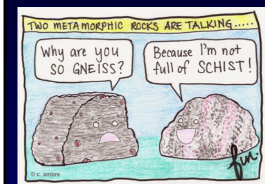
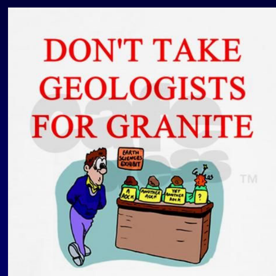
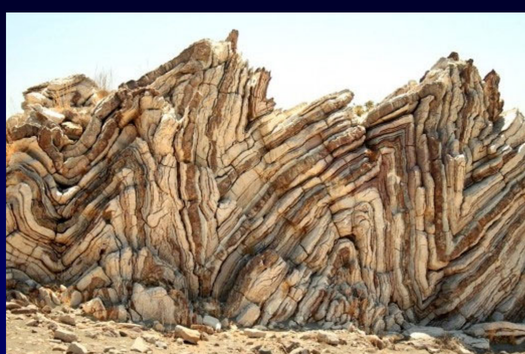
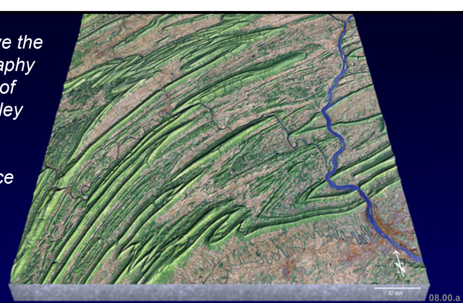
Deformation and Metamorphism
Chap 8

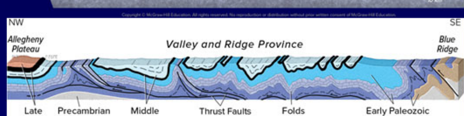


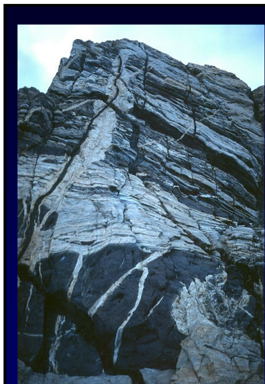


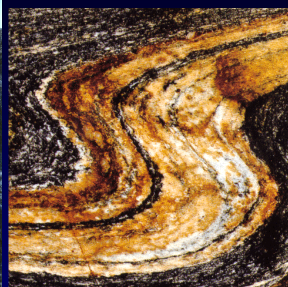


Observe the topography of part of the Valley and Ridge Province



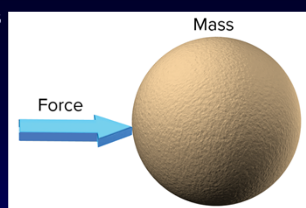






Force and Stress

Force is push or pull, expressed as amount of acceleration experienced by a mass

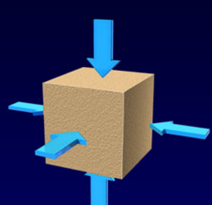


What happens if same amount of force is applied to two wooden pillars?

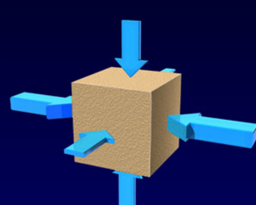
Stress = force per area

08.01.a

Different Kinds of Stress

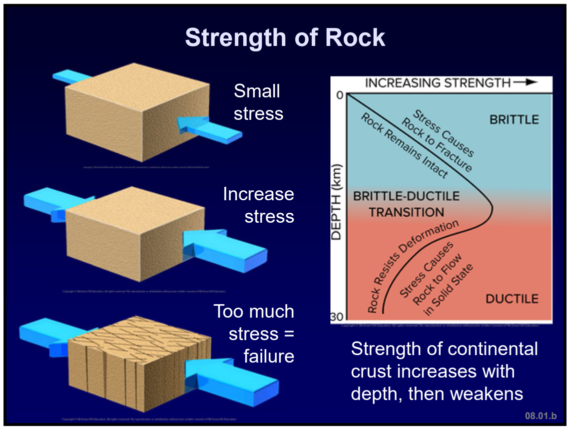


Confining pressure: same amount of stress from all directions

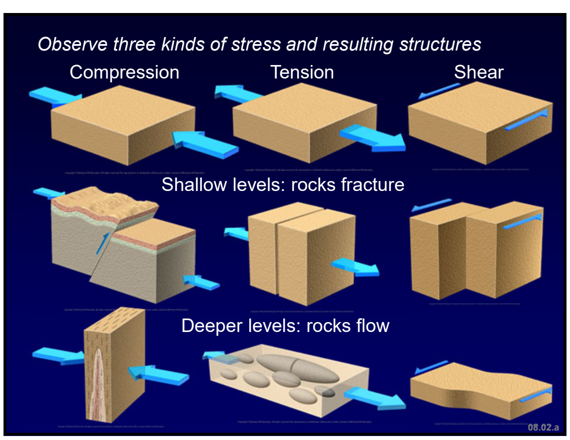


Differential stress: different amounts of stresses from different directions

08.01.b


Strength of Rock
Small stress
Increase stress
Too much stress = failure
INCREASING STRENGTH
BRITTLE
Stress Causes Rock to Fracture
Rock Remains Intact
BRITTLE-DUCTILE TRANSITION
DEPTH (km)
0
30
Rock Resists Deformation
Stress Causes Rock to Flow in Solid State
DUCTILE
Strength of continental crust increases with depth, then weakens
08.01.b


How Rocks Respond to Force and Stress
Small amount of stress: block remains unchanged
08.01.c
Displacement
Rotation
Strain


Observe three kinds of stress and resulting structures
Compression
Tension
Shear
Shallow levels: rocks fracture
Deeper levels: rocks flow
08.02.a

Change in Deformation as Temperature and Pressure Increase with Depth

At shallow depths and low temperatures, most rocks are brittle and break

At greater depths, temperature and pressure are higher and rocks flow as weak solids

08.02.b

Change in Mineral Response as T and P Increase with Depth

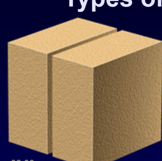
At shallow depth and low temperatures, minerals may be unaffected

Deeper and at higher temperatures, minerals may recrystallize or new minerals may grow

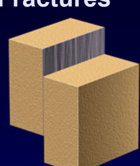
08.02.b

Types of Fractures

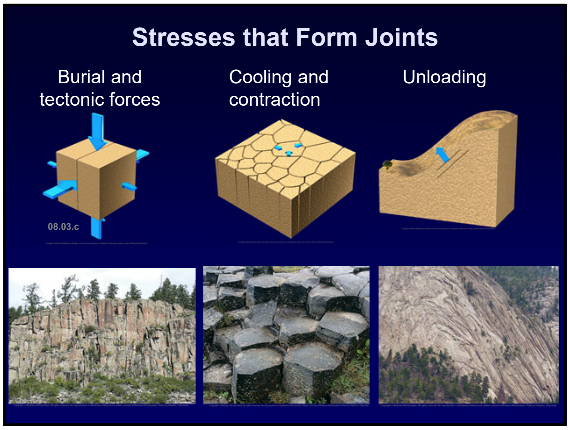
Joint: crack where rock pulled apart

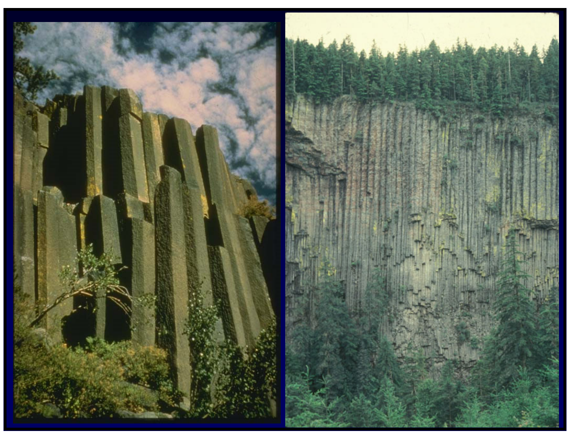


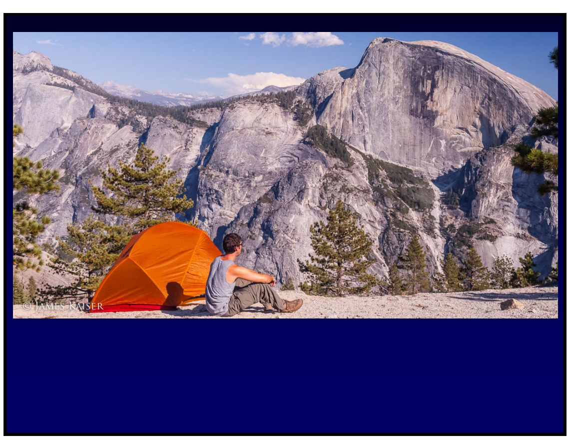
08.03.a

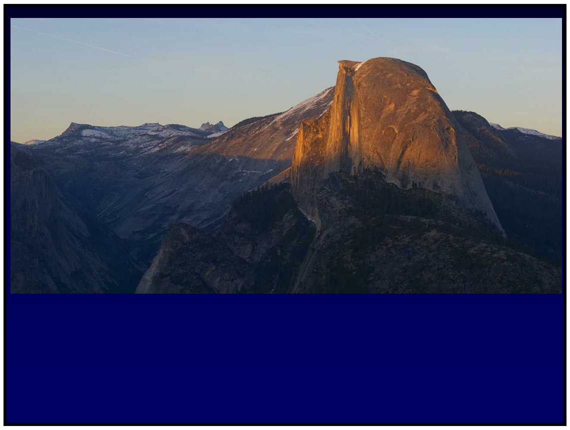


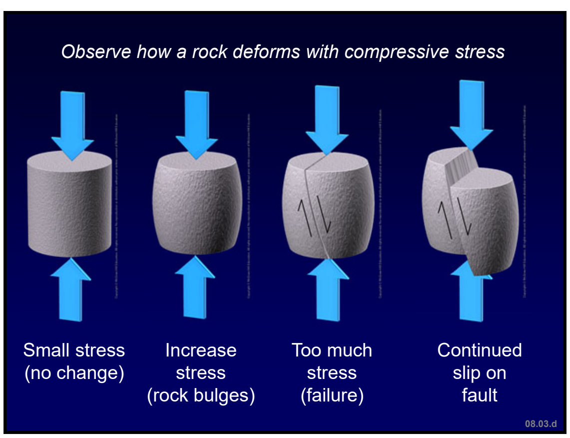
Fault: rocks have slipped past one another

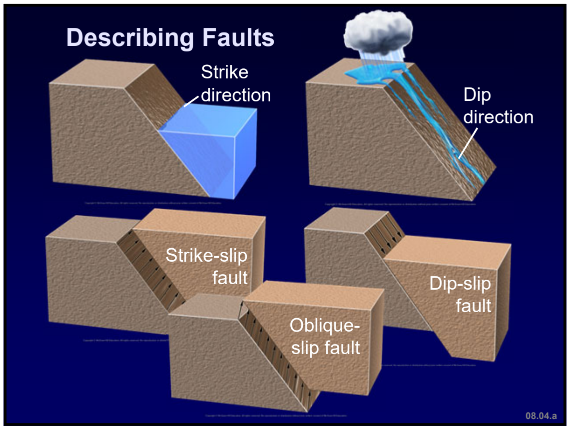

Stresses that Form Joints
Burial and tectonic forces
Cooling and contraction
Unloading
08.03.c

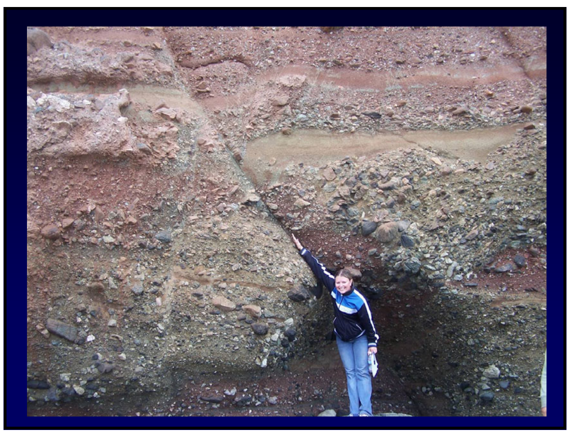


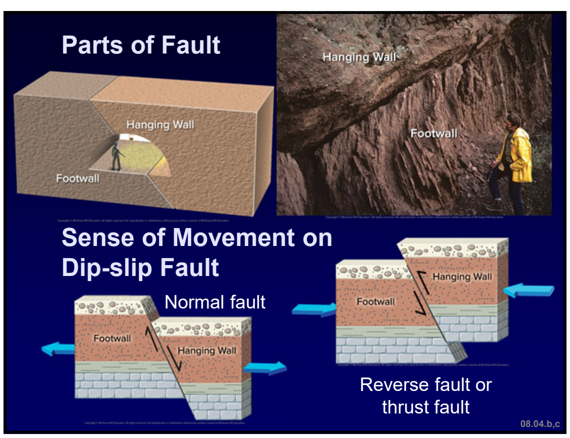


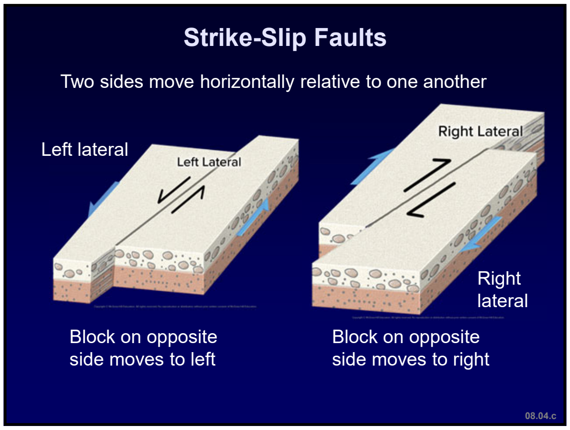


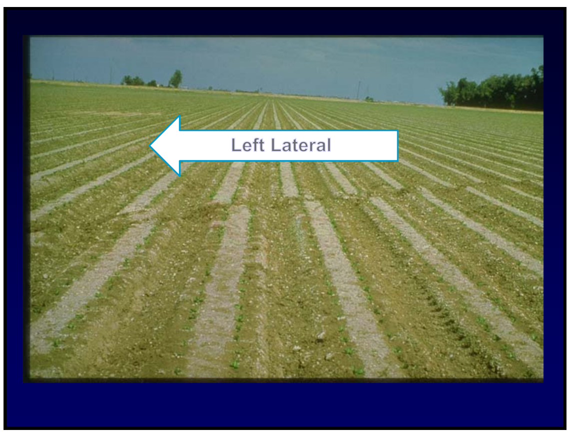

Observe how a rock deforms with compressive stress
Small stress (no change)
Increase stress (rock bulges)
Too much stress (failure)
Continued slip on fault
08.03.d

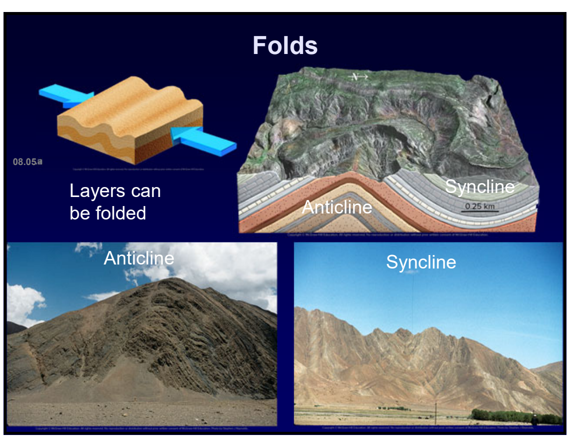

Describing Faults
Strike direction
Dip direction
Strike-slip fault
Dip-slip fault
Oblique-slip fault
08.04.a

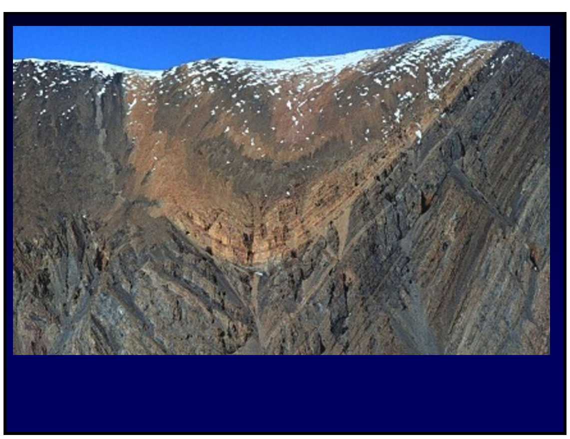


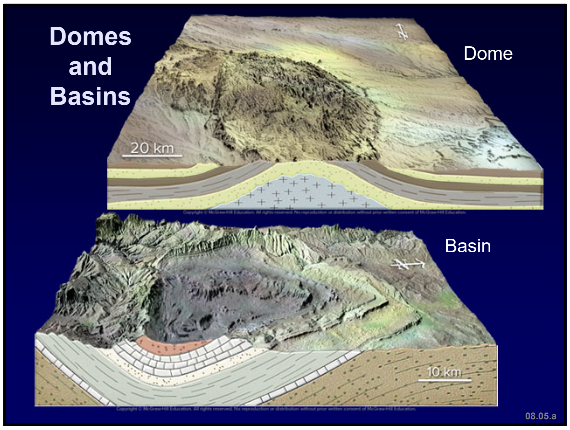

Parts of Fault
Hanging Wall
Footwall
Hanging Wall
Footwall
Sense of Movement on Dip-slip Fault
Normal fault
Footwall
Hanging Wall
Footwall
Hanging Wall
Reverse fault or thrust fault
08.04.b,c


Strike-Slip Faults
Two sides move horizontally relative to one another
Left lateral
Left Lateral
Right Lateral
Right lateral
Block on opposite side moves to left
Block on opposite side moves to right
08.04.c

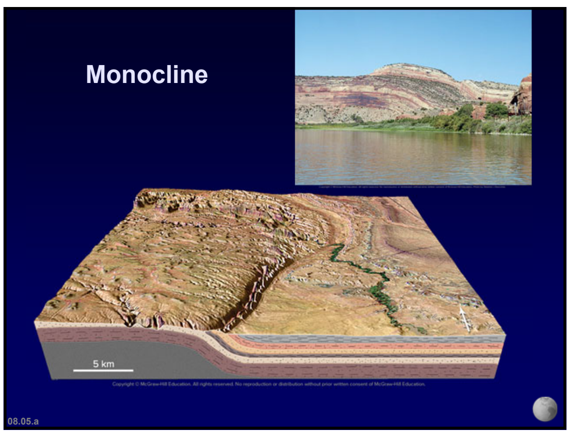

Left Lateral


Folds
08.05a
Layers can be folded
Syncline
Anticline
Anticline
Syncline

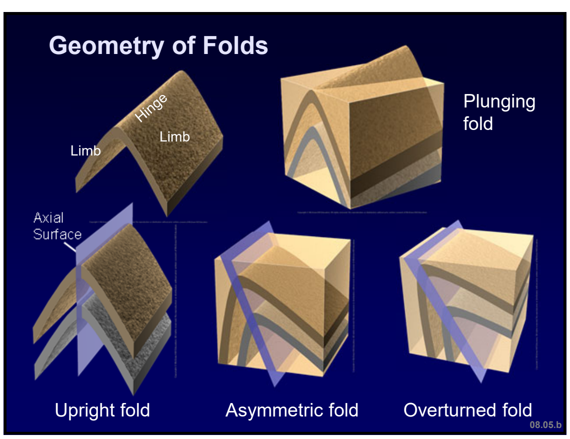




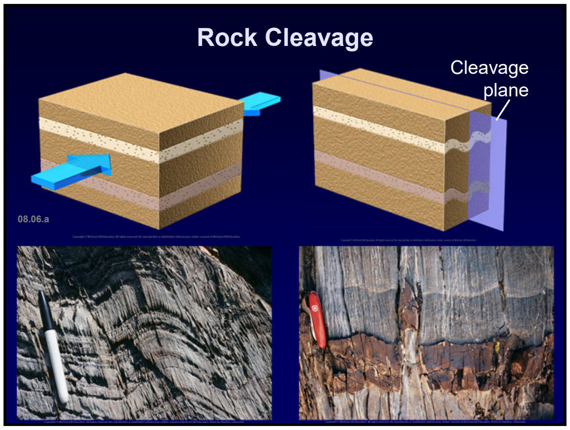
Domes and Basins
Dome
20 km
Basin
10 km
08.05.a

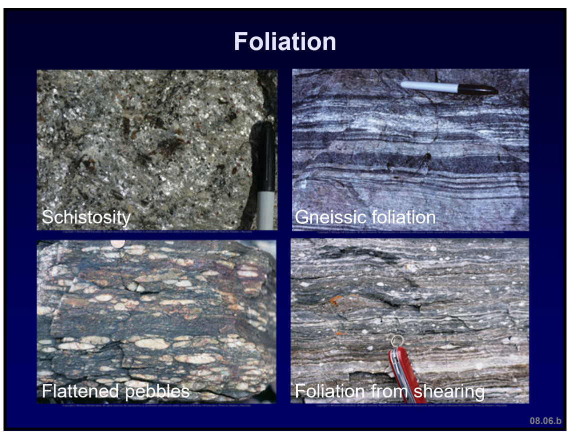


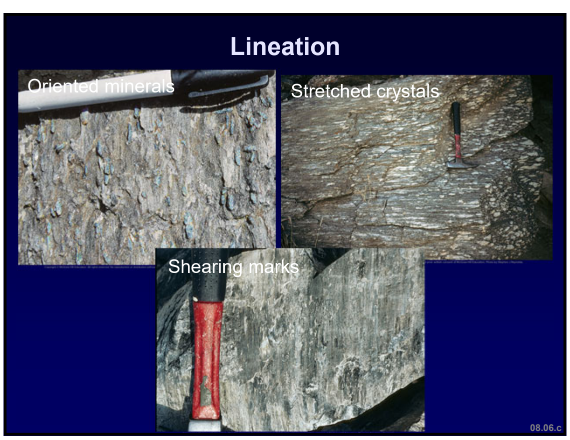
Monocline
5 km
08.05.a

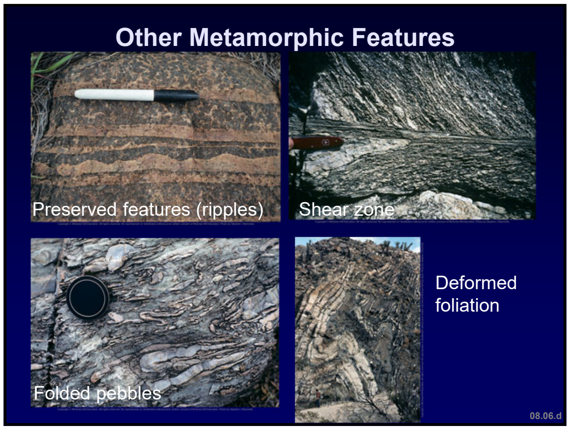


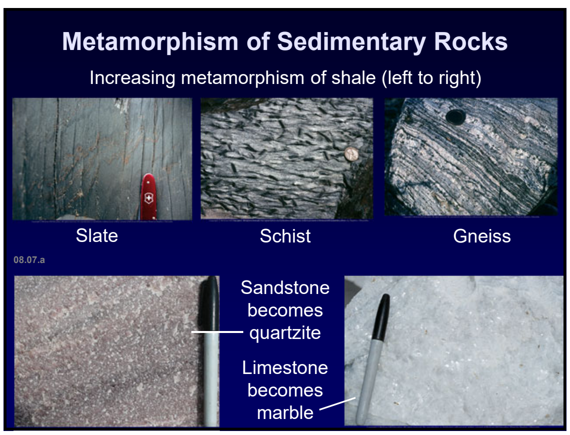
Geometry of Folds
Hinge
Limb
Limb
Plunging fold
Axial Surface
Upright fold
Asymmetric fold
Overturned fold
08.05.b

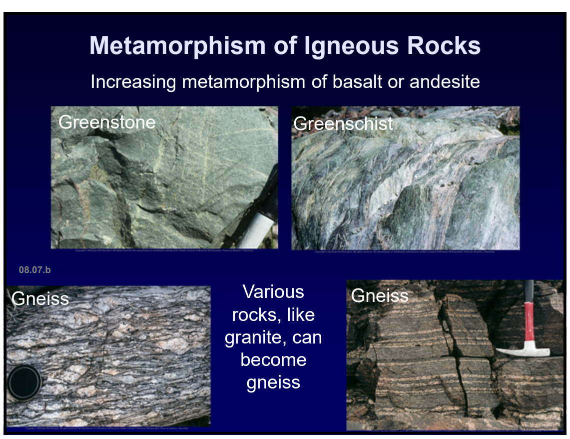

Rock Cleavage
Cleavage plane
08.06.a

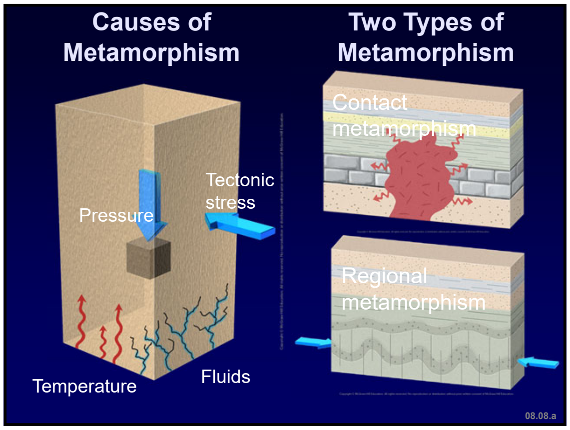

Foliation
Schistosity
Gneissic foliation
Flattened pebbles
Foliation from shearing
08.06.b

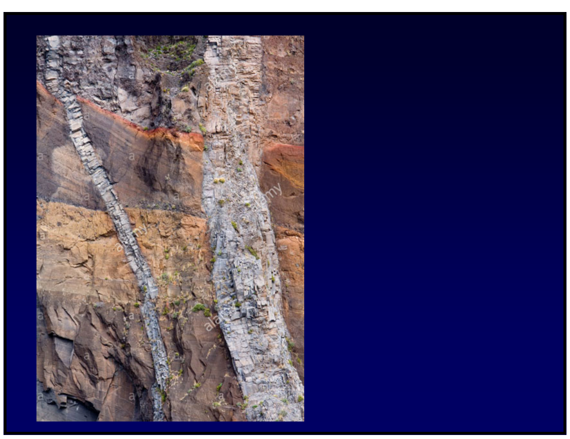

Lineation
Oriented minerals
Stretched crystals
Shearing marks
08.06.c

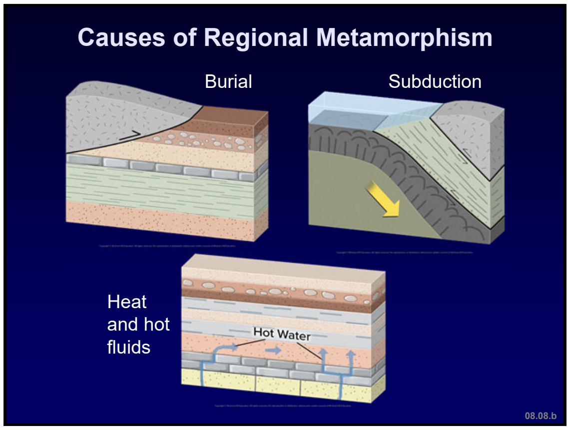

Other Metamorphic Features
Preserved features (ripples)
Shear zone
Folded pebbles
Deformed foliation
08.06.d

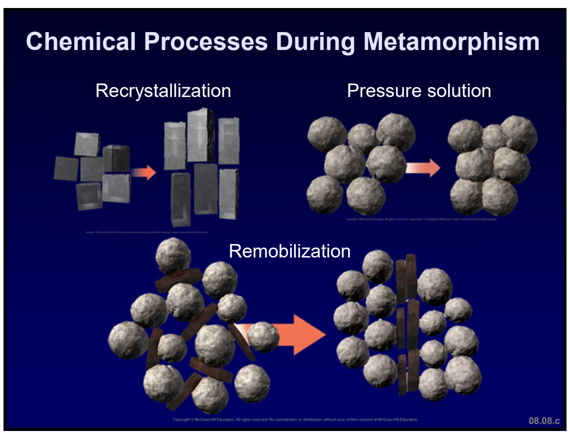

Metamorphism of Sedimentary Rocks
Increasing metamorphism of shale (left to right)
Slate
Schist
Gneiss
08.07.a
Sandstone becomes quartzite
Limestone becomes marble

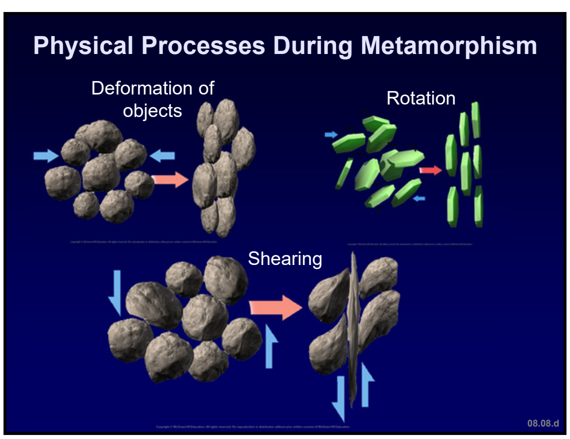

Metamorphism of Igneous Rocks
Increasing metamorphism of basalt or andesite
Greenstone
Greenschist
08.07.b
Gneiss
Various rocks, like granite, can become gneiss
Gneiss


Causes of Metamorphism
Two Types of Metamorphism
Contact metamorphism
Tectonic stress
Pressure
Regional metamorphism
Temperature
Fluids
08.08.a

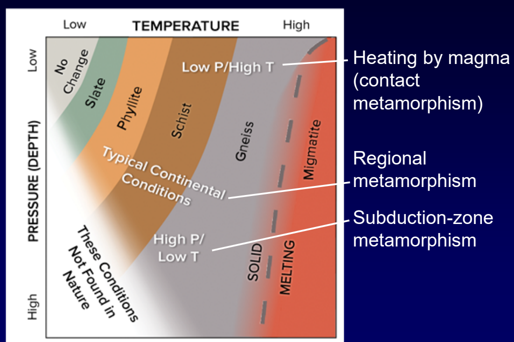



Causes of Regional Metamorphism
Burial
Subduction
Heat
and hot
fluids
Hot Water
08.08.b

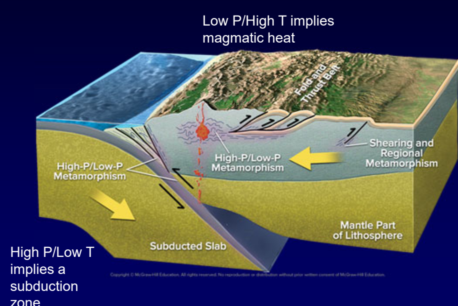

Chemical Processes During Metamorphism
Recrystallization
Pressure solution
Remobilization
08.08.c


Physical Processes During Metamorphism
Deformation of
objects
Rotation
Shearing
08.08.d

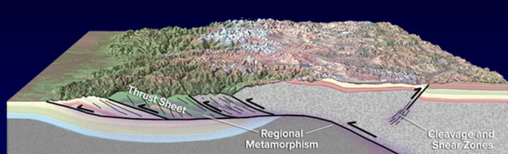
Observe how metamorphic conditions vary with depth

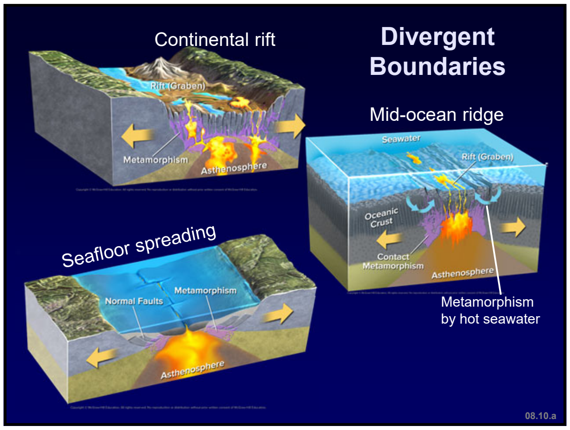


Observe settings of metamorphism associated with subduction zones

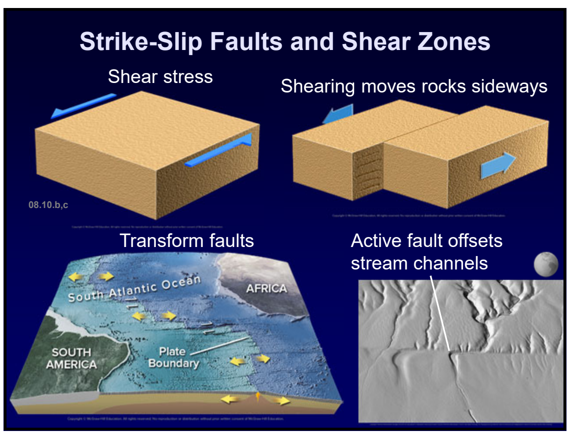


Observe settings of metamorphism along continental collisions

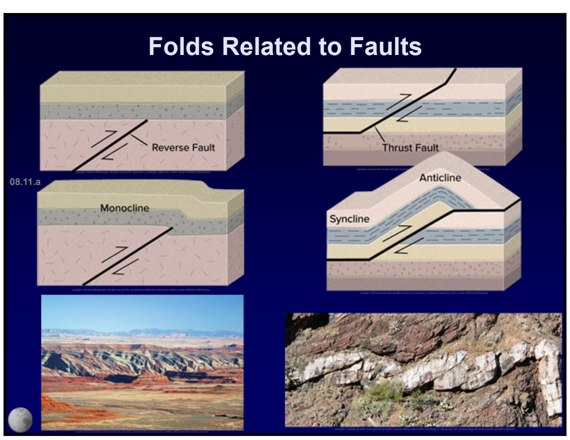




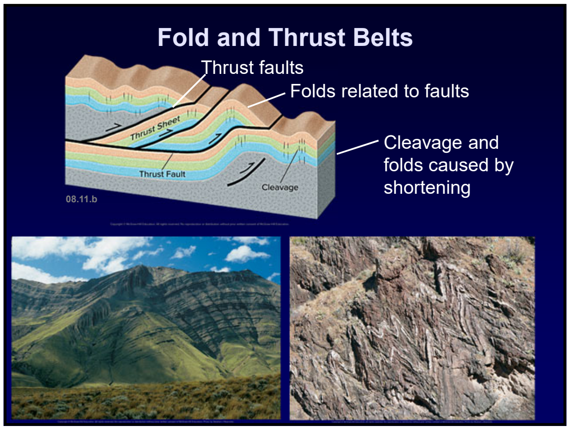
Divergent Boundaries
Continental rift
Rift (Graben)
Metamorphism
Asthenosphere
Mid-ocean ridge
Seawater
Rift (Graben)
Oceanic Crust
Contact Metamorphism
Asthenosphere
Metamorphism by hot seawater
Seafloor spreading
Normal Faults
Metamorphism
Asthenosphere
08.10.a

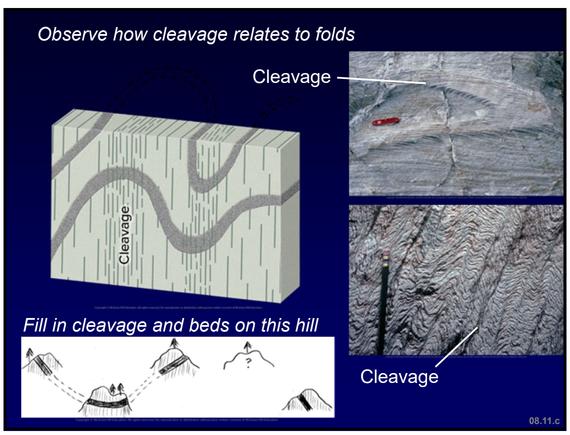


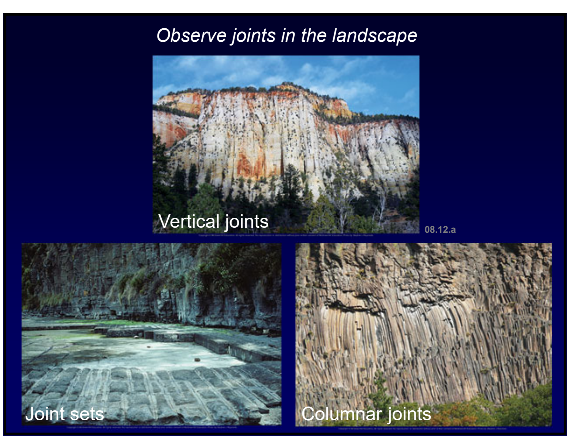
Strike-Slip Faults and Shear Zones
Shear stress
Shearing moves rocks sideways
08.10.b,c
Transform faults
South Atlantic Ocean
AFRICA
SOUTH AMERICA
Plate Boundary
Active fault offsets stream channels

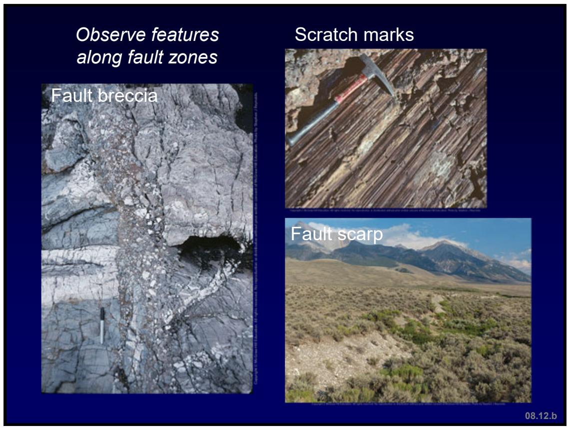


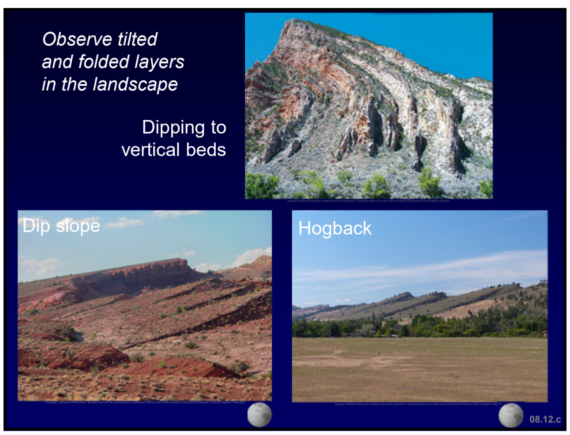
Folds Related to Faults
Reverse Fault
Thrust Fault
08.11.a
Monocline
Anticline
Syncline

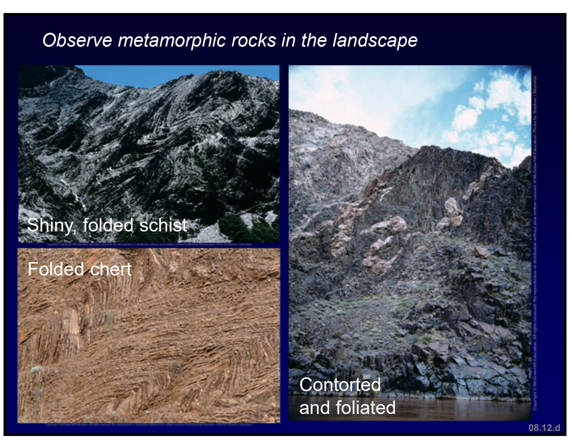

Fold and Thrust Belts
Thrust faults
Folds related to faults
Cleavage and folds caused by shortening
Thrust Sheet
Thrust Fault
Cleavage
08.11.b

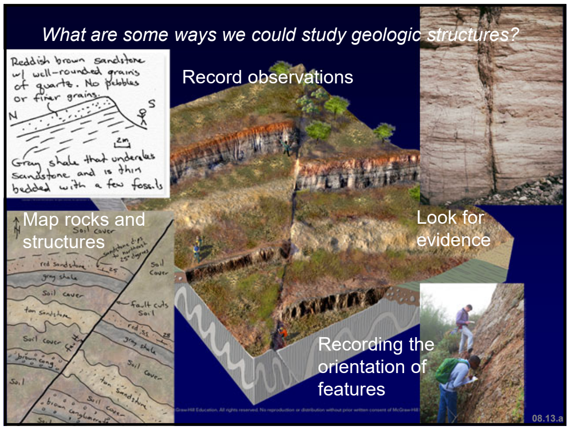

Observe how cleavage relates to folds
Cleavage
Cleavage
Fill in cleavage and beds on this hill
Cleavage
08.11.c

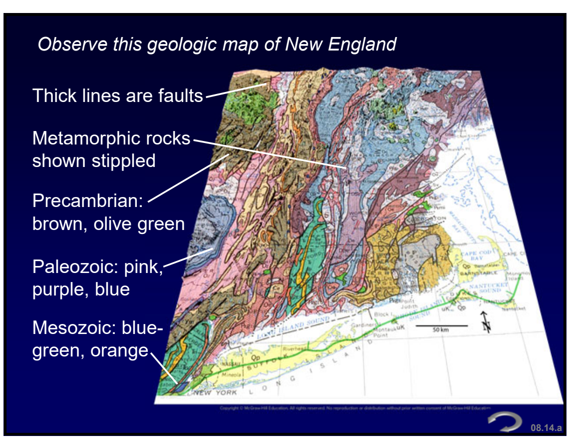

Observe joints in the landscape
Vertical joints
08.12.a
Joint sets
Columnar joints

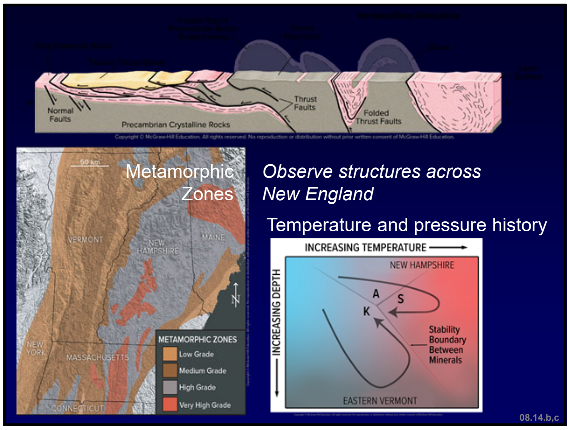

Observe features along fault zones
Scratch marks
Fault breccia
Fault scarp
08.12.b

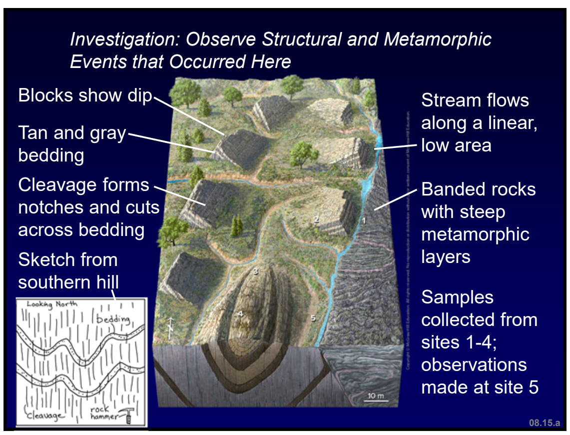

Observe tilted and folded layers in the landscape
Dipping to vertical beds
Dip slope
Hogback
08.12.c


Observe metamorphic rocks in the landscape
Shiny, folded schist
Folded chert
Contorted and foliated
08.12.d

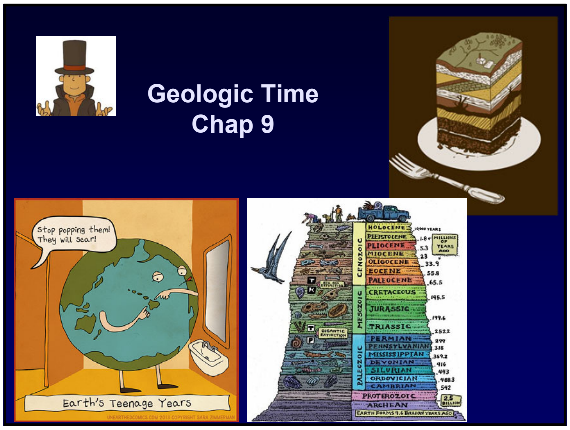

What are some ways we could study geologic structures?
Reddish brown sandstone w/ well-rounded grains of quartz. No pebbles or finer grains
N
S
Gray shale that underlies sandstone and is thin bedded with a few fossils
Record observations
Map rocks and structures
Look for evidence
Recording the orientation of features
08.13.a

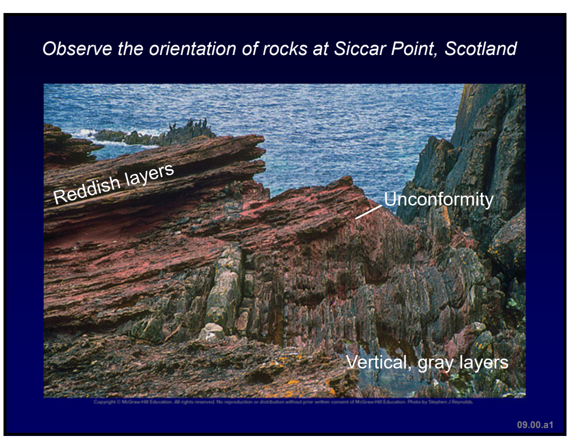

Observe this geologic map of New England
Thick lines are faults
Metamorphic rocks shown stippled
Precambrian: brown, olive green
Paleozoic: pink, purple, blue
Mesozoic: blue-green, orange
NEW YORK
50 km
N
08.14.a


Normal Faults
Thrust Faults
Folded Thrust Faults
Precambrian Crystalline Rocks
Metamorphic Zones
Observe structures across New England
Temperature and pressure history
VERMONT
NEW HAMPSHIRE
MAINE
NEW YORK
MASSACHUSETTS
CONNECTICUT
METAMORPHIC ZONES
Low Grade
Medium Grade
High Grade
Very High Grade
INCREASING TEMPERATURE
INCREASING DEPTH
NEW HAMPSHIRE
A
S
K
Stability Boundary Between Minerals
EASTERN VERMONT
08.14.b,c


Investigation: Observe Structural and Metamorphic Events that Occurred Here
Blocks show dip
Tan and gray bedding
Cleavage forms notches and cuts across bedding
Sketch from southern hill
Stream flows along a linear, low area
Banded rocks with steep metamorphic layers
Samples collected from sites 1-4; observations made at site 5
08.15.a

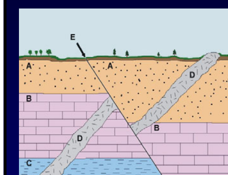

1
Swirled bands
Observe rocks from the investigation area
3
Cleavage related to folds
2
Not shiny with cleavage
4
Cleavage perpendicular to bedding

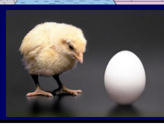

Geologic Time
Chap 9
Stop popping them! They will scar!
Earth's Teenage Years


Observe the orientation of rocks at Siccar Point, Scotland
Reddish layers
Unconformity
Vertical, gray layers
09.00.a1

Geologic Time

- Relative Time





- Absolute Time

Parent → Daughter	Half-Life (years)	Minerals Containing the Isotopes
$^{147}Sm \rightarrow {}^{143}Nd$	106.0 billion	Garnets, micas
$^{87}Rb \rightarrow {}^{87}Sr$	48.8 billion	Potassium-bearing minerals (mica, feldspar, hornblende)
$^{238}U \rightarrow {}^{206}Pb$	4.5 billion	Uranium-bearing minerals (zircon, uraninite)
$^{40}K \rightarrow {}^{40}Ar$	1.3 billion	Potassium-bearing minerals (mica, feldspar, hornblende)
$^{235}U \rightarrow {}^{207}Pb$	713.0 million	Uranium-bearing minerals (zircon, uraninite)

Sm = samarium, Nd = neodymium, Rb = rubidium, Sr = strontium, U = uranium, Pb = lead, K = potassium, Ar = argon

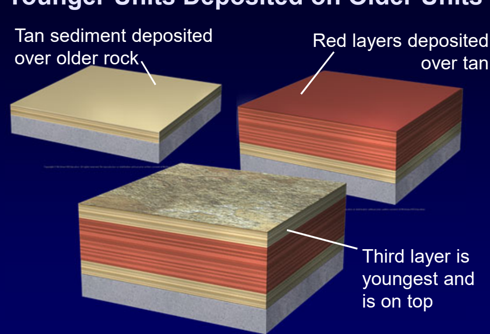
Observe the layers in these two photographs, which show the same sequence of rocks. What is different and what do you think happened?

