- Displacement diminishes with distance.
- Faulting changes landscapes.
  - Uplift
  - Subsidence
  - Offset
- Changes are measurable.
  - Interferometry

Seismic Waves

- Body Waves – Pass through Earth’s interior.
  - Compressional or Primary (P) waves
    - Push-pull (compress and expand) motion.
    - Travel through solids, liquids, and gases.
    - Fastest.
  - Shear or Secondary (S) waves
    - “Shaking” motion.
    - Travel only through solids; not liquids.
    - Slower.

Seismic Waves

- Surface Waves – Travel along Earth’s surface.
  - Love waves – s waves intersecting the surface.
    - Move back and forth like a writhing snake.
  - Rayleigh waves – p waves intersecting the surface.
    - Move like ripples on a pond.
- These waves are the slowest and most destructive.

Seismology

- Seismology is the study of earthquake waves.
- Seismographs - Instruments that record seismicity.
  - Record Earth motion in relation to a stationary mass or rotating drum.
  - Deployed worldwide.
  - Can detect earthquakes from around the entire planet.
  - Seismology reveals much about earthquakes.
    - Size (How big?)
    - Location (Where is it?)

Seismograph Operation

- Straight line = background.
- Arrival of 1st wave causes frame to sink (pen goes up).
- Next vibration causes opposite motion.
- Waves always arrive in sequence.
  - P-waves 1st
  - S-waves 2nd
  - Surface waves last.
- A seismogram measures...
  - Wave arrival times
  - Magnitude of ground motion.

Locating an Epicenter

- Locating an epicenter depends upon the different velocities of p and s waves.
- Because they travel at different velocities, they located by comparing p and s wave arrival times from a minimum of three seismic stations.
Locating an Epicenter

• First arrival of p and s waves compared for (at least) 3 stations.

• A travel-time graph plots the distance of each station to the epicenter.

Locating an Epicenter

• A circle with a radius equal to the distance to the epicenter is drawn around each station.

• Data from three stations needed.

• The point where three circles intersect is the epicenter.

Earthquake Size

• Two means of describing earthquake size
  – Intensity (Mercalli scale)
  – Magnitude (Richter & Moment)

• Mercalli Intensity Scale
  – Intensity – The degree of shaking based on damage (subjective scale).
  – Roman numerals assigned to different levels of damage.
  – Damage occurs in zones.
  – Damage diminishes in intensity with distance.

Earthquake Size

• Magnitude – The amount of energy released.
  – Maximum amplitude of ground motion from a seismogram.
  – Value is normalized for seismograph distance.

• Several magnitude scales.
  – Richter (most common)
  – Moment (most accurate)

• Magnitude scales are logarithmic.
  – Increase of 1 Richter unit = 10 fold increase in ground motion however this = a 30 fold increase in energy.

Measuring Earthquake Size

• Earthquake energy release can be calculated.
  – Energy of Hiroshima bomb is ~ 6.0 magnitude quake
  – Annual energy released by all quakes is ~ 8.9 magnitude.

• Small earthquakes are frequent.
  – ~100,000 earthquakes (of >3 magnitude) per year.

• Large earthquakes are rare.
  – There are ~ 32 earthquakes of >7 magnitude per year.

Earthquake Occurrence

• Earthquakes are closely linked to plate tectonic boundaries.
• Shallow earthquakes - Divergent and transform boundaries.
• Intermediate & deep earthquakes – Convergent boundaries.
Convergent Plate Boundaries

- Populous nations in convergent tectonic settings have to content with frequent earthquakes.
- 80% of all earthquakes occur in the circum-Pacific belt (around Pacific Ocean).

Another 15% occur in Mediterranean-Asiatic belt (Mediterranean to Himalayas to Indonesia)

Earthquake Focal Depths

- Shallow – 0-20 km depth
  - Along the mid-ocean ridge.
  - Transform boundaries.
  - Shallow part of trenches.
  - Continental crust.
- Intermediate and deep earthquakes occur along the path of a subducting plate called the Benioff-Wadati zone
  - Intermediate – 20-300 km depth as downgoing plate remains brittle.
  - Deep - 300-670km depth - Mineral transformations?
- Earthquakes rare below 670 km because the mantle is ductile

Continental Earthquakes

- Earthquakes in continental crust.
  - Continental transform faults (San Andreas, Anatolian).
  - Continental rifts (Basin and Range, East African rift).
  - Collision zones (Himalayas, Alps).
  - Intraplate settings (Ancient crustal weaknesses).

