Deformation of Rocks

Why study rock deformation?
- Earthquakes represent a powerful and violent force
- Earthquakes are also integral in the formation of valuable economic resources
  - Mineral deposits contain such things as gold and copper – commonly form in areas of bent and contorted rock
  - Metal-rich fluids move through cracks and fractures as do migrating oil and natural gas

Objectives: In this chapter you will
- observe and describe the types of deformation visible at Earth’s surface.
- understand the relationship between deformation and the forces that drive it.
- learn the causes and effects of earthquakes.

11.1 What do deformed rocks look like?
- Describing the orientation of rocks – tilted or dipping beds
  - Strike: the compass orientation of a line formed by the intersection of an imaginary horizontal line with the dipping bed
  - Dip: the angle between the imaginary horizontal plane and the inclined rock layer

11.1 What do deformed rocks look like?
- Visualizing strike and dip

Fig 11.2
11.1 What do deformed rocks look like?

Describing folded rocks
- **Lims**: the two dipping sides of a fold…
- **Hinge line**: where the dipping limbs join…
- **Plunging fold**: when the hinge line plunges downward into the ground…
- **Anticline**: a folded structure that arches upward in the center (limbs dip away from hinge line)…
- **Syncline**: a folded structure that arches down in the center (limbs dip in towards hinge line)

Visualizing folded rocks

Remember "A" for anticline

Centralia Coal Mine 2005 field trip—looking south
Steeper dip here
Less steep dip here—we are looking at part of a syncline!

More dipping beds—Beach #4 on the Olympic Coast—note angular unconformity!
11.1 What do deformed rocks look like?

Visualizing folded rocks

- Anticline
- Syncline

Anticline and syncline exposed in roadcut, New Jersey

Visualizing folded rocks

Fig 11.4 bottom left

Aerial view of plunging anticline, Sheep Mountain, Wyoming

Visualizing folded rocks

Fig 11.4 bottom right

11.1 What do deformed rocks look like?

Describing broken rocks – faults

- **Footwall**: the rock below the fault plane
- **Hanging wall**: the segment of rock above the fault plane...
- **Dip-slip**: motion along a fracture that is primarily vertical displacement along the dip-plane surface...
- **Strike-slip**: motion along a fault that results in rock displacement in a compass direction...
- **Oblique-slip fault**: a combination of dip- and strike-slip displacements

Visualizing broken rocks

The footwall and hanging wall convention is an old miner’s term referring to the rock under one’s feet, and the wall where you would hang your lamp.

Fig 11.7

11.1 What do deformed rocks look like?

Visualizing faults – a normal (dip-slip) fault, one where the hanging wall goes down relative to the footwall

Visualizing faults – a reverse (dip-slip) fault, one where the footwall goes down relative to the hanging wall

Fig 11.8
11.1 What do deformed rocks look like?

Visualizing faults – thrust fault, a low-angle (<45°) reverse (dip-slip) fault

11.3 Why do rocks deform?

- Rocks strain when stress exceeds strength
  - **Stress**: a force applied to a given area (Section 6.3)
  - **Strain**: the measurable rock deformation resulting from stress
- Three types of stress and strain
  - Compressive stress – results in shortening strain
  - Tensional stress – results in elongation strain
  - Shear stress – results in shear strain

11.3 Why do rocks deform?

- Faulting, folding, and flowing are strain

Here, in this experiment using layered sand, we can clearly see the strain resulting from applied stress.

A similar experiment using wax layers, which tend to bend before they break as a result of stress. Folded structures form as a result of stress. We also see flow and faulting under continued stress.
11.3 Why do rocks deform?

- **Stress** = magnitude of a force applied over a given area.
- **Strain** = measure of deformation that results from said stress.
- **Rock strength** = amount of stress that a material can endure before it strains.
- When applied stress exceeds the strength of a rock, the rock deforms by folding, faulting, or flowing.
- **Compressive stress** shortens rocks parallel to the stress, whereas tension elongates them.
- **Shear stress** moves materials in opposite directions without shortening or lengthening.