Most sediment is deposited in horizontal layers

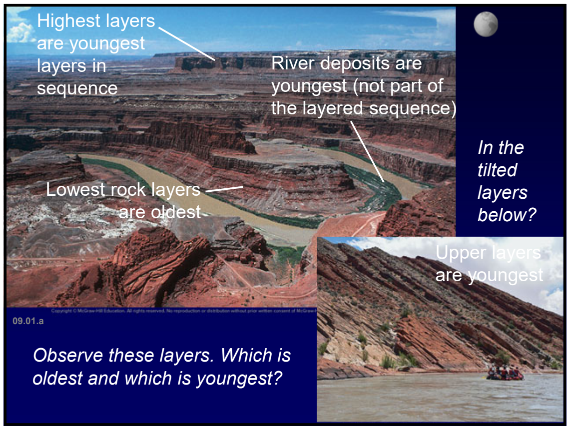
If layers are not horizontal, something has happened (deformation)

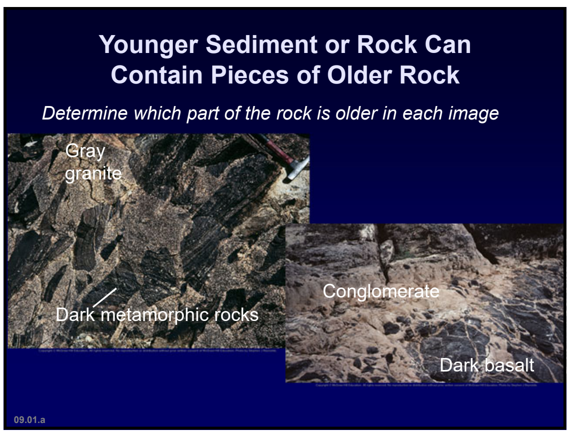
09.01.a

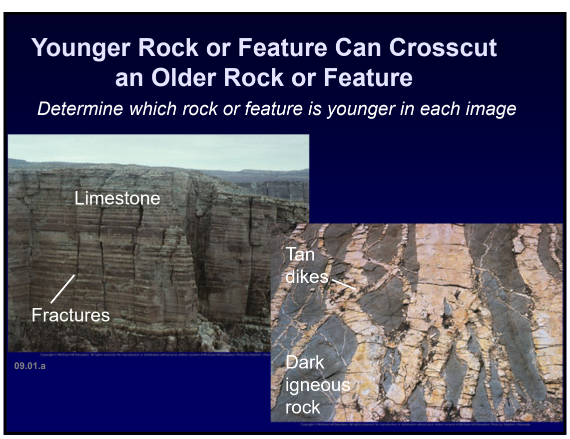
Younger Units Deposited on Older Units



09.01.a

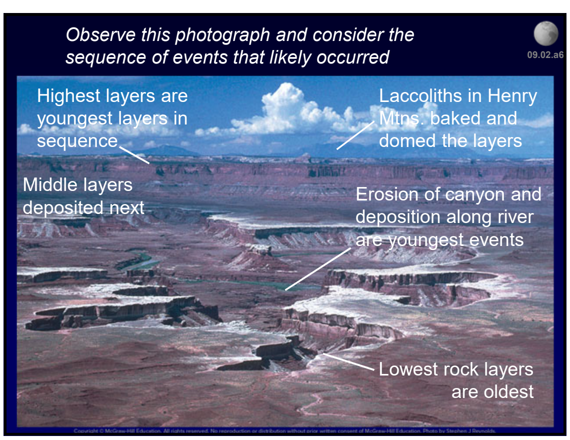

Highest layers are youngest layers in sequence
River deposits are youngest (not part of the layered sequence)
In the tilted layers below?
Lowest rock layers are oldest
Upper layers are youngest
09.01.a
Observe these layers. Which is oldest and which is youngest?

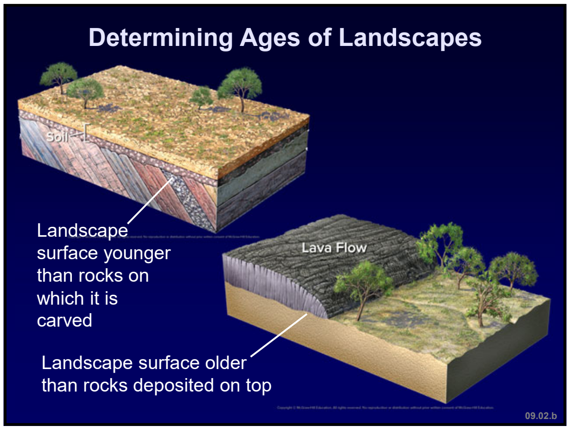

Younger Sediment or Rock Can Contain Pieces of Older Rock
Determine which part of the rock is older in each image
Gray granite
Dark metamorphic rocks
Conglomerate
Dark basalt
09.01.a

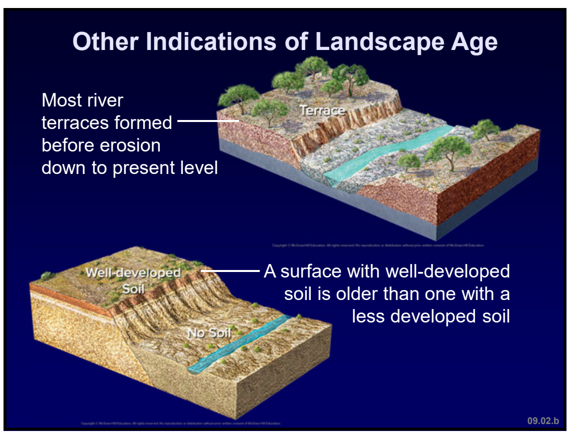

Younger Rock or Feature Can Crosscut an Older Rock or Feature
Determine which rock or feature is younger in each image
Limestone
Fractures
Tan dikes
Dark igneous rock
09.01.a

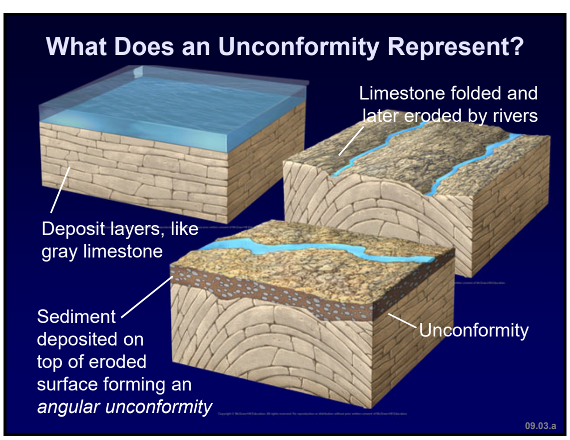

Younger Rocks and Features Can Cause Changes Along Contacts with Older Rocks
Observe the boundaries between different rock types
Older gray rock
Dark dike
Baking along contact
Lava flow
Older rock
Baking along base of lava flow (but not on top)
Sill can bake rocks below and above
09.01.a

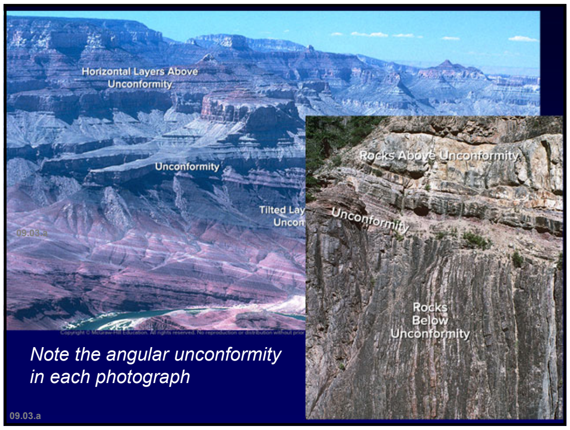

How a Typical Landscape Forms
Sediment covers preexisting rock
Environment changes, depositing more rock
Deposition stops
Area eroded by rivers, etc.
Continued erosion cuts and widens a canyon
09.02.a

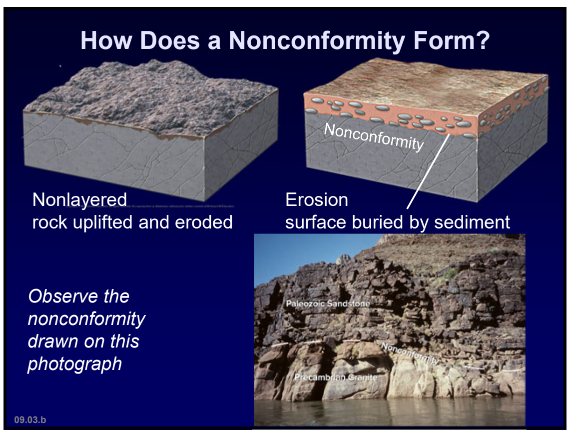

Observe this photograph and consider the sequence of events that likely occurred
09.02.a6
Highest layers are youngest layers in sequence
Laccoliths in Henry Mtns. baked and domed the layers
Middle layers deposited next
Erosion of canyon and deposition along river are youngest events
Lowest rock layers are oldest

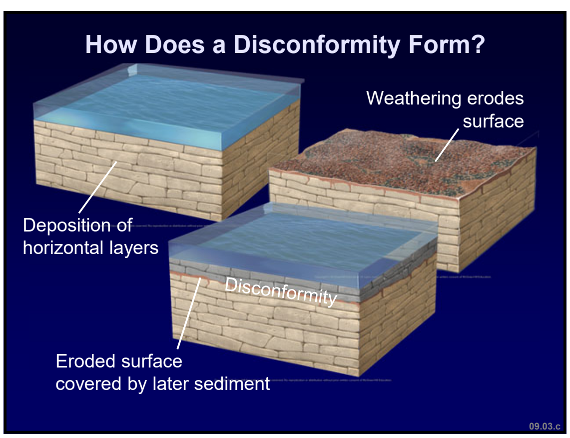

Determining Ages of Landscapes
Soil
Landscape surface younger than rocks on which it is carved
Lava Flow
Landscape surface older than rocks deposited on top
09.02.b


Other Indications of Landscape Age
Most river terraces formed before erosion down to present level
Terrace
Well-developed Soil
No Soil
A surface with well-developed soil is older than one with a less developed soil
09.02.b

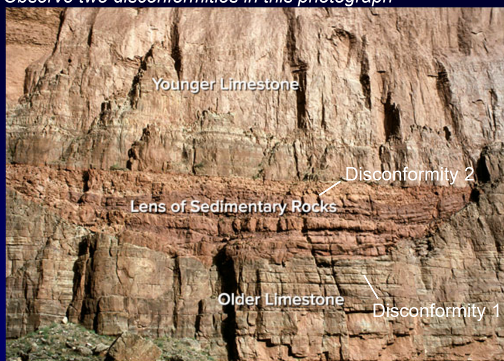

What Does an Unconformity Represent?
Limestone folded and later eroded by rivers
Deposit layers, like gray limestone
Sediment deposited on top of eroded surface forming an angular unconformity
Unconformity
09.03.a


Horizontal Layers Above Unconformity
Unconformity
Rocks Above Unconformity
Unconformity
Rocks Below Unconformity
Note the angular unconformity in each photograph
09.03.a


How Does a Nonconformity Form?
Nonlayered rock uplifted and eroded
Nonconformity
Erosion surface buried by sediment
Observe the nonconformity drawn on this photograph
Paleozoic Sandstone
Precambrian Granite
09.03.b

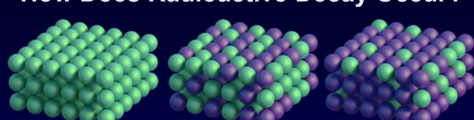

How Does a Disconformity Form?
Weathering erodes surface
Deposition of horizontal layers
Disconformity
Eroded surface covered by later sediment
09.03.c

Observe two disconformities in this photograph



09.03.c4

How Does Radioactive Decay Occur?

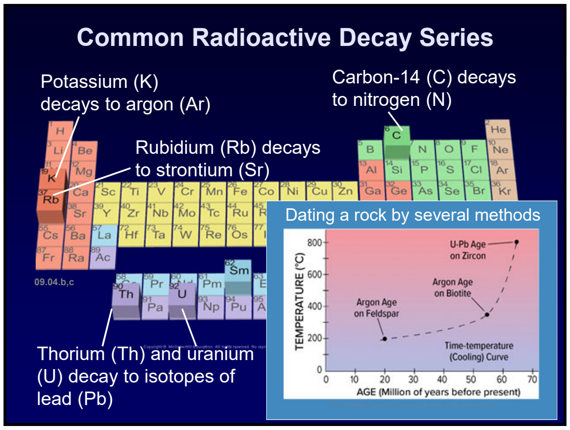


Before decay, unstable parent atoms	Half the parent atoms decayed to daughter atoms (time = half life)	After a second half life, only ¼ parent atoms remain

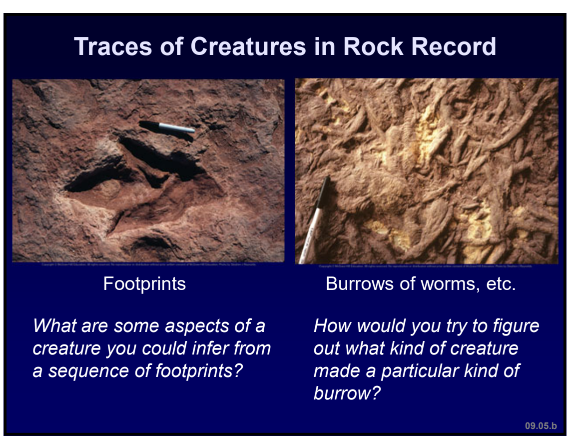
Example for 1000 atoms

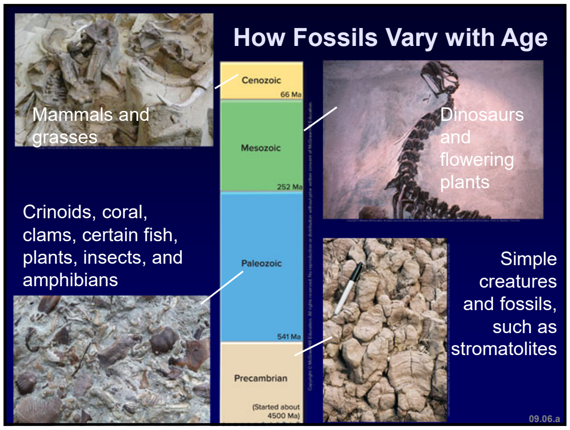
	Before Any Decay	After One Half-Life	After Two Half-Lives
Atoms of Parent	1,000	500	250
Atoms of Daughter	0	500	750

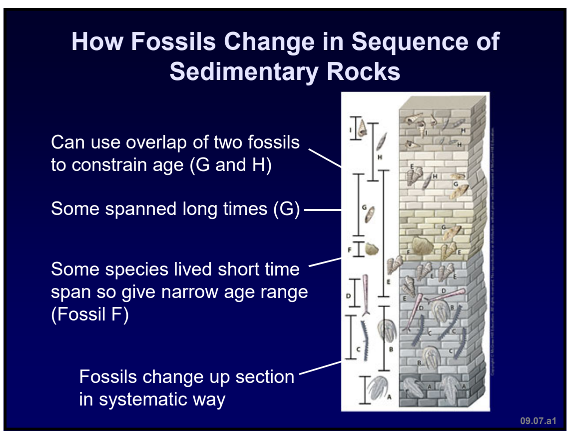
09.04.a

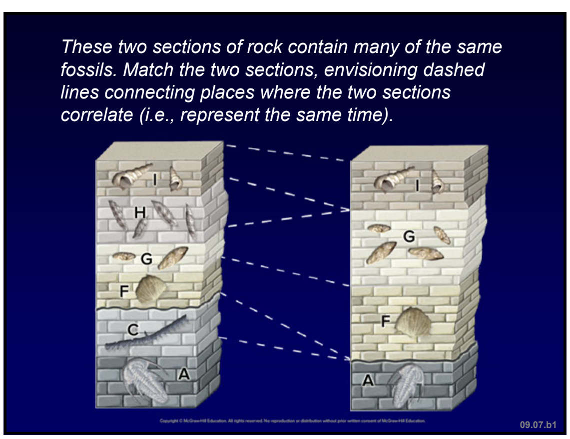

Common Radioactive Decay Series
Potassium (K) decays to argon (Ar)
Carbon-14 (C) decays to nitrogen (N)
Rubidium (Rb) decays to strontium (Sr)
Thorium (Th) and uranium (U) decay to isotopes of lead (Pb)
Dating a rock by several methods
U-Pb Age on Zircon
Argon Age on Biotite
Argon Age on Feldspar
Time-temperature (Cooling) Curve
TEMPERATURE (°C)
AGE (Million of years before present)
09.04.b,c

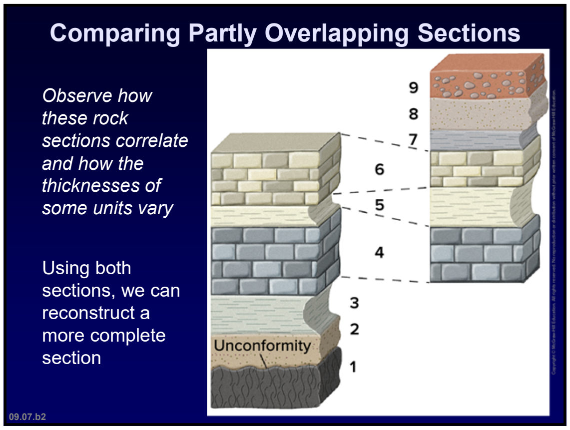

How Are Fossils Preserved?
Shells/hard parts
Bones
Replacement
Cast or mold
Thin film of material
Impressions
Amber
Constructed feature
09.05.a

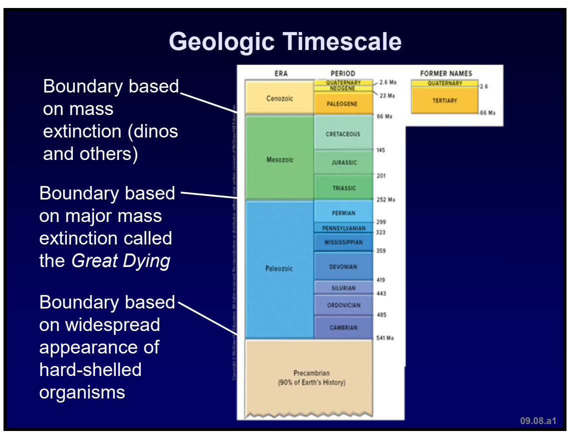

Traces of Creatures in Rock Record
Footprints
Burrows of worms, etc.
What are some aspects of a creature you could infer from a sequence of footprints?
How would you try to figure out what kind of creature made a particular kind of burrow?
09.05.b

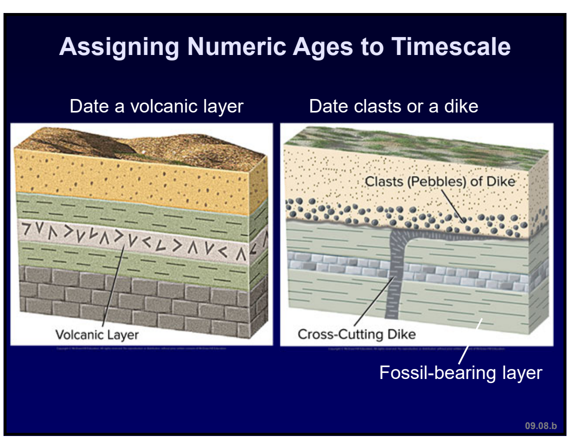

How Fossils Vary with Age
Mammals and grasses
Cenozoic
66 Ma
Mesozoic
252 Ma
Paleozoic
541 Ma
Precambrian
(Started about 4500 Ma)
Dinosaurs and flowering plants
Crinoids, coral, clams, certain fish, plants, insects, and amphibians
Simple creatures and fossils, such as stromatolites
09.06.a

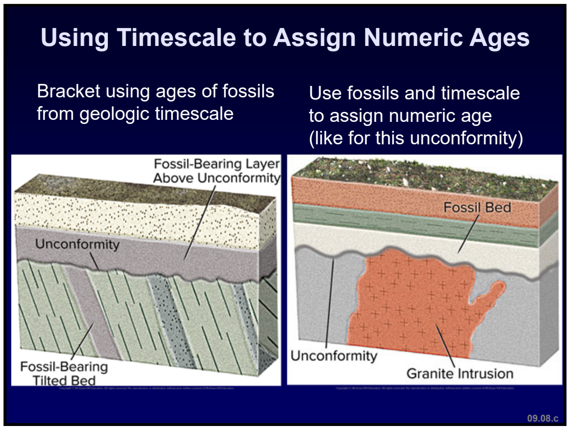

How Fossils Change in Sequence of Sedimentary Rocks
Can use overlap of two fossils to constrain age (G and H)
Some spanned long times (G)
Some species lived short time span so give narrow age range (Fossil F)
Fossils change up section in systematic way
09.07.a1


These two sections of rock contain many of the same fossils. Match the two sections, envisioning dashed lines connecting places where the two sections correlate (i.e., represent the same time).
I
H
G
F
C
A
I
G
F
A
09.07.b1

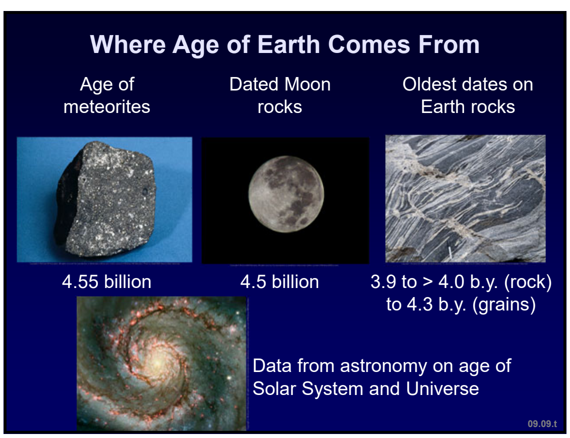

Comparing Partly Overlapping Sections
Observe how these rock sections correlate and how the thicknesses of some units vary
Using both sections, we can reconstruct a more complete section
9
8
7
6
5
4
3
2
1
Unconformity
09.07.b2

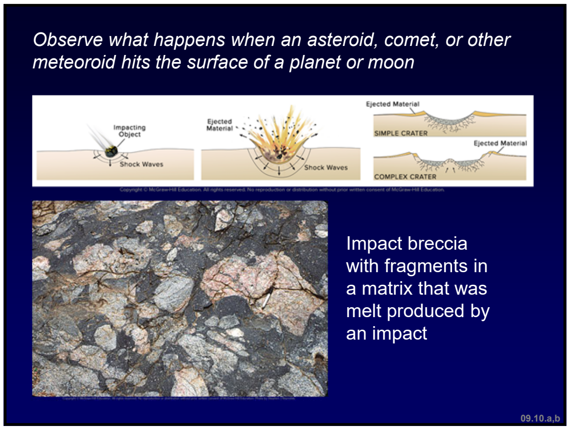

Geologic Timescale
Boundary based on mass extinction (dinos and others)
Boundary based on major mass extinction called the Great Dying
Boundary based on widespread appearance of hard-shelled organisms
ERA
PERIOD
FORMER NAMES
Cenozoic
Mesozoic
Paleozoic
QUATERNARY
NEOGENE
PALEOGENE
CRETACEOUS
JURASSIC
TRIASSIC
PERMIAN
PENNSYLVANIAN
MISSISSIPPIAN
DEVONIAN
SILURIAN
ORDOVICIAN
CAMBRIAN
Precambrian (90% of Earth's History)
TERTIARY
2.6 Ma
23 Ma
66 Ma
145
201
252 Ma
299
323
359
419
443
485
541 Ma
09.08.a1

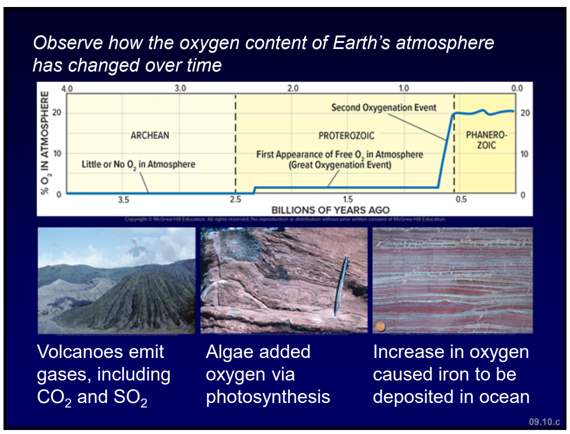

Assigning Numeric Ages to Timescale
Date a volcanic layer
Date clasts or a dike
Volcanic Layer
Clasts (Pebbles) of Dike
Cross-Cutting Dike
Fossil-bearing layer
09.08.b

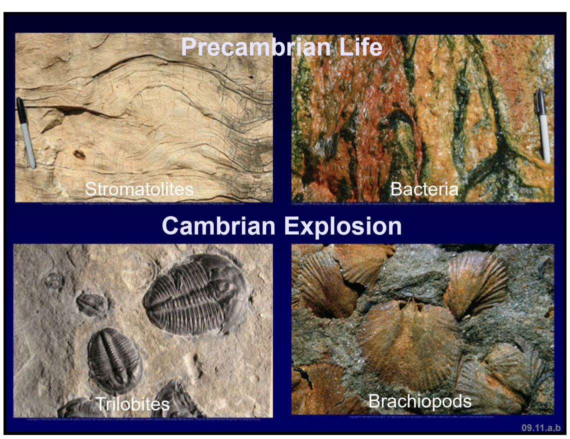

Using Timescale to Assign Numeric Ages
Bracket using ages of fossils from geologic timescale
Use fossils and timescale to assign numeric age (like for this unconformity)
Fossil-Bearing Layer Above Unconformity
Unconformity
Fossil-Bearing Tilted Bed
Fossil Bed
Unconformity
Granite Intrusion
09.08.c


Evidence that Earth's History is Not Short
Seasonal layers in tree rings
Seasonal layers in varves (lake sediment)
Seasonal layers in ice cores
Measured rates of modern plate movement are consistent with long-term rates
09.09.b


Where Age of Earth Comes From
Age of meteorites
Dated Moon rocks
Oldest dates on Earth rocks
4.55 billion
4.5 billion
3.9 to > 4.0 b.y. (rock) to 4.3 b.y. (grains)
Data from astronomy on age of Solar System and Universe
09.09.t


Observe what happens when an asteroid, comet, or other meteoroid hits the surface of a planet or moon
Impacting Object
Shock Waves
Ejected Material
Shock Waves
Ejected Material
SIMPLE CRATER
Ejected Material
COMPLEX CRATER
Impact breccia with fragments in a matrix that was melt produced by an impact
09.10.a,b


Observe how the oxygen content of Earth's atmosphere has changed over time
% O_2 IN ATMOSPHERE
4.0
3.0
2.0
1.0
0.0
20
10
0
ARCHEAN
Little or No O_2 in Atmosphere
PROTEROZOIC
Second Oxygenation Event
First Appearance of Free O_2 in Atmosphere (Great Oxygenation Event)
PHANERO-ZOIC
3.5
2.5
1.5
0.5
BILLIONS OF YEARS AGO
Volcanoes emit gases, including CO_2 and SO_2
Algae added oxygen via photosynthesis
Increase in oxygen caused iron to be deposited in ocean
09.10.c


Precambrian Life
Stromatolites
Bacteria
Cambrian Explosion
Trilobites
Brachiopods
09.11.a,b

Life in the Paleozoic

Early Paleozoic

Middle Paleozoic

Late Paleozoic

09.11.c

Life in the Mesozoic

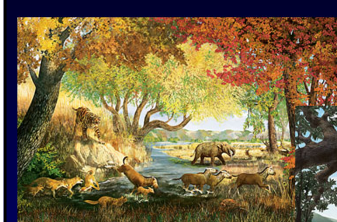
Early Mesozoic: Triassic

Middle Mesozoic: Jurassic

Late Mesozoic: Cretaceous

09.12.a

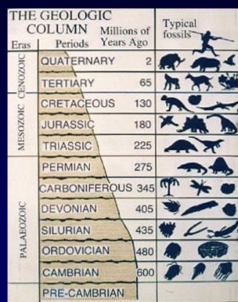
Life in the Cenozoic

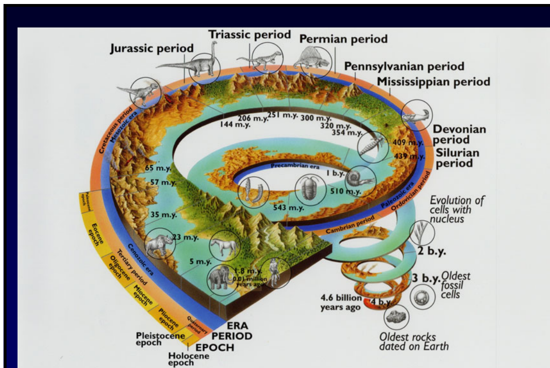


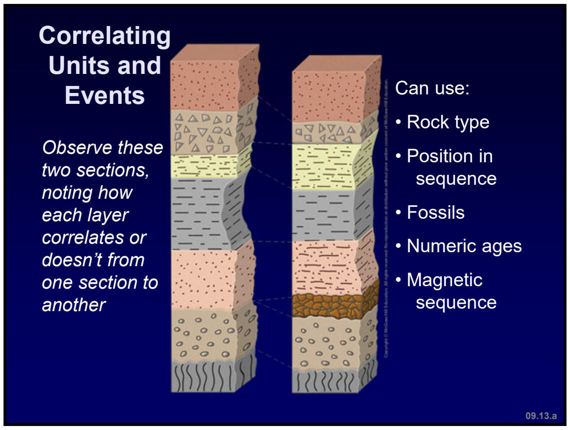
Early Cenozoic

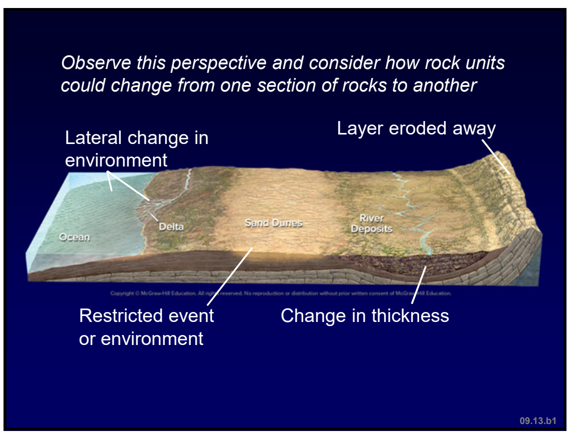
Late Cenozoic

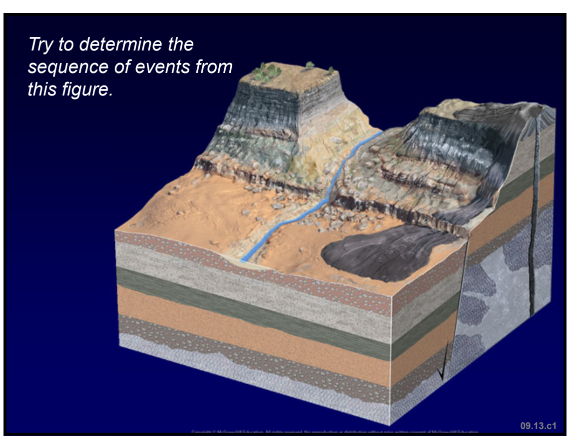
09.12.c

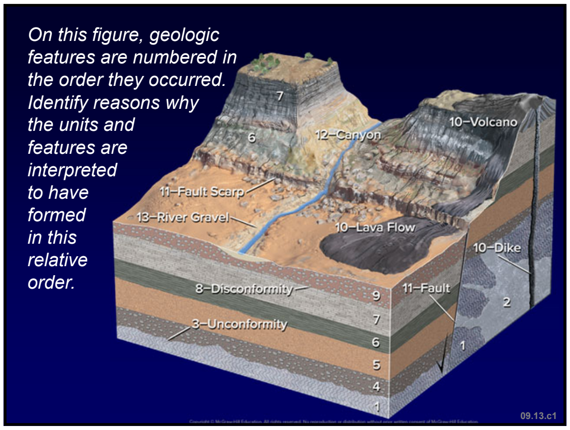

THE GEOLOGIC COLUMN
Eras
Periods
Millions of Years Ago
Typical fossils
CENOZOIC
MESOZOIC
PALAEOZOIC
QUATERNARY 2
TERTIARY 65
CRETACEOUS 130
JURASSIC 180
TRIASSIC 225
PERMIAN 275
CARBONIFEROUS 345
DEVONIAN 405
SILURIAN 435
ORDOVICIAN 480
CAMBRIAN 600
PRE-CAMBRIAN

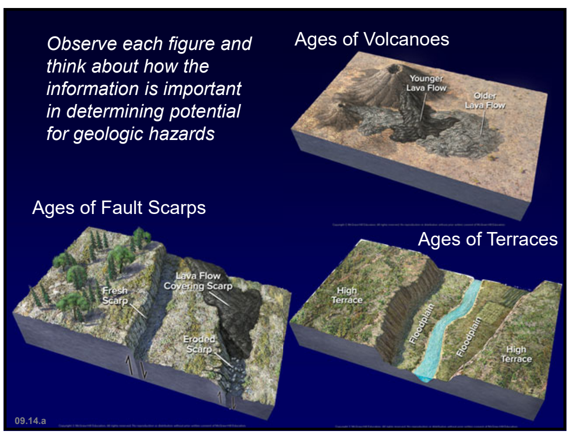

Jurassic period
Triassic period
Permian period
Pennsylvanian period
Mississippian period
Devonian period
Silurian period
Cretaceous period
Mesozoic era
206 m.y.
251 m.y.
300 m.y.
144 m.y.
320 m.y.
354 m.y.
409 m.y.
439 m.y.
Precambrian era
1 b.y.
65 m.y.
57 m.y.
510 m.y.
543 m.y.
Paleozoic era
Ordovician period
Evolution of cells with nucleus
Cambrian period
35 m.y.
23 m.y.
5 m.y.
1.8 m.y.
0.01 million years ago
2 b.y.
3 b.y.
Oldest fossil cells
4.6 billion years ago
4 b.y.
Oldest rocks dated on Earth
Paleocene epoch
Eocene epoch
Oligocene epoch
Miocene epoch
Pliocene epoch
Cenozoic era
Tertiary period
Quaternary period
ERA
PERIOD
EPOCH
Pleistocene epoch
Holocene epoch

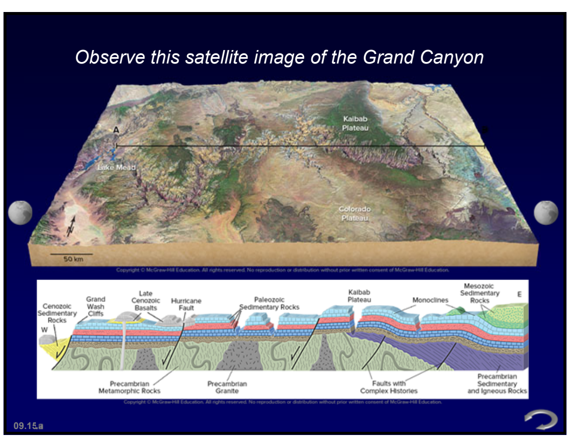

Correlating Units and Events
Observe these two sections, noting how each layer correlates or doesn't from one section to another
Can use:
• Rock type
• Position in sequence
• Fossils
• Numeric ages
• Magnetic sequence
09.13.a

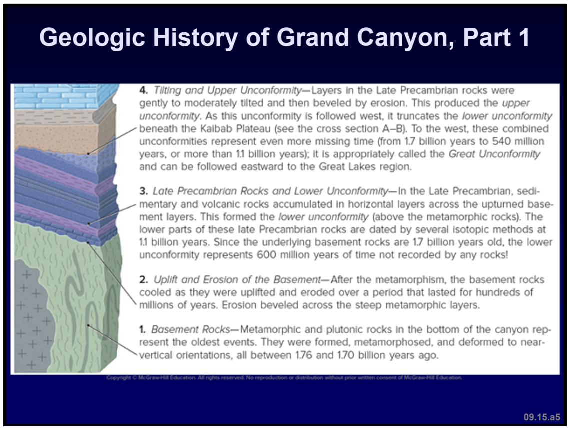

Observe this perspective and consider how rock units could change from one section of rocks to another
Lateral change in environment
Layer eroded away
Ocean
Delta
Sand Dunes
River Deposits
Restricted event or environment
Change in thickness
09.13.b1


Try to determine the sequence of events from this figure.
09.13.c1


On this figure, geologic features are numbered in the order they occurred. Identify reasons why the units and features are interpreted to have formed in this relative order.
7
6
12–Canyon
10–Volcano
11–Fault Scarp
13–River Gravel
10–Lava Flow
10–Dike
8–Disconformity
9
11–Fault
2
3–Unconformity
7
6
5
4
1
1
09.13.c1


Observe each figure and think about how the information is important in determining potential for geologic hazards
Ages of Volcanoes
Younger Lava Flow
Older Lava Flow
Ages of Fault Scarps
Fresh Scarp
Lava Flow Covering Scarp
Eroded Scarp
Ages of Terraces
High Terrace
Floodplain
Floodplain
High Terrace
09.14.a


Observe this satellite image of the Grand Canyon
Kaibab Plateau
A
Lake Mead
Colorado Plateau
50 km
Cenozoic Sedimentary Rocks
Grand Wash Cliffs
Late Cenozoic Basalts
Hurricane Fault
Paleozoic Sedimentary Rocks
Kaibab Plateau
Monoclines
Mesozoic Sedimentary Rocks
W
E
Precambrian Metamorphic Rocks
Precambrian Granite
Faults with Complex Histories
Precambrian Sedimentary and Igneous Rocks
09.15.a


Geologic History of Grand Canyon, Part 1
4. Tilting and Upper Unconformity—Layers in the Late Precambrian rocks were gently to moderately tilted and then beveled by erosion. This produced the upper unconformity. As this unconformity is followed west, it truncates the lower unconformity beneath the Kaibab Plateau (see the cross section A–B). To the west, these combined unconformities represent even more missing time (from 1.7 billion years to 540 million years, or more than 1.1 billion years); it is appropriately called the Great Unconformity and can be followed eastward to the Great Lakes region.
3. Late Precambrian Rocks and Lower Unconformity—In the Late Precambrian, sedimentary and volcanic rocks accumulated in horizontal layers across the upturned basement layers. This formed the lower unconformity (above the metamorphic rocks). The lower parts of these late Precambrian rocks are dated by several isotopic methods at 1.1 billion years. Since the underlying basement rocks are 1.7 billion years old, the lower unconformity represents 600 million years of time not recorded by any rocks!
2. Uplift and Erosion of the Basement—After the metamorphism, the basement rocks cooled as they were uplifted and eroded over a period that lasted for hundreds of millions of years. Erosion beveled across the steep metamorphic layers.
1. Basement Rocks—Metamorphic and plutonic rocks in the bottom of the canyon represent the oldest events. They were formed, metamorphosed, and deformed to near-vertical orientations, all between 1.76 and 1.70 billion years ago.
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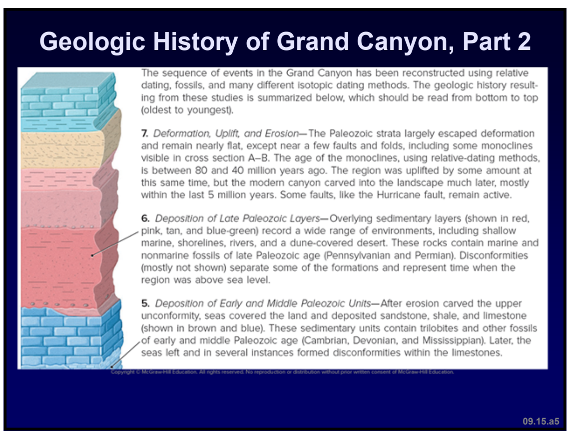
09.15.a5


Geologic History of Grand Canyon, Part 2
The sequence of events in the Grand Canyon has been reconstructed using relative dating, fossils, and many different isotopic dating methods. The geologic history resulting from these studies is summarized below, which should be read from bottom to top (oldest to youngest).
7. Deformation, Uplift, and Erosion—The Paleozoic strata largely escaped deformation and remain nearly flat, except near a few faults and folds, including some monoclines visible in cross section A–B. The age of the monoclines, using relative-dating methods, is between 80 and 40 million years ago. The region was uplifted by some amount at this same time, but the modern canyon carved into the landscape much later, mostly within the last 5 million years. Some faults, like the Hurricane fault, remain active.
6. Deposition of Late Paleozoic Layers—Overlying sedimentary layers (shown in red, pink, tan, and blue-green) record a wide range of environments, including shallow marine, shorelines, rivers, and a dune-covered desert. These rocks contain marine and nonmarine fossils of late Paleozoic age (Pennsylvanian and Permian). Disconformities (mostly not shown) separate some of the formations and represent time when the region was above sea level.
5. Deposition of Early and Middle Paleozoic Units—After erosion carved the upper unconformity, seas covered the land and deposited sandstone, shale, and limestone (shown in brown and blue). These sedimentary units contain trilobites and other fossils of early and middle Paleozoic age (Cambrian, Devonian, and Mississippian). Later, the seas left and in several instances formed disconformities within the limestones.
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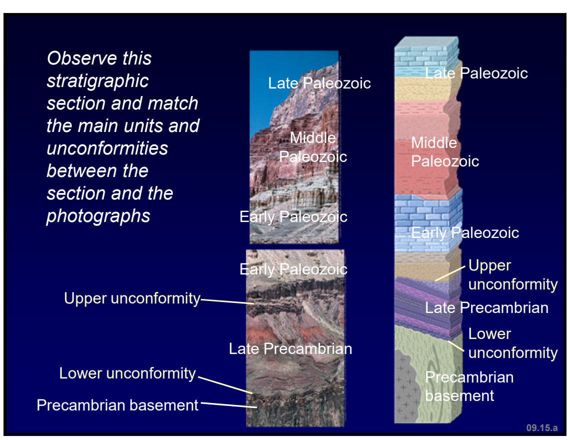
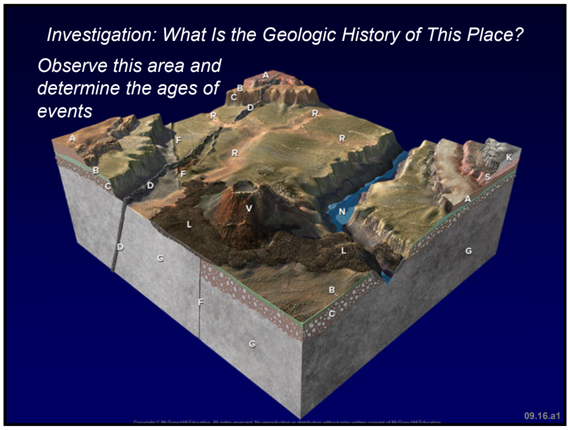
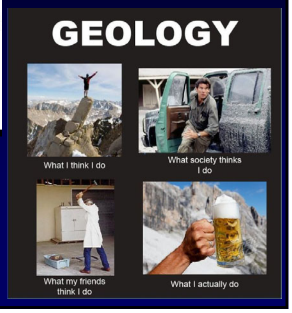
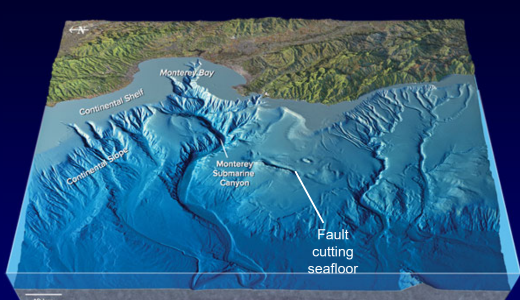