San Andreas Fault

- Pacific plate meets the North American plate on the western edge of California.
  - Very dangerous fault.
  - Hundreds of earthquakes each year.
  - 12 + major temblors since 1800.

Intraplate Earthquakes

- 5% of earthquakes are not associated with plate boundaries.
- These intraplate earthquakes are not well understood.
  - Possible causes.
    - Remnant crustal weakness.
    - Failed rifts.
    - Shear zones.
    - Stress transmitted inboard.
    - Isostatic adjustments.
- Clusters
  - New Madrid, Missouri.
  - Charleston, South Carolina
  - Montreal, P.Q.
  - Adirondacks, New York.

Earthquake Damage

- Earthquakes kill people and destroy cities.
- The death and damage resulting from a large earthquake can be horrific and heart-rending.
- Learning about the characteristics of earthquakes, what they do and how they do it, can improve your chances of surviving one of these potentially deadly events.
Ground Shaking and Displacement
- Earthquake waves arrive in a distinct sequence.
- Different waves cause different motion.

P waves
- 1st to arrive.
- Rapid up–down motion.

S waves
- 2nd to arrive.
- Back and forth motion.
- Stronger than P-wave motion.

L waves
- Follow S-waves
- Ground writhes like a snake.

R waves
- Last to arrive.
- Like ripples in a pond.
- May last longer than others.

Severity of shaking and damage depends on...
- Magnitude (energy) of the earthquake. More energy = more shaking & damage.
- Distance from the hypocenter.
- Intensity and duration of the vibrations.
- The nature of subsurface material.
  - Bedrock transmits waves quickly = less damage
  - Sediments bounce waves = amplified damage
  - Wave frequency and resonance

Shaking Effects on Buildings.
- Slabs disconnect.
- Masonry disintegrates.
- Buildings collide.
- Slopes collapse.
- Bridges topple.
- Bridges come apart.
Earthquake Damage

- Landslides and Avalanches
  - Shaking can destabilize slopes to the point of failure.
  - Often hazardous slopes bear evidence of ancient slope failures
  - Evidence that is not recognized.
  - In mountainous landscapes, earthquakes can bring down rockslides or snow avalanches.
  - An earthquake was the immediate precursor to the landslide that unleashed the Mount St. Helens eruption, May 18th, 1980.

Liquefaction

- Water saturated sediments become liquefied when shaken.
  - High fluid pore pressures force grains apart.
  - This reduces friction and they move as a slurry.
  - Sand becomes "quicksand."
  - Clay will become "quickclay."
  - Liquefied sediments flow.
    - Injected as sand dikes.
    - Erupt as sand volcanoes.
    - Preserve distorted layering.

Earthquake Damage

- Fire
  - Shaking topples stoves, candles and power lines.
  - Broken gas mains and petroleum storage tanks can ignite a conflagration.
  - Earthquakes destroy infrastructure such as water, sewer, telephone, and electrical lines as well as roads.
    - Firefighters often can’t help.
      - No road access
      - No water
      - Too many hotspots
    - Good planning is crucial.

Earthquake Damage

- Disease
  - Earthquake devastation may fuel large disease outbreaks.
    - Food, water and medicines are scarce.
    - Basic sanitation capabilities disabled.
    - Hospitals damaged or destroyed.
    - Health professionals overtaxed.
    - There may be many decaying corpses.

Tsunami or Seismic Sea Waves

- Often incorrectly called "tidal waves."
- Caused when earthquakes change the seafloor.
- Thrust faulting raises the seabed; normal faulting drops it.
- This displaces all the overlying water (up or down).
- Resulting in a giant mound (or trough) on the sea surface.
- This feature may be enormous (up to a 10,000 mi² area).
- The surface feature quickly collapses, creating waves that race rapidly away from the disturbance.
Earthquake Damage
• Destructive tsunamis occur frequently - about once/yr.
• There have been many tsunami disasters in recorded history.
  – 94 destructive tsunamis in the last 100 years.
  – 51,000 victims (not including Sumatra in 12/26/04)
• Many tsunami disasters lurk in the future of humanity.
  – Larger human population than at any time.
  – Concentrations of people in low-lying coastal areas.
• Education about tsunamis can save many lives.