11.4 How do we know ... why some rocks break and others flow?

**TABLE 11.1** Relative Rock Strength at Surface Temperature and Pressure

<table>
<thead>
<tr>
<th>Strength and deformation</th>
<th>Rock type</th>
<th>Some rock types and their strength at surface conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>High strength, brittle deformation</td>
<td>Quartzite</td>
<td>Weak materials such as rock salt and glacial ice flow under less extreme conditions</td>
</tr>
<tr>
<td></td>
<td>Gneiss</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Quartz-cemented sandstone</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Basalt</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Limestone</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Calcite-cemented sandstone</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shale</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Schist</td>
<td></td>
</tr>
<tr>
<td>Low strength, plastic deformation</td>
<td>Marble</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shale and mudstone</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rock salt</td>
<td></td>
</tr>
</tbody>
</table>

**Near surface (shallow)**

- More brittle—joints, faults.

**Deeper**

- More ductile—plastic deformation.

11.5 How do geologic structures relate to stress, strain, and strength?

**Fig 11.21**

- **Tapestry of Time and Terrain**

**Great Basin**
11.5 How do geologic structures relate to stress, strain, and strength?
- Brittle faults/joints form close to the surface; plastic flow occurs at deeper levels (high pressure inhibits fracturing and high temperature lowers rock strength).
- Compression shortens & thickens crust by producing folds, reverse faults, & thrust faults in shallow rock, & plastic flow in deeper rock.
- Tension elongates and thins crust by movement on normal faults in shallow rocks and taffy-like stretching of plastic rocks at deeper levels.
- Folds form by plastic flow in deep crust but also develop at and near the surface in sedimentary rocks where bending of thin layers and slippage along layers takes place.

11.6 How does strength vary in the lithosphere?
- The significance of composition and crust thickness
  - Mantle rock under oceanic crust is probably dry, whereas continental lithospheric mantle contains water and water-bearing minerals.
  - The wetter continental crust is very weak below ~15 km in contrast to the same depth of dry mantle under oceanic crust at that depth. Continental lithosphere becomes weaker below 12–15 km while oceanic lithosphere becomes stronger until about 40 km.

11.7 How do earthquakes relate to rock deformation?
Earthquakes in the field, as in lab simulations, absorb stress up to a finite limit and then release it when they break. It should be no surprise that earthquakes line up along the strike of a fault (left) as well as along the dip direction of the fault plane in cross section (right).

Motion along faults: Note the displacement in the highway (left) of a right-lateral strike-slip fault (the farther block moved to the right relative to the closer one), and the fault scarp (right) on the footwall of a normal dip-slip fault.

Fault motion without earthquakes – some faults are so weak that little energy is stored from stress. Instead the fault “creeps” through small increments of strain.
11.7 How do earthquakes relate to rock deformation?

- **Foreshocks.** mainshock. aftershocks
  - Foreshocks are a (or groups of) small displacement(s) that occur prior to the main shock...
  - Mainshock is the "main event," the large release of energy along the stressed system...
  - Aftershocks are small displacements that occur after the mainshock. Often these occur by the hundreds, which while usually weak, often hamper relief efforts...
  - Foreshocks are not useful indicators in predicting earthquakes as there is no way to tell a foreshock (as a portent of impending rupture) from a lone, small earthquake.

### Foreshocks

Elastic rebound along the Hayward fault in California. Elastic rebound is a "bend-bend, break, snap-back" perspective. Not possible to know how much bend a given interval can take.

### Mainshock

- **Mainshock** is the "main event," the large release of energy along the stressed system.

### Aftershocks

- **Aftershocks** are small displacements that occur after the mainshock. Often these occur by the hundreds, which while usually weak, often hamper relief efforts.

### Podcasts

- google: PNSN Pacific Northwest seismic network

### Recap!!!

- **Earthquakes result from motion along faults.** Earthquakes = brittle failure of rock (hence occur in the upper crust where temperature and pressure are relatively low)... Not all motion on faults produces earthquakes; rocks can creep along faults if the fault is too weak to store up the energy of prolonged stress...
- **Elastic rebound theory** explains deformation before and during earthquakes as brittle failure following accumulation of elastic strain...
- **Foreshocks and aftershocks** are smaller earthquakes that occur before and after the main earthquake.

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**Fig 11.31**

Elastic rebound along the Hayward fault in California. Elastic rebound is a "bend-bend, break, snap-back" perspective. Not possible to know how much bend a given interval can take.

**Fig 11.32**

Plot of aftershocks along a fault system in Alaska. Aftershocks may stay in the mainshock region, or may transfer to adjoining faults as stresses change and adjust.
11.8 How are earthquakes measured?

- **Intensity** – a measure of the violence of an earthquake. The human-realized effects such as damage to structures and secondary effects like landslides...
  