Observe this stratigraphic section and match the main units and unconformities between the section and the photographs
Late Paleozoic
Middle Paleozoic
Early Paleozoic
Early Paleozoic
Upper unconformity
Late Precambrian
Lower unconformity
Precambrian basement
Late Paleozoic
Middle Paleozoic
Early Paleozoic
Upper unconformity
Late Precambrian
Lower unconformity
Precambrian basement
09.15.a


Investigation: What Is the Geologic History of This Place?
Observe this area and determine the ages of events
09.16.a1

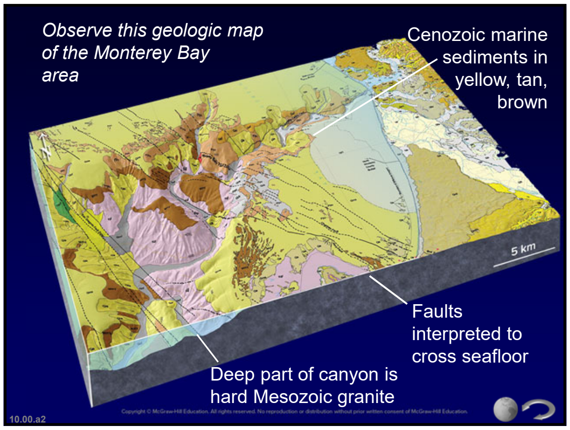
The Seafloor, Continental Margins and Mountains
Chaps 10 and 11

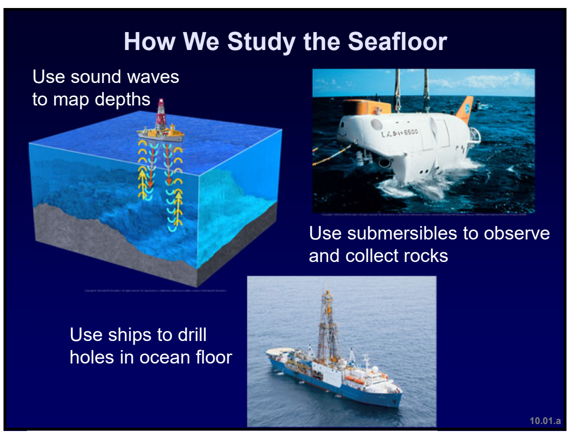


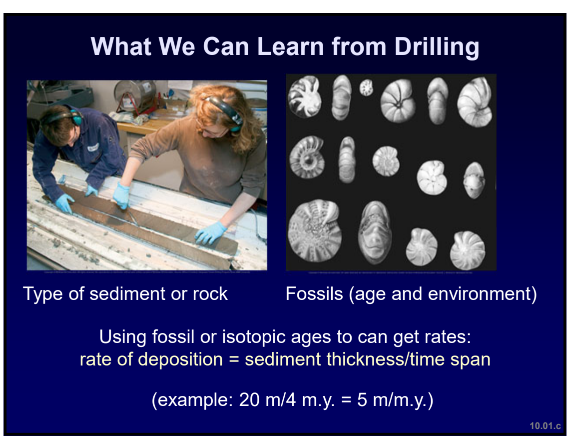
Observe the seafloor around Monterey Bay, California

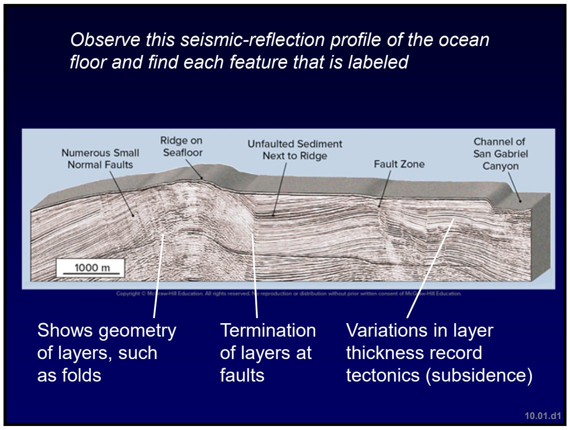


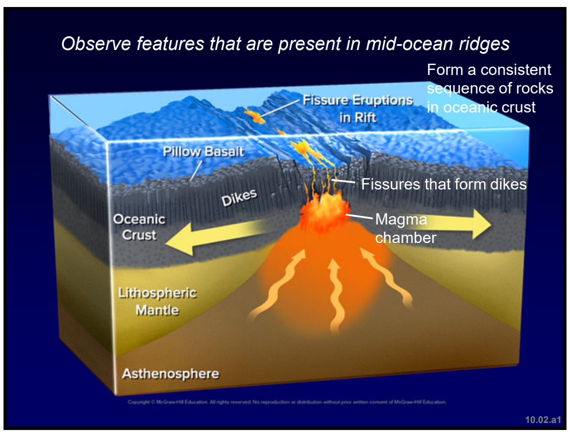
10.00.a1

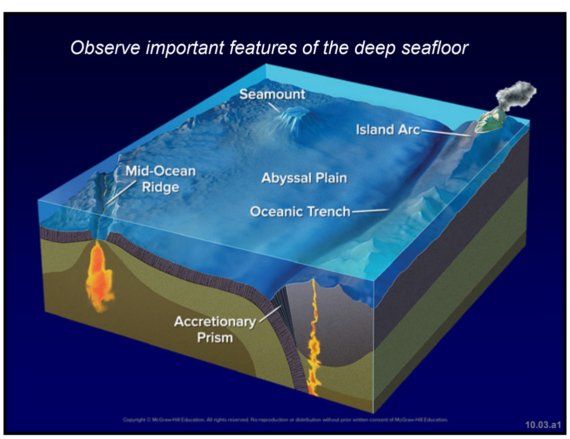

Observe this geologic map of the Monterey Bay area
Cenozoic marine sediments in yellow, tan, brown
5 km
Faults interpreted to cross seafloor
Deep part of canyon is hard Mesozoic granite
10.00.a2

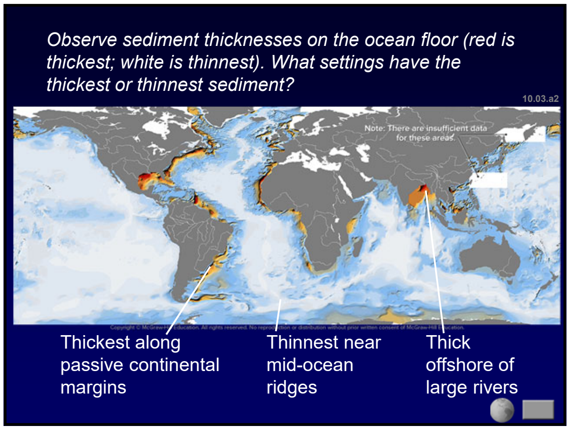

How We Study the Seafloor
Use sound waves to map depths
Use submersibles to observe and collect rocks
Use ships to drill holes in ocean floor
10.01.a

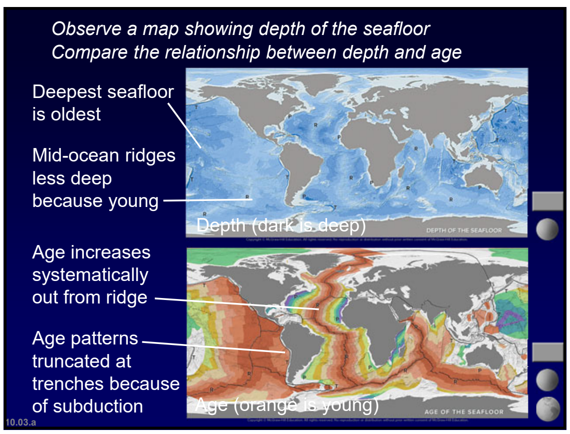

What We Can Learn from Drilling
Type of sediment or rock
Fossils (age and environment)
Using fossil or isotopic ages to can get rates:
rate of deposition = sediment thickness/time span
(example: 20 m/4 m.y. = 5 m/m.y.)
10.01.c

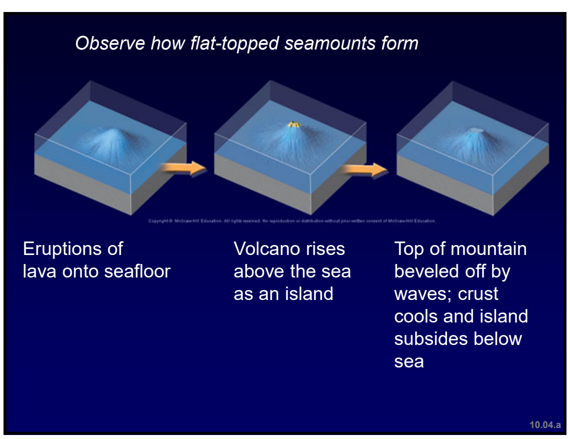

Observe this seismic-reflection profile of the ocean floor and find each feature that is labeled
Numerous Small Normal Faults
Ridge on Seafloor
Unfaulted Sediment Next to Ridge
Fault Zone
Channel of San Gabriel Canyon
1000 m
Shows geometry of layers, such as folds
Termination of layers at faults
Variations in layer thickness record tectonics (subsidence)
10.01.d1

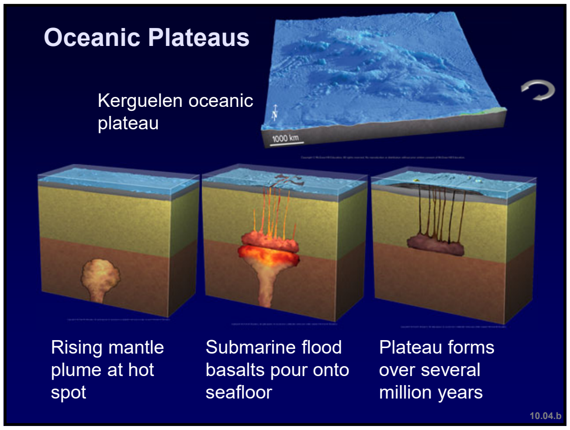

Observe features that are present in mid-ocean ridges
Form a consistent sequence of rocks in oceanic crust
Fissure Eruptions in Rift
Pillow Basalt
Fissures that form dikes
Dikes
Oceanic Crust
Magma chamber
Lithospheric Mantle
Asthenosphere
10.02.a1

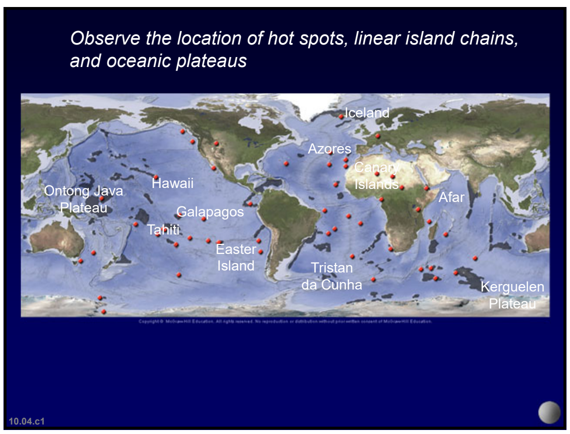

Observe important features of the deep seafloor
Seamount
Island Arc
Mid-Ocean Ridge
Abyssal Plain
Oceanic Trench
Accretionary Prism
10.03.a1

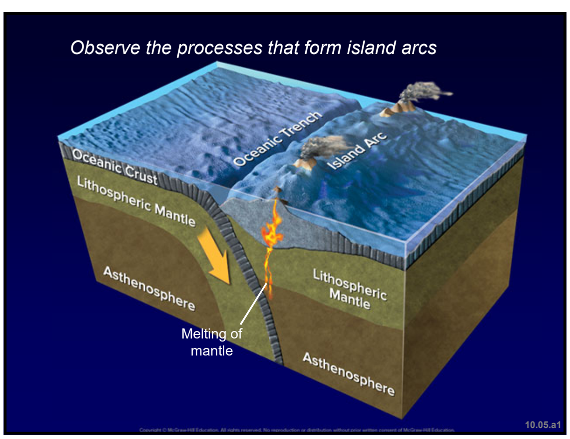

Observe sediment thicknesses on the ocean floor (red is thickest; white is thinnest). What settings have the thickest or thinnest sediment?
10.03.a2
Note: There are insufficient data for these areas.
Thickest along passive continental margins
Thinnest near mid-ocean ridges
Thick offshore of large rivers

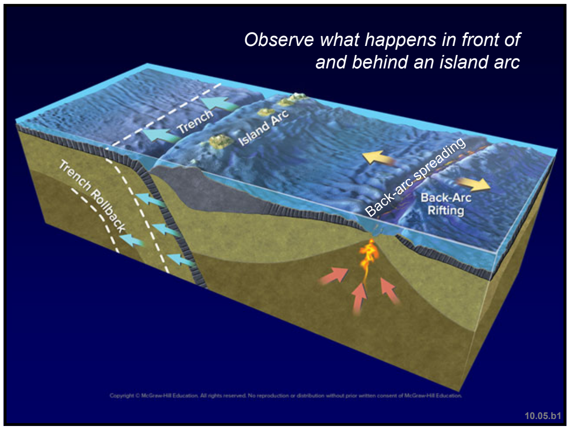

Observe a map showing depth of the seafloor
Compare the relationship between depth and age
Deepest seafloor is oldest
Mid-ocean ridges less deep because young
Depth (dark is deep)
Age increases systematically out from ridge
Age patterns truncated at trenches because of subduction
Age (orange is young)
10.03.a


Observe how flat-topped seamounts form
Eruptions of lava onto seafloor
Volcano rises above the sea as an island
Top of mountain beveled off by waves; crust cools and island subsides below sea
10.04.a


Oceanic Plateaus
Kerguelen oceanic plateau
1000 km
Rising mantle plume at hot spot
Submarine flood basalts pour onto seafloor
Plateau forms over several million years
10.04.b


Observe the location of hot spots, linear island chains, and oceanic plateaus
Iceland
Azores
Canary Islands
Hawaii
Ontong Java Plateau
Galapagos
Tahiti
Afar
Easter Island
Tristan da Cunha
Kerguelen Plateau
10.04.c1


Observe the processes that form island arcs
Oceanic Crust
Lithospheric Mantle
Oceanic Trench
Island Arc
Asthenosphere
Lithospheric Mantle
Melting of mantle
Asthenosphere
10.05.a1


Observe what happens in front of
and behind an island arc
Trench
Island Arc
Trench Rollback
Back-arc spreading
Back-Arc
Rifting
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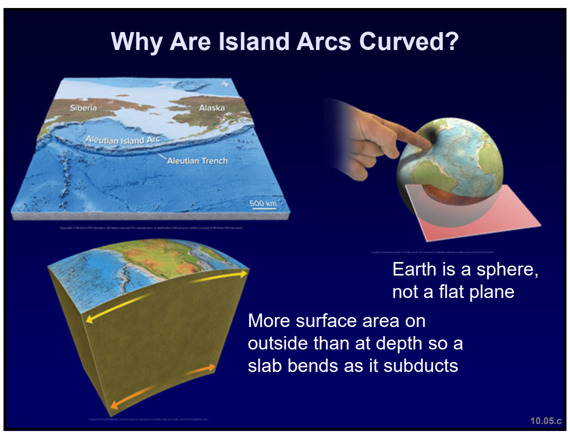
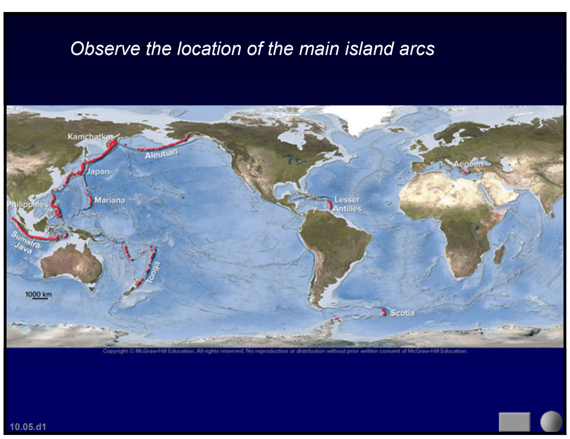
10.05.b1


Why Are Island Arcs Curved?
Siberia
Alaska
Aleutian Island Arc
Aleutian Trench
500 km
Earth is a sphere,
not a flat plane
More surface area on
outside than at depth so a
slab bends as it subducts
10.05.c


Observe the location of the main island arcs
Kamchatka
Aleutian
Japan
Mariana
Philippines
Sumatra
Java
Tonga
1000 km
Lesser
Antilles
Aegean
Scotia
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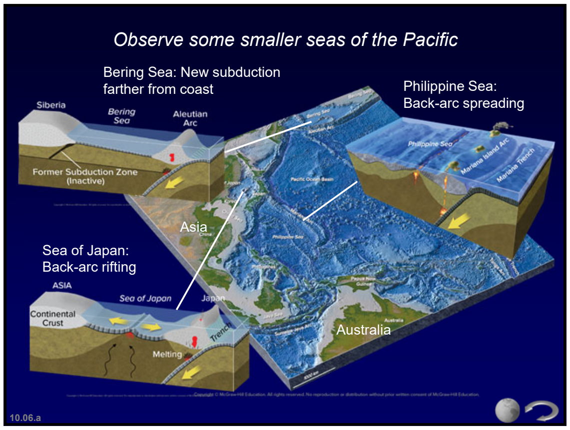
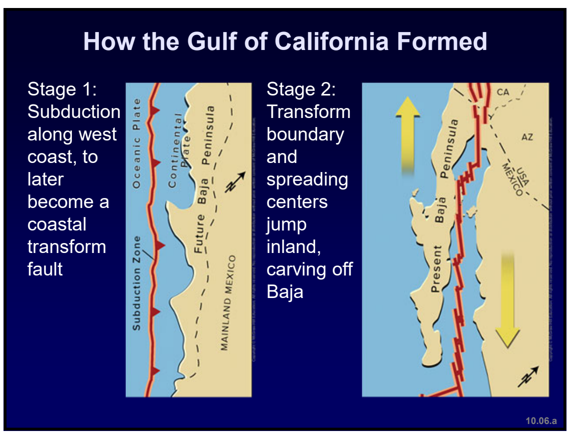
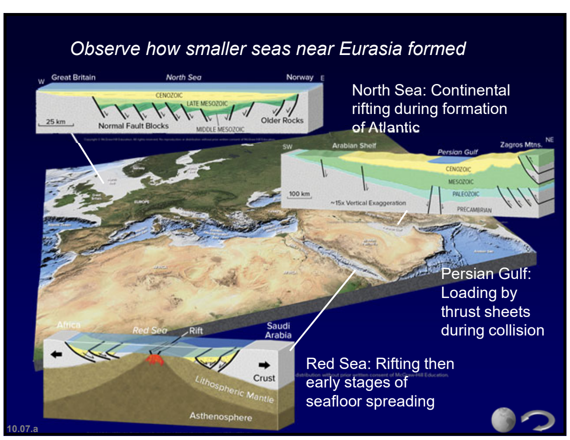
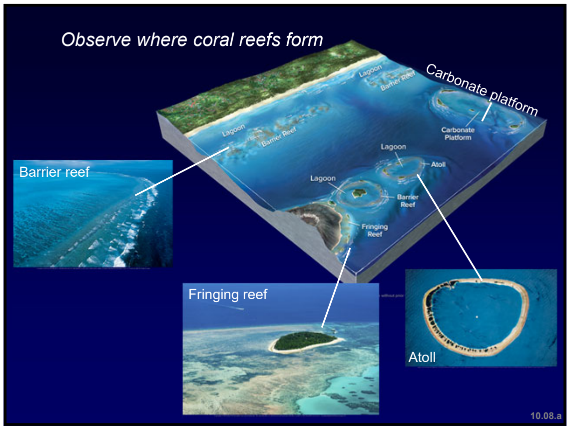
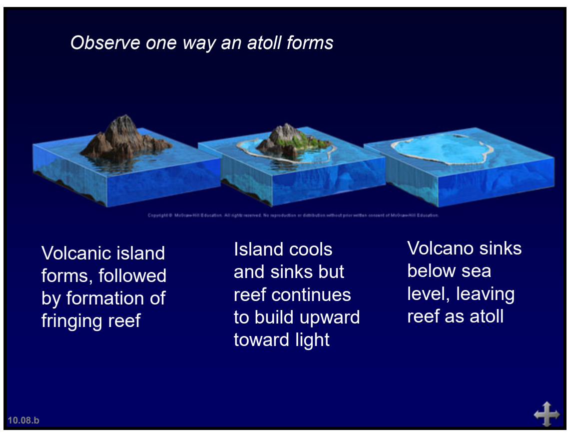
10.05.d1

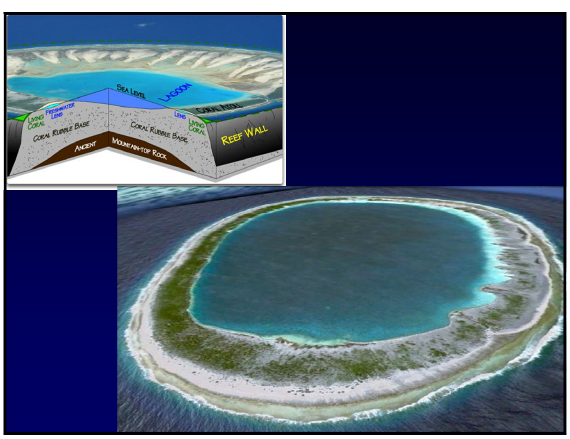

Observe some smaller seas of the Pacific
Bering Sea: New subduction farther from coast
Philippine Sea: Back-arc spreading
Siberia
Bering Sea
Aleutian Arc
Former Subduction Zone (Inactive)
Asia
Sea of Japan: Back-arc rifting
ASIA
Sea of Japan
Japan
Continental Crust
Trench
Melting
Australia
10.06.a

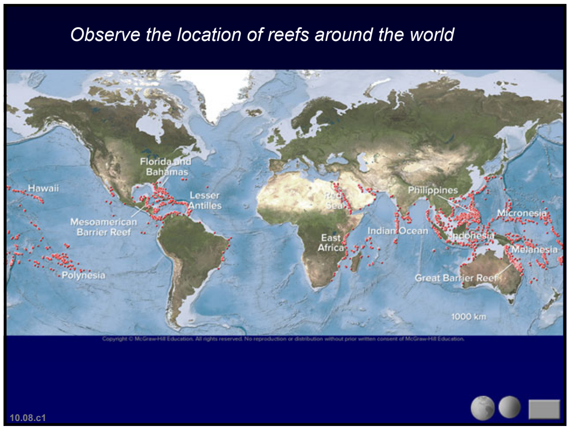

How the Gulf of California Formed
Stage 1: Subduction along west coast, to later become a coastal transform fault
Oceanic Plate
Continental Plate
Future Baja Peninsula
Subduction Zone
MAINLAND MEXICO
Stage 2: Transform boundary and spreading centers jump inland, carving off Baja
CA
AZ
USA
MEXICO
Present Baja Peninsula
10.06.a

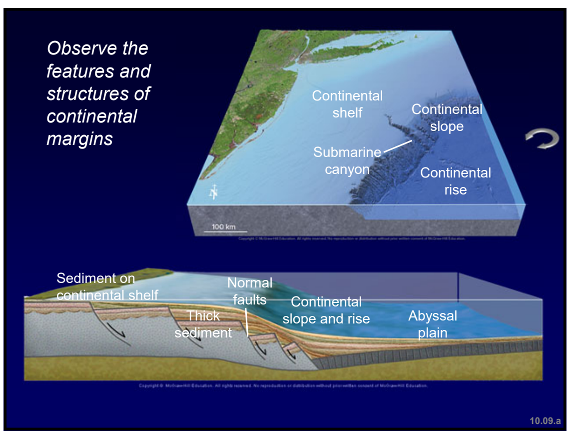

Observe how smaller seas near Eurasia formed
Great Britain
North Sea
Norway
Normal Fault Blocks
Older Rocks
North Sea: Continental rifting during formation of Atlantic
Arabian Shelf
Persian Gulf
Zagros Mtns.
Persian Gulf: Loading by thrust sheets during collision
Africa
Red Sea
Rift
Saudi Arabia
Crust
Lithospheric Mantle
Asthenosphere
Red Sea: Rifting then early stages of seafloor spreading
10.07.a

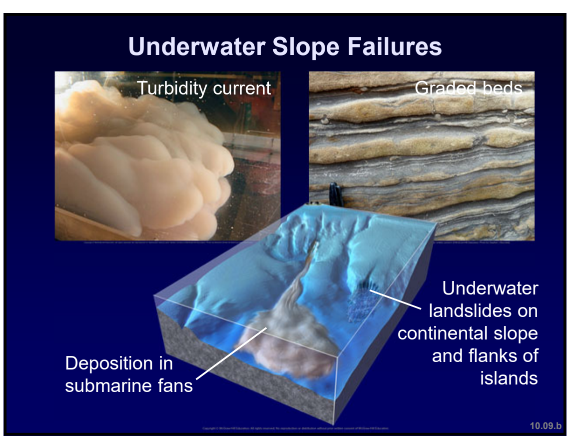

Observe where coral reefs form
Carbonate platform
Lagoon
Barrier Reef
Carbonate Platform
Atoll
Fringing Reef
Barrier reef
Fringing reef
Atoll
10.08.a

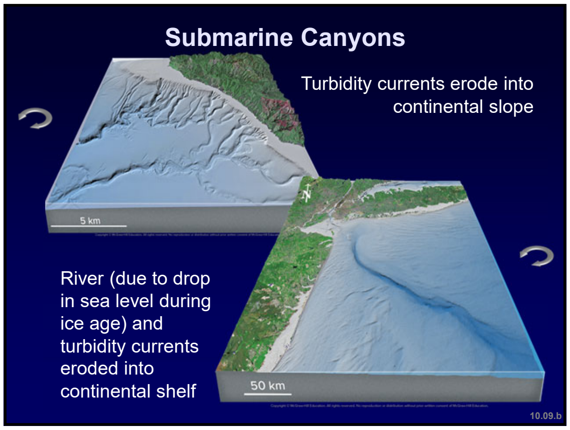

Observe one way an atoll forms
Volcanic island forms, followed by formation of fringing reef
Island cools and sinks but reef continues to build upward toward light
Volcano sinks below sea level, leaving reef as atoll
10.08.b

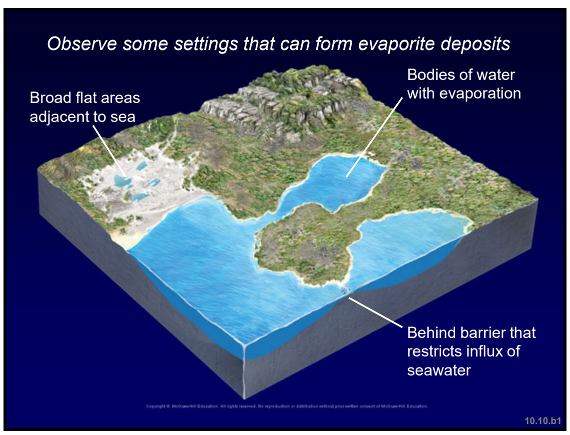

Sea Level
Lagoon
Coral Atoll
Reef Wall
Coral Rubble Base
Mountain-top Rock

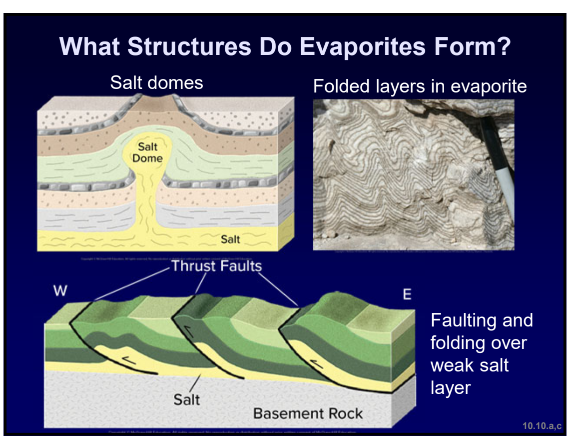

Observe the location of reefs around the world
Florida and Bahamas
Hawaii
Lesser Antilles
Mesoamerican Barrier Reef
Polynesia
Red Sea
East Africa
Indian Ocean
Philippines
Micronesia
Indonesia
Melanesia
Great Barrier Reef
1000 km
10.08.c1


Observe the features and structures of continental margins
Continental shelf
Continental slope
Submarine canyon
Continental rise
100 km
Sediment on continental shelf
Normal faults
Thick sediment
Continental slope and rise
Abyssal plain
10.09.a

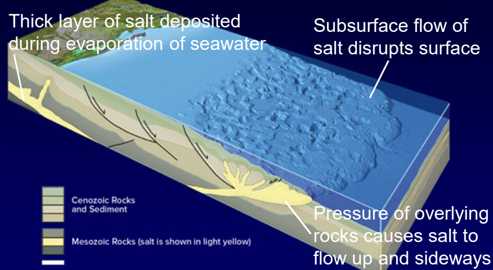

Underwater Slope Failures
Turbidity current
Graded beds
Underwater landslides on continental slope and flanks of islands
Deposition in submarine fans
10.09.b


Submarine Canyons
Turbidity currents erode into continental slope
5 km
River (due to drop in sea level during ice age) and turbidity currents eroded into continental shelf
50 km
10.09.b


Observe some settings that can form evaporite deposits
Broad flat areas adjacent to sea
Bodies of water with evaporation
Behind barrier that restricts influx of seawater
10.10.b1


What Structures Do Evaporites Form?
Salt domes
Salt Dome
Salt
Folded layers in evaporite
Thrust Faults
W
E
Salt
Basement Rock
Faulting and folding over weak salt layer
10.10.a,c

Observe the setting of salt structures along the Gulf Coast of the United States. Salt is shown in black.



10.10.d1

Mountains, Basins, and Continents

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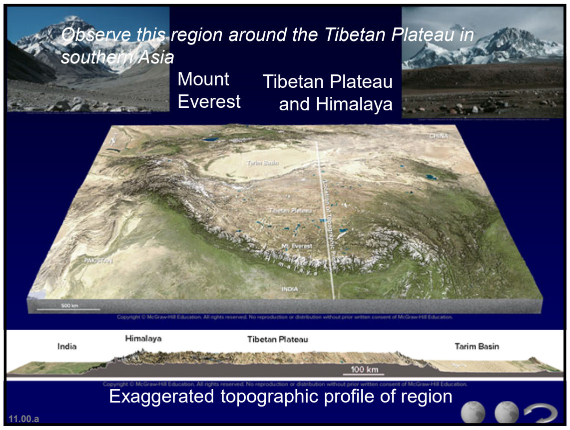
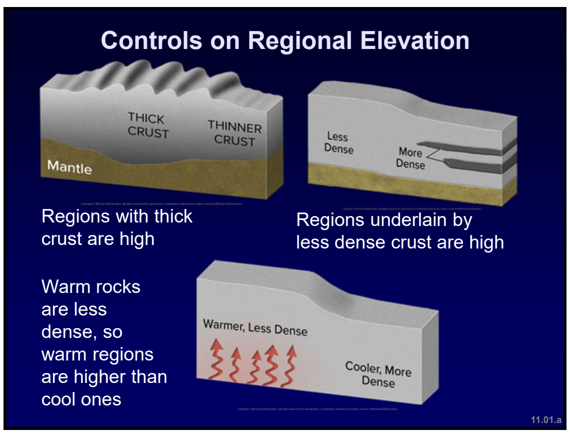
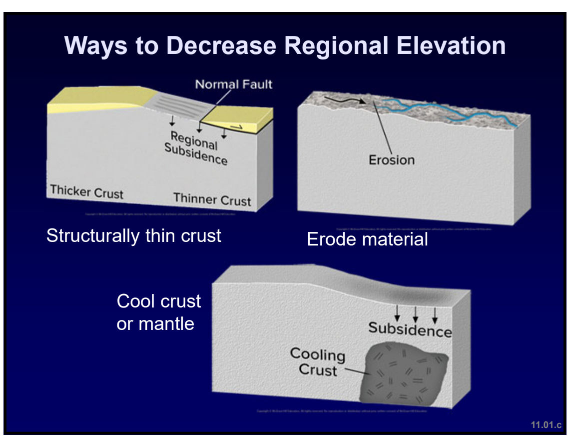
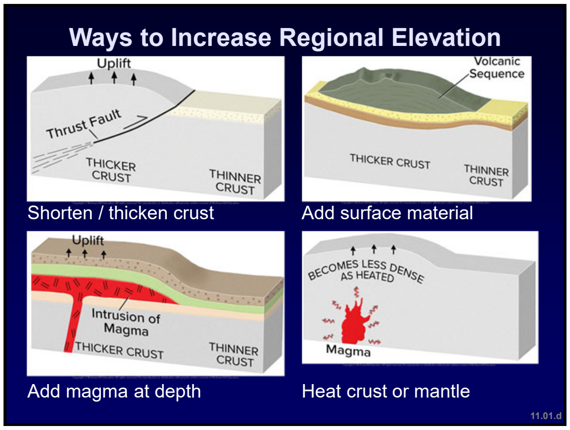
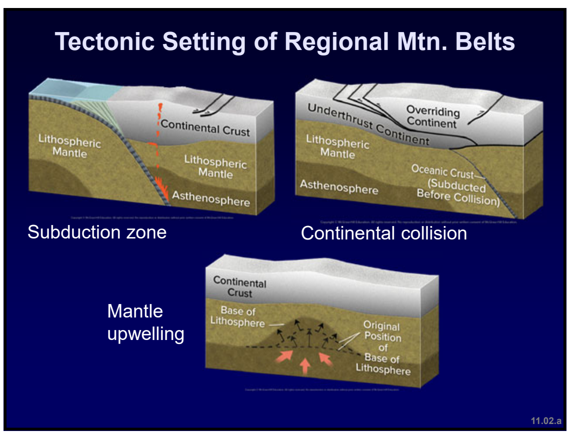
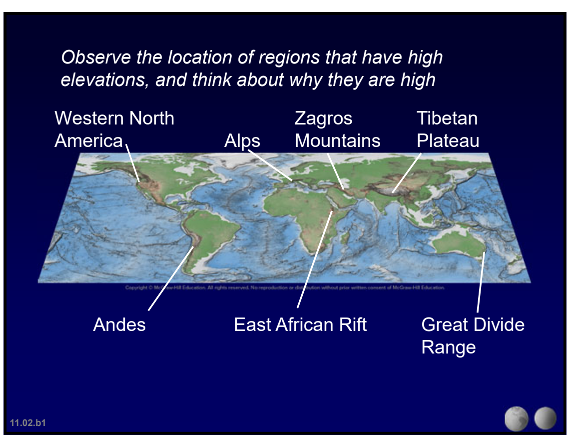

Observe this region around the Tibetan Plateau in southern Asia
Mount Everest
Tibetan Plateau and Himalaya
India
Himalaya
Tibetan Plateau
Tarim Basin
100 km
Exaggerated topographic profile of region
11.00.a

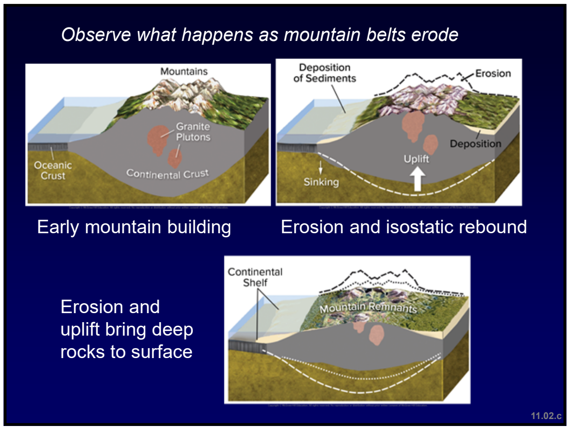

Controls on Regional Elevation
THICK CRUST
THINNER CRUST
Mantle
Less Dense
More Dense
Regions with thick crust are high
Regions underlain by less dense crust are high
Warm rocks are less dense, so warm regions are higher than cool ones
Warmer, Less Dense
Cooler, More Dense
11.01.a

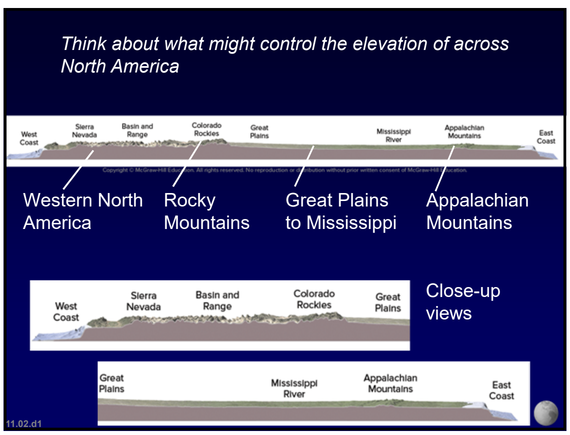

Ways to Decrease Regional Elevation
Normal Fault
Regional Subsidence
Thicker Crust
Thinner Crust
Erosion
Structurally thin crust
Erode material
Cool crust or mantle
Subsidence
Cooling Crust
11.01.c

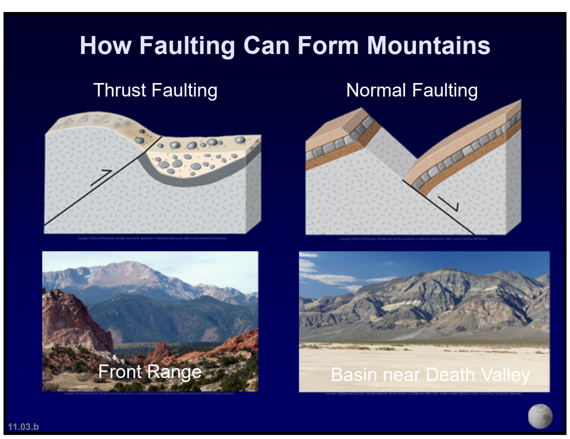

Ways to Increase Regional Elevation
Uplift
Thrust Fault
THICKER CRUST
THINNER CRUST
Shorten / thicken crust
Volcanic Sequence
THICKER CRUST
THINNER CRUST
Add surface material
Uplift
Intrusion of Magma
THICKER CRUST
THINNER CRUST
Add magma at depth
BECOMES LESS DENSE AS HEATED
Magma
Heat crust or mantle
11.01.d

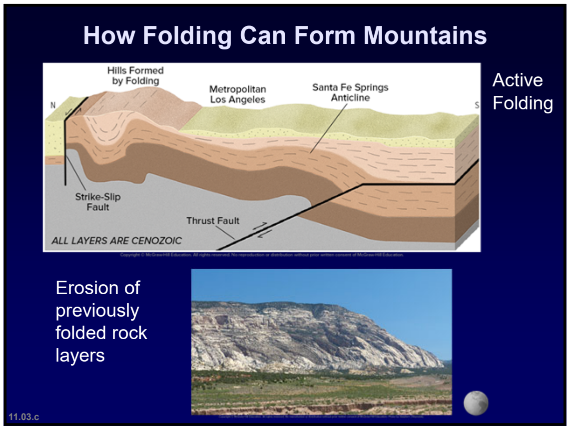

Tectonic Setting of Regional Mtn. Belts
Continental Crust
Lithospheric Mantle
Lithospheric Mantle
Asthenosphere
Subduction zone
Underthrust Continent
Overriding Continent
Lithospheric Mantle
Asthenosphere
Oceanic Crust (Subducted Before Collision)
Continental collision
Mantle upwelling
Continental Crust
Base of Lithosphere
Original Position of Base of Lithosphere
11.02.a

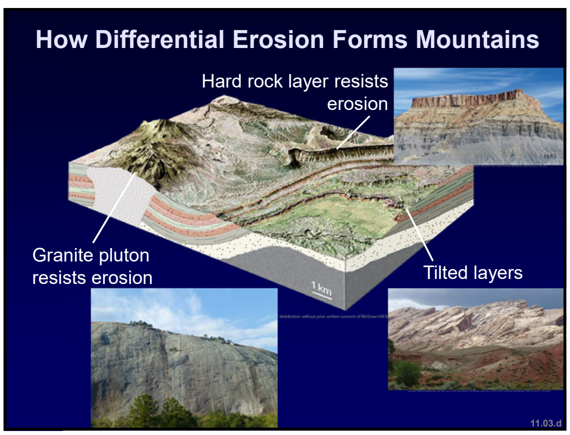

Observe the location of regions that have high elevations, and think about why they are high
Western North America
Alps
Zagros Mountains
Tibetan Plateau
Andes
East African Rift
Great Divide Range
11.02.b1

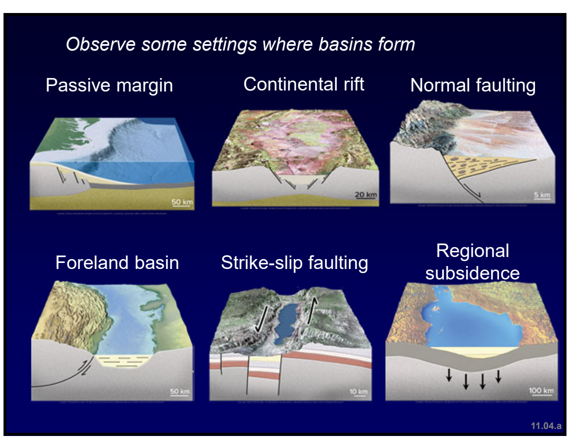

Observe what happens as mountain belts erode
Mountains
Granite Plutons
Oceanic Crust
Continental Crust
Deposition of Sediments
Erosion
Deposition
Uplift
Sinking
Early mountain building
Erosion and isostatic rebound
Continental Shelf
Mountain Remnants
Erosion and uplift bring deep rocks to surface
11.02.c

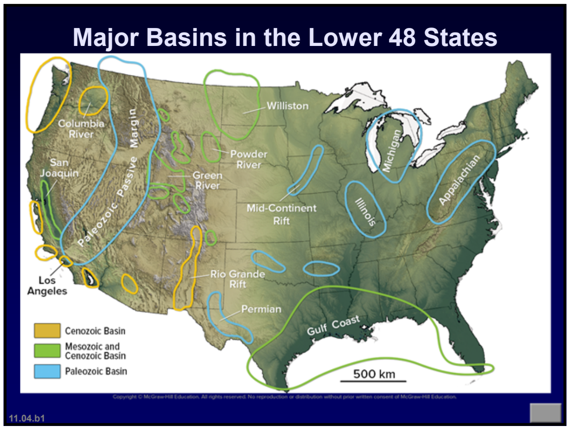

Think about what might control the elevation of across North America
West Coast
Sierra Nevada
Basin and Range
Colorado Rockies
Great Plains
Mississippi River
Appalachian Mountains
East Coast
Western North America
Rocky Mountains
Great Plains to Mississippi
Appalachian Mountains
Close-up views
West Coast
Sierra Nevada
Basin and Range
Colorado Rockies
Great Plains
Great Plains
Mississippi River
Appalachian Mountains
East Coast
11.02.d1

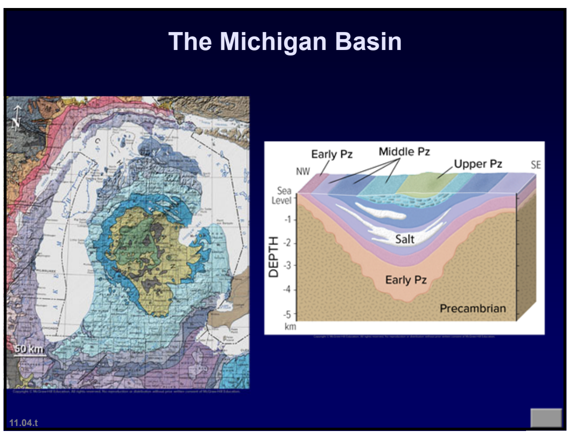

How Faulting Can Form Mountains
Thrust Faulting
Normal Faulting
Front Range
Basin near Death Valley
11.03.b

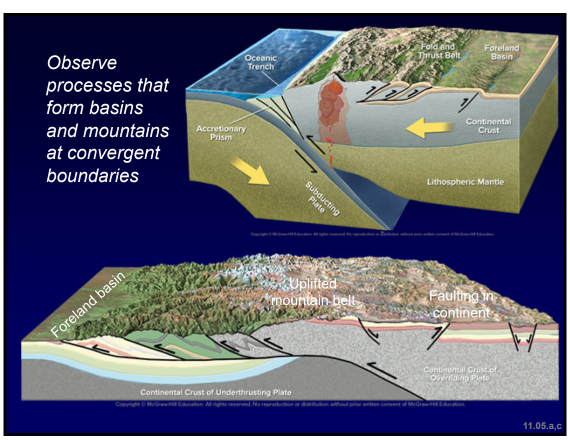

How Folding Can Form Mountains
Hills Formed by Folding
Metropolitan Los Angeles
Santa Fe Springs Anticline
N
S
Strike-Slip Fault
Thrust Fault
ALL LAYERS ARE CENOZOIC
Active Folding
Erosion of previously folded rock layers
11.03.c