Tsunami vs. Wind Waves
• Wind waves
  – Influence the upper ~100 m.
  – Have wavelengths of several 10s to 100s of meters.
  – Wave height and wavelength related to windspeed.
  – Wave velocity maximum several 10s of kph.
  – Waves break in shallow water and expend all stored energy.
• Tsunami waves
  – Influence the entire water depth (avg. 2½ miles).
  – Have wavelengths of several 10s to 100s of kilometers.
  – Wave height and wavelength unaffected by windspeed.
  – Wave velocity maximum several 100s of kph.
  – Waves come ashore as a raised plateau of water that pours onto the land.

Tsunami Behavior
• Tsunamis race at jetliner speed across the deep ocean.
• Tsunami waves may be imperceptible in the deep ocean.
  – Low wave height (amplitude).
  – Long wavelength (frequency).
• As water shallows…
  – Waves slow from frictional drag.
  – Waves grow in height.
    • Waves may reach 10-15 m.

The Aftermath
• Tsunami destruction limited to low-lying coastal land.
• The magnitude of the run-up is a result of...
  • Offshore bathymetry.
  – Broad shallows
    • Shallows sap wave energy.
    • Waves become higher, but...
    • Have less energy and dissipate sooner.
  – Rapid deep to shallow offshore.
    • Waves have maximal energy.
    • Wave heights are modest.
    • Water pours onto land as a sheet.
    • Deadliest condition.
• Topography of shore.
  – Broad low land – maximum damage.
  – Steep rise of land – less damage.

The Destructive Effects of Earthquakes

© Tsunami: Killer Waves a magnitude 9.0 earthquake offshore Sumatra caused deadliest tsunami in history.
Dec. 26, 2004

The Aftermath
Dec. 26, 2004

Banda Ache, Sumatra
The Indian Ocean Tsunami

- On December 26, 2004, a strong megathrust earthquake (Mw 9.0) originated in the oceanic trench to the west of northern Sumatra.
- The earthquake was the largest in 40 years.
- A rupture length of 1100 km and a rupture width of 100 km were estimated from aftershocks.
- Fault displacement was as much as 15 m.
- The earthquake generated a devastating tsunami that killed people in 10 countries surrounding the Indian Ocean.

The Indian Ocean Tsunami

- Killed more people than any tsunami in recorded history.
  - ~283,100 deaths with 14,100 still missing (as of 5/05)
  - 1,126,900 people were displaced.
- The death toll was so horrific for several reasons.
  - The earthquake was so large.
  - Low-lying coastal areas were heavily populated
    - Resorts on the Malaysian Peninsula were full of Christmas tourists.
  - The tsunami destroyed low-lying coastal areas around the Ocean.
  - Northern Sumatra was particularly hard hit. Large portions of Banda Aceh were erased from the map.

The Indian Ocean Tsunami

- Western Sumatra is a typical subduction setting.
  - Deep oceanic trench.
  - East dipping subduction zone.
  - Oceanic volcanic island arc.
- The Indian Plate is subducting at an oblique angle (N23E) beneath the Burma Microplate.
- This results in a complicated geometry that includes...
  - Strike-slip (transform) faults
  - Thrust faults

The Indian Ocean Tsunami

- Destruction limited to land below the “run-up” elevation.
- Dense coastal development suffered the greatest devastation.
- In Banda Aceh, the tsunami erased entire communities.
Surviving a Tsunami

- Heed natural and official warnings.
  - An earthquake in a coastal setting.
  - Retreat of water from the shoreline is sign of an impending tsunami.
- Expect many waves.
  - Bigger waves may be next.
  - Wave arrival may last for hours.
- Abandon belongings.
- Get to high ground and stay there.
- Climb a sturdy building or a tree.
- Grab something that floats.
- Expect debris.
  - Sediment
  - Wreckage
  - Corpses
- Expect landscape changes.

Source: Brian F. Atwater and others, 1999, Surviving a Tsunami – Lessons from Chile, Hawaii and Japan, USGS Circular 1187

U.S. Coastal Risk

- Coastal Oregon and Washington
  - Cascadia subduction zone.
  - Geological evidence of numerous tsunami events.
- Hawaii - Kilauea volcano
- East Coast of the United States
  - Cumbre Vieja volcano on La Palma (Canary Islands).
  - Volcano has a gigantic fracture system.
  - At some point in the future, eruption will cause this fracture to fail.
  - 500 km$^3$ of rock will enter the ocean.
  - The ensuing tsunami may devastate the entire U.S. East Coast.