- **Mercalli scale** – made by Giuseppe Mercalli (c. 1902) and runs from a low of I to a high value of XII
  
  - Current revision is the Modified Mercalli scale
  
  - Intensities are commonly plotted on maps with intensity contours
  
  - Can be used to determine intensities of historic earthquakes through newspapers, diaries, etc.

- **Magnitude** – a measure of earthquake size based on the energy released during the earthquake.
  
  - Richter scale – the first magnitude scale (c. 1935) developed by Charles Richter.
    
    - Measured by the wave amplitude on a certain type of seismometer and the time interval between P-S waves (Section 8.2).
    
    - Scale is logarithmic, each numeric value is 10x the amplitude of the one before.

- **Moment-magnitude scale** – based on physical parameters of the earthquake event. Similar to Richter scale in that each number increase ~ 10x increase in seismic moment.
  
  - Area of fault slippage occurring during the earthquake.
  
  - Rock strength (square meter)
  
  - Energy change ~32x
  
  - So => M7 has 100x more "seismic moment" than a M5 (10 x 10). However, the energy difference is 1024 (32 x 32).
11.8 How are earthquakes measured?

<table>
<thead>
<tr>
<th>Date</th>
<th>Place</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>December 16, 1811</td>
<td>New Madrid, MO</td>
<td>8.1</td>
</tr>
<tr>
<td>January 23, 1912</td>
<td>New Madrid, MO</td>
<td>7.8</td>
</tr>
<tr>
<td>February 9, 1912</td>
<td>New Madrid, MO</td>
<td>8.0</td>
</tr>
<tr>
<td>April 16, 1906</td>
<td>San Francisco, CA</td>
<td>7.8</td>
</tr>
<tr>
<td>November 4, 1952</td>
<td>Krichkheba, Racco</td>
<td>9.0</td>
</tr>
<tr>
<td>May 22, 1960</td>
<td>Chile</td>
<td>9.5</td>
</tr>
<tr>
<td>March 28, 1964</td>
<td>Prince William Sound, AK</td>
<td>9.2</td>
</tr>
<tr>
<td>July 27, 1970</td>
<td>Tangshan, China</td>
<td>7.5</td>
</tr>
<tr>
<td>December 2, 1988</td>
<td>Asahiy, Armenia</td>
<td>6.8</td>
</tr>
<tr>
<td>October 12, 1989</td>
<td>Lima-Petsa, CA</td>
<td>6.0</td>
</tr>
<tr>
<td>June 28, 1992</td>
<td>Landers, CA</td>
<td>7.3</td>
</tr>
<tr>
<td>January 17, 1994</td>
<td>Northridge, CA</td>
<td>6.7</td>
</tr>
<tr>
<td>January 16, 1995</td>
<td>Kobe, Japan</td>
<td>6.9</td>
</tr>
<tr>
<td>August 7, 1999</td>
<td>Erciyes, Turkey</td>
<td>7.6</td>
</tr>
<tr>
<td>September 21, 1999</td>
<td>Sichang, Sawan</td>
<td>7.8</td>
</tr>
<tr>
<td>December 26, 2004</td>
<td>Sumatra, Indonesia</td>
<td>9.0</td>
</tr>
</tbody>
</table>

Fig 11.36: Energy comparison of specific earthquake events to energy release of other “significant” events.

Some epicenters of noteworthy quakes in the Puget Lowland.

Fig 11.37: 26 February 2001 Puget Lowland Earthquake.

Cascadia earthquake sources.

Fig 11.38: Major players of the Earth’s crust.
11.8 How are earthquakes measured?
- Earthquake intensity, or violence, estimated from assessments of damage and numerous eyewitness accounts. Values are usually higher near the epicenter or on soft soils.
- Earthquake magnitude relates to the energy released. Each whole number increase in magnitude is ~32-fold increase in energy released.
- There is only one magnitude value on any given scale per earthquake. Richter Scale relies more on response of seismometers to passing waves; The moment-magnitude scale is based on the area of fault-plane ruptured, the displacement, and the rock strength.

11.9 Why are earthquakes destructive?
- Ground shaking...
  - Surface waves radiating outward from the epicenter cause ground motion: up/down and side to side. The stress damages buildings, bridges, dams, etc...
  - Disrupts infrastructure (water, gas, power, and roads), starting fires and limiting ability to respond and often damaging more property than ground shaking itself...
  - Ground shaking also triggers mass movement (landslides).

Damage from ground shaking

11.9 Why are earthquakes destructive?
Damage from ground shaking

Damage from ground shaking
11.9 Why are earthquakes destructive?