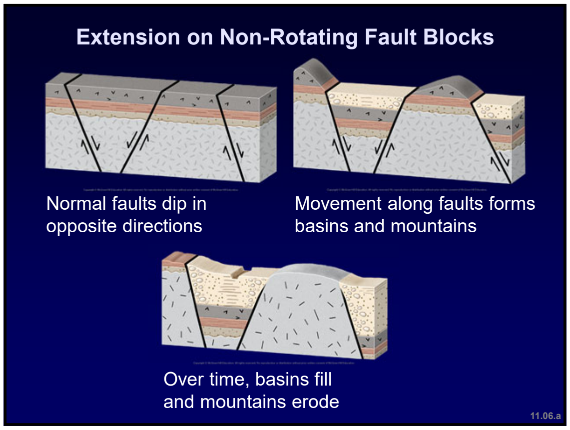

How Differential Erosion Forms Mountains
Hard rock layer resists erosion
Granite pluton resists erosion
Tilted layers
1 km
11.03.d

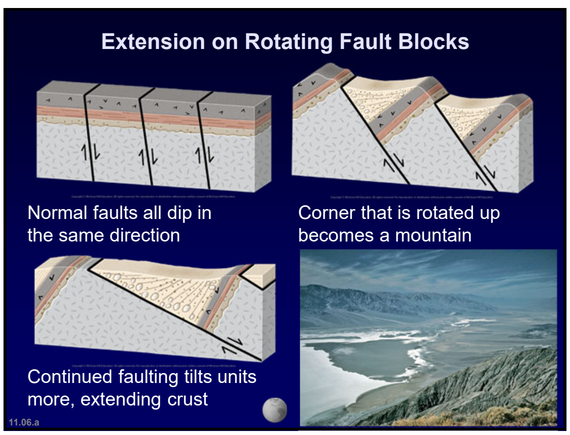

Observe some settings where basins form
Passive margin
Continental rift
Normal faulting
50 km
20 km
5 km
Foreland basin
Strike-slip faulting
Regional subsidence
50 km
10 km
100 km
11.04.a

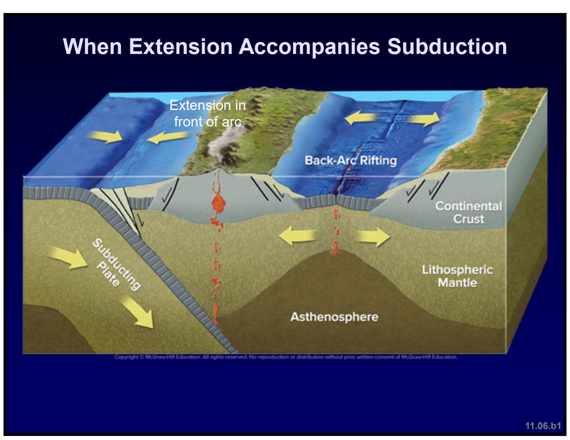

Major Basins in the Lower 48 States
Columbia River
San Joaquin
Paleozoic Passive Margin
Williston
Powder River
Green River
Michigan
Appalachian
Illinois
Mid-Continent Rift
Rio Grande Rift
Permian
Gulf Coast
Los Angeles
Cenozoic Basin
Mesozoic and Cenozoic Basin
Paleozoic Basin
500 km
11.04.b1

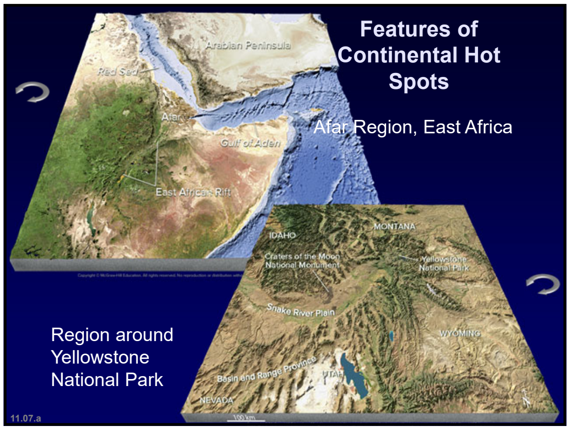

The Michigan Basin
50 km
Early Pz
Middle Pz
Upper Pz
NW
SE
Sea Level
DEPTH
-1
-2
-3
-4
-5
km
Salt
Early Pz
Precambrian
11.04.t

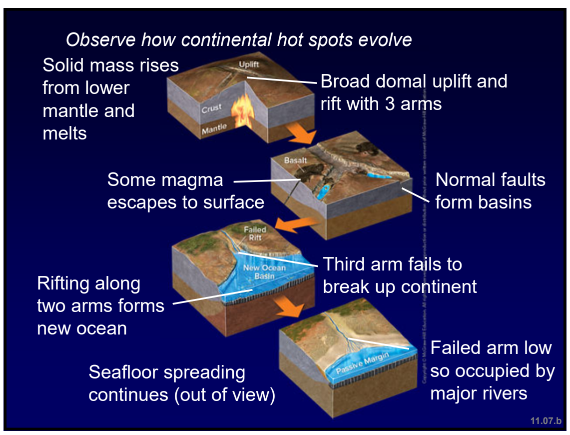

Observe processes that form basins and mountains at convergent boundaries
Oceanic Trench
Fold and Thrust Belt
Foreland Basin
Accretionary Prism
Continental Crust
Lithospheric Mantle
Subducting Plate
Foreland basin
Uplifted mountain belt
Faulting in continent
Continental Crust of Overriding Plate
Continental Crust of Underthrusting Plate
11.05.a,c

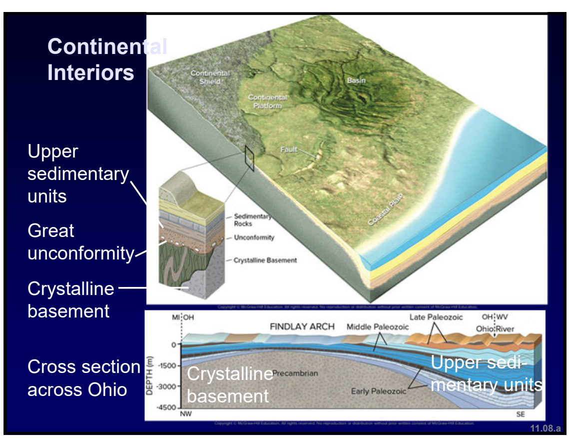

Extension on Non-Rotating Fault Blocks
Normal faults dip in opposite directions
Movement along faults forms basins and mountains
Over time, basins fill and mountains erode
11.06.a

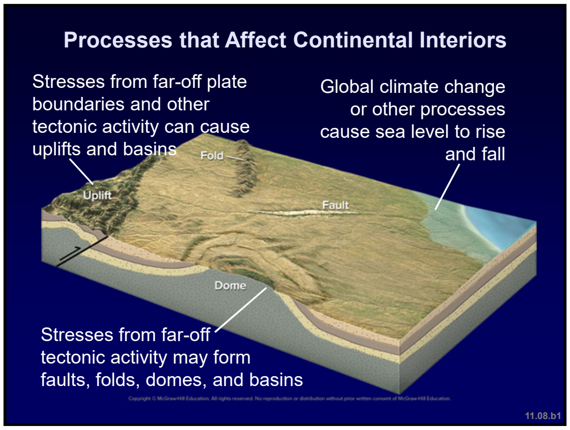

Extension on Rotating Fault Blocks
Normal faults all dip in the same direction
Corner that is rotated up becomes a mountain
Continued faulting tilts units more, extending crust
11.06.a

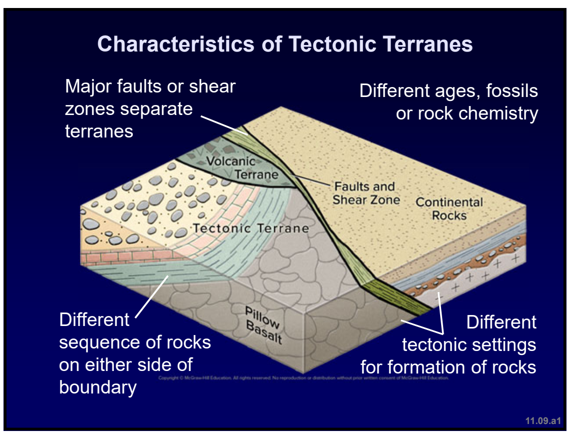

When Extension Accompanies Subduction
Extension in front of arc
Back-Arc Rifting
Continental Crust
Subducting Plate
Lithospheric Mantle
Asthenosphere
11.06.b1

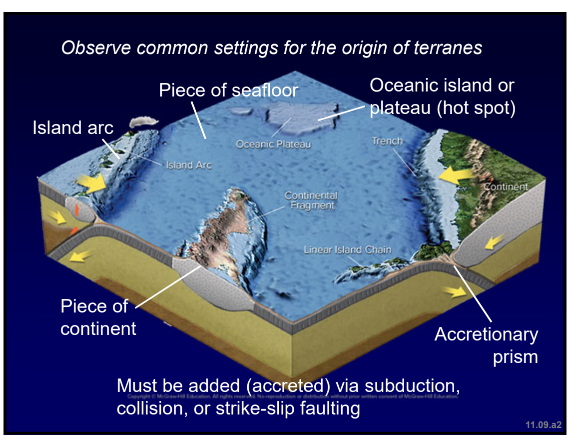

Features of Continental Hot Spots
Afar Region, East Africa
Region around Yellowstone National Park
Arabian Peninsula
Red Sea
Gulf of Aden
East African Rift
IDAHO
MONTANA
Craters of the Moon National Monument
Yellowstone National Park
Snake River Plain
WYOMING
Basin and Range Province
UTAH
NEVADA
11.07.a

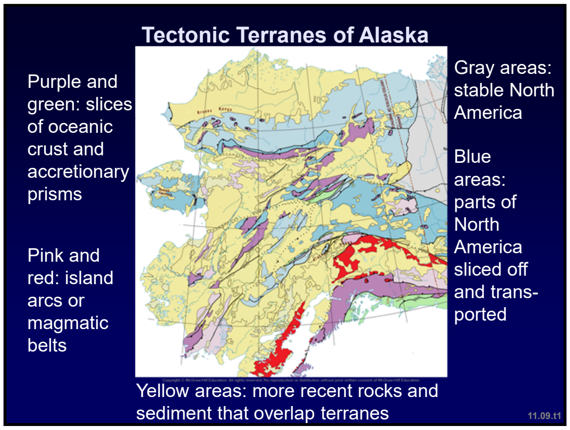

Observe how continental hot spots evolve
Solid mass rises from lower mantle and melts
Broad domal uplift and rift with 3 arms
Some magma escapes to surface
Normal faults form basins
Rifting along two arms forms new ocean
Third arm fails to break up continent
Seafloor spreading continues (out of view)
Failed arm low so occupied by major rivers
Uplift
Crust
Mantle
Basalt
Failed Rift
New Ocean Basin
Passive Margin
11.07.b

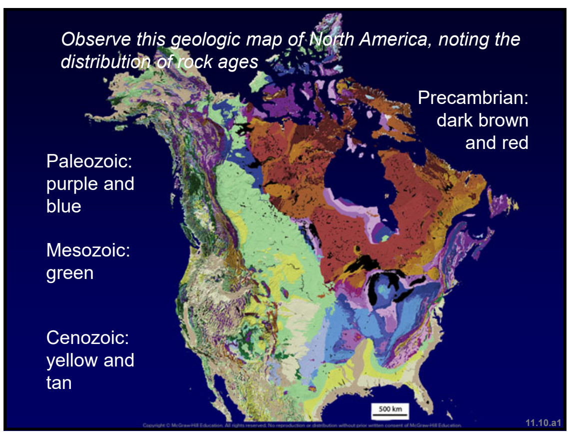

Continental Interiors
Upper sedimentary units
Great unconformity
Crystalline basement
Cross section across Ohio
Continental Shield
Continental Platform
Basin
Fault
Sedimentary Rocks
Unconformity
Crystalline Basement
FINDLAY ARCH
Middle Paleozoic
Late Paleozoic
Ohio River
Precambrian
Early Paleozoic
Crystalline basement
Upper sedimentary units
DEPTH (m)
NW
SE
11.08.a

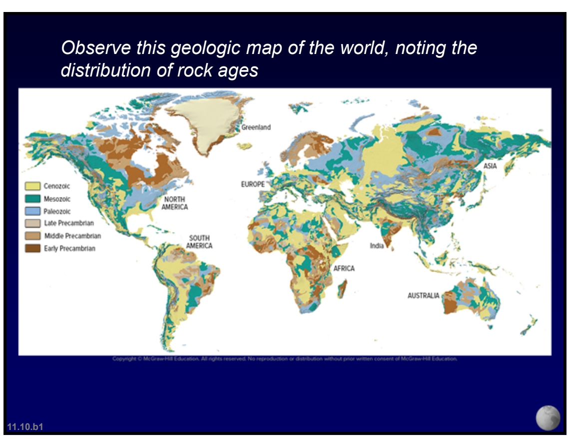

Processes that Affect Continental Interiors
Stresses from far-off plate boundaries and other tectonic activity can cause uplifts and basins
Global climate change or other processes cause sea level to rise and fall
Fold
Uplift
Fault
Dome
Stresses from far-off tectonic activity may form faults, folds, domes, and basins
11.08.b1

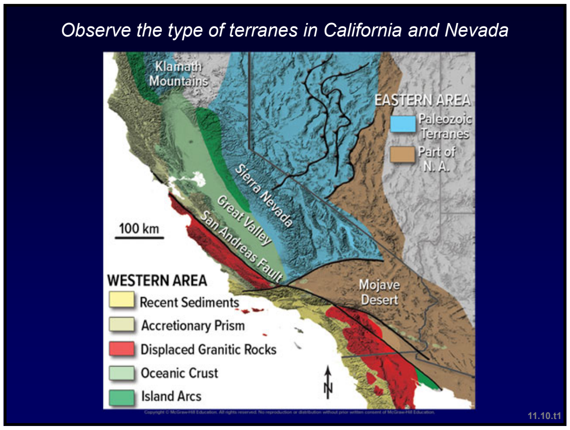

Characteristics of Tectonic Terranes
Major faults or shear zones separate terranes
Different ages, fossils or rock chemistry
Volcanic Terrane
Faults and Shear Zone
Continental Rocks
Tectonic Terrane
Pillow Basalt
Different sequence of rocks on either side of boundary
Different tectonic settings for formation of rocks
11.09.a1

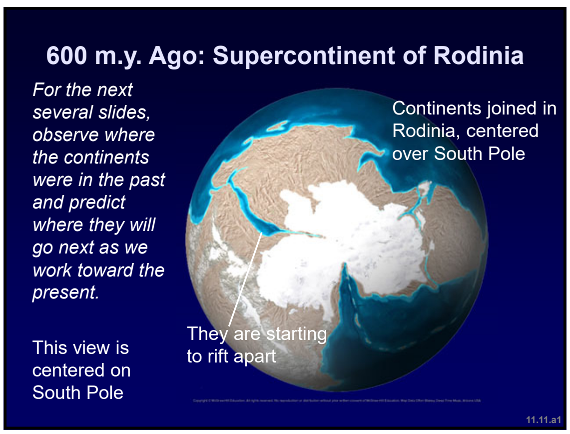

Observe common settings for the origin of terranes
Piece of seafloor
Oceanic island or plateau (hot spot)
Island arc
Oceanic Plateau
Trench
Island Arc
Continent
Continental Fragment
Linear Island Chain
Piece of continent
Accretionary prism
Must be added (accreted) via subduction, collision, or strike-slip faulting
11.09.a2

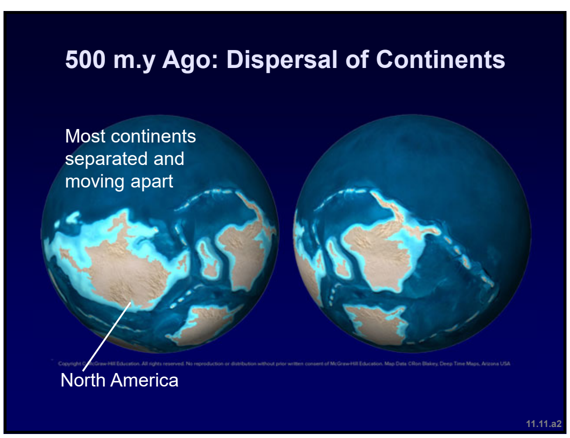

Tectonic Terranes of Alaska
Purple and green: slices of oceanic crust and accretionary prisms
Pink and red: island arcs or magmatic belts
Gray areas: stable North America
Blue areas: parts of North America sliced off and trans-ported
Yellow areas: more recent rocks and sediment that overlap terranes
11.09.t1

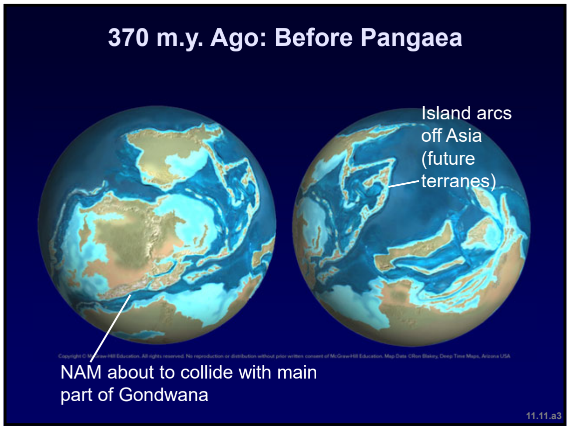

Observe this geologic map of North America, noting the distribution of rock ages
Precambrian: dark brown and red
Paleozoic: purple and blue
Mesozoic: green
Cenozoic: yellow and tan
500 km
11.10.a1

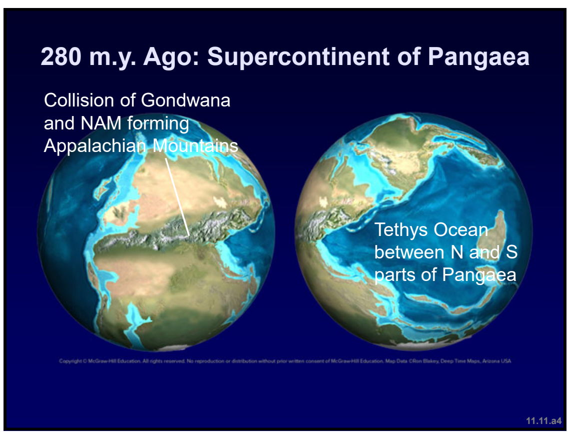

Observe this geologic map of the world, noting the distribution of rock ages
Cenozoic
Mesozoic
Paleozoic
Late Precambrian
Middle Precambrian
Early Precambrian
Greenland
NORTH AMERICA
EUROPE
ASIA
SOUTH AMERICA
AFRICA
India
AUSTRALIA
11.10.b1

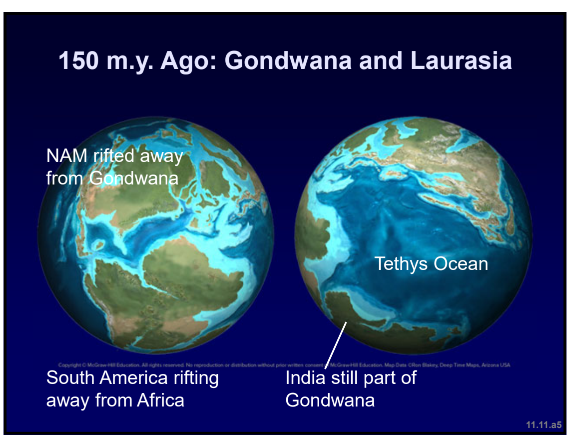

Observe the type of terranes in California and Nevada
Klamath Mountains
EASTERN AREA
Paleozoic Terranes
Part of N. A.
Sierra Nevada
Great Valley
San Andreas Fault
100 km
WESTERN AREA
Recent Sediments
Accretionary Prism
Displaced Granitic Rocks
Oceanic Crust
Island Arcs
Mojave Desert
N
11.10.t1


600 m.y. Ago: Supercontinent of Rodinia
For the next several slides, observe where the continents were in the past and predict where they will go next as we work toward the present.
Continents joined in Rodinia, centered over South Pole
They are starting to rift apart
This view is centered on South Pole
11.11.a1

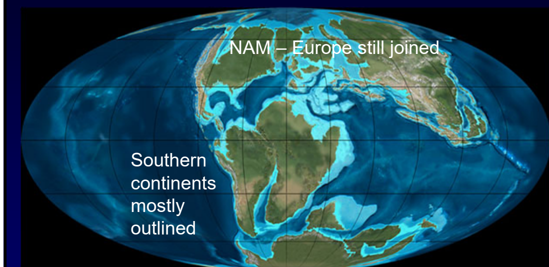

500 m.y Ago: Dispersal of Continents
Most continents separated and moving apart
North America
11.11.a2


370 m.y. Ago: Before Pangaea
Island arcs
off Asia
(future
terranes)
NAM about to collide with main
part of Gondwana
11.11.a3


280 m.y. Ago: Supercontinent of Pangaea
Collision of Gondwana
and NAM forming
Appalachian Mountains
Tethys Ocean
between N and S
parts of Pangaea
11.11.a4

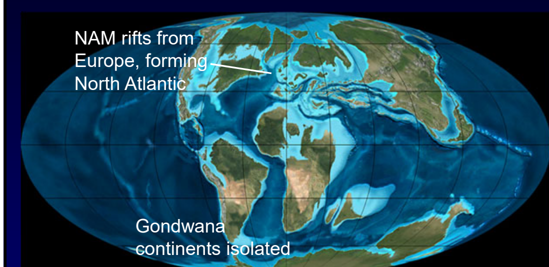

150 m.y. Ago: Gondwana and Laurasia
NAM rifted away
from Gondwana
Tethys Ocean
South America rifting
away from Africa
India still part of
Gondwana
11.11.a5

120 m.y. Ago: Dispersal of Gondwana



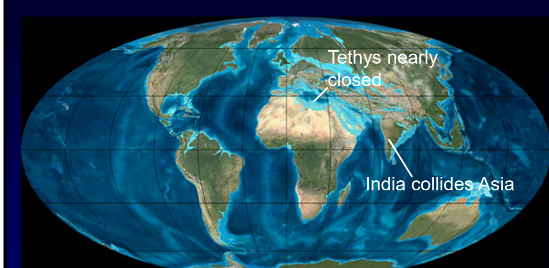
10.12.a3

90 m.y. Ago: Atlantic Ocean Open

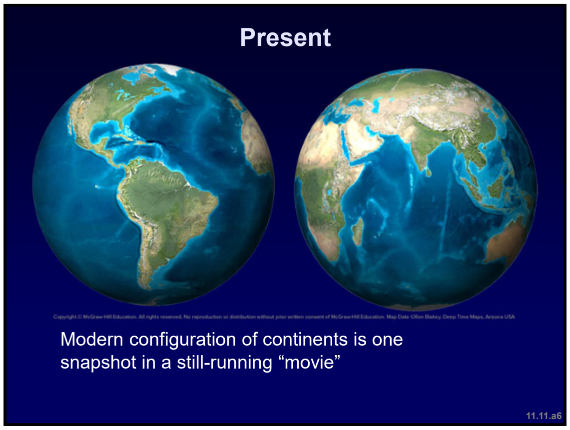


10.12.a4

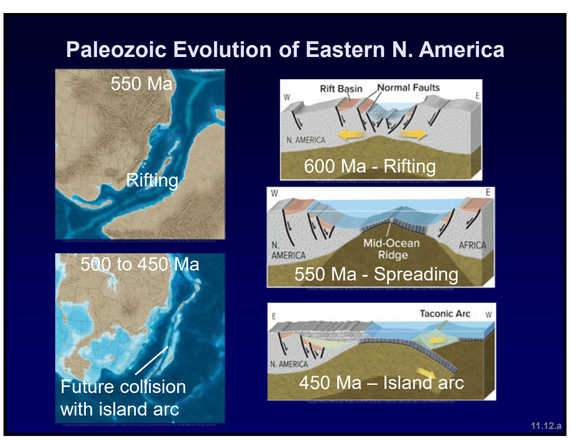
30 m.y. Ago: Closing Tethys Sea

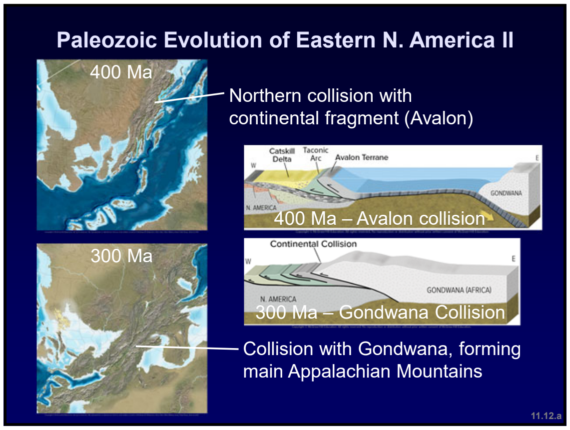


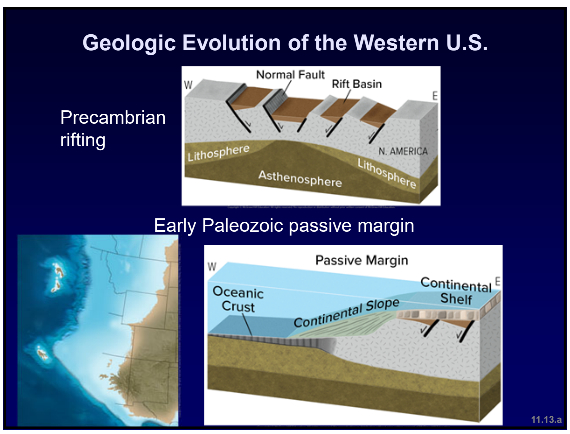
10.12.a5

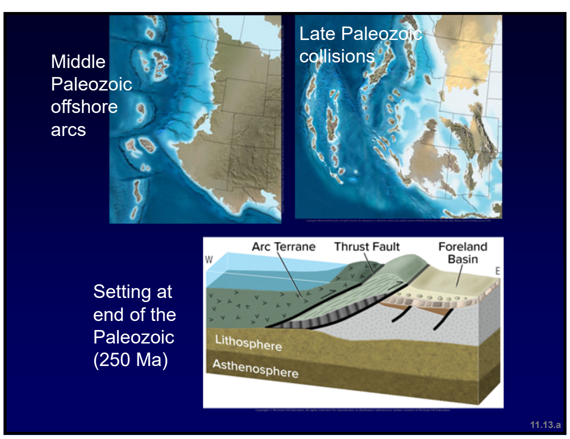

Present
Modern configuration of continents is one snapshot in a still-running "movie"
11.11.a6

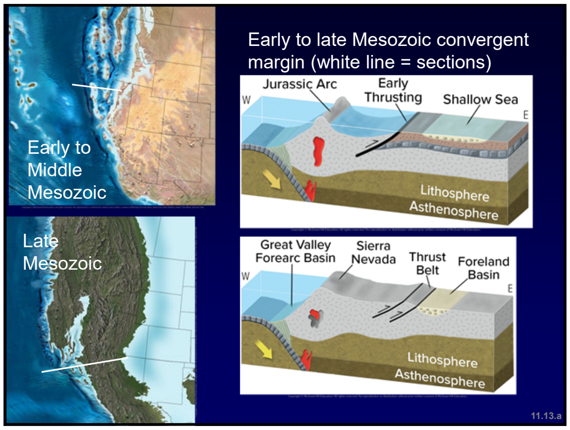

Geologic History of the Appalachian and Ouachita Mountains
Rocky Mountains
Ouachita Mountains
Appalachian Mountains
11.12.a1

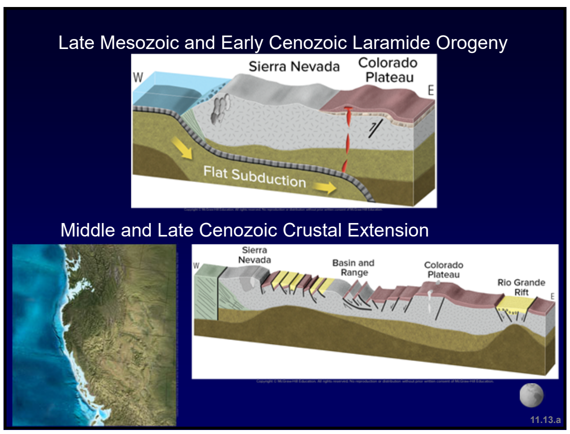

Paleozoic Evolution of Eastern N. America
550 Ma
Rifting
500 to 450 Ma
Future collision with island arc
Rift Basin
Normal Faults
N. AMERICA
600 Ma - Rifting
Mid-Ocean Ridge
AFRICA
550 Ma - Spreading
Taconic Arc
450 Ma – Island arc
11.12.a


Paleozoic Evolution of Eastern N. America II
400 Ma
Northern collision with
continental fragment (Avalon)
Catskill Delta
Taconic Arc
Avalon Terrane
N. AMERICA
GONDWANA
400 Ma – Avalon collision
300 Ma
Continental Collision
N. AMERICA
GONDWANA (AFRICA)
300 Ma – Gondwana Collision
Collision with Gondwana, forming
main Appalachian Mountains
11.12.a


Geologic Evolution of the Western U.S.
Precambrian
rifting
Normal Fault
Rift Basin
N. AMERICA
Lithosphere
Asthenosphere
Lithosphere
Early Paleozoic passive margin
Passive Margin
Oceanic
Crust
Continental Slope
Continental
Shelf
11.13.a

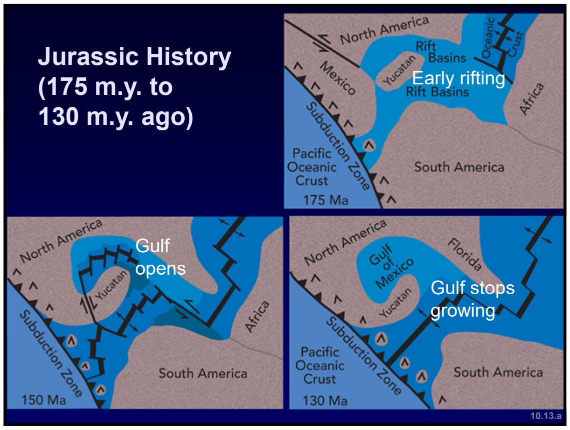

Middle
Paleozoic
offshore
arcs
Late Paleozoic
collisions
Arc Terrane
Thrust Fault
Foreland
Basin
Setting at
end of the
Paleozoic
(250 Ma)
Lithosphere
Asthenosphere
11.13.a


Early to late Mesozoic convergent margin (white line = sections)
Early to Middle Mesozoic
Late Mesozoic
Jurassic Arc
Early Thrusting
Shallow Sea
W
E
Lithosphere
Asthenosphere
Great Valley Forearc Basin
Sierra Nevada
Thrust Belt
Foreland Basin
11.13.a

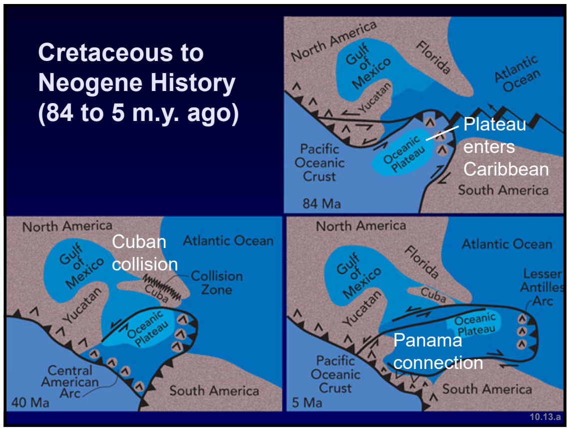

Late Mesozoic and Early Cenozoic Laramide Orogeny
Sierra Nevada
Colorado Plateau
W
E
Flat Subduction
Middle and Late Cenozoic Crustal Extension
Sierra Nevada
Basin and Range
Colorado Plateau
Rio Grande Rift
11.13.a

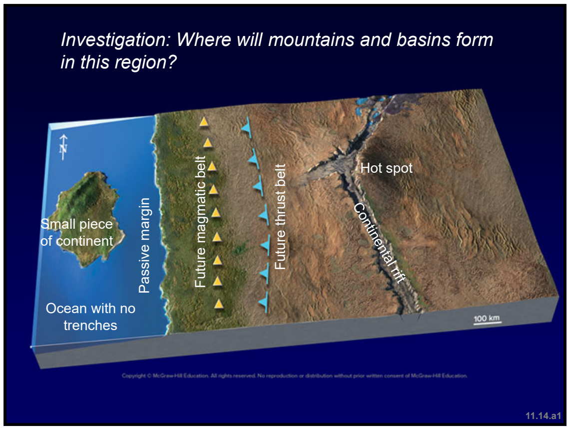

Observe the present setting of the Gulf of Mexico and the Caribbean region
NORTH AMERICAN PLATE
Texas
Florida
Gulf of Mexico
Bahamas
Cuba
Subduction beneath Lesser Antilles
Subduction beneath Central Am.
Transform
Yucatan Peninsula
Cayman Trough
CARIBBEAN PLATE
Central America
COCOS PLATE
Complex area
SOUTH AMERICAN PLATE
250 Km
10.13.a1
3D

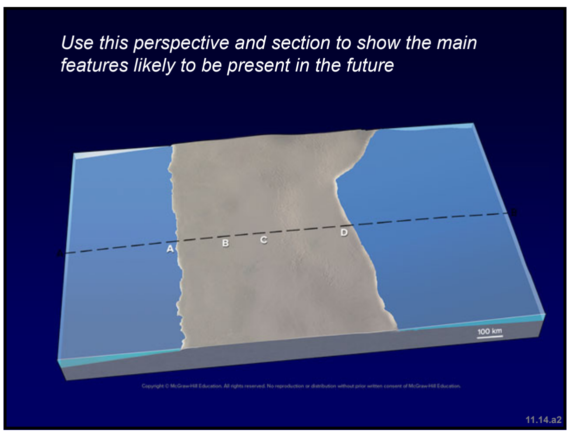
Jurassic History (175 m.y. to 130 m.y. ago)

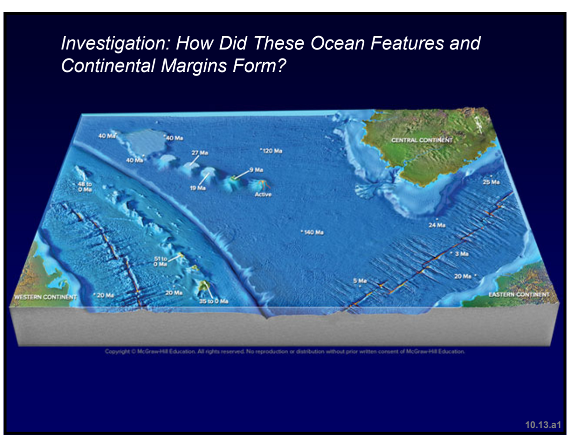


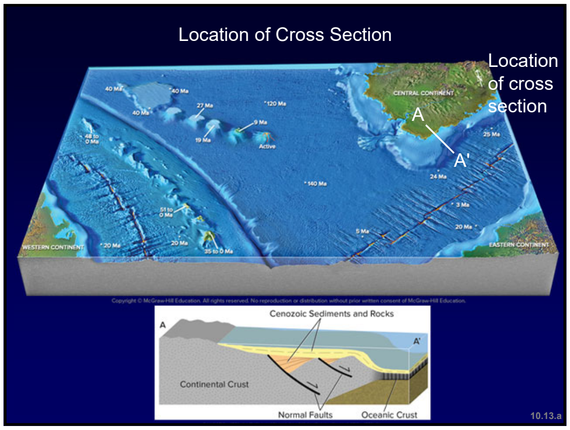
Cretaceous to Neogene History (84 to 5 m.y. ago)



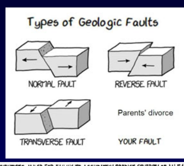

Investigation: Where will mountains and basins form in this region?
Small piece of continent
Passive margin
Future magmatic belt
Future thrust belt
Hot spot
Continental rift
Ocean with no trenches
100 km
11.14.a1


Use this perspective and section to show the main features likely to be present in the future
A
B
C
D
100 km
11.14.a2

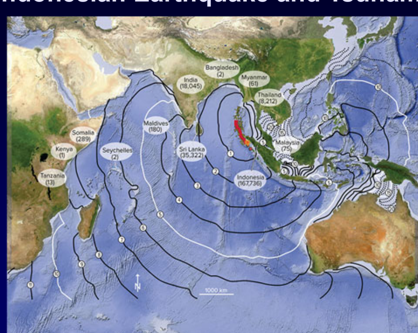

Investigation: How Did These Ocean Features and Continental Margins Form?
CENTRAL CONTINENT
WESTERN CONTINENT
EASTERN CONTINENT
10.13.a1


Location of Cross Section
Location of cross section
A
A'
Cenozoic Sediments and Rocks
A
A'
Continental Crust
Normal Faults
Oceanic Crust
10.13.a

Earthquakes
Chap 12

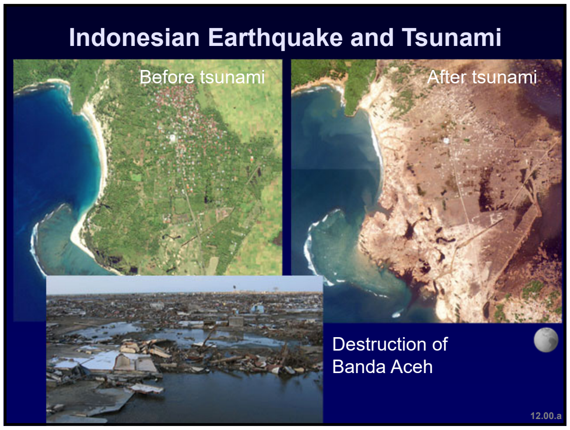


Indonesian Earthquake and Tsunami



Number of deaths and missing shown in ovals

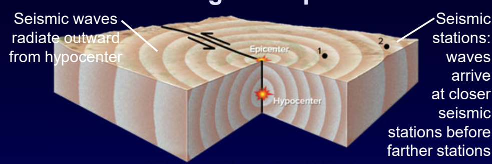
12.00.a1


Indonesian Earthquake and Tsunami
Before tsunami
After tsunami
Destruction of Banda Aceh
12.00.a

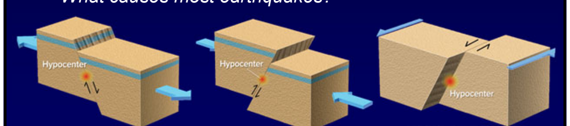

Indonesian Earthquake and Tsunami
Destruction of Banda Aceh
12.00.a


Friday, March 11

Describing Earthquakes

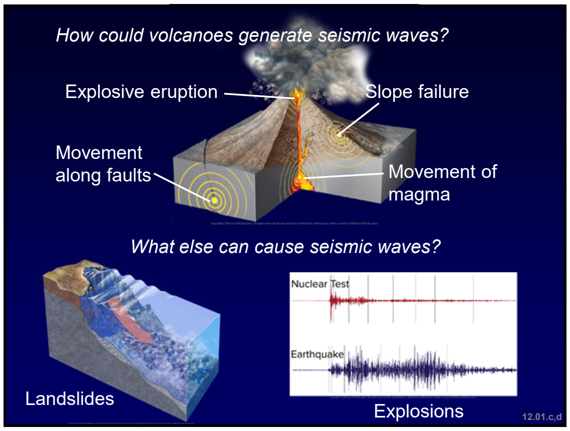


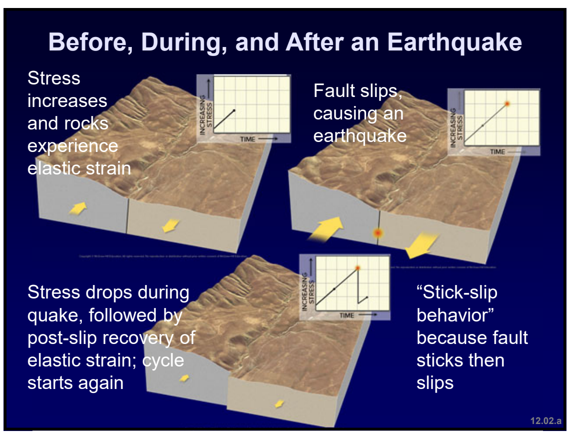
What causes most earthquakes?