Source: Brian F. Atwater and others, 1999, Surviving a Tsunami – Lessons from Chile, Hawaii and Japan, USGS Circular 1187

Tsunami Prediction

- Scientific modeling helps to predict tsunami behavior.
- Detection systems exist in the Pacific; are planned for Indian Ocean.
  - Tsunami detectors are placed on the deep seafloor.
  - Sense increases in pressure from subtle changes in sea thickness.
- Prediction / detection can save 1000s of lives.

Earthquake Prediction

- Prediction would help reduce catastrophic losses.
- Can seismologists predict earthquakes? Yes and no.
  - CAN be predicted on a long-term (10-100s of years) basis.
  - CANNOT be predicted in the short-term (hours-months).
- Data analysis for prediction is “seismic hazard assessment.”
  - Seismic hazards are shown on maps of seismic risk.
  - This information is useful for...
    - Developing building codes.
    - Land-use planning.
    - Disaster planning.

Earthquake Prediction

- Long-Term Predictions
  - Probability of a certain magnitude earthquake occurring on a time scale of 30 to 100 years, or more.
  - Based on the premise that earthquakes are repetitive.
  - Require determination of seismic zones, by...
    - Mapping historical epicenters (after ~ 1950).
    - Evidence of ancient earthquakes (before seismographs).
  - Evidence of seismicity – Fault scarps, sand volcanoes, etc.
    - Historical records.

- Seismic gaps, places that haven’t slipped recently, are likely candidates.
Earthquake Prediction

- **Short-Term Predictions**
  - Goal: warn of the location & magnitude of large earthquakes
  - Currently, no reliable short-range predictions are possible.
  - But known precursors to earthquakes, including…
    - Clustered foreshocks.
    - Crustal strain.
    - Stress triggering.
    - And, possibly…
      - Water level changes in wells.
      - Increases gases (Rn, He) in wells.
      - Unusual animal behavior.
  - On May 18th, 2005, the USGS began daily 24-hour earthquake hazard assessments for California.
  

Preparing for Earthquakes

- Can’t stop earthquakes but we can be ready.
  - Understand what happens during an earthquake.
  - Map active faults & areas likely to liquefy during shaking.
  - Developing construction codes to reduce building failures.
  - Land-use regulation to control development.
  - Community earthquake preparedness training.
  - Education on safe earthquake behavior and response.
  - Keep viable stores of emergency supplies.

### Notable Earthquakes

<table>
<thead>
<tr>
<th>Location</th>
<th>Magnitude</th>
<th>Date</th>
<th>Comments</th>
</tr>
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<tbody>
<tr>
<td>Kobe, Japan</td>
<td>7.9</td>
<td>Mar 11, 1995</td>
<td>Largest in Japan, huge landslides</td>
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<tr>
<td>Niigata, Japan</td>
<td>7.3</td>
<td>Aug 17, 1999</td>
<td>120,000 buildings destroyed, 17,829 deaths</td>
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<tr>
<td>Kobe, Japan</td>
<td>6.9</td>
<td>Jan 17, 1994</td>
<td>120,000 buildings, $147 billion</td>
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<td>Nisqually, Wa, USA</td>
<td>6.8</td>
<td>Mar 28, 2001</td>
<td>100,000 buildings, 515 lives</td>
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<td>Oct 17, 1995</td>
<td>'Wold Series'</td>
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<tr>
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<td>Jul 21, 1975</td>
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<tr>
<td>Italy</td>
<td>7.8</td>
<td>May 31, 1972</td>
<td>Large landslide</td>
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<td>Prince William Sound, Al, USA</td>
<td>8.3</td>
<td>Mar 26, 1964</td>
<td>&quot;Good Friday&quot; - Tsunami</td>
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<td>Messina, Italy</td>
<td>7.5</td>
<td>Dec 28, 1968</td>
<td>120,000 buildings</td>
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<td>Hartford, CT, USA</td>
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<td>Aug 18, 1969</td>
<td>Fall in Boston, Chicago and St. Louis, 91</td>
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<td>Christchurch, NZ, New Zealand</td>
<td>7.5</td>
<td>Aug 19, 1969</td>
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<td>New Madrid, Mex, MX</td>
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<td>Dec 16, 1985</td>
<td>Fall in Mexico, Changed Mex, 5, 900 lives</td>
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<td>Great Alaskan</td>
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<tr>
<td>Christchurch, NZ, New Zealand</td>
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<td>Mar 11, 1995</td>
<td>Largest in Japan, huge landslides</td>
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The End