Liquefaction
Underlying material greatly affects susceptibility of an area to ground shaking damage.
Saturated sediments undergo liquefaction (become fluidal) during strong ground motion.

Fig 11.38

Fig 11.39


Fig 11.39

Brown, sediment-laden water surges inland more than 500 meters.

Fig 11.39

Generation of a seismic sea wave, aka tsunami, erroneously called “tidal wave” by some.
Subduction zone earthquakes
Where? Along the interface between the Juan de Fuca and North American Plates

Why? Locked fault fails and slips!

What can happen when the subduction zone breaks? Tsunami!!!

Sand volcano caused by the 2/28/01 Nisqually quake at Nisqually Wildlife Refuge.

The sand is full of pumice and charred wood that had been deposited here by lahar-derived floods from Mount Rainier!
2/28/01 Nisqually quake: ground cracks and liquefaction at Timberline High School baseball field. Fill over peat.


Nisqually quake 2001: damage to road around Capital Lake

Magnitude 5.8

1999 Satsop Earthquake

Magnitude 6.8

2001 Nisqually Earthquake

Landslide into home at Salmon Beach near Tacoma.

chimney is damaged beneath flashing!
SEATAC control tower after 2001 Nisqually quake!

Top: forest killed by inundation of sea water after tectonic subsidence during 1964 Alaska earthquake

Bottom: forest killed by inundation of sea water after tectonic subsidence 300 years ago on the Copalis River SW Washington coast!

Historic Examples:

Alaska, 1964 M 9.2

Chile, 1960 M 9.5

Subsidence

Dating of Cascadia Earthquakes

1100 yr B.P. subsidence

1600 yr B.P. subsided stump

Subsidence “footprints” of Cascadia earthquakes

Johns River, Washington, 1988; photo by Pat Pringle

How frequent?

13 major events in 7,600 yrs

Figure 26: Sequence of events involved with Cascadia Earthquakes. The number on ages in thousands of years is the date estimated for the major earthquakes. The result line is calculated using the method of cross-matching. All dates are in years B.C. and A.D.; the map shows a range of earthquakes, locations of Ancestral, and 13 A.D. earthquake.
Use of tree rings to correlate geologic events (with or without calendric ages) to study the Seattle fault

Cross section of Benioff zone (subduction zone as defined by the trend of earthquakes)

A “shake map” shows intensities of the 2001 quake after post quake recalibration of local seismic models.
11.9 Why are earthquakes destructive?

- Risk assessment tools:
  - Earthquake research saves lives and property...
  - Seismic hazard mapping (Fig. 11.40) rates areas on probability of ground-shaking hazards, liquefaction, and likelihood of seismic event occurring...
  - Such risk maps commonly used by municipal planners, insurance companies, engineers, etc. to guide construction and building codes to withstand such forces.

Liquefaction hazards for the Olympia area by Palmer, Walsh, & Gerstel

Subsidence "footprints" of Cascadia earthquakes
Johns River, Washington

AD 1700 tsunami deposit near coastal WA + intertidal muds on top (evidence of coseismic subsidence)
Young fault in Middle Fork Satsop River discovered by Tim Walsh and Josh Logan. Note ladder for scale!

Spider Lake, SE Olympic Mountains

landslide deposit

Dots show buried or submerged trees; fuscia lines are faults or inferred faults; brown volcanic hazards

Glacier Lake, SW WA Cascade Range—oblique-aerial view.
11.9 Why are earthquakes destructive?

Earthquake prediction

- Can they be predicted?
  - At present, seismologists cannot reliably predict the specific time, place, or magnitude of an earthquake.
  - What they can offer is general probabilities (forecasts) that areas may undergo some size of seismic activity within a time span (very much like a weather forecast, but not quite so certain) such as a 67% chance that San Francisco Bay will see a M6.7 in the next 30 years.

11.9 Why are earthquakes destructive?

- Earthquakes cause damage by fault rupture, ground shaking, landslides, and tsunami.
- Seismic surface waves cause ground shaking. The amplitude of the waves and hence the damage resulting varies with earthquake intensity and the nature of the geologic material the waves traverse.
- Earthquake rupture of the seafloor generates tsunami that cause destruction both close to the epicenter and as far as thousands of kilometers away.
- Predictions for specific earthquakes are still not possible, but risk maps identify hazards for consideration in land-use planning, building codes, and engineering designs that diminish the destructive effects of earthquakes.