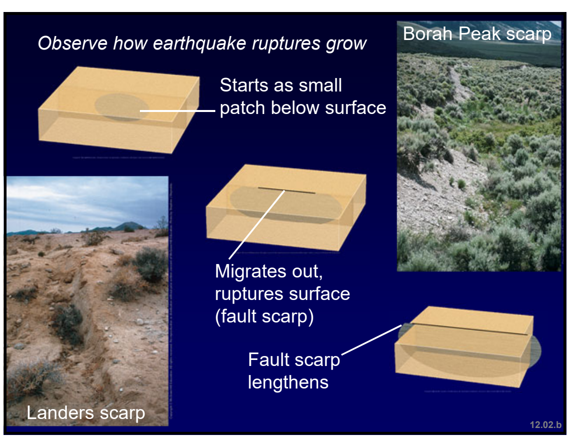


Normal faults | Reverse and thrust faults | Strike-slip faults

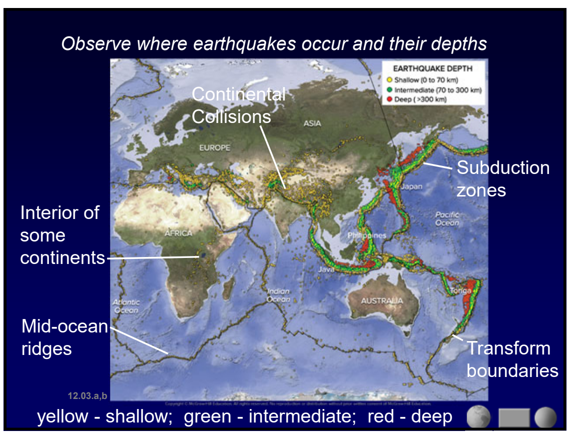
12.01.a,b

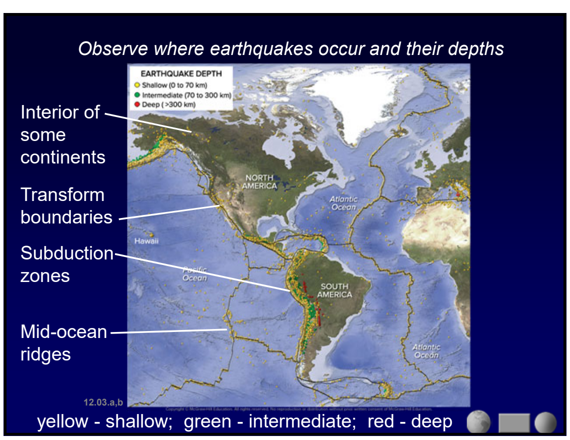

How could volcanoes generate seismic waves?
Explosive eruption
Slope failure
Movement along faults
Movement of magma
What else can cause seismic waves?
Nuclear Test
Earthquake
Landslides
Explosions
12.01.c,d

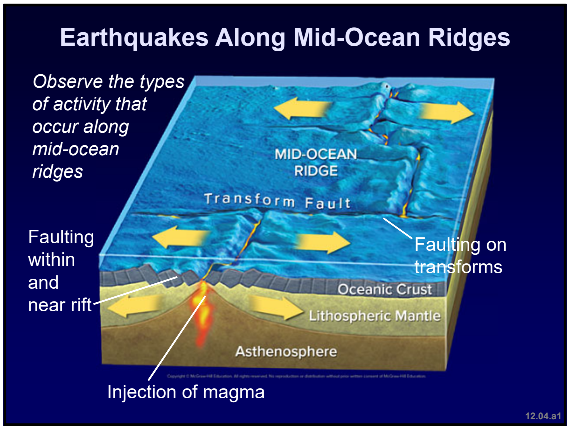

Before, During, and After an Earthquake
Stress increases and rocks experience elastic strain
Fault slips, causing an earthquake
Stress drops during quake, followed by post-slip recovery of elastic strain; cycle starts again
"Stick-slip behavior" because fault sticks then slips
12.02.a

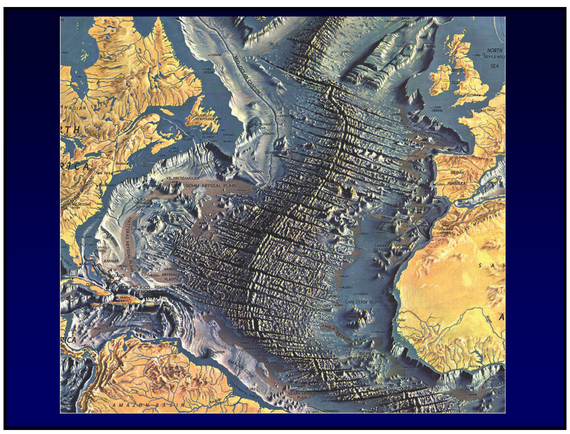

Observe how earthquake ruptures grow
Borah Peak scarp
Starts as small patch below surface
Migrates out, ruptures surface (fault scarp)
Fault scarp lengthens
Landers scarp
12.02.b

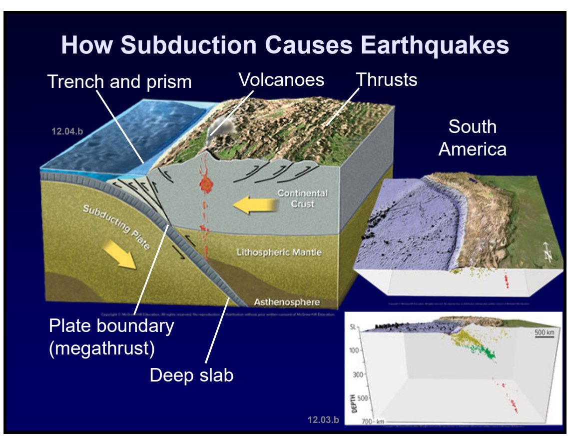

Scarp height ~8m
Riverbed
OSL sample
Scarp height ~3m

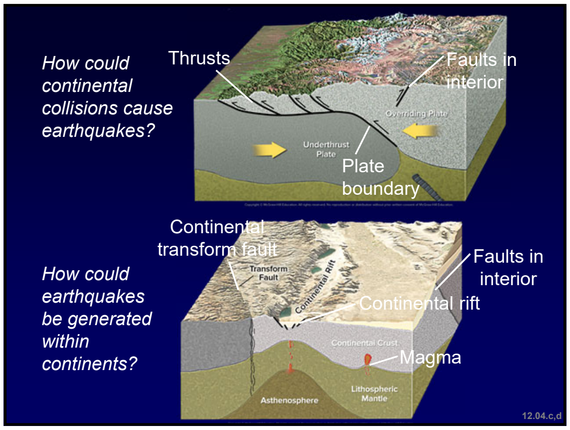

Observe where earthquakes occur and their depths
EARTHQUAKE DEPTH
Shallow (0 to 70 km)
Intermediate (70 to 300 km)
Deep (>300 km)
Continental Collisions
Subduction zones
Interior of some continents
Mid-ocean ridges
Transform boundaries
ASIA
EUROPE
AFRICA
AUSTRALIA
12.03.a,b
yellow - shallow; green - intermediate; red - deep

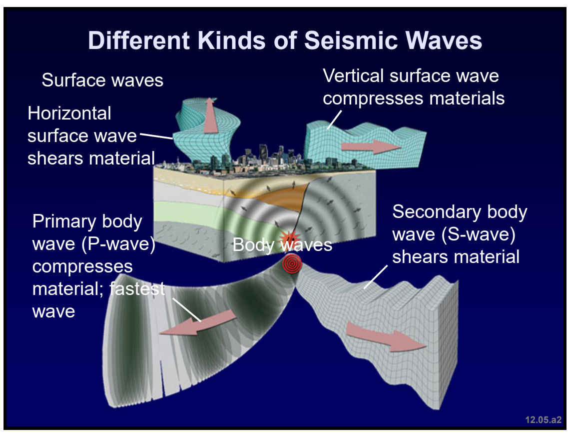

Observe where earthquakes occur and their depths
EARTHQUAKE DEPTH
Shallow (0 to 70 km)
Intermediate (70 to 300 km)
Deep (>300 km)
Interior of some continents
Transform boundaries
Subduction zones
Mid-ocean ridges
NORTH AMERICA
SOUTH AMERICA
12.03.a,b
yellow - shallow; green - intermediate; red - deep

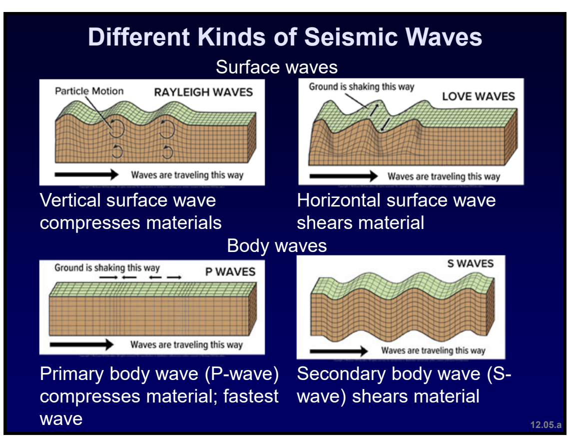

Earthquakes Along Mid-Ocean Ridges
Observe the types of activity that occur along mid-ocean ridges
MID-OCEAN RIDGE
Transform Fault
Faulting within and near rift
Faulting on transforms
Oceanic Crust
Lithospheric Mantle
Asthenosphere
Injection of magma
12.04.a1

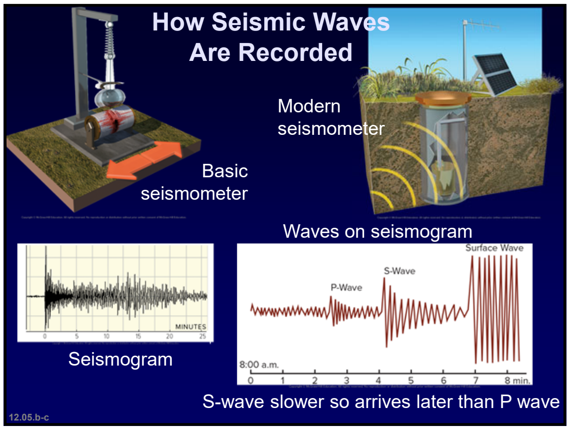


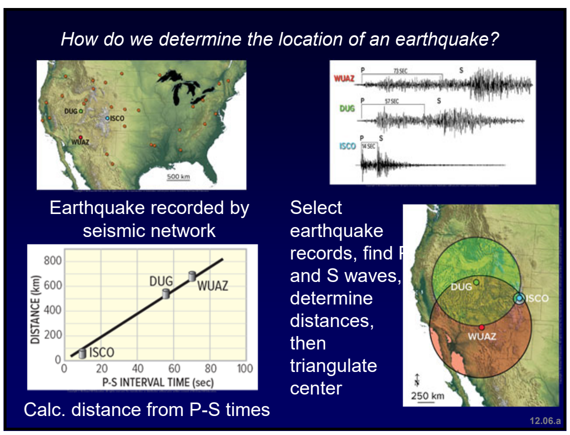

How Subduction Causes Earthquakes
Trench and prism
Volcanoes
Thrusts
South America
12.04.b
Subducting Plate
Continental Crust
Lithospheric Mantle
Asthenosphere
Plate boundary (megathrust)
Deep slab
12.03.b

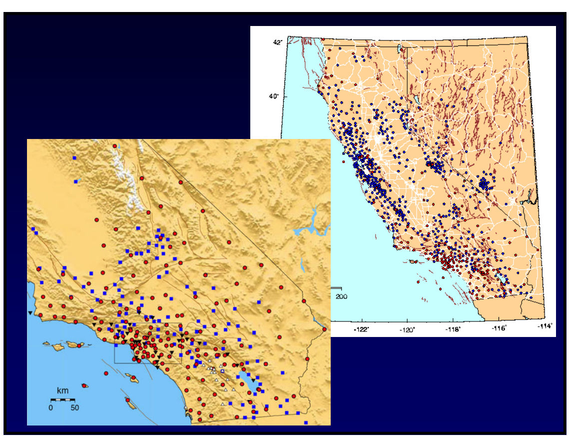

How could continental collisions cause earthquakes?
Thrusts
Faults in interior
Overriding Plate
Underthrust Plate
Plate boundary
Continental transform fault
Transform Fault
Continental Rift
Faults in interior
Continental rift
How could earthquakes be generated within continents?
Continental Crust
Magma
Lithospheric Mantle
Asthenosphere
12.04.c,d

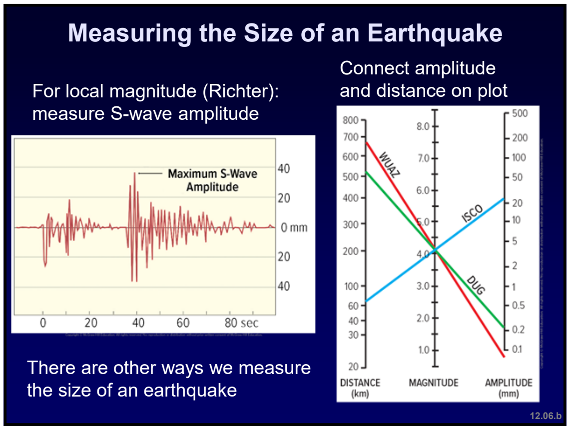

Different Kinds of Seismic Waves
Surface waves
Vertical surface wave compresses materials
Horizontal surface wave shears material
Primary body wave (P-wave) compresses material; fastest wave
Body waves
Secondary body wave (S-wave) shears material
12.05.a2

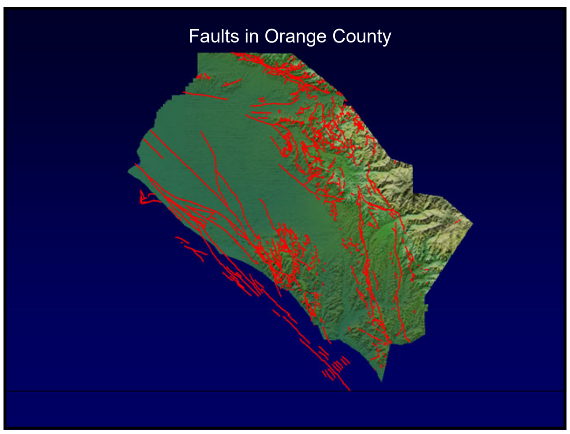

Different Kinds of Seismic Waves
Surface waves
Particle Motion
RAYLEIGH WAVES
Waves are traveling this way
Ground is shaking this way
LOVE WAVES
Waves are traveling this way
Vertical surface wave compresses materials
Horizontal surface wave shears material
Body waves
Ground is shaking this way
P WAVES
Waves are traveling this way
S WAVES
Waves are traveling this way
Primary body wave (P-wave) compresses material; fastest wave
Secondary body wave (S-wave) shears material
12.05.a


How Seismic Waves Are Recorded
Modern seismometer
Basic seismometer
Waves on seismogram
Surface Wave
S-Wave
P-Wave
MINUTES
Seismogram
8:00 a.m.
S-wave slower so arrives later than P wave
12.05.b-c

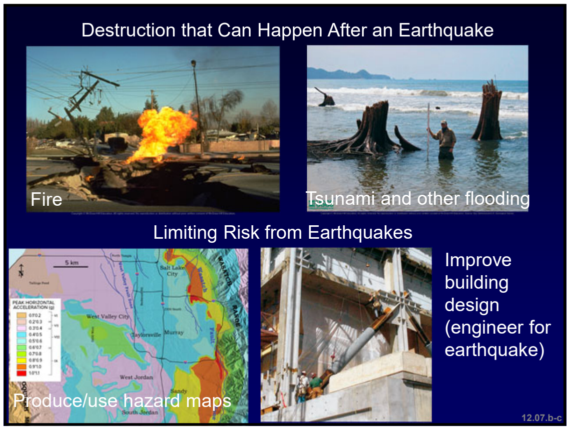

How do we determine the location of an earthquake?
WUAZ
DUG
ISCO
500 km
Earthquake recorded by seismic network
Select earthquake records, find P and S waves, determine distances, then triangulate center
800
600
400
200
DISTANCE (km)
DUG
WUAZ
ISCO
P-S INTERVAL TIME (sec)
250 km
Calc. distance from P-S times
12.06.a

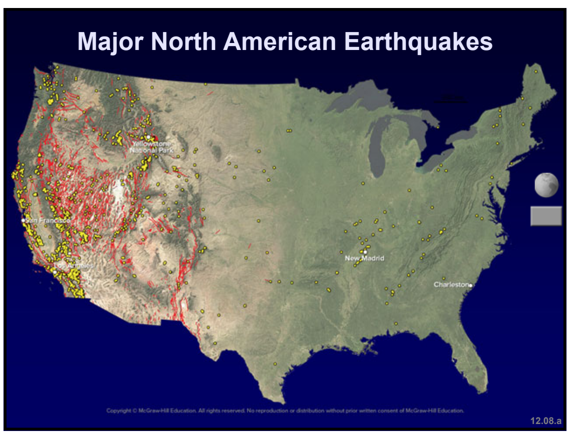


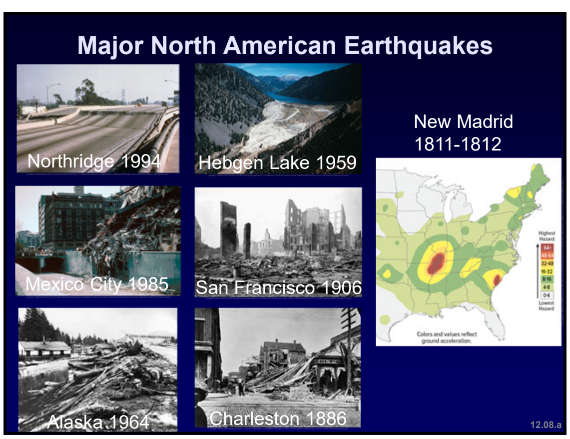

Measuring the Size of an Earthquake
For local magnitude (Richter): measure S-wave amplitude
Maximum S-Wave Amplitude
Connect amplitude and distance on plot
DISTANCE (km)
MAGNITUDE
AMPLITUDE (mm)
WUAZ
ISCO
DUG
There are other ways we measure the size of an earthquake
12.06.b

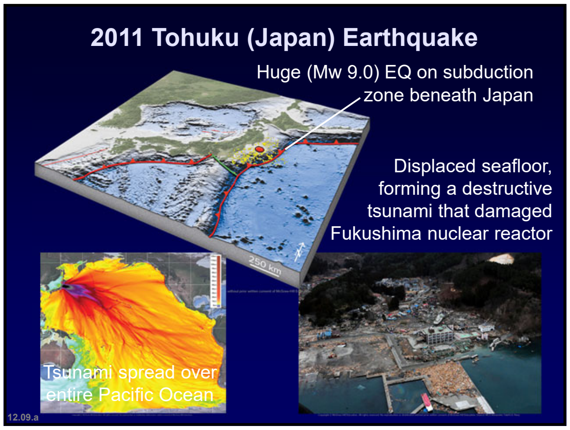

Faults in Orange County

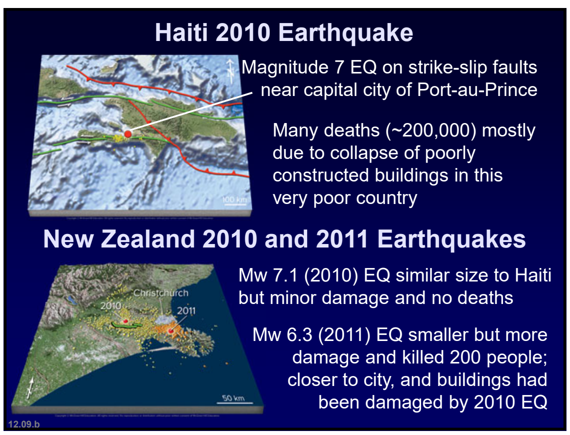

Predict what destruction arises from ground motion during an earthquake
Loma Prieta
Rupture
Landslide
Structural damage
Tsunami
Bridge failure on weak materials
Worse if poor construction
Liquefaction of fill
Aftershocks cause further damage
Loma Prieta
12.07.a

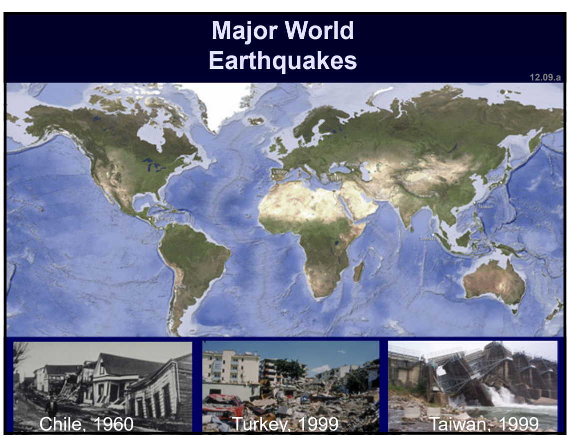

Destruction that Can Happen After an Earthquake
Fire
Tsunami and other flooding
Limiting Risk from Earthquakes
Produce/use hazard maps
Improve building design (engineer for earthquake)
12.07.b-c

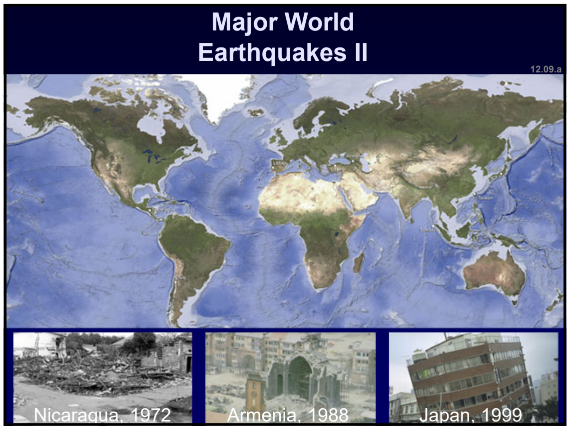

Major North American Earthquakes
New Madrid
Charleston
12.08.a

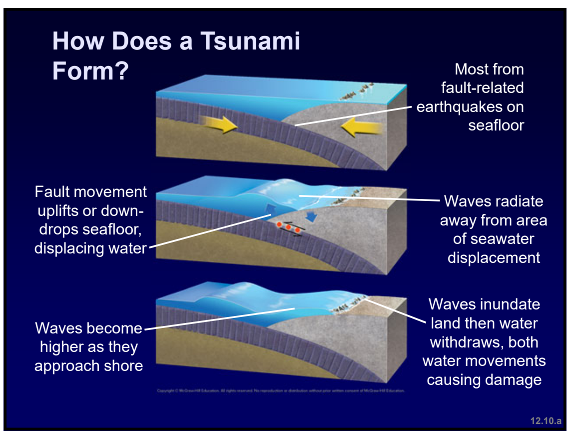

Major North American Earthquakes
Northridge 1994
Hebgen Lake 1959
New Madrid 1811-1812
Mexico City 1985
San Francisco 1906
Alaska 1964
Charleston 1886
12.08.a

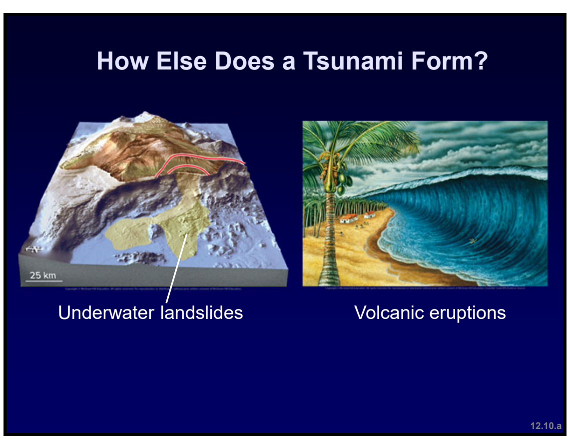

2011 Tohuku (Japan) Earthquake
Huge (Mw 9.0) EQ on subduction zone beneath Japan
Displaced seafloor, forming a destructive tsunami that damaged Fukushima nuclear reactor
Tsunami spread over entire Pacific Ocean
250 km
12.09.a

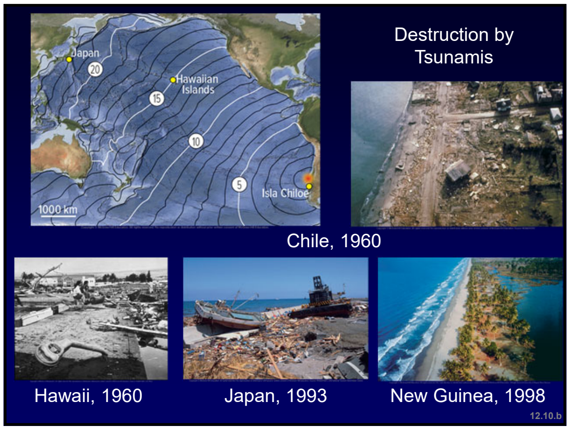

Haiti 2010 Earthquake
Magnitude 7 EQ on strike-slip faults near capital city of Port-au-Prince
Many deaths (~200,000) mostly due to collapse of poorly constructed buildings in this very poor country
New Zealand 2010 and 2011 Earthquakes
Christchurch
2010
2011
Mw 7.1 (2010) EQ similar size to Haiti but minor damage and no deaths
Mw 6.3 (2011) EQ smaller but more damage and killed 200 people; closer to city, and buildings had been damaged by 2010 EQ
50 km
12.09.b

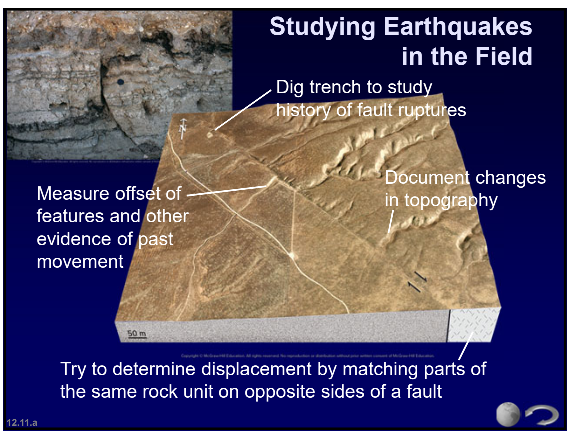

Major World Earthquakes
12.09.a
Chile, 1960
Turkey, 1999
Taiwan, 1999

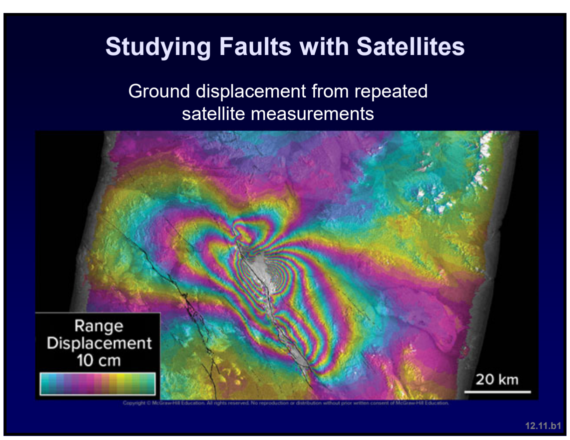

Major World
Earthquakes II
12.09.a
Nicaragua, 1972
Armenia, 1988
Japan, 1999

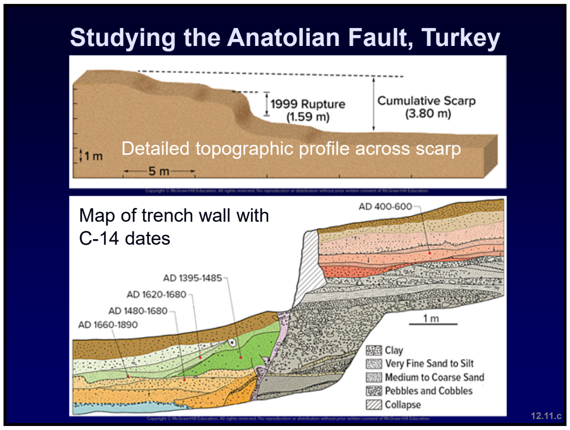

How Does a Tsunami Form?
Most from fault-related earthquakes on seafloor
Fault movement uplifts or down-drops seafloor, displacing water
Waves radiate away from area of seawater displacement
Waves become higher as they approach shore
Waves inundate land then water withdraws, both water movements causing damage
12.10.a

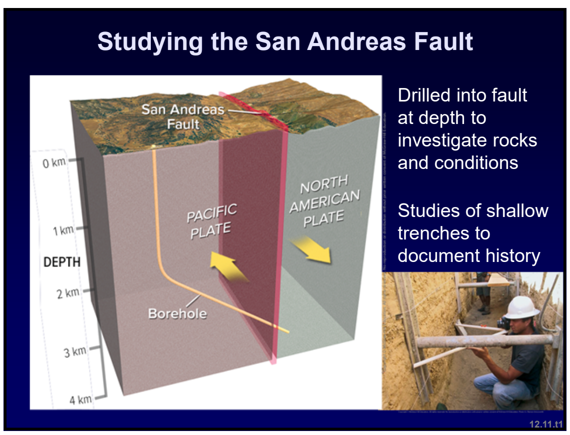

How Else Does a Tsunami Form?
25 km
Underwater landslides
Volcanic eruptions
12.10.a

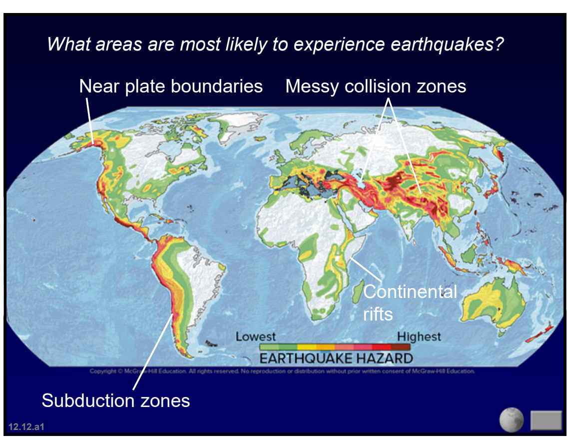

Destruction by
Tsunamis
Japan
Hawaiian Islands
Isla Chiloe
1000 km
Chile, 1960
Hawaii, 1960
Japan, 1993
New Guinea, 1998
12.10.b

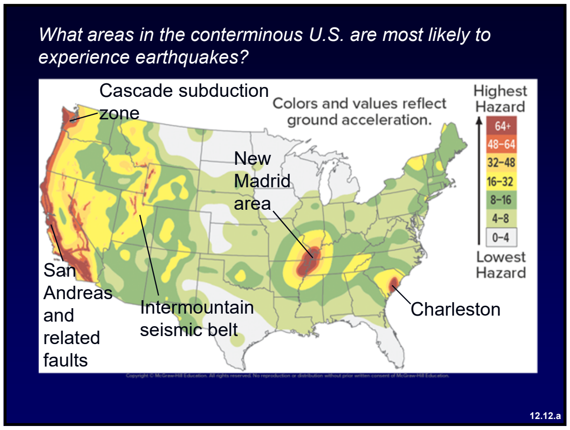

Studying Earthquakes
in the Field
Dig trench to study
history of fault ruptures
Measure offset of
features and other
evidence of past
movement
Document changes
in topography
Try to determine displacement by matching parts of
the same rock unit on opposite sides of a fault
12.11.a

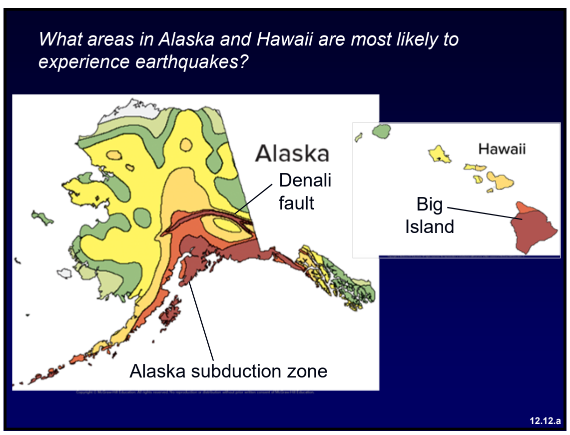

Studying Faults with Satellites
Ground displacement from repeated
satellite measurements
Range
Displacement
10 cm
20 km
12.11.b1

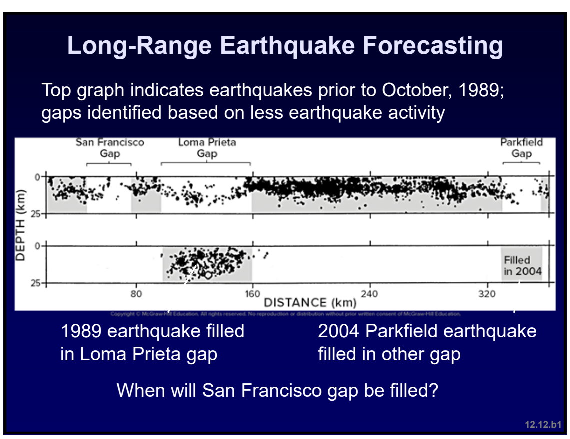

Studying the Anatolian Fault, Turkey
1999 Rupture (1.59 m)
Cumulative Scarp (3.80 m)
1 m
5 m
Detailed topographic profile across scarp
Map of trench wall with C-14 dates
AD 400-600
AD 1395-1485
AD 1620-1680
AD 1480-1680
AD 1660-1890
1 m
Clay
Very Fine Sand to Silt
Medium to Coarse Sand
Pebbles and Cobbles
Collapse
12.11.c


Studying the San Andreas Fault
San Andreas Fault
0 km
1 km
DEPTH
2 km
3 km
4 km
PACIFIC PLATE
NORTH AMERICAN PLATE
Borehole
Drilled into fault at depth to investigate rocks and conditions
Studies of shallow trenches to document history
12.11.t1


What areas are most likely to experience earthquakes?
Near plate boundaries
Messy collision zones
Continental rifts
Lowest
Highest
EARTHQUAKE HAZARD
Subduction zones
12.12.a1


What areas in the conterminous U.S. are most likely to experience earthquakes?
Cascade subduction zone
Colors and values reflect ground acceleration.
Highest Hazard
64+
48–64
32–48
16–32
8–16
4–8
0–4
Lowest Hazard
New Madrid area
San Andreas and related faults
Intermountain seismic belt
Charleston
12.12.a


What areas in Alaska and Hawaii are most likely to experience earthquakes?
Alaska
Denali fault
Alaska subduction zone
Hawaii
Big Island
12.12.a


Long-Range Earthquake Forecasting
Top graph indicates earthquakes prior to October, 1989; gaps identified based on less earthquake activity
San Francisco Gap
Loma Prieta Gap
Parkfield Gap
DEPTH (km)
0
25
Filled in 2004
80
160
240
320
DISTANCE (km)
1989 earthquake filled in Loma Prieta gap
2004 Parkfield earthquake filled in other gap
When will San Francisco gap be filled?
12.12.b1

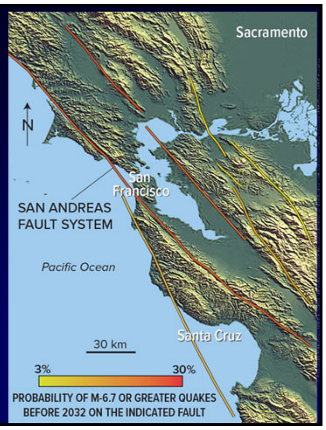
Long-Range Earthquake Forecasting

USGS assigned probability to each main fault in San Francisco area

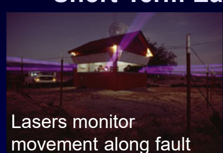
Combined probability of major earthquake before 2032 is over 60 percent

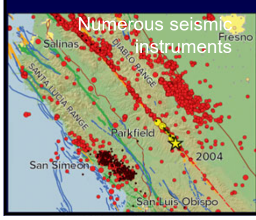
90% probability of Mw 6.7 or greater in next 30 years in California

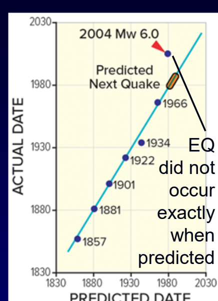
12.12.b2



Short-Term Earthquake Prediction







Predictions based on past history of Parkfield segment

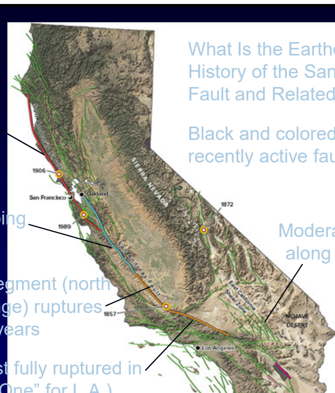
12.12.c

Red: segment ruptured 1906 S.F. earthquake

Blue: creeping segment

Parkfield segment (north end of orange) ruptures every ~20 years

Orange: last fully ruptured in 1857 ("Big One" for L.A.)

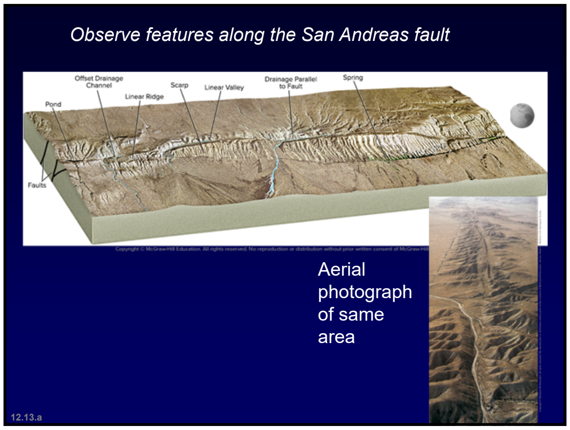


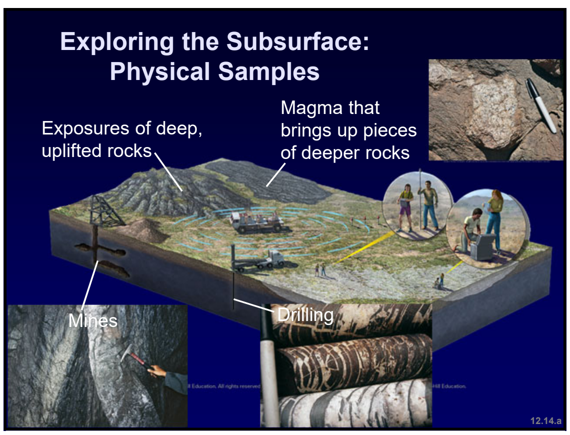
What Is the Earthquake History of the San Andreas Fault and Related Faults?

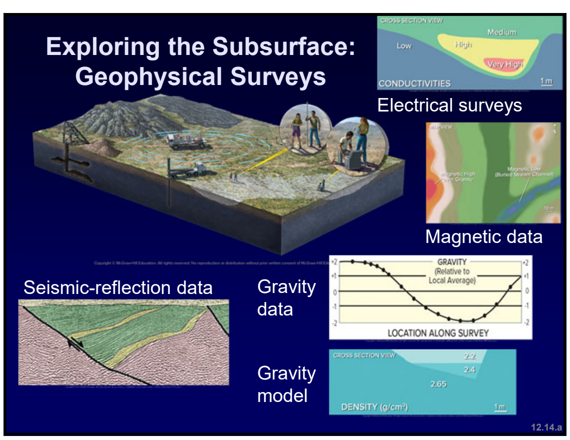
Black and colored lines: recently active faults

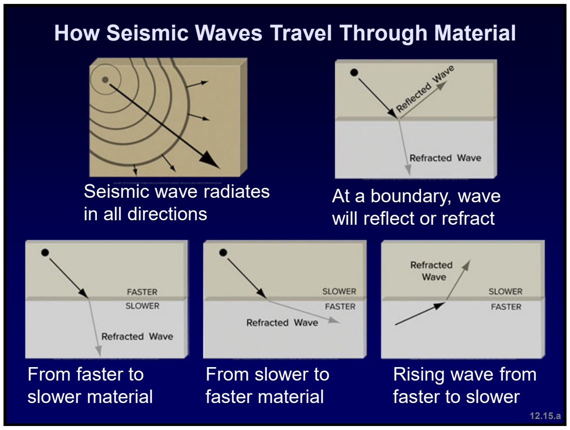
Moderate EQs along eastern zone

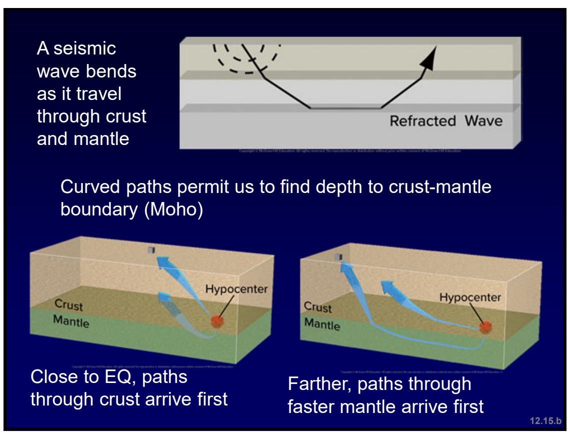
12.13.a1

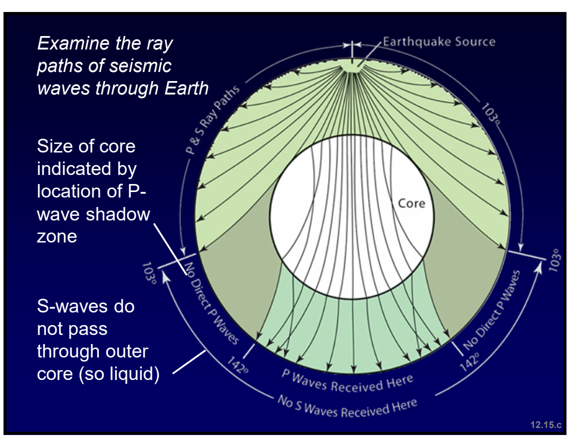

Observe features along the San Andreas fault
Offset Drainage Channel
Linear Ridge
Scarp
Linear Valley
Drainage Parallel to Fault
Spring
Pond
Faults
Aerial photograph of same area
12.13.a

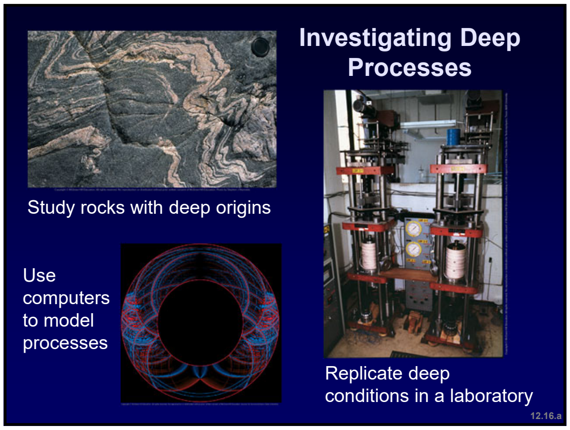

Exploring the Subsurface: Physical Samples
Exposures of deep, uplifted rocks
Magma that brings up pieces of deeper rocks
Mines
Drilling
12.14.a

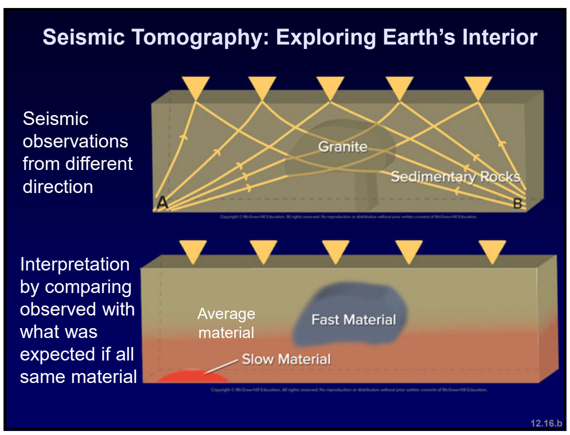

Exploring the Subsurface: Geophysical Surveys
CROSS SECTION VIEW
Low
High
Medium
Very High
CONDUCTIVITIES
Electrical surveys
Magnetic data
Seismic-reflection data
Gravity data
GRAVITY (Relative to Local Average)
LOCATION ALONG SURVEY
Gravity model
2.2
2.4
2.65
DENSITY (g/cm³)
12.14.a

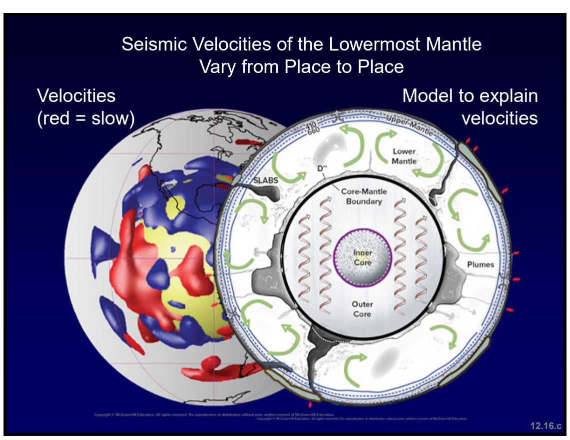

How Seismic Waves Travel Through Material
Reflected Wave
Refracted Wave
Seismic wave radiates in all directions
At a boundary, wave will reflect or refract
FASTER
SLOWER
Refracted Wave
SLOWER
FASTER
Refracted Wave
Refracted Wave
SLOWER
FASTER
From faster to slower material
From slower to faster material
Rising wave from faster to slower
12.15.a


A seismic wave bends as it travel through crust and mantle
Refracted Wave
Curved paths permit us to find depth to crust-mantle boundary (Moho)
Hypocenter
Crust
Mantle
Hypocenter
Crust
Mantle
Close to EQ, paths through crust arrive first
Farther, paths through faster mantle arrive first
12.15.b


Examine the ray paths of seismic waves through Earth
Size of core indicated by location of P-wave shadow zone
S-waves do not pass through outer core (so liquid)
Earthquake Source
P & S Ray Paths
103°
Core
103°
103°
No Direct P Waves
No Direct P Waves
142°
142°
P Waves Received Here
No S Waves Received Here
12.15.c


Investigating Deep Processes
Study rocks with deep origins
Use computers to model processes
Replicate deep conditions in a laboratory
12.16.a

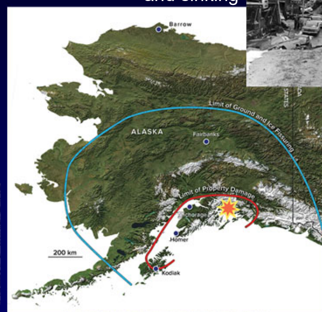

Seismic Tomography: Exploring Earth's Interior
Seismic observations from different direction
Granite
Sedimentary Rocks
A
B
Interpretation by comparing observed with what was expected if all same material
Average material
Fast Material
Slow Material
12.16.b


Seismic Velocities of the Lowermost Mantle Vary from Place to Place
Velocities (red = slow)
Model to explain velocities
Upper Mantle
Lower Mantle
SLABS
D"
Core-Mantle Boundary
Inner Core
Outer Core
Plumes
12.16.c

Great Alaskan Earthquake of 1964

Landslides

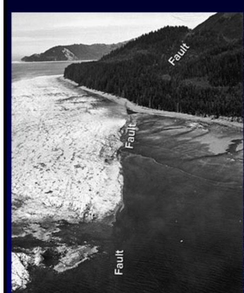
Sliding along clay



Shaking and sinking

12.17.a

Manifestations of the Earthquake in the Sea



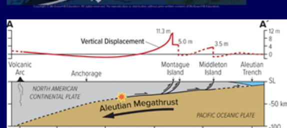
Seafloor uplifted 4 to 5 m along faults

Tsunami destroys coastal areas

12.17.b

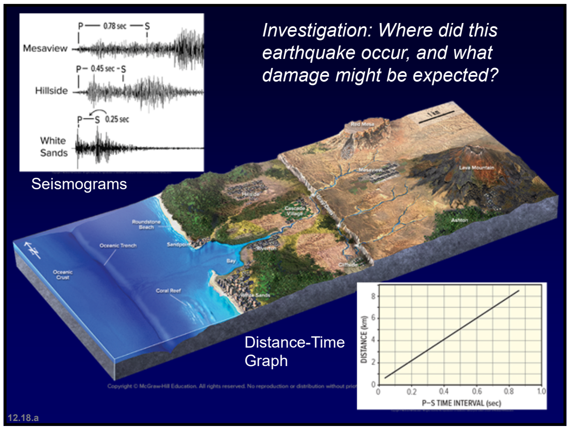
How Geologists Studied the Earthquake

Mapped areas uplifted and subsided by earthquake



Generalized cross section of megathrust

12.17.c


Investigation: Where did this earthquake occur, and what damage might be expected?
P — 0.78 sec — S
Mesaview
P — 0.45 sec - S
Hillside
P — S 0.25 sec
White Sands
Seismograms
Red Mesa
1 km
Lava Mountain
Mesaview
Hillside
Cascade Village
Ashton
Roundstone Beach
Oceanic Trench
Sandpoint
Riverton
Bay
Cliffside
Oceanic Crust
Coral Reef
White Sands
Distance-Time Graph
DISTANCE (km)
0
2
4
6
8
0
0.2
0.4
0.6
0.8
1.0
P–S TIME INTERVAL (sec)
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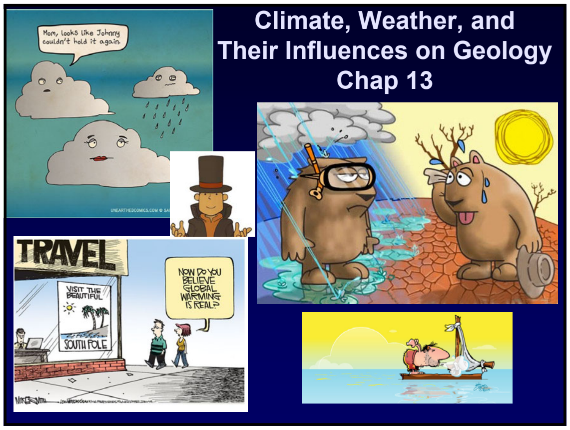
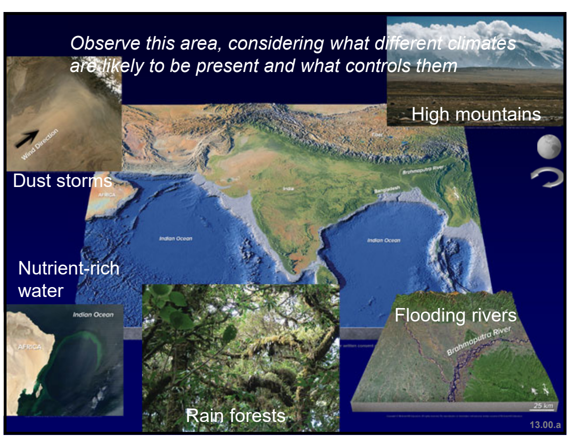
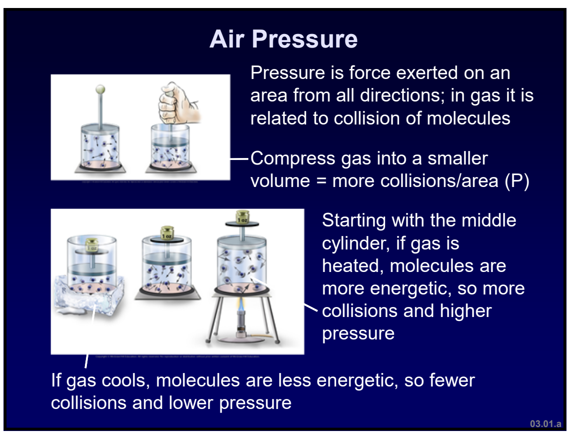
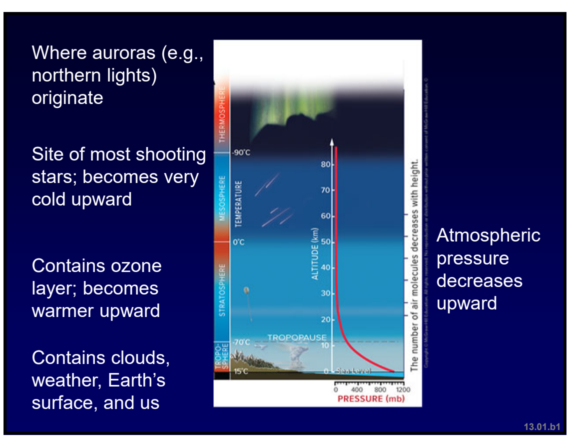
12.18.a


Climate, Weather, and
Their Influences on Geology
Chap 13
Mom, looks like Johnny couldn't hold it again.
TRAVEL
VISIT THE BEAUTIFUL
SOUTH POLE
NOW DO YOU BELIEVE GLOBAL WARMING IS REAL?

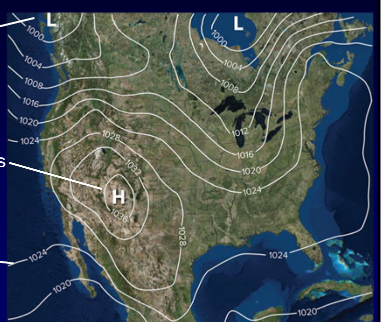

Observe this area, considering what different climates are likely to be present and what controls them
High mountains
Dust storms
Nutrient-rich water
Flooding rivers
Rain forests
13.00.a


Continental Arctic
Bitterly cold, dry
Maritime Polar
Cool, moist
Continental Polar
Cold, dry
Maritime Polar
Cool, moist
Continental Tropic
Hot, dry
Maritime Tropic
Warm, moist
Maritime Tropic
Warm, moist


Air Pressure
Pressure is force exerted on an area from all directions; in gas it is related to collision of molecules
Compress gas into a smaller volume = more collisions/area (P)
Starting with the middle cylinder, if gas is heated, molecules are more energetic, so more collisions and higher pressure
If gas cools, molecules are less energetic, so fewer collisions and lower pressure
03.01.a


Where auroras (e.g., northern lights) originate
Site of most shooting stars; becomes very cold upward
Contains ozone layer; becomes warmer upward
Contains clouds, weather, Earth's surface, and us
THERMOSPHERE
MESOSPHERE
STRATOSPHERE
TEMPERATURE
-90°C
0°C
-70°C
15°C
ALTITUDE (km)
TROPOPAUSE
PRESSURE (mb)
The number of air molecules decreases with height.
Atmospheric pressure decreases upward
13.01.b1

Observe this map of air pressures (on some day) and note the features, main patterns, and values on lines



Center of low pressure (L); lines define a cyclone or trough

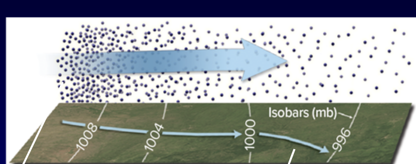
Center of high pressure (H); lines define an anticyclone or ridge

Line of equal pressure is *isobar*; values in millibars

13.01.c1

Air Pressure and Horizontal Motion

Air pressure varies laterally (between adjacent areas)



Gas molecules in area of high pressure tend to spread out, flowing from high pressure to lower pressure (causing wind)

If only responding to pressure difference, wind would blow perpendicular to isobars

13.01.d1

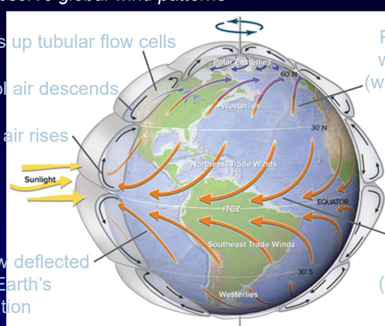
Local Winds along Coasts

During the day, heating of land causes air to rise, causing low pressure and wind from sea (*sea breeze)*

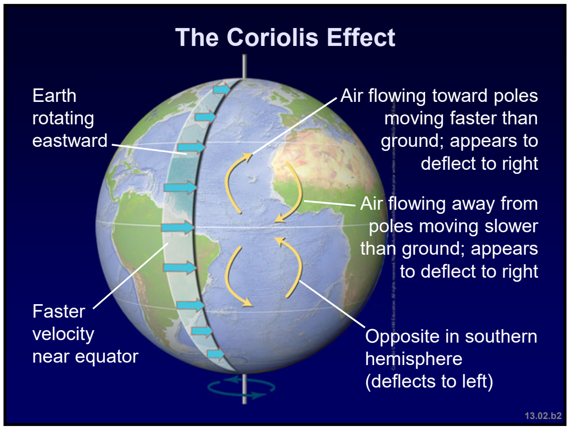
Land cools more at night, so air sinks, increases pressure, and blows out to sea (*land breeze)*

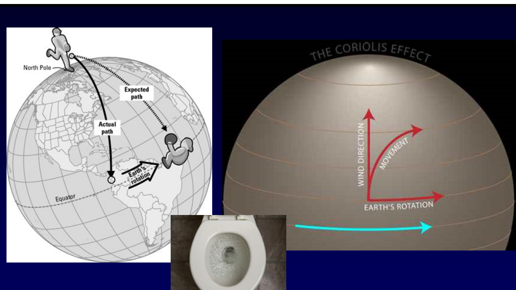
13.02.a

Observe global wind patterns

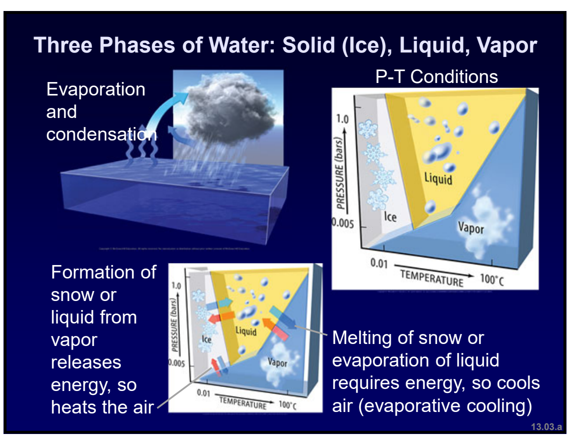


13.02.b1

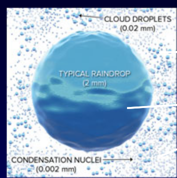




an effect whereby a mass moving in a rotating system experiences a force (the *Coriolis force*) acting perpendicular to the direction of motion and to the axis of rotation. On the earth, the effect tends to deflect moving objects to the right in the northern hemisphere and to the left in the southern and is important in the formation of cyclonic weather systems.



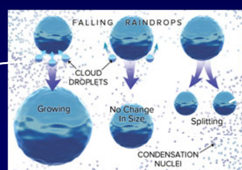
Precipitation



Involves three sizes of particles

- Cloud droplets: water drops too small to fall, so stay aloft
- Raindrops: large enough to fall
- Smallest: condensation nuclei, such as dust particles

Drops can grow by incorporating other drops

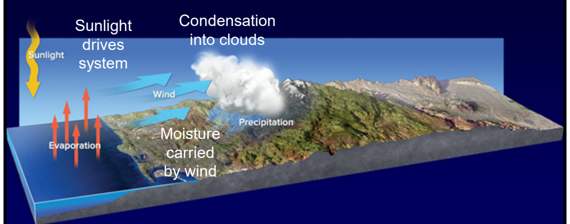


Drops become smaller if split apart

May not change in size

13.03.b

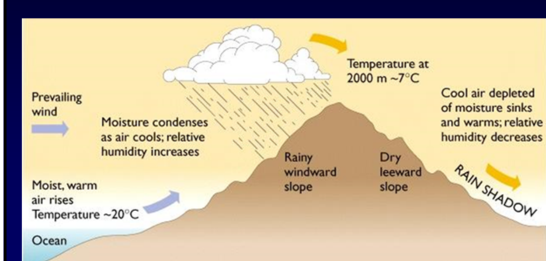
How does water move between the surface and atmosphere?



13.04.a1

Rain Shadow Deserts

Orographic Relief

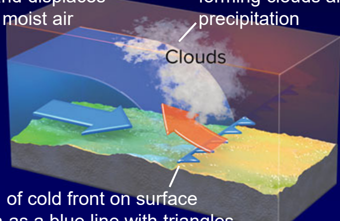


Cold Front

Fronts are boundaries between two types of air masses, such as a warm, humid one and a cold, dry one

Cold front: cold air moves and displaces warmer, moist air

Cold air lifts warm air, forming clouds and precipitation



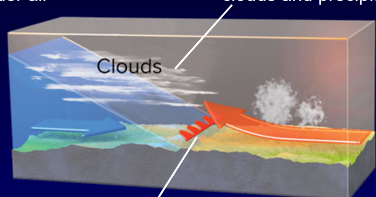
Location of cold front on surface is shown as a blue line with triangles pointing in the direction of movement

13.04.b1

Warm Front

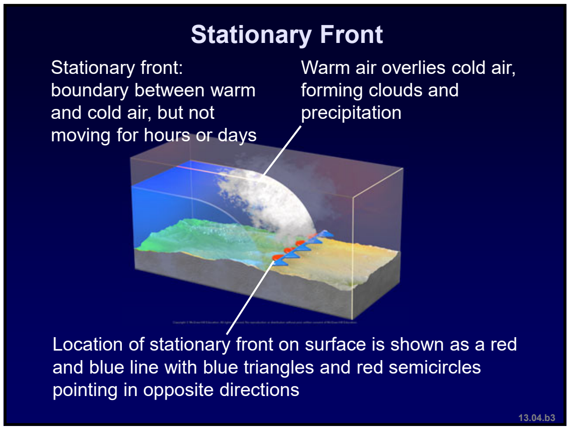
Warm front: warm air moves and displaces colder air

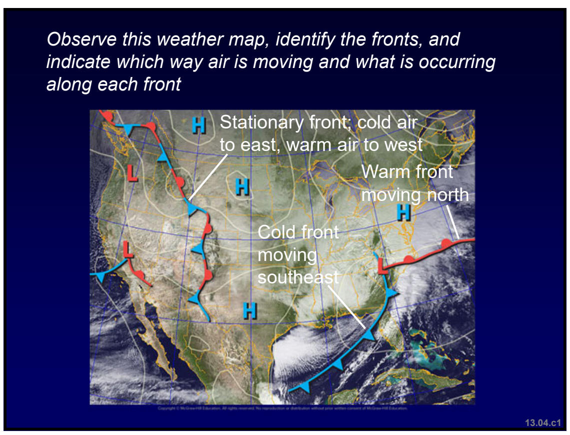
Warm air rides over cold air, forming layered clouds and precipitation

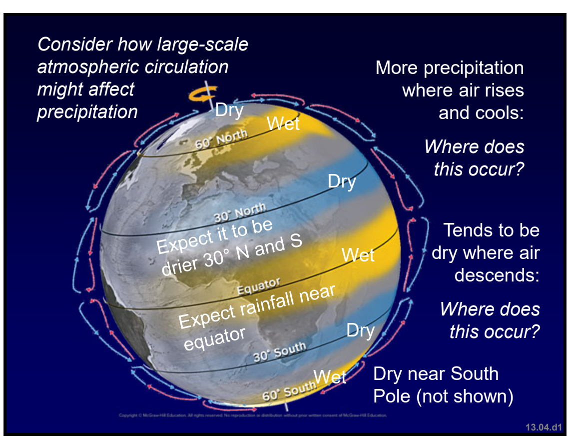


Location of warm front on surface is shown as a red line with semicircles pointing in the direction of movement

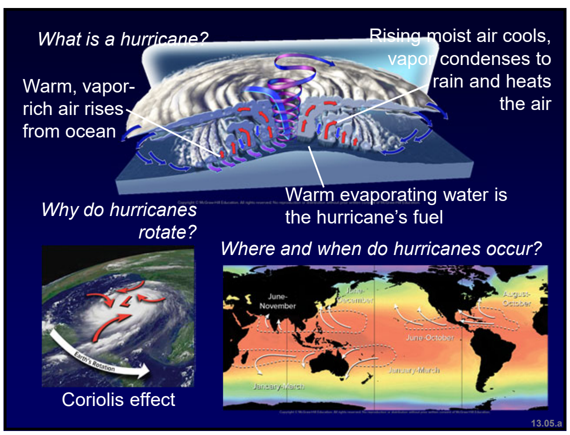
13.04.b2

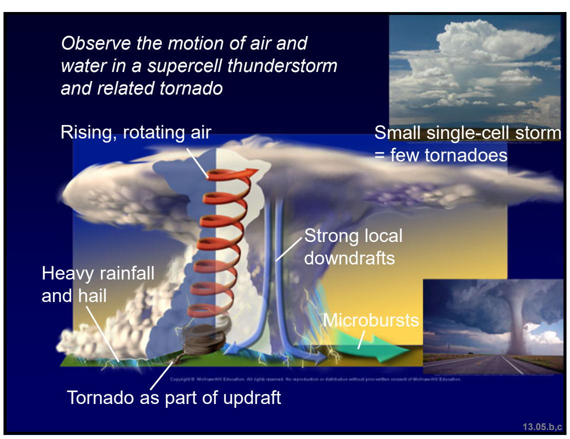

Stationary Front
Stationary front: boundary between warm and cold air, but not moving for hours or days
Warm air overlies cold air, forming clouds and precipitation
Location of stationary front on surface is shown as a red and blue line with blue triangles and red semicircles pointing in opposite directions
13.04.b3

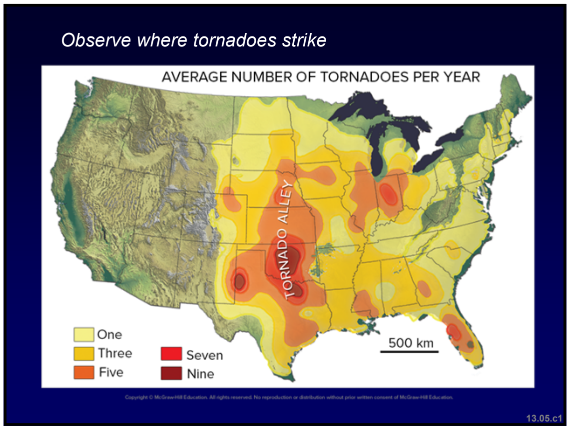

Observe this weather map, identify the fronts, and indicate which way air is moving and what is occurring along each front
Stationary front; cold air to east, warm air to west
Warm front moving north
Cold front moving southeast
H
H
H
H
L
L
L
13.04.c1

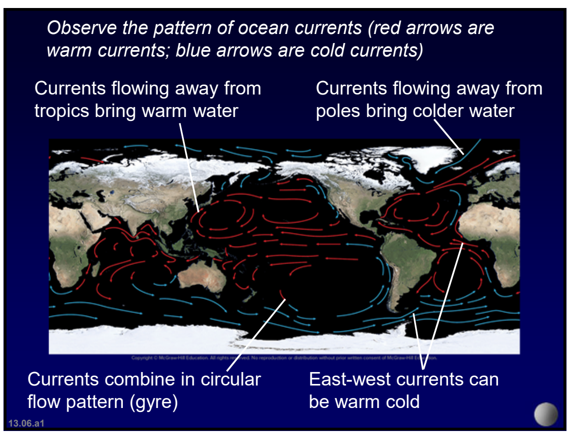

Consider how large-scale atmospheric circulation might affect precipitation
More precipitation where air rises and cools:
Where does this occur?
Tends to be dry where air descends:
Where does this occur?
Dry near South Pole (not shown)
Dry
Wet
60° North
Dry
30° North
Expect it to be drier 30° N and S
Wet
Equator
Expect rainfall near equator
Dry
30° South
Wet
60° South
13.04.d1

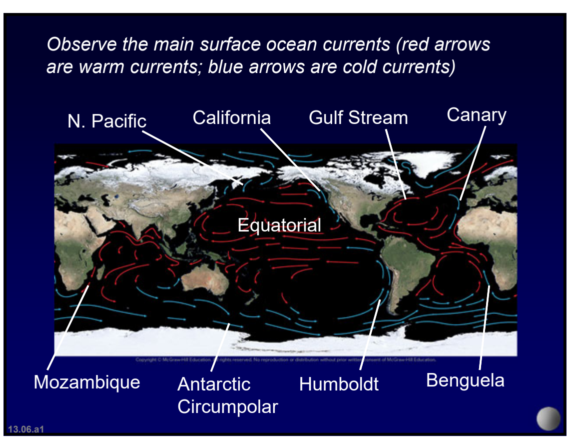

Northern Horse Latitudes
Tropic of Cancer
Equator
Tropic of Capricorn
Southern Horse Latitudes

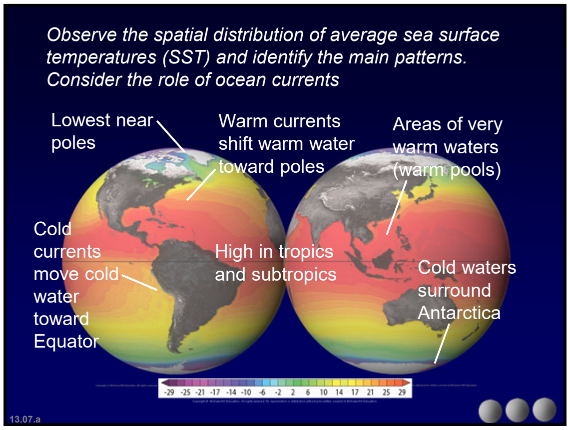

What is a hurricane?
Rising moist air cools, vapor condenses to rain and heats the air
Warm, vapor-rich air rises from ocean
Warm evaporating water is the hurricane's fuel
Why do hurricanes rotate?
Where and when do hurricanes occur?
June-November
August-October
June-October
January-March
Coriolis effect
13.05.a

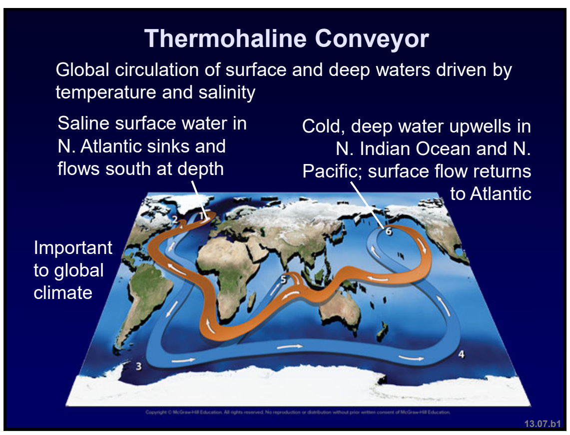

Observe the motion of air and water in a supercell thunderstorm and related tornado
Rising, rotating air
Small single-cell storm = few tornadoes
Strong local downdrafts
Heavy rainfall and hail
Microbursts
Tornado as part of updraft
13.05.b,c

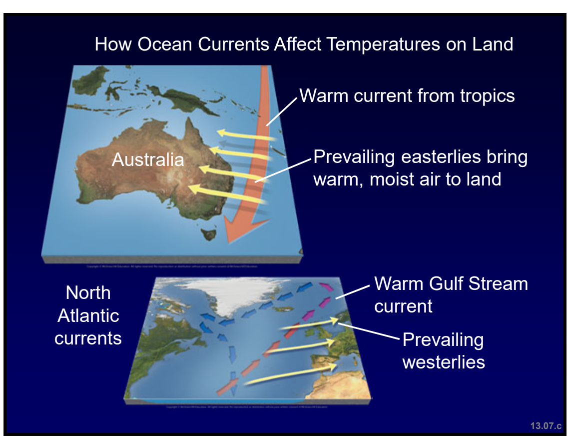

Observe where tornadoes strike
AVERAGE NUMBER OF TORNADOES PER YEAR
TORNADO ALLEY
One
Three
Five
Seven
Nine
500 km
13.05.c1

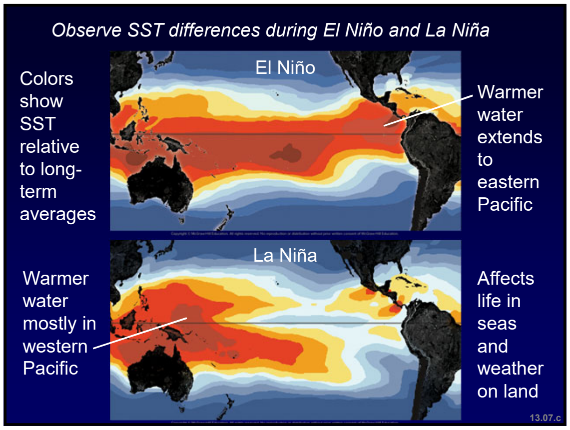

Observe the pattern of ocean currents (red arrows are warm currents; blue arrows are cold currents)
Currents flowing away from tropics bring warm water
Currents flowing away from poles bring colder water
Currents combine in circular flow pattern (gyre)
East-west currents can be warm cold
13.06.a1

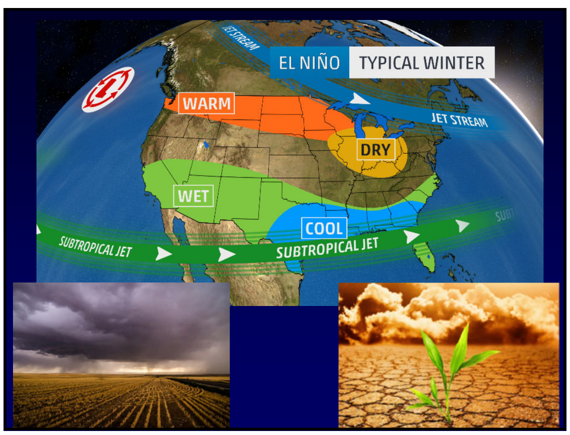

Observe the main surface ocean currents (red arrows are warm currents; blue arrows are cold currents)
N. Pacific
California
Gulf Stream
Canary
Equatorial
Mozambique
Antarctic Circumpolar
Humboldt
Benguela
13.06.a1

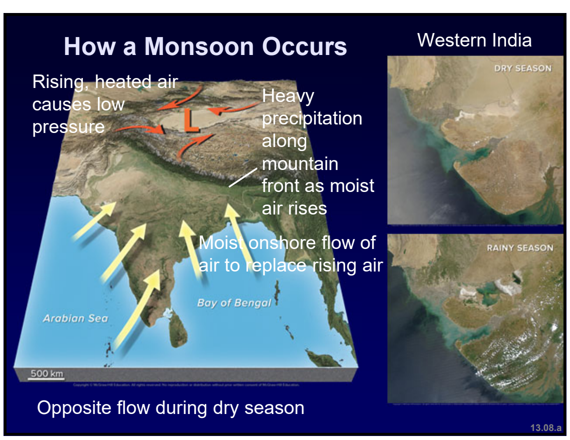

Observe the spatial distribution of average sea surface temperatures (SST) and identify the main patterns. Consider the role of ocean currents
Lowest near poles
Warm currents shift warm water toward poles
Areas of very warm waters (warm pools)
Cold currents move cold water toward Equator
High in tropics and subtropics
Cold waters surround Antarctica
13.07.a

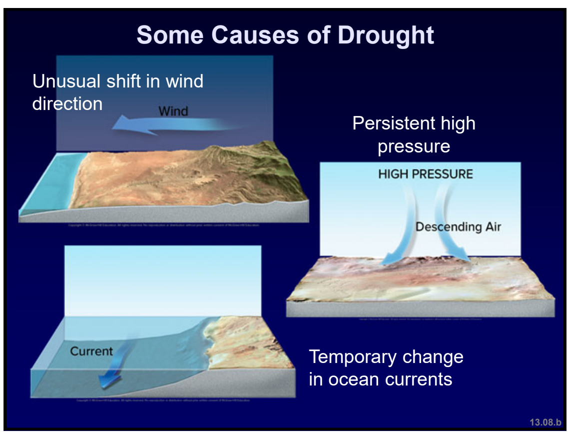

Thermohaline Conveyor
Global circulation of surface and deep waters driven by temperature and salinity
Saline surface water in N. Atlantic sinks and flows south at depth
Cold, deep water upwells in N. Indian Ocean and N. Pacific; surface flow returns to Atlantic
Important to global climate
13.07.b1

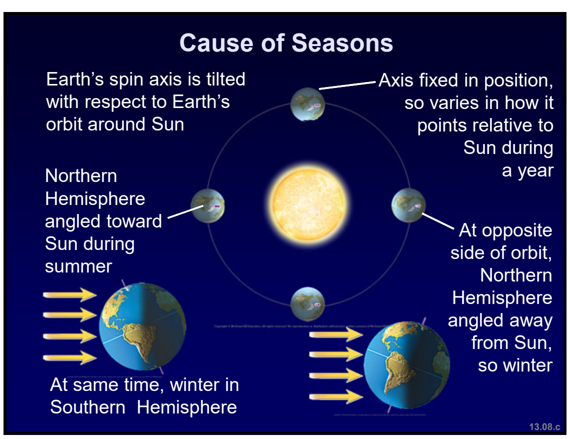

How Ocean Currents Affect Temperatures on Land
Warm current from tropics
Australia
Prevailing easterlies bring warm, moist air to land
North Atlantic currents
Warm Gulf Stream current
Prevailing westerlies
13.07.c

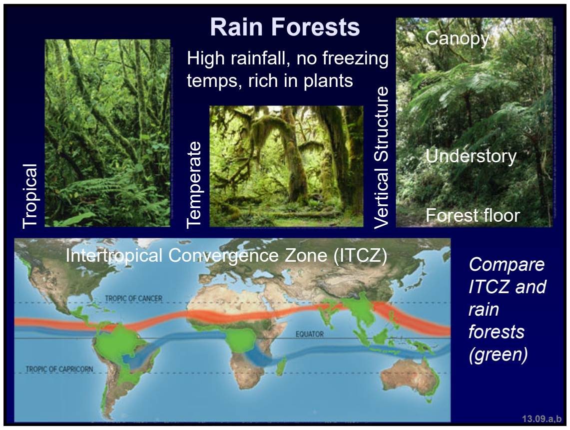

Observe SST differences during El Niño and La Niña
Colors show SST relative to long-term averages
El Niño
Warmer water extends to eastern Pacific
La Niña
Warmer water mostly in western Pacific
Affects life in seas and weather on land
13.07.c

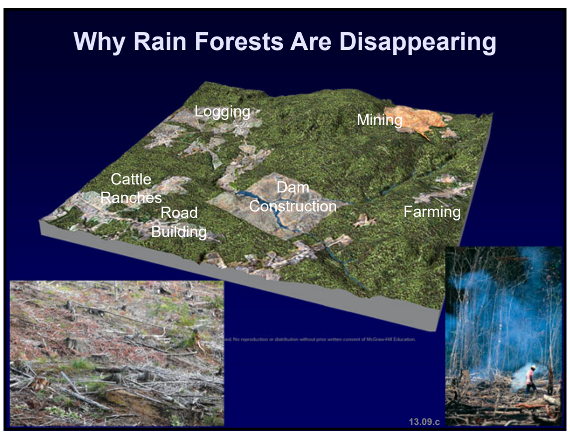

JET STREAM
EL NIÑO
TYPICAL WINTER
WARM
JET STREAM
DRY
WET
COOL
SUBTROPICAL JET
SUBTROPICAL JET


How a Monsoon Occurs
Rising, heated air causes low pressure
L
Heavy precipitation along mountain front as moist air rises
Moist onshore flow of air to replace rising air
Arabian Sea
Bay of Bengal
500 km
Opposite flow during dry season
Western India
DRY SEASON
RAINY SEASON
13.08.a

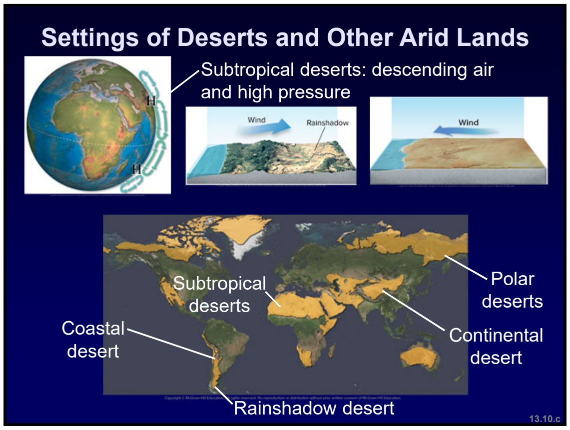

Some Causes of Drought
Unusual shift in wind direction
Wind
Persistent high pressure
HIGH PRESSURE
Descending Air
Current
Temporary change in ocean currents
13.08.b

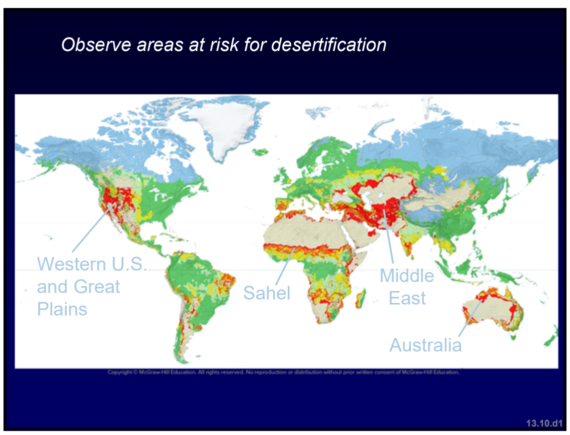

Cause of Seasons
Earth's spin axis is tilted with respect to Earth's orbit around Sun
Axis fixed in position, so varies in how it points relative to Sun during a year
Northern Hemisphere angled toward Sun during summer
At opposite side of orbit, Northern Hemisphere angled away from Sun, so winter
At same time, winter in Southern Hemisphere
13.08.c

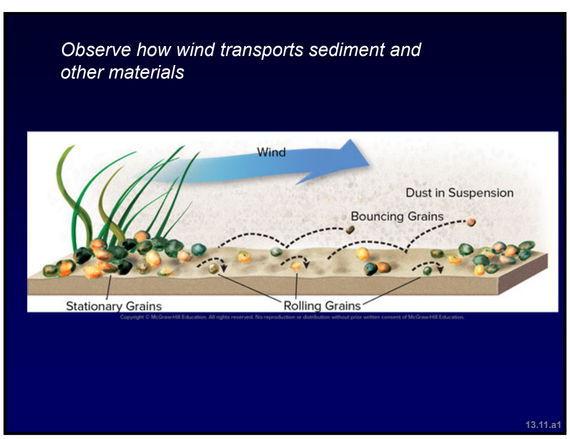

Rain Forests
High rainfall, no freezing temps, rich in plants
Tropical
Temperate
Vertical Structure
Canopy
Understory
Forest floor
Intertropical Convergence Zone (ITCZ)
TROPIC OF CANCER
EQUATOR
TROPIC OF CAPRICORN
Compare ITCZ and rain forests (green)
13.09.a,b


Why Rain Forests Are Disappearing
Logging
Mining
Cattle Ranches
Road Building
Dam Construction
Farming
13.09.c


Observe locations of deserts and other arid lands
Mojave Desert
Sonoran Desert
13.10.a,b


Settings of Deserts and Other Arid Lands
Subtropical deserts: descending air and high pressure
Wind
Rainshadow
Wind
Subtropical deserts
Polar deserts
Coastal desert
Continental desert
Rainshadow desert
13.10.c


Observe areas at risk for desertification
Western U.S. and Great Plains
Sahel
Middle East
Australia
13.10.d1

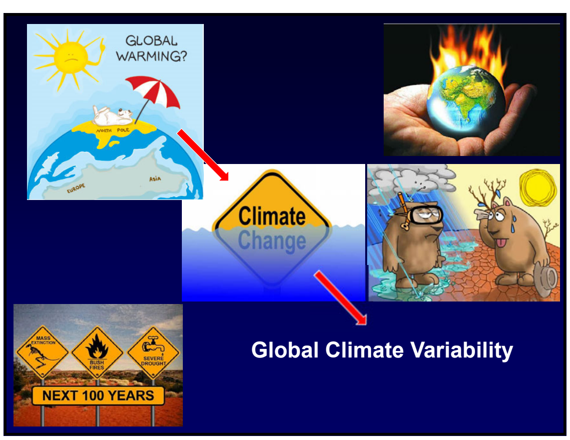

Observe how wind transports sediment and other materials
Wind
Dust in Suspension
Bouncing Grains
Stationary Grains
Rolling Grains
13.11.a1


Dust Storms and Whirlwinds
Sand and dust storm originating from North Africa
NORTH AFRICA
Dust storm (related to thunder-storm)
Whirlwinds
13.11.b

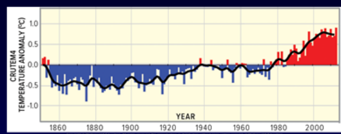

Deposition and Erosion by Wind
Sand Dunes
Loess: Windblown Silt
Wind Erosion
13.11.c


Landscape Features Characteristic of Deserts
Alluvial fan
Desert wash
Playa
Fans,
washes, playas
Sand dunes
13.12.a

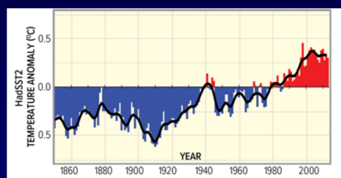

Features the Develop Over Time in Deserts
Pediment
Desert pavement
Caliche
Desert varnish
Natural stains
13.12.b


GLOBAL
WARMING?
Climate
Change
NEXT 100 YEARS
Global Climate Variability

Evidence of Climate Change



Increase in global average air temperature beginning ~1890

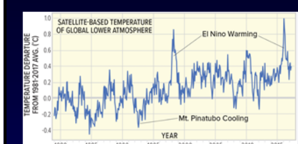


Sea-surface temperatures show similar warming since ~1910

Anomaly: difference between a value and the average of that value

13.13.a

Evidence of Climate Change II

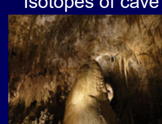


Satellite measurements also record times of warming, cooling, and little change in temperature

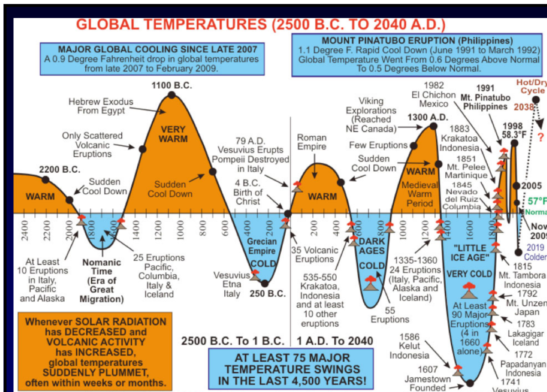
Correlate these changes to various types of events

We use other types of data, called *proxies*, to reconstruct temperature before thermometers existed

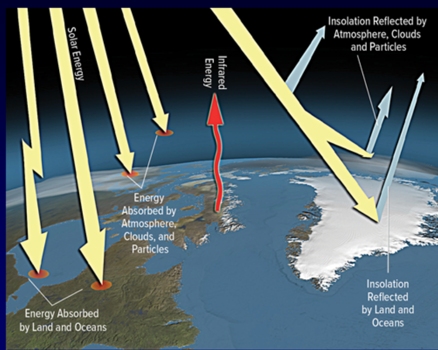
Isotopes of cave deposits and fossils



13.13.a

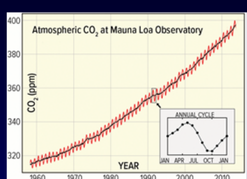


Interaction of Insolation with Earth



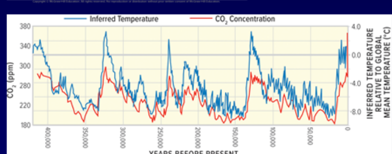
13.14.a1

Factors Affecting Climate Change I



Greenhouse gases, like water vapor and carbon dioxide (CO_2), absorb heat radiated from the Earth, warming the planet

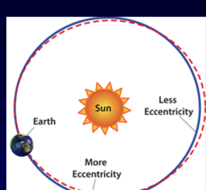
Human activities have added CO_2 into atmosphere from burning forests and fossil fuels

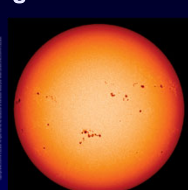


Ice cores indicate that temperature and CO_2 changed together during ice advances

13.14.a

Factors Affecting Climate Change II

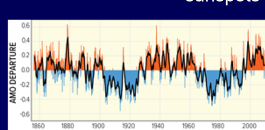




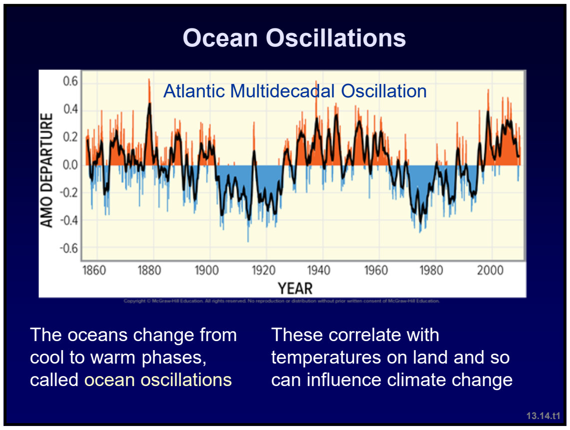
Changes in energy from Sun, as either measured directly or estimated from sunspots

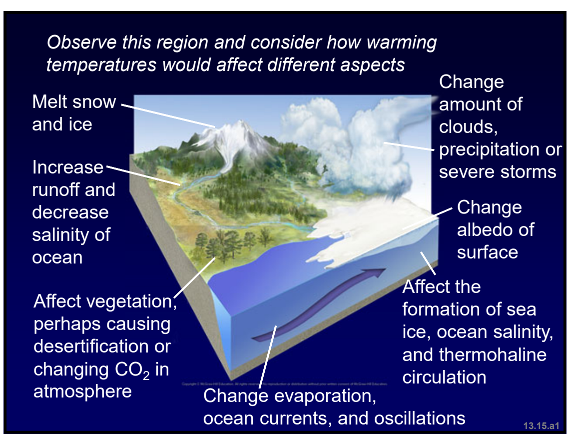
Changes in Earth's orbit and in tilt of spin axis

Ocean oscillations, such as ENSO, Pacific Decadal Oscillation, and North Atlantic Oscillation



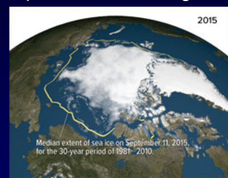
13.14.a,t


Ocean Oscillations
Atlantic Multidecadal Oscillation
AMO DEPARTURE
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
1860
1880
1900
1920
1940
1960
1980
2000
YEAR
The oceans change from cool to warm phases, called ocean oscillations
These correlate with temperatures on land and so can influence climate change


Observe this region and consider how warming temperatures would affect different aspects
Melt snow and ice
Increase runoff and decrease salinity of ocean
Affect vegetation, perhaps causing desertification or changing CO_2 in atmosphere
Change evaporation, ocean currents, and oscillations
Change amount of clouds, precipitation or severe storms
Change albedo of surface
Affect the formation of sea ice, ocean salinity, and thermohaline circulation

Implications of Climate Change

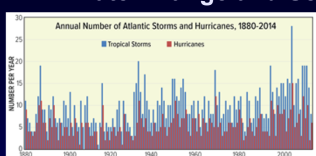
The computer-generated images below depict the decrease in sea ice in the Arctic between 1979 (left globe) and 2003 (right globe), while the planet was warming

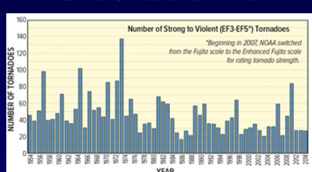


Melting of sea ice does not affect sea levels but does decrease the albedo of the surface, habitats of arctic creatures, and the salinity of underlying sea water (which can affect the thermohaline circulation)

13.15.a

Climate Change and Severe Weather





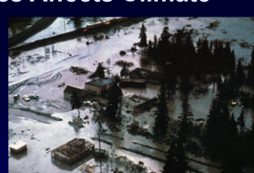
Climate change could affect the frequency or strength of severe storms

What do data for number of tropical cyclones in the Atlantic (top graph) or number of strong U.S.A. tornadoes (bottom graph) suggest during times of rising temperature?

13.15.b

How Plate Tectonics Affects Climate

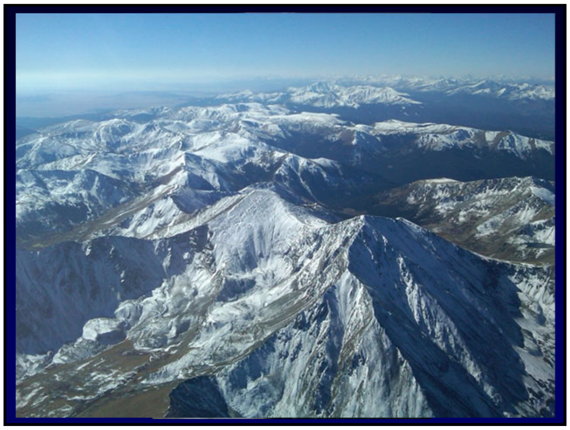
Mountains influence regional climates

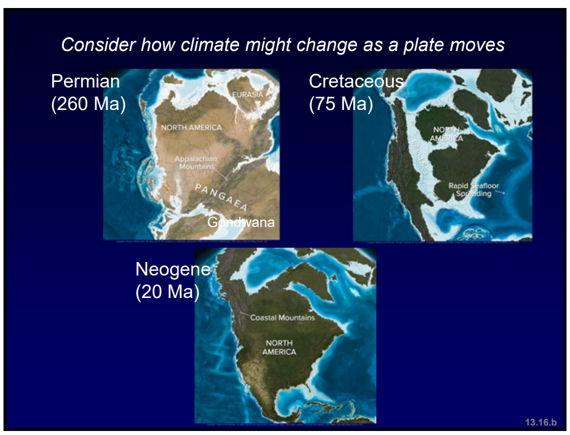


Changes in seafloor spreading affect sea level

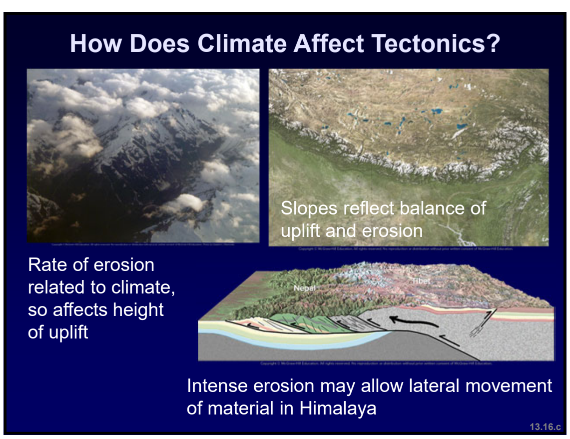
Volcanoes release gas and dust

13.16.a

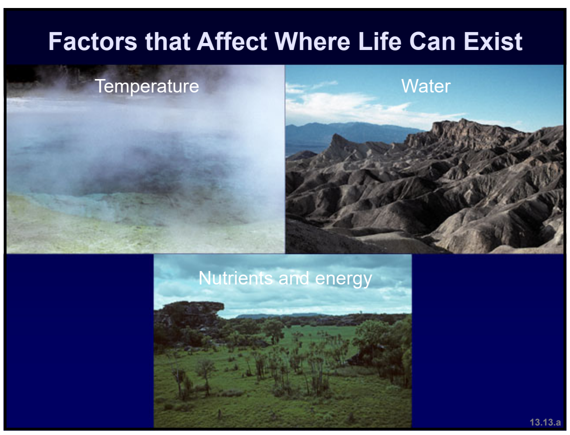


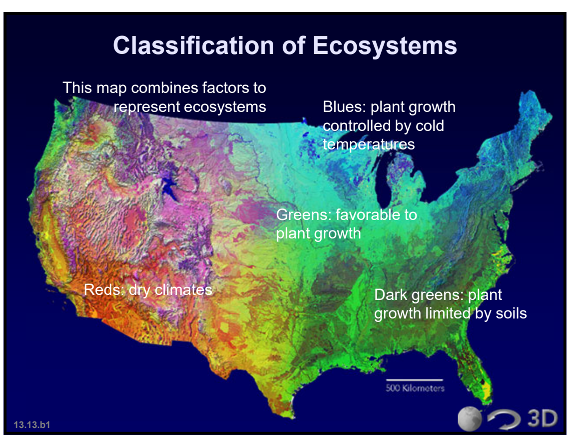


Consider how climate might change as a plate moves
Permian
(260 Ma)
Cretaceous
(75 Ma)
Neogene
(20 Ma)
Gondwana
13.16.b



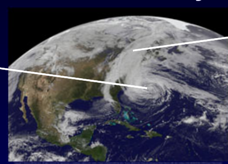
How Does Climate Affect Tectonics?
Slopes reflect balance of uplift and erosion
Rate of erosion related to climate, so affects height of uplift
Intense erosion may allow lateral movement of material in Himalaya
13.16.c


Factors that Affect Where Life Can Exist
Temperature
Water
Nutrients and energy
13.13.a


Classification of Ecosystems
This map combines factors to represent ecosystems
Blues: plant growth controlled by cold temperatures
Greens: favorable to plant growth
Reds: dry climates
Dark greens: plant growth limited by soils
500 Kilometers
13.13.b1
3D

Hurricane Sandy

Began as tropical cyclone that moved up East Coast in October 2012



Encountered cold front and mid-latitude cyclone coming from west

Coastal erosion and wind damage

Surge damage, especially New Jersey

05.17.a,t

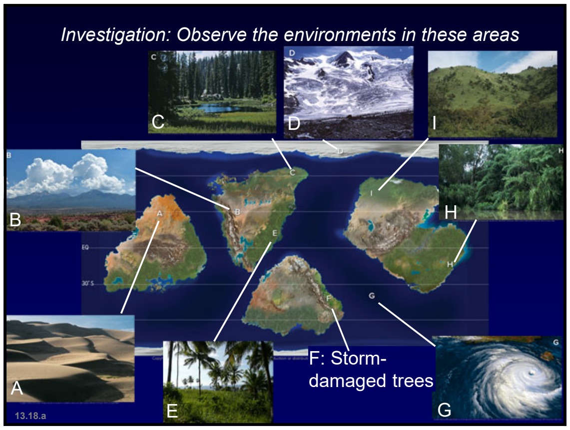
Observe the progression of Hurricane Sandy through time and identify processes that are occurring in different areas

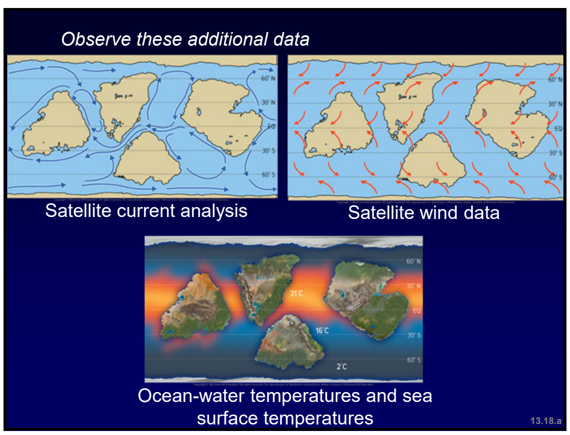
Started in tropics, moved west, and then turned north; arcuate cold front is to west

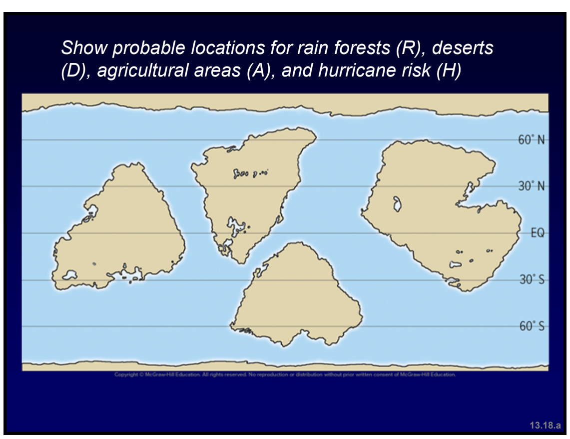
Moved up East Coast; stayed over water and within warmer waters of Gulf Stream

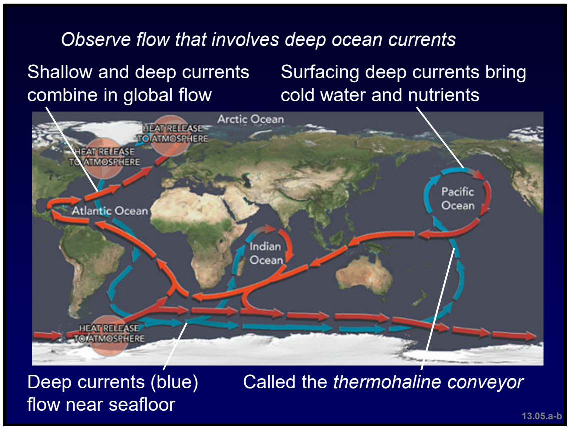
Merged with cold front and came onshore in New Jersey while weakening from hurricane status

13.17.a

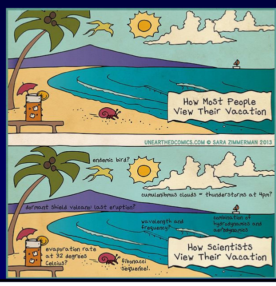

Investigation: Observe the environments in these areas
C
D
I
B
H
A
E
F: Storm-
damaged trees
G
13.18.a


Observe these additional data
Satellite current analysis
Satellite wind data
Ocean-water temperatures and sea
surface temperatures
13.18.a


Show probable locations for rain forests (R), deserts
(D), agricultural areas (A), and hurricane risk (H)
60° N
30° N
EQ
30° S
60° S
13.18.a

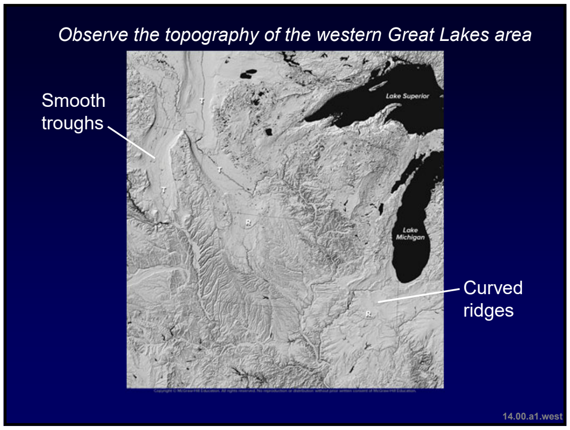

Observe flow that involves deep ocean currents
Shallow and deep currents combine in global flow
Surfacing deep currents bring cold water and nutrients
Arctic Ocean
HEAT RELEASE TO ATMOSPHERE
HEAT RELEASE TO ATMOSPHERE
Atlantic Ocean
Pacific Ocean
Indian Ocean
HEAT RELEASE TO ATMOSPHERE
Deep currents (blue) flow near seafloor
Called the *thermohaline conveyor*
13.05.a-b

Shorelines, Glaciers, and Changing Sea Levels
Chap 14



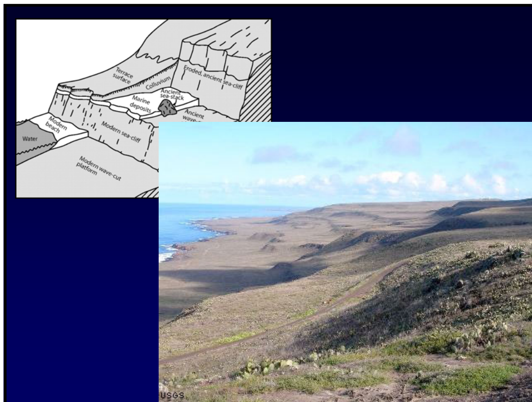
Observe the topography of the northeastern U.S.

14.00.a1


Observe the topography of the western Great Lakes area
Smooth troughs
Lake Superior
Lake Michigan
Curved ridges
14.00.a1.west


Observe the topography of the Great Lakes area
Numerous lakes
Lake Superior
CANADA
CANADA
Lake Huron
Lake Michigan
Lake Ontario
Lake Erie
Curved ridges
Long Island
Delaware Bay
14.00.a1.central


Observe the topography of the northeastern U.S.
Lake Superior
CANADA
CANADA
Smooth trough
Lake Huron
Lake Michigan
Lake Ontario
Lake Erie
Embayments in coast
Cape Cod
Long Island
Delaware Bay
Rough areas
50 km
14.00.a1.east



Glaciers

Characteristics of a Glacier

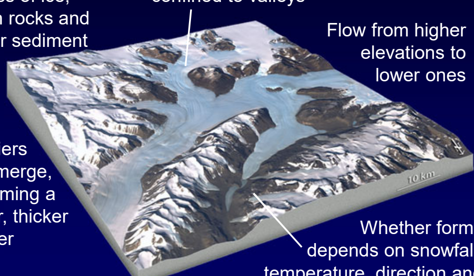
Glacier: moving mass of ice, with rocks and finer sediment

Cover broad areas or confined to valleys

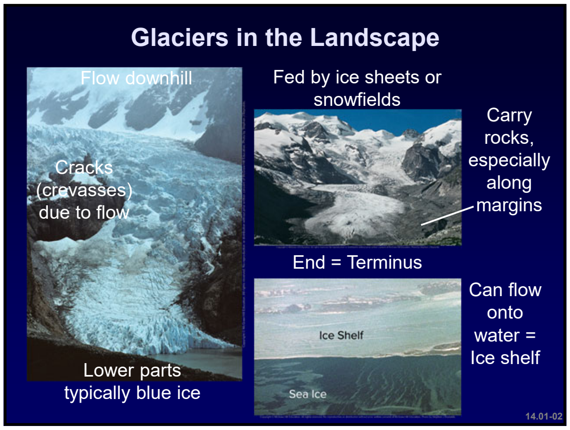
Flow from higher elevations to lower ones

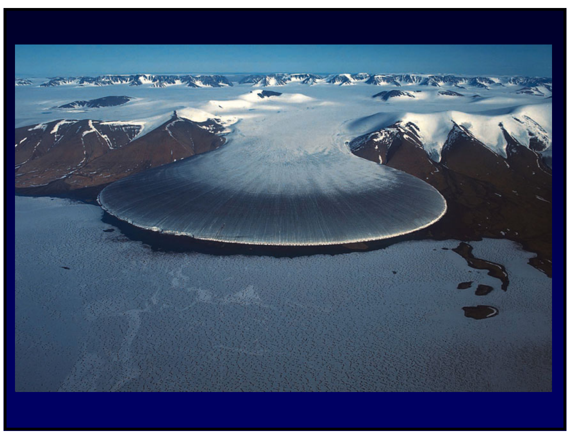
Glaciers can merge, becoming a wider, thicker glacier

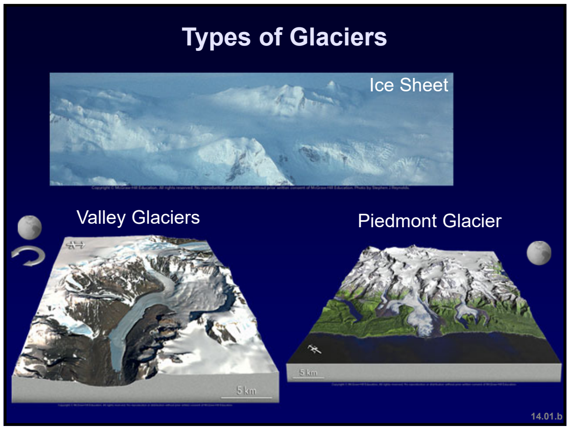
Whether forms depends on snowfall, temperature, direction and steepness of slopes, etc.

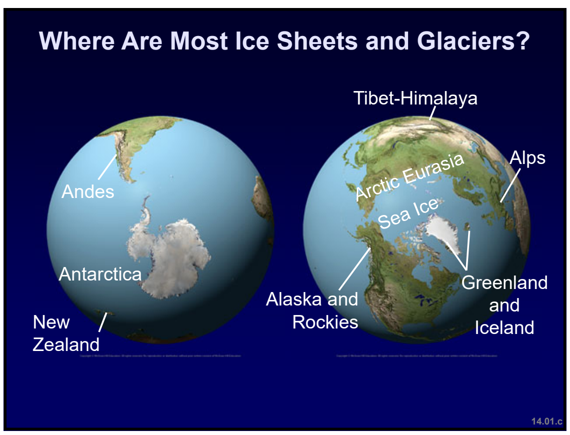


14.01.a1


Glaciers in the Landscape
Flow downhill
Cracks (crevasses) due to flow
Lower parts typically blue ice
Fed by ice sheets or snowfields
Carry rocks, especially along margins
End = Terminus
Ice Shelf
Sea Ice
Can flow onto water = Ice shelf
14.01-02




Types of Glaciers
Ice Sheet
Valley Glaciers
Piedmont Glacier
5 km
5 km
14.01.b


Where Are Most Ice Sheets and Glaciers?
Tibet-Himalaya
Andes
Alps
Arctic Eurasia
Sea Ice
Antarctica
Greenland and Iceland
Alaska and Rockies
New Zealand
14.01.c


Artic

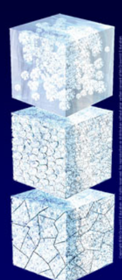
Antarctica

How Snow and Ice Accumulate in Glaciers

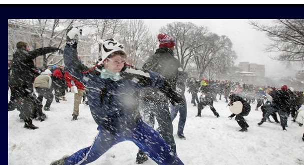
Snowflakes pressed together by weight of other snowflakes

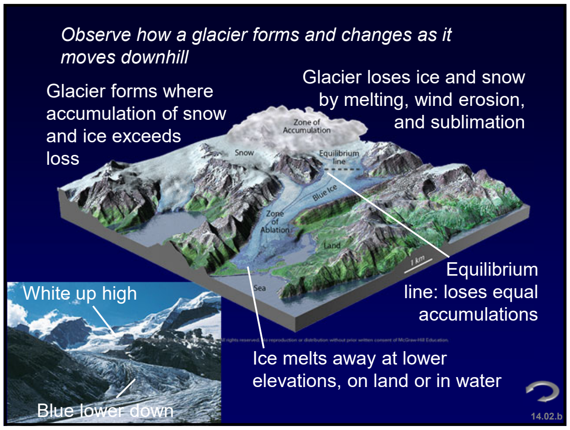
More snow adds weight and compresses flakes into small spheres

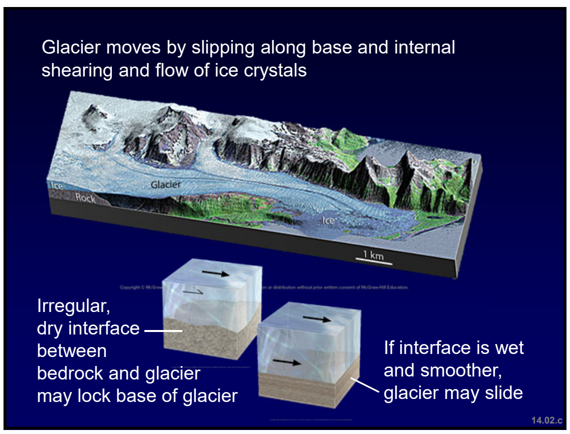
Increasing depth and pressure cause snow to become crystalline ice; commonly bluish from trapped air

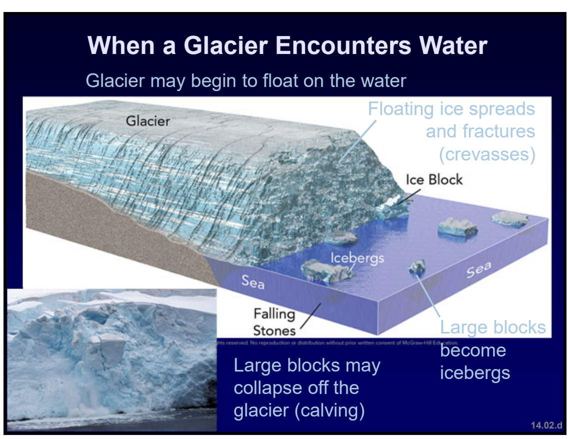


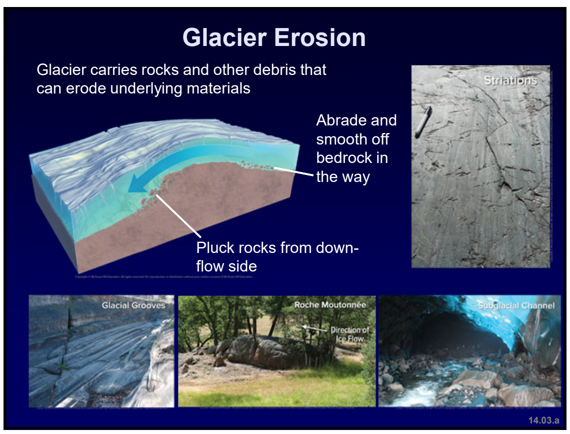
14.02.a2

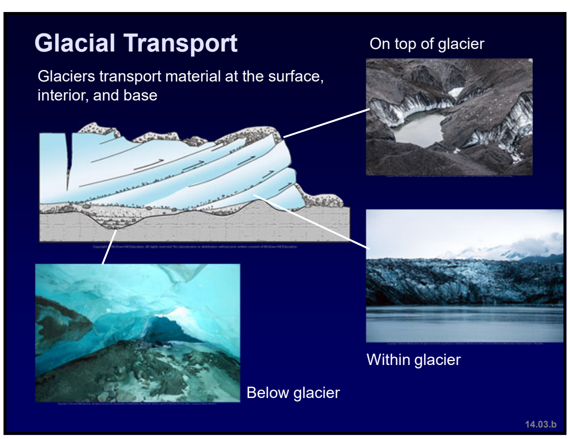


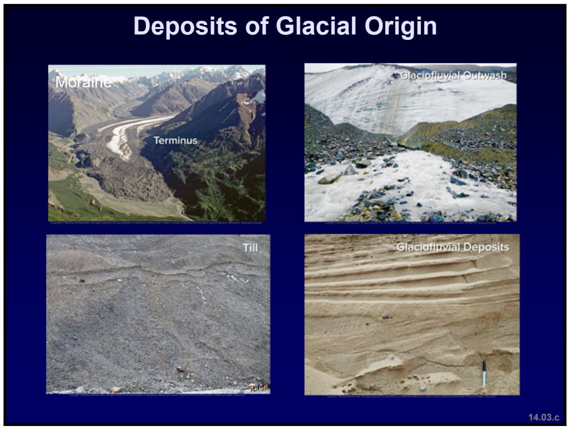

Observe how a glacier forms and changes as it moves downhill
Glacier forms where accumulation of snow and ice exceeds loss
Glacier loses ice and snow by melting, wind erosion, and sublimation
White up high
Blue lower down
Equilibrium line: loses equal accumulations
Ice melts away at lower elevations, on land or in water
14.02.b

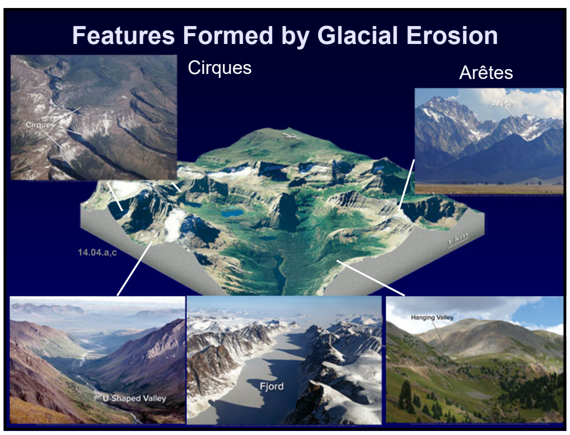

Glacier moves by slipping along base and internal shearing and flow of ice crystals
Glacier
1 km
Irregular, dry interface between bedrock and glacier may lock base of glacier
If interface is wet and smoother, glacier may slide
14.02.c

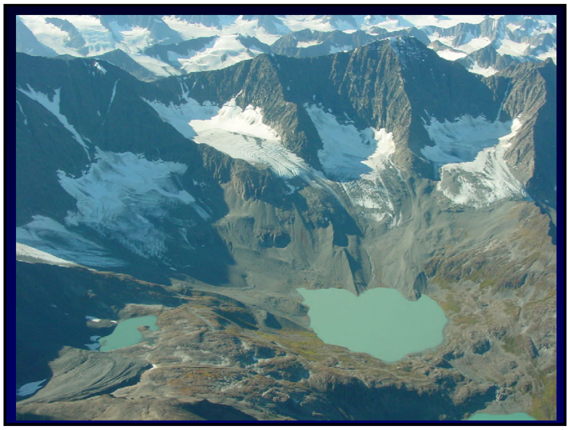

When a Glacier Encounters Water
Glacier may begin to float on the water
Glacier
Floating ice spreads and fractures (crevasses)
Ice Block
Icebergs
Sea
Sea
Falling Stones
Large blocks become icebergs
Large blocks may collapse off the glacier (calving)
14.02.d

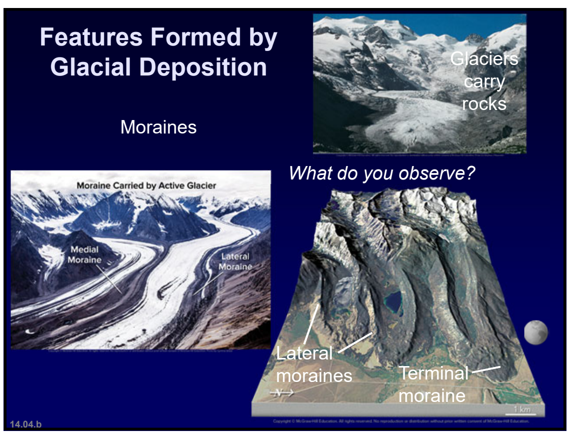

Glacier Erosion
Glacier carries rocks and other debris that can erode underlying materials
Abrade and smooth off bedrock in the way
Pluck rocks from down-flow side
Striations
Glacial Grooves
Roche Moutonnée
Direction of Ice Flow
Subglacial Channel
14.03.a


Glacial Transport
Glaciers transport material at the surface, interior, and base
On top of glacier
Within glacier
Below glacier
14.03.b

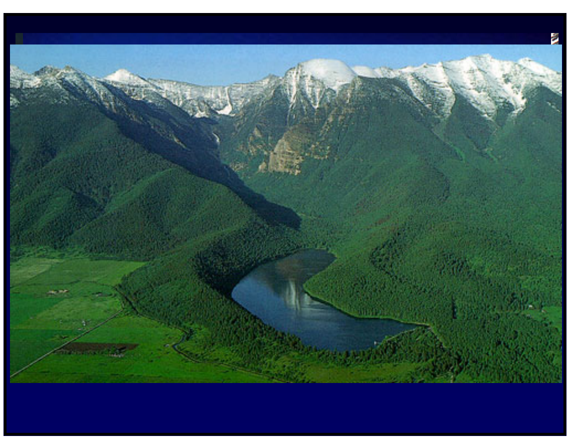

Deposits of Glacial Origin
Moraine
Terminus
Glaciofluvial Outwash
Till
Glaciofluvial Deposits
14.03.c

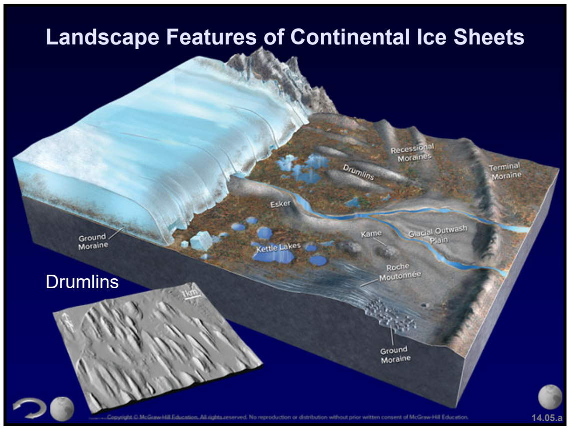

Features Formed by Glacial Erosion
Cirques
Arêtes
14.04.a,c
U-Shaped Valley
Fjord
Hanging Valley





Features Formed by Glacial Deposition
Moraines
Glaciers carry rocks
Moraine Carried by Active Glacier
Medial Moraine
Lateral Moraine
What do you observe?
Lateral moraines
Terminal moraine
14.04.b




Landscape Features of Continental Ice Sheets
Recessional Moraines
Drumlins
Terminal Moraine
Esker
Glacial Outwash Plain
Kame
Ground Moraine
Kettle Lakes
Roche Moutonnee
Ground Moraine
Drumlins
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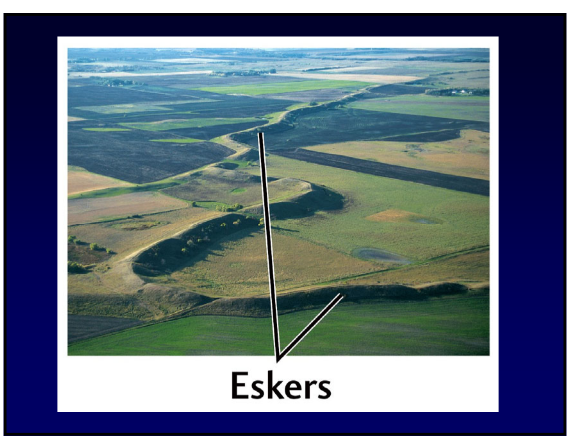
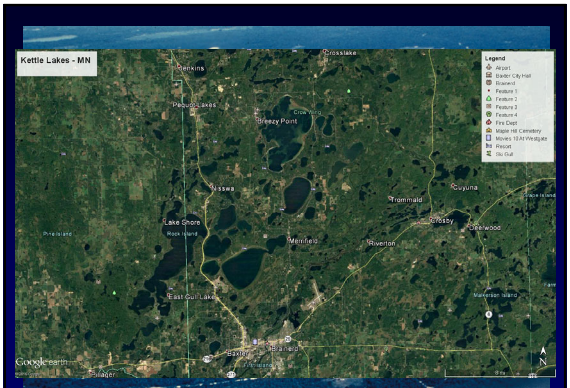
14.05.a


Eskers



Features Peripheral to Glaciers

Outwash plain

Loess

Permanently frozen ground (permafrost)

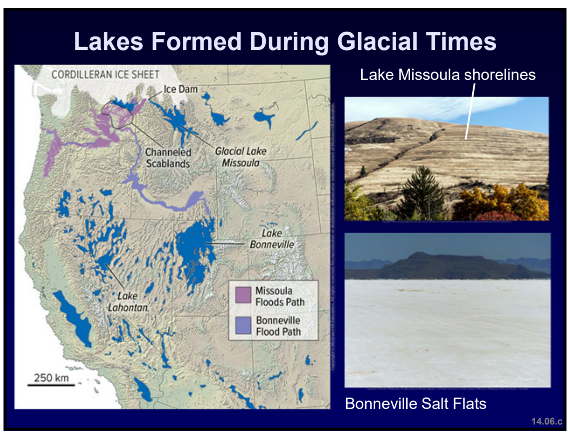
14.06.a,b

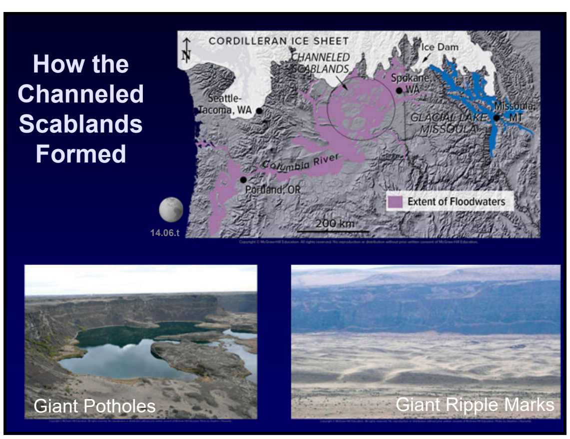
Where Is Permafrost?

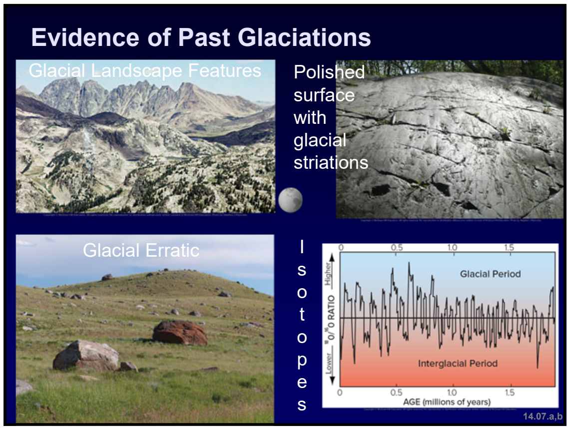
Permafrost in N. Am. mostly restricted to northern Canada and Alaska

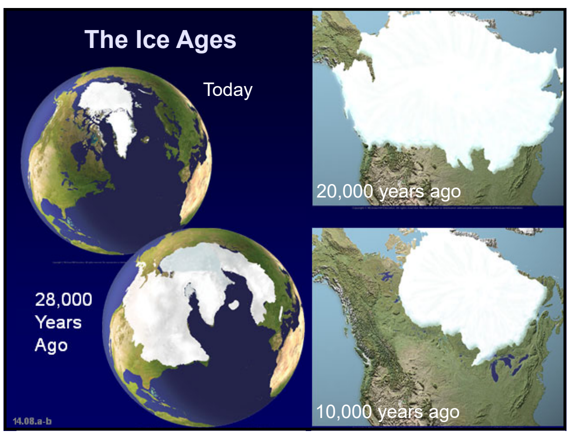
14.06.b2

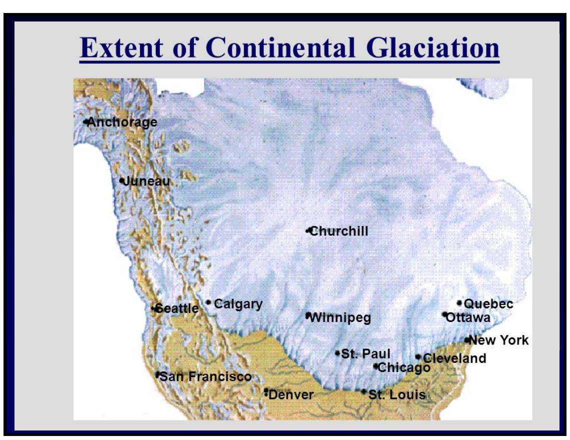

Active layer
supra-permafrost
Permafrost
intra-permafrost
Sub-permafrost talik

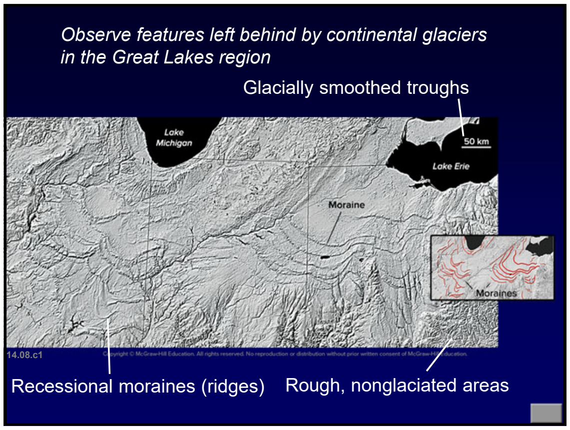

Lakes Formed During Glacial Times
CORDILLERAN ICE SHEET
Ice Dam
Channeled Scablands
Glacial Lake Missoula
Lake Bonneville
Lake Lahontan
Missoula Floods Path
Bonneville Flood Path
250 km
Lake Missoula shorelines
Bonneville Salt Flats
14.06.c

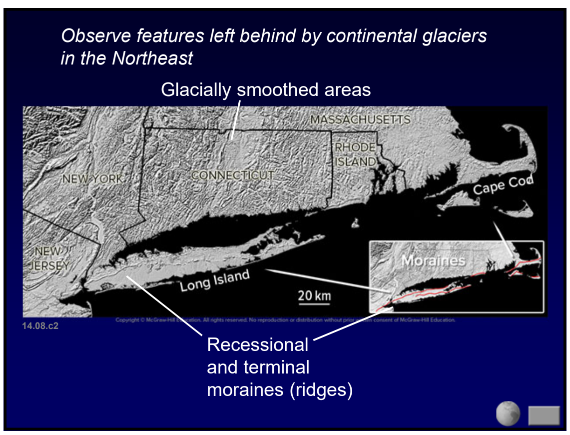

How the Channeled Scablands Formed
CORDILLERAN ICE SHEET
CHANNELED SCABLANDS
Ice Dam
Spokane, WA
Seattle-Tacoma, WA
GLACIAL LAKE MISSOULA
Missoula, MT
Columbia River
Portland, OR
Extent of Floodwaters
200 km
14.06.t
Giant Potholes
Giant Ripple Marks

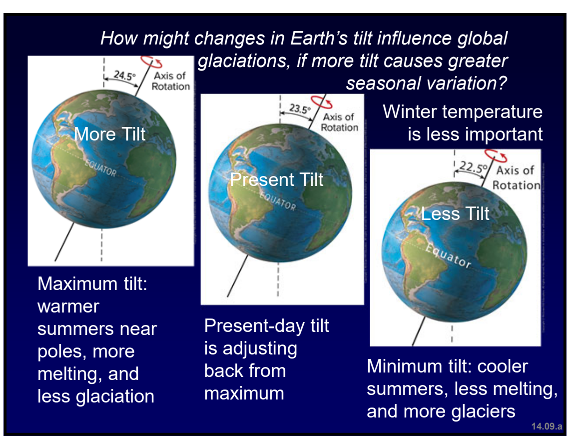

Evidence of Past Glaciations
Glacial Landscape Features
Polished surface with glacial striations
Glacial Erratic
Isotopes
Glacial Period
Interglacial Period
Higher
Lower
0 0.5 1.0 1.5
AGE (millions of years)
14.07.a,b

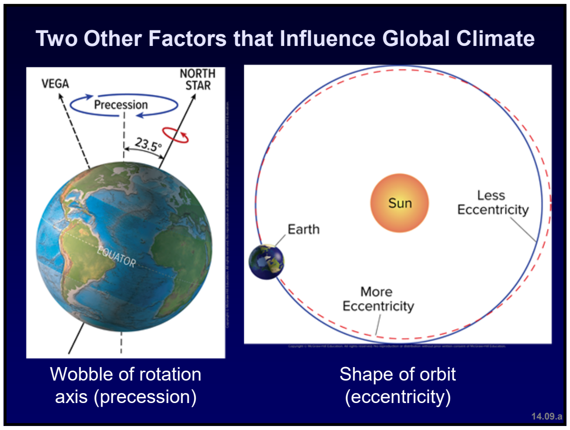

The Ice Ages
Today
28,000 Years Ago
20,000 years ago
10,000 years ago
14.08.a-b


Extent of Continental Glaciation
Anchorage
Juneau
Churchill
Seattle
Calgary
Winnipeg
Quebec
Ottawa
New York
St. Paul
Chicago
Cleveland
San Francisco
Denver
St. Louis

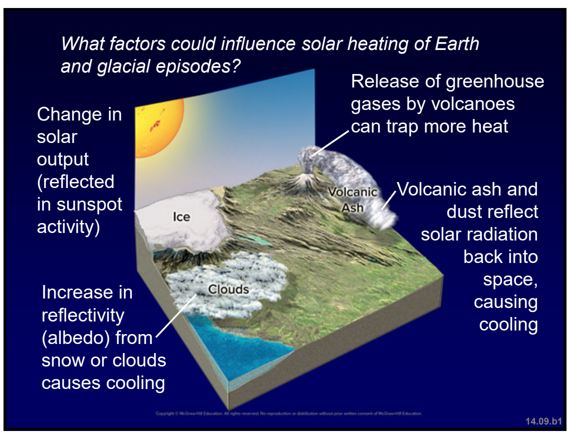

Observe features left behind by continental glaciers in the Great Lakes region
Glacially smoothed troughs
Lake Michigan
Lake Erie
50 km
Moraine
Moraines
14.08.c1
Recessional moraines (ridges)
Rough, nonglaciated areas


Observe features left behind by continental glaciers in the Northeast
Glacially smoothed areas
MASSACHUSETTS
RHODE ISLAND
NEW YORK
CONNECTICUT
Cape Cod
NEW JERSEY
Moraines
Long Island
20 km
14.08.c2
Recessional and terminal moraines (ridges)

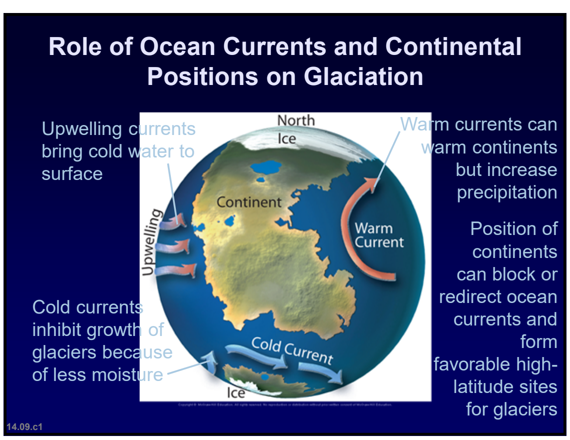

How might changes in Earth's tilt influence global glaciations, if more tilt causes greater seasonal variation?
24.5°
Axis of Rotation
More Tilt
23.5°
Axis of Rotation
Present Tilt
Winter temperature is less important
22.5°
Axis of Rotation
Less Tilt
Equator
Maximum tilt: warmer summers near poles, more melting, and less glaciation
Present-day tilt is adjusting back from maximum
Minimum tilt: cooler summers, less melting, and more glaciers
14.09.a



Two Other Factors that Influence Global Climate
VEGA
NORTH STAR
Precession
23.5°
EQUATOR
Sun
Earth
Less Eccentricity
More Eccentricity
Wobble of rotation axis (precession)
Shape of orbit (eccentricity)
14.09.a

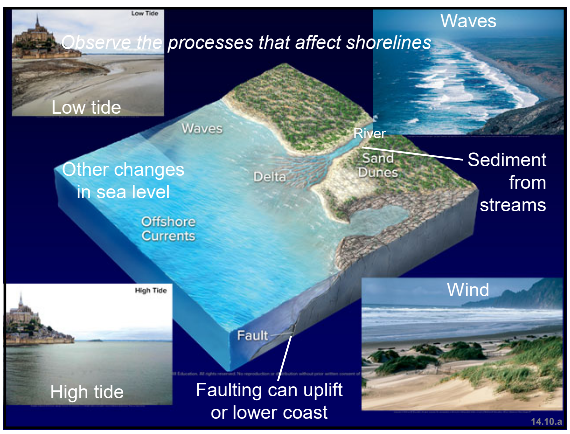


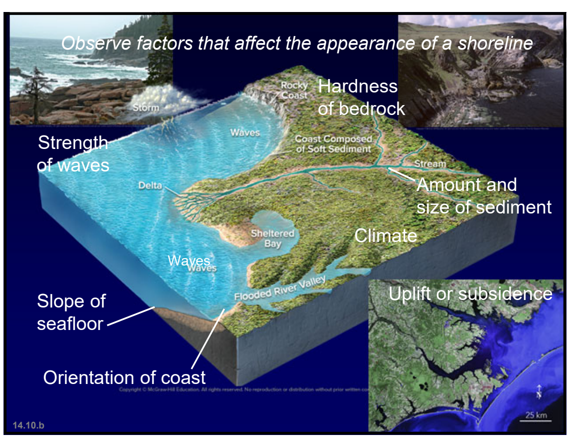
What factors could influence solar heating of Earth and glacial episodes?
Change in solar output (reflected in sunspot activity)
Release of greenhouse gases by volcanoes can trap more heat
Ice
Volcanic Ash
Clouds
Volcanic ash and dust reflect solar radiation back into space, causing cooling
Increase in reflectivity (albedo) from snow or clouds causes cooling
14.09.b1

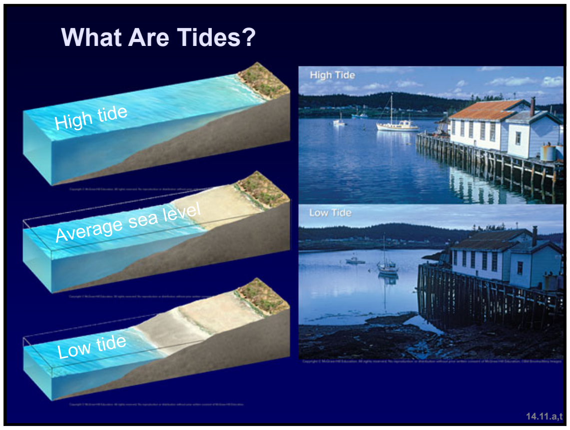


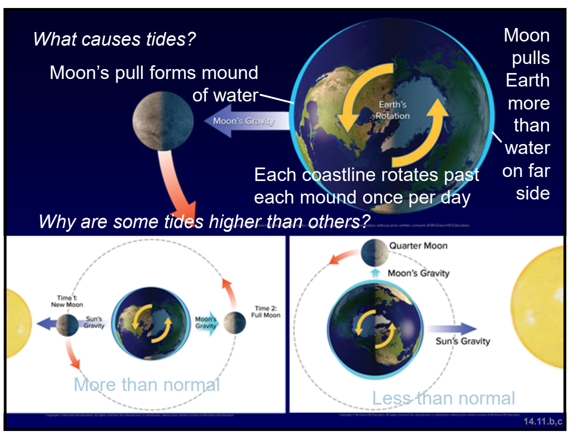
Role of Ocean Currents and Continental Positions on Glaciation
Upwelling currents bring cold water to surface
North Ice
Continent
Upwelling
Warm Current
Cold Current
Ice
Warm currents can warm continents but increase precipitation
Position of continents can block or redirect ocean currents and form favorable high-latitude sites for glaciers
Cold currents inhibit growth of glaciers because of less moisture
14.09.c1

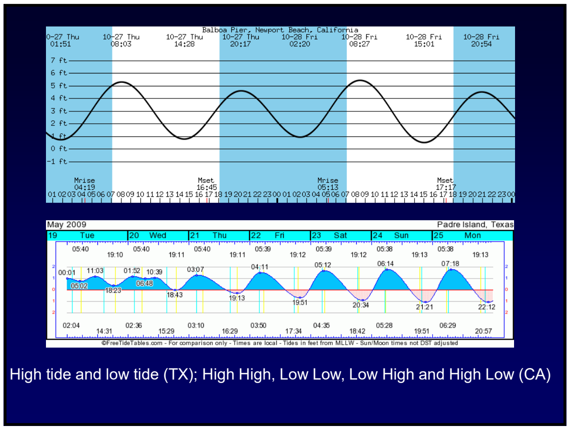

SHORELINES
Where water meets land!

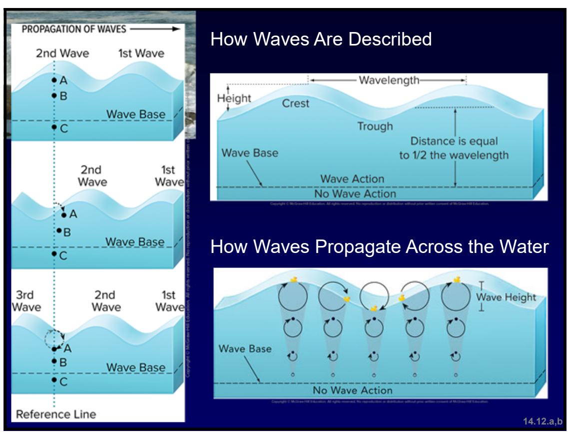

Observe the processes that affect shorelines
Low Tide
Low tide
Waves
Waves
River
Sand
Dunes
Sediment
from
streams
Delta
Other changes
in sea level
Offshore
Currents
High Tide
High tide
Fault
Faulting can uplift
or lower coast
Wind
14.10.a

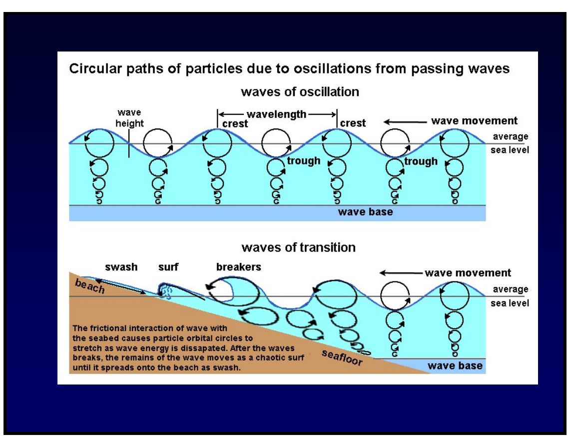

Observe factors that affect the appearance of a shoreline
Storm
Rocky
Coast
Hardness
of bedrock
Waves
Coast Composed
of Soft Sediment
Strength
of waves
Delta
Stream
Amount and
size of sediment
Sheltered
Bay
Climate
Waves
Waves
Flooded River Valley
Uplift or subsidence
Slope of
seafloor
Orientation of coast
25 km
14.10.b

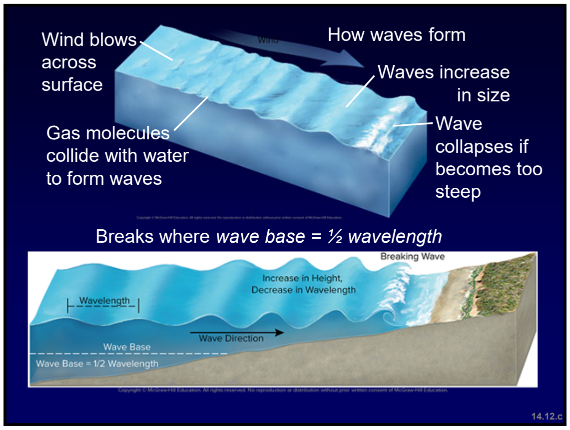

What Are Tides?
High tide
Average sea level
Low tide
High Tide
Low Tide


What causes tides?
Moon's pull forms mound of water
Moon's Gravity
Earth's Rotation
Moon pulls Earth more than water on far side
Each coastline rotates past each mound once per day
Why are some tides higher than others?
Time 1: New Moon
Sun's Gravity
Moon's Gravity
Time 2: Full Moon
More than normal
Quarter Moon
Moon's Gravity
Sun's Gravity
Less than normal
14.11.b,c

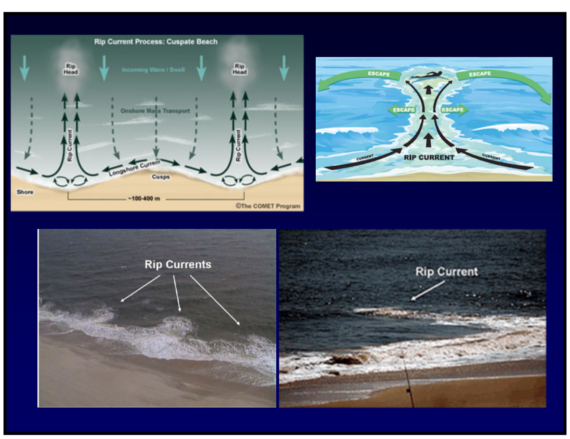

Balboa Pier, Newport Beach, California
May 2009
Padre Island, Texas
High tide and low tide (TX); High High, Low Low, Low High and High Low (CA)

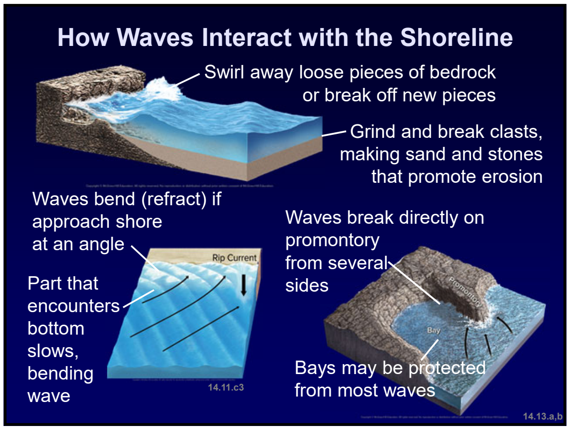

PROPAGATION OF WAVES
2nd Wave
1st Wave
A
B
C
Wave Base
3rd Wave
Reference Line
How Waves Are Described
Wavelength
Height
Crest
Trough
Distance is equal to 1/2 the wavelength
Wave Base
Wave Action
No Wave Action
How Waves Propagate Across the Water
Wave Height
Wave Base
No Wave Action
14.12.a,b

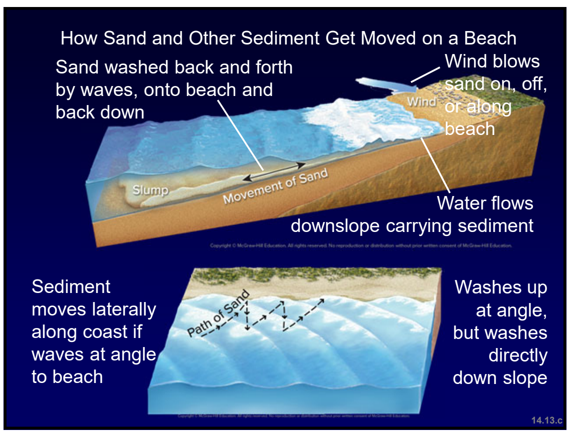

Circular paths of particles due to oscillations from passing waves
waves of oscillation
wave height
wavelength
crest
crest
wave movement
average sea level
trough
trough
wave base
waves of transition
swash
surf
breakers
wave movement
beach
average sea level
The frictional interaction of wave with the seabed causes particle orbital circles to stretch as wave energy is dissapated. After the waves breaks, the remains of the wave moves as a chaotic surf until it spreads onto the beach as swash.
seafloor
wave base

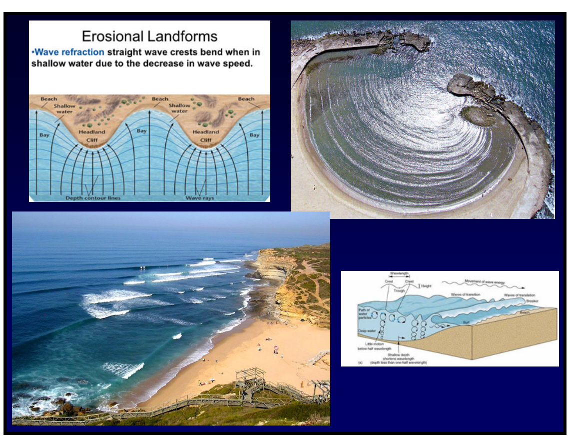

How waves form
Wind blows across surface
Waves increase in size
Gas molecules collide with water to form waves
Wave collapses if becomes too steep
Breaks where *wave base* = ½ *wavelength*
Breaking Wave
Increase in Height, Decrease in Wavelength
Wavelength
Wave Direction
Wave Base
Wave Base = 1/2 Wavelength
14.12.c

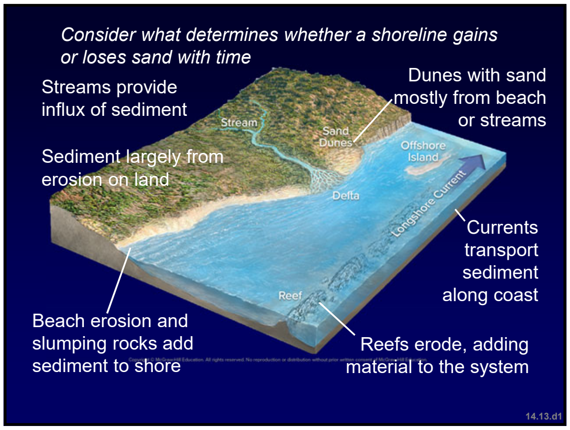

RELAX


Rip Current Process: Cuspate Beach
RIP CURRENT
ESCAPE
Rip Currents
Rip Current
©The COMET Program


How Waves Interact with the Shoreline
Swirl away loose pieces of bedrock or break off new pieces
Grind and break clasts, making sand and stones that promote erosion
Waves bend (refract) if approach shore at an angle
Part that encounters bottom slows, bending wave
Rip Current
14.11.c3
Waves break directly on promontory from several sides
Bay
Bays may be protected from most waves
14.13.a,b

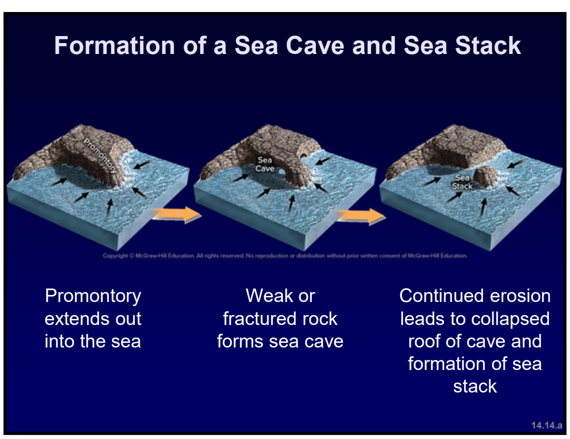

How Sand and Other Sediment Get Moved on a Beach
Sand washed back and forth by waves, onto beach and back down
Wind blows sand on, off, or along beach
Wind
Slump
Movement of Sand
Water flows downslope carrying sediment
Sediment moves laterally along coast if waves at angle to beach
Path of Sand
Washes up at angle, but washes directly down slope
14.13.c


Erosional Landforms
•Wave refraction straight wave crests bend when in shallow water due to the decrease in wave speed.

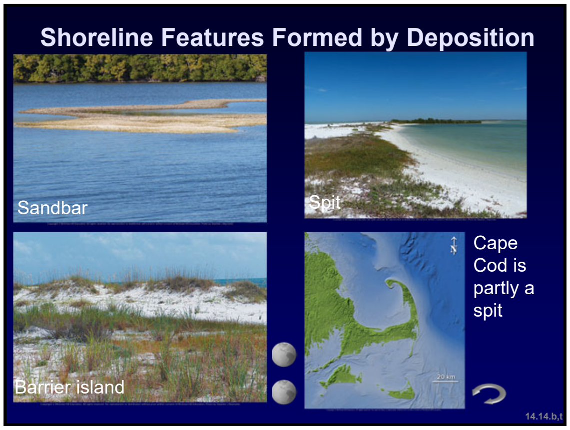


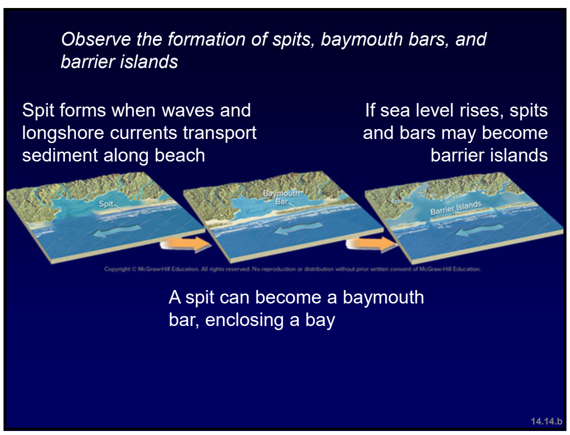
Consider what determines whether a shoreline gains or loses sand with time
Streams provide influx of sediment
Stream
Sand Dunes
Dunes with sand mostly from beach or streams
Offshore Island
Sediment largely from erosion on land
Delta
Longshore Current
Currents transport sediment along coast
Reef
Beach erosion and slumping rocks add sediment to shore
Reefs erode, adding material to the system
14.13.d1

Shoreline Features Carved by Erosion
Sea cliffs
Caves and sea arches
Pinnacles and sea stacks
Wave-cut platforms
14.14.a

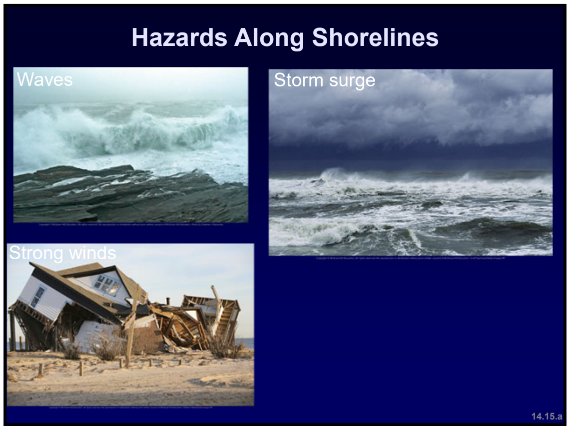


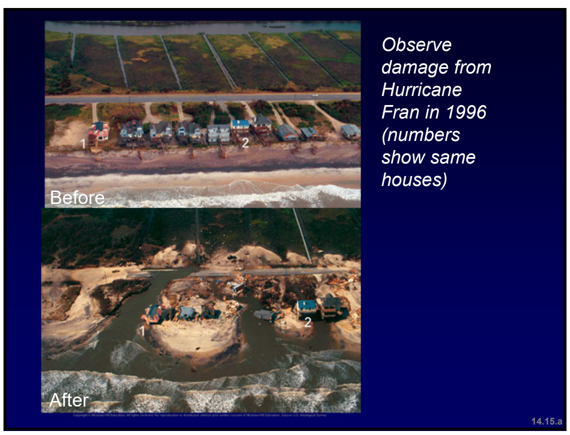
Formation of a Sea Cave and Sea Stack
Promontory
Sea Cave
Sea Stack
Promontory extends out into the sea
Weak or fractured rock forms sea cave
Continued erosion leads to collapsed roof of cave and formation of sea stack
14.14.a


Shoreline Features Formed by Deposition
Sandbar
Spit
Barrier island
Cape Cod is partly a spit
20 km
14.14.b,t

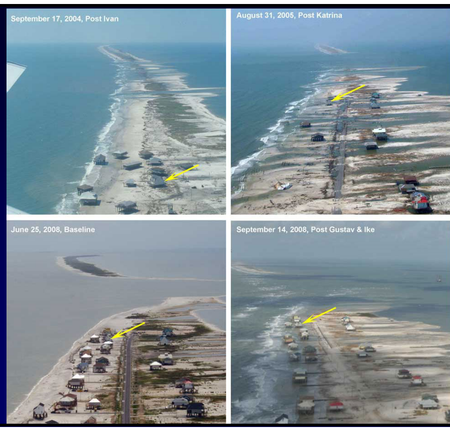

Observe the formation of spits, baymouth bars, and barrier islands
Spit forms when waves and longshore currents transport sediment along beach
If sea level rises, spits and bars may become barrier islands
Spit
Baymouth Bar
Barrier Islands
A spit can become a baymouth bar, enclosing a bay
14.14.b


Malibu Lagoon - Open
Legend
Google earth
1000 ft


Hazards Along Shorelines
Waves
Storm surge
Strong winds
14.15.a

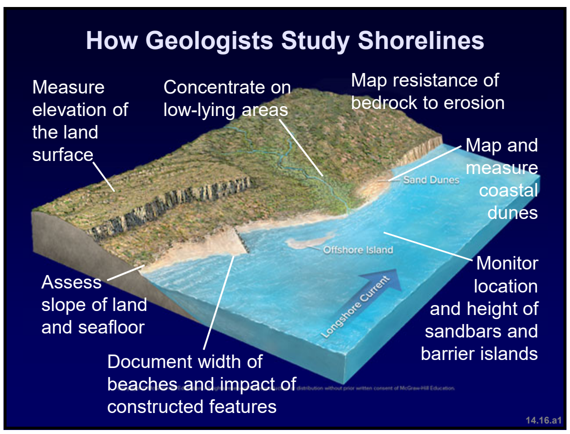

Observe damage from Hurricane Fran in 1996 (numbers show same houses)
1
2
Before
After
14.15.a

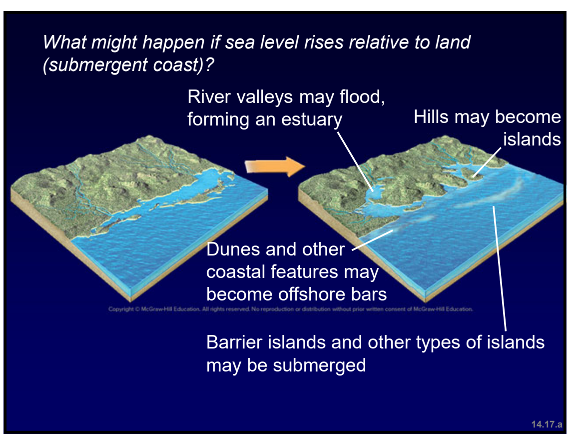
Barrier Islands

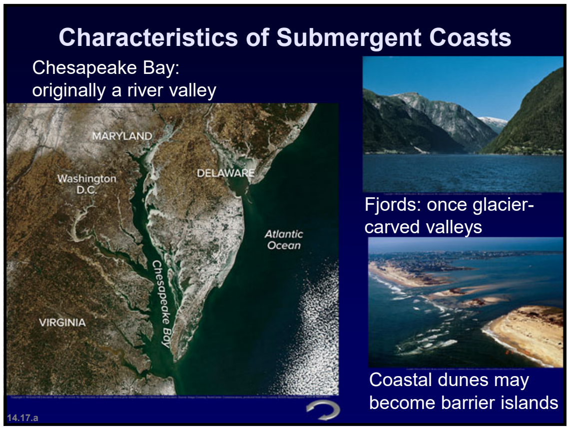


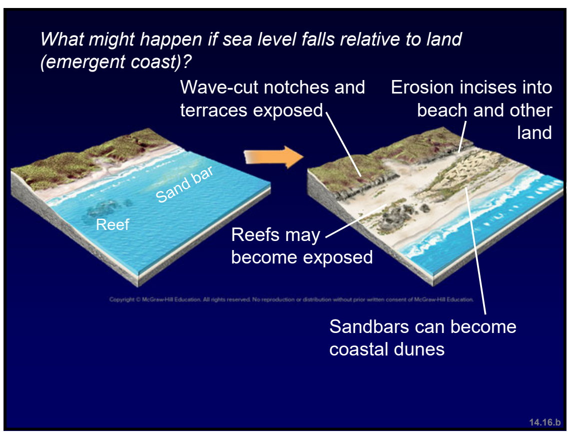
Approaches to Shoreline Problems

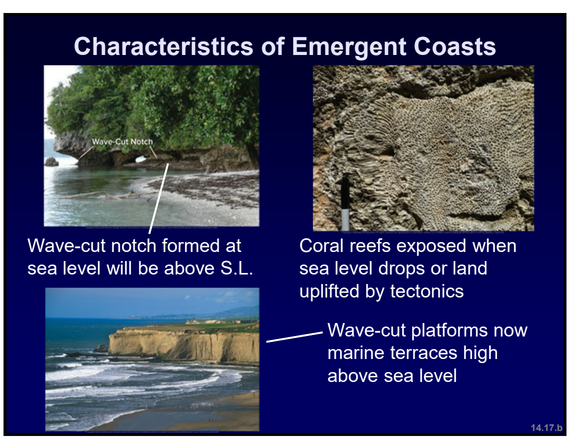
14.15.b

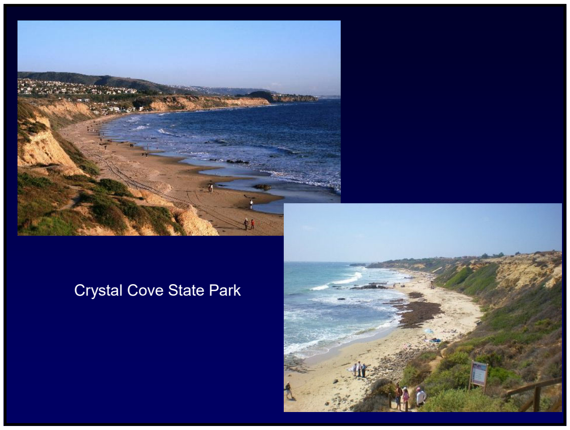

How Geologists Study Shorelines
Measure elevation of the land surface
Concentrate on low-lying areas
Map resistance of bedrock to erosion
Map and measure coastal dunes
Sand Dunes
Offshore Island
Longshore Current
Monitor location and height of sandbars and barrier islands
Assess slope of land and seafloor
Document width of beaches and impact of constructed features
14.16.a1

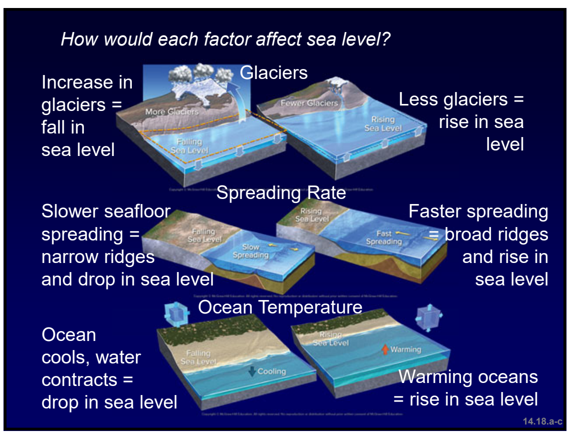

What might happen if sea level rises relative to land (submergent coast)?
River valleys may flood, forming an estuary
Hills may become islands
Dunes and other coastal features may become offshore bars
Barrier islands and other types of islands may be submerged
14.17.a

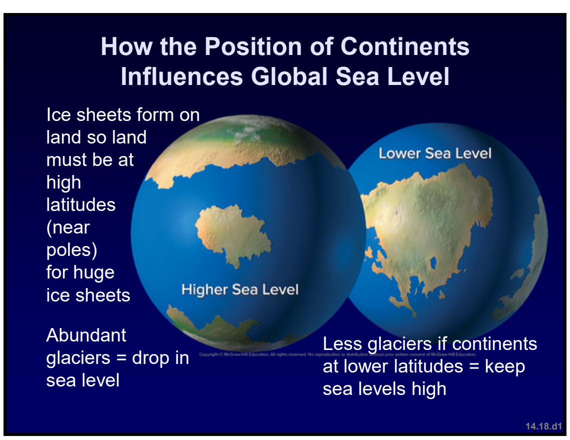

Characteristics of Submergent Coasts
Chesapeake Bay:
originally a river valley
MARYLAND
Washington D.C.
DELAWARE
Atlantic Ocean
Chesapeake Bay
VIRGINIA
Fjords: once glacier-carved valleys
Coastal dunes may become barrier islands
14.17.a

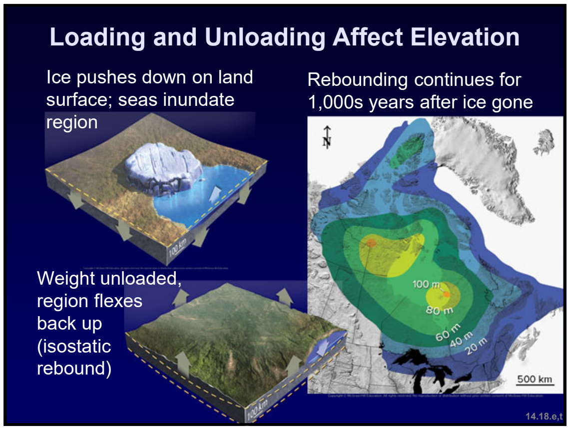

What might happen if sea level falls relative to land (emergent coast)?
Wave-cut notches and terraces exposed
Erosion incises into beach and other land
Sand bar
Reef
Reefs may become exposed
Sandbars can become coastal dunes
14.16.b

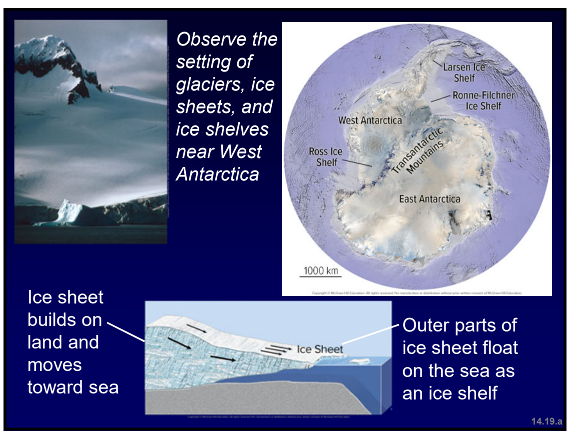

Characteristics of Emergent Coasts
Wave-Cut Notch
Wave-cut notch formed at sea level will be above S.L.
Coral reefs exposed when sea level drops or land uplifted by tectonics
Wave-cut platforms now marine terraces high above sea level
14.17.b

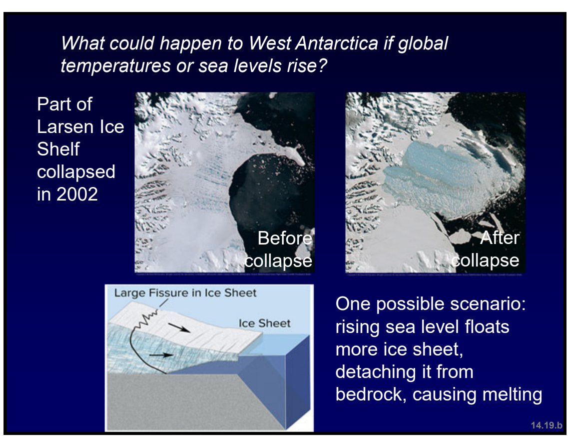

Crystal Cove State Park

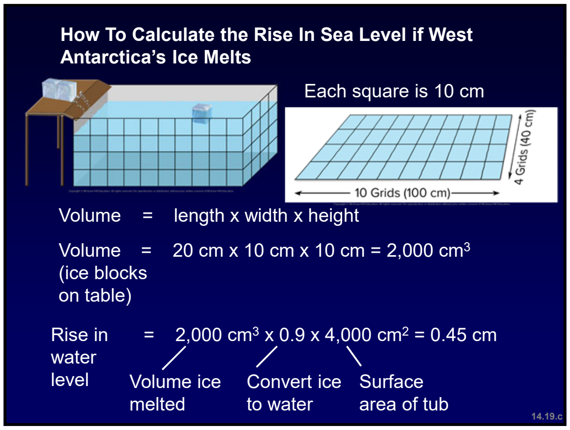

How would each factor affect sea level?
Glaciers
Increase in glaciers = fall in sea level
More Glaciers
Falling Sea Level
Fewer Glaciers
Rising Sea Level
Less glaciers = rise in sea level
Spreading Rate
Slower seafloor spreading = narrow ridges and drop in sea level
Falling Sea Level
Slow Spreading
Rising Sea Level
Fast Spreading
Faster spreading = broad ridges and rise in sea level
Ocean Temperature
Ocean cools, water contracts = drop in sea level
Falling Sea Level
Cooling
Rising Sea Level
Warming
Warming oceans = rise in sea level
14.18.a-c

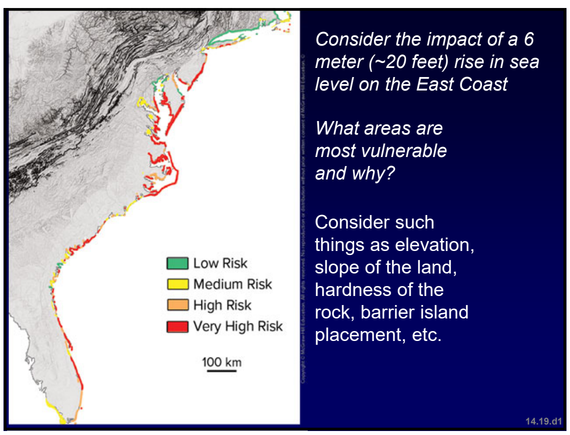

How the Position of Continents Influences Global Sea Level
Ice sheets form on land so land must be at high latitudes (near poles) for huge ice sheets
Abundant glaciers = drop in sea level
Lower Sea Level
Higher Sea Level
Less glaciers if continents at lower latitudes = keep sea levels high
14.18.d1


Loading and Unloading Affect Elevation
Ice pushes down on land surface; seas inundate region
Rebounding continues for 1,000s years after ice gone
Weight unloaded, region flexes back up (isostatic rebound)
100 m
80 m
60 m
40 m
20 m
500 km
14.18.e,f


Observe the setting of glaciers, ice sheets, and ice shelves near West Antarctica
Larsen Ice Shelf
Ronne-Filchner Ice Shelf
West Antarctica
Ross Ice Shelf
Transantarctic Mountains
East Antarctica
1000 km
Ice sheet builds on land and moves toward sea
Ice Sheet
Outer parts of ice sheet float on the sea as an ice shelf
14.19.a

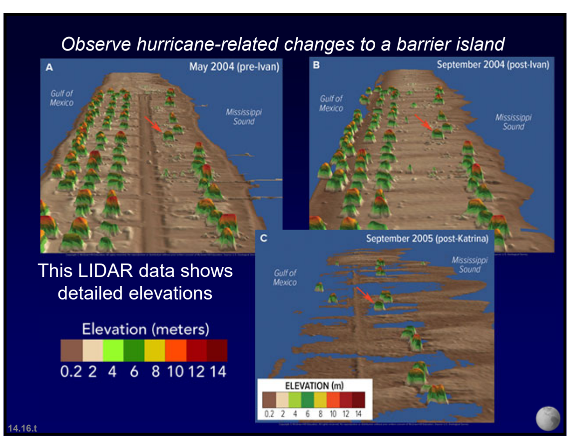

What could happen to West Antarctica if global temperatures or sea levels rise?
Part of Larsen Ice Shelf collapsed in 2002
Before collapse
After collapse
Large Fissure in Ice Sheet
Ice Sheet
One possible scenario: rising sea level floats more ice sheet, detaching it from bedrock, causing melting
14.19.b


How To Calculate the Rise In Sea Level if West Antarctica's Ice Melts
Each square is 10 cm
4 Grids (40 cm)
10 Grids (100 cm)
Volume = length x width x height
Volume (ice blocks on table) = 20 cm x 10 cm x 10 cm = 2,000 cm^3
Rise in water level = 2,000 cm^3 x 0.9 x 4,000 cm^2 = 0.45 cm
Volume ice melted
Convert ice to water
Surface area of tub
14.19.c

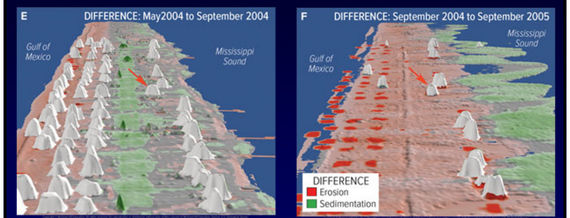

Consider the impact of a 6 meter (~20 feet) rise in sea level on the East Coast
What areas are most vulnerable and why?
Consider such things as elevation, slope of the land, hardness of the rock, barrier island placement, etc.
Low Risk
Medium Risk
High Risk
Very High Risk
100 km
14.19.d1


U.S.A.
VA
Virginia Beach, VA
NC
SC
GA
AL
MS
LA
TX
Atlantic Ocean
Jacksonville, FL
Houston, TX
New Orleans, LA
Tampa, FL
FL
Miami, FL
Gulf of Mexico
0
500
km
≤ 1 m
≤ 6 m
state boundary
land
waterbody


Investigation: What Is Happening Along the Coast of This Island?
14.20.a1

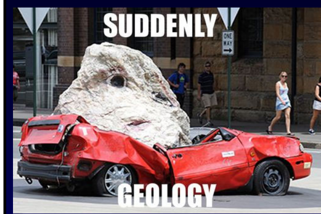

Observe hurricane-related changes to a barrier island
A
May 2004 (pre-Ivan)
Gulf of Mexico
Mississippi Sound
B
September 2004 (post-Ivan)
Gulf of Mexico
Mississippi Sound
C
September 2005 (post-Katrina)
Gulf of Mexico
Mississippi Sound
This LIDAR data shows detailed elevations
Elevation (meters)
0.2 2 4 6 8 10 12 14
ELEVATION (m)
0.2 2 4 6 8 10 12 14
14.16.t

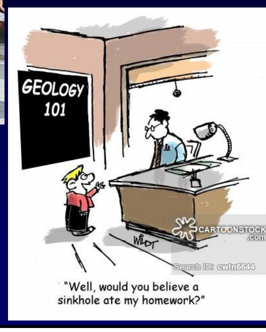
Observe the calculated changes caused by the storms



14.16.t

Weathering, Soil, and Unstable Slopes Chap 15

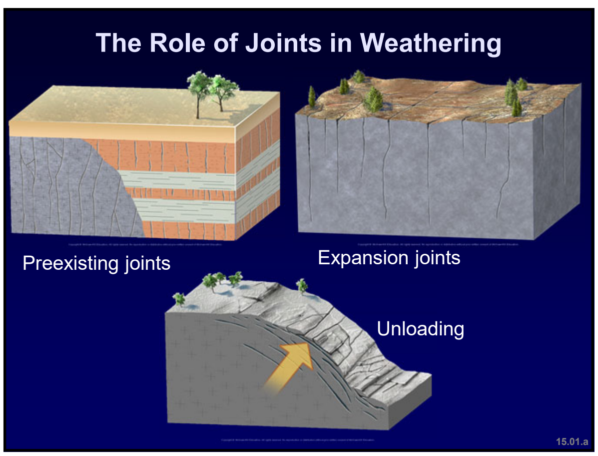




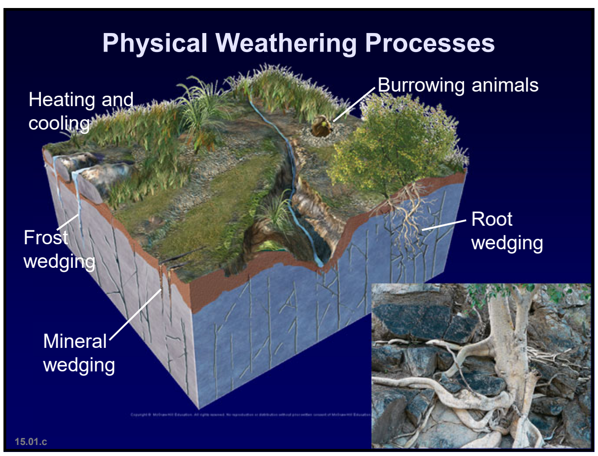
Rock takes out Hwy in Washington!

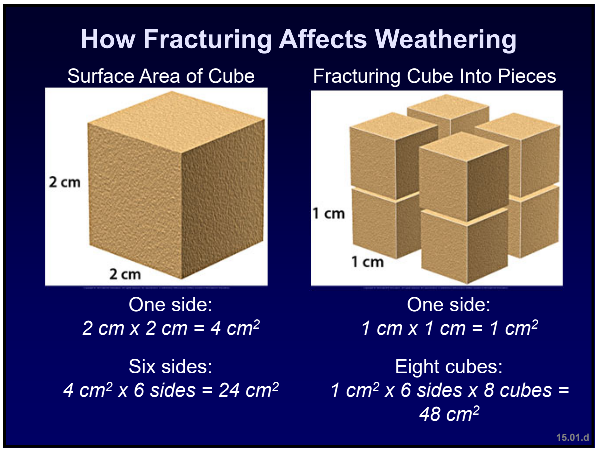
Observe the location of cities with respect to mountains and valleys

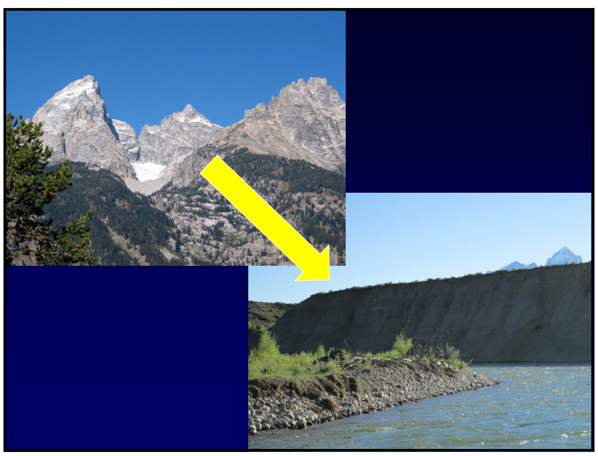

Mt. San Antonio
Sheep Mountain
Wrightwood
Mudflow scars
Wrightwood
San Andreas fault

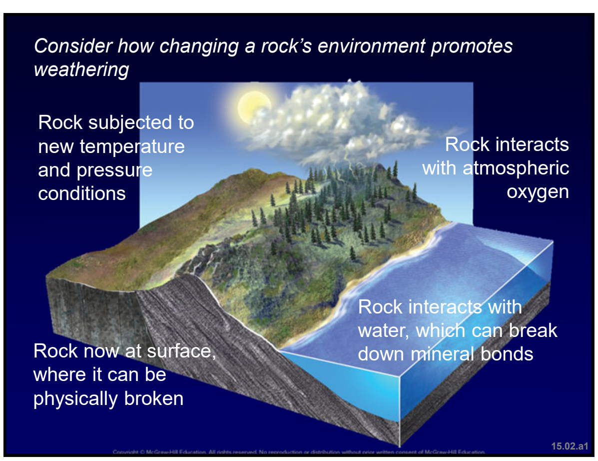

The Role of Joints in Weathering
Preexisting joints
Expansion joints
Unloading
15.01.a

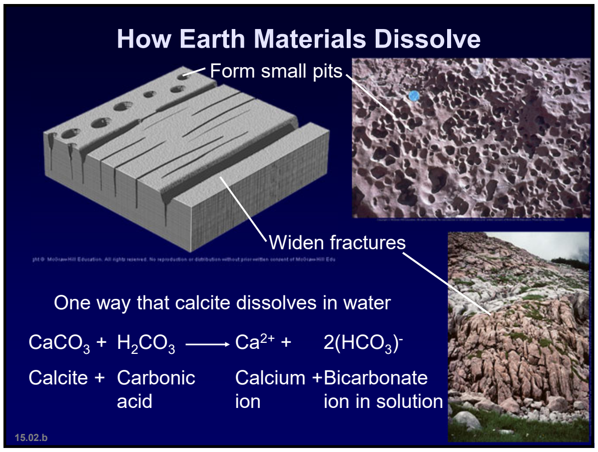

Observe how joints are expressed in the landscape
Amount of jointing
Spacing of joints
Exfoliation joints
15.01.b

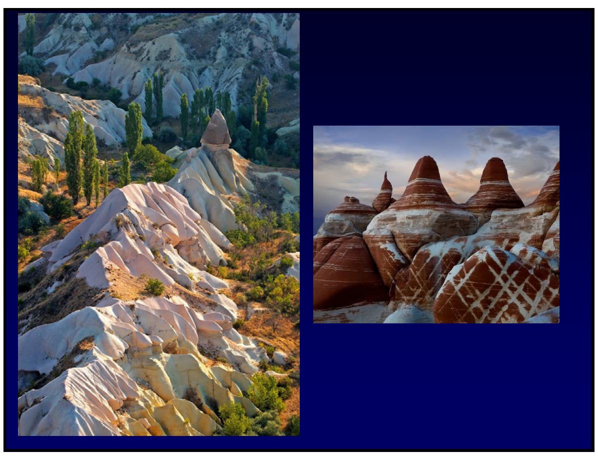

Physical Weathering Processes
Heating and cooling
Burrowing animals
Frost wedging
Root wedging
Mineral wedging
15.01.c

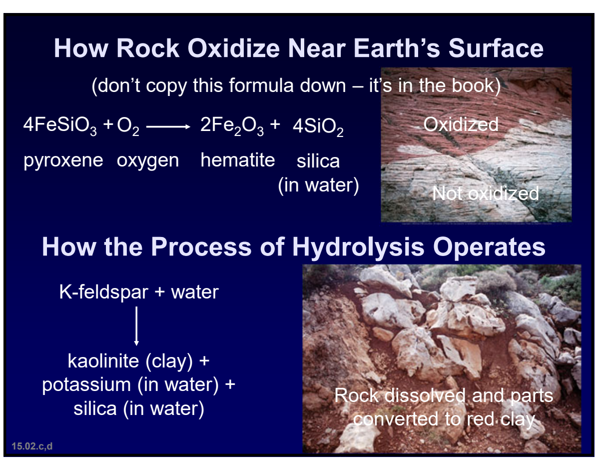

How Fracturing Affects Weathering
Surface Area of Cube
Fracturing Cube Into Pieces
2 cm
2 cm
1 cm
1 cm
One side:
$2\ cm \times 2\ cm = 4\ cm^2$
Six sides:
$4\ cm^2 \times 6$ sides = $24\ cm^2$
One side:
$1\ cm \times 1\ cm = 1\ cm^2$
Eight cubes:
$1\ cm^2 \times 6$ sides $\times 8$ cubes = $48\ cm^2$
15.01.d

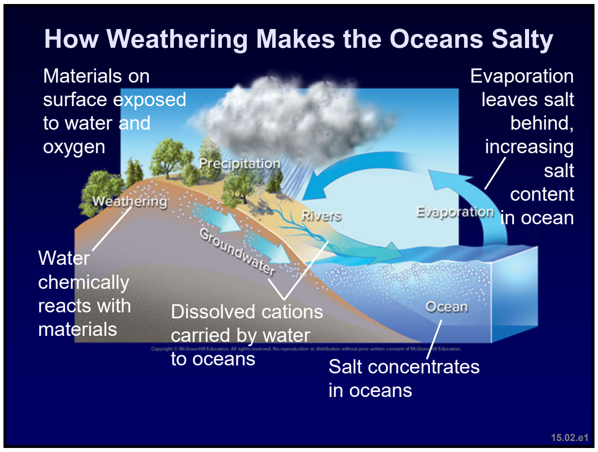


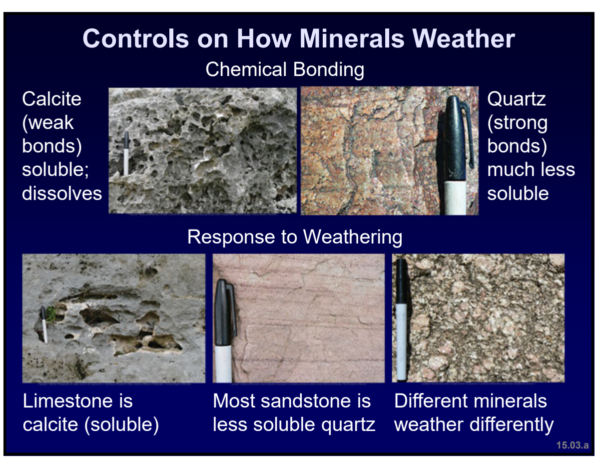

Consider how changing a rock's environment promotes weathering
Rock subjected to new temperature and pressure conditions
Rock interacts with atmospheric oxygen
Rock interacts with water, which can break down mineral bonds
Rock now at surface, where it can be physically broken
15.02.a1

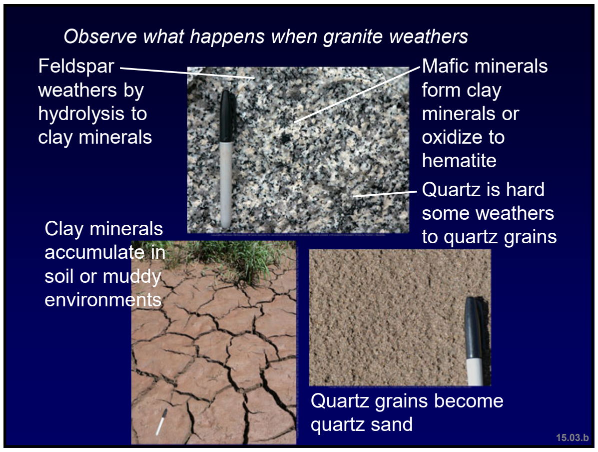

How Earth Materials Dissolve
Form small pits
Widen fractures
One way that calcite dissolves in water
$CaCO_3$ + H_2CO_3 ⟶ Ca^{2+} + $2(HCO_3)^-$
Calcite + Carbonic acid
Calcium ion + Bicarbonate ion in solution
15.02.b



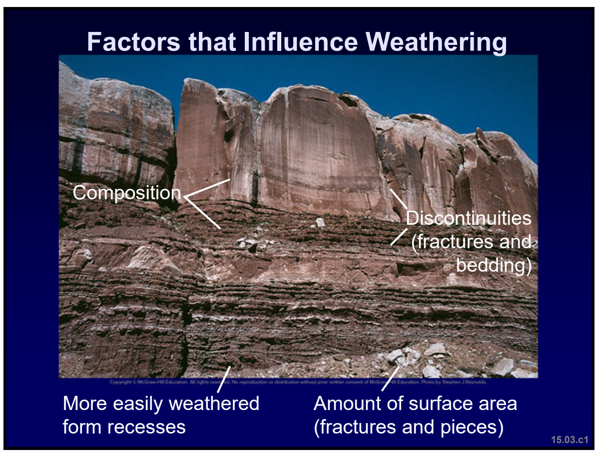

How Rock Oxidize Near Earth's Surface
(don't copy this formula down – it's in the book)
$4FeSiO_3$ + O_2 ⟶ $2Fe_2O_3$ + $4SiO_2$
pyroxene oxygen hematite silica (in water)
Oxidized
Not oxidized
How the Process of Hydrolysis Operates
K-feldspar + water
kaolinite (clay) +
potassium (in water) +
silica (in water)
Rock dissolved and parts converted to red clay
15.02.c,d


How Weathering Makes the Oceans Salty
Materials on surface exposed to water and oxygen
Evaporation leaves salt behind, increasing salt content in ocean
Precipitation
Weathering
Rivers
Evaporation
Groundwater
Ocean
Water chemically reacts with materials
Dissolved cations carried by water to oceans
Salt concentrates in oceans
15.02.e1

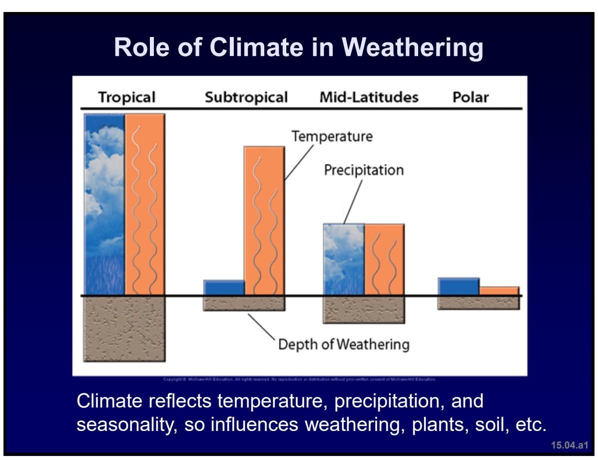

Controls on How Minerals Weather
Chemical Bonding
Calcite (weak bonds) soluble; dissolves
Quartz (strong bonds) much less soluble
Response to Weathering
Limestone is calcite (soluble)
Most sandstone is less soluble quartz
Different minerals weather differently
15.03.a



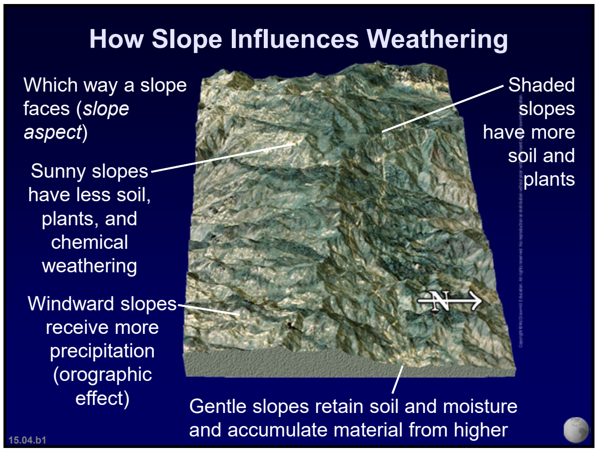
Observe what happens when granite weathers
Feldspar weathers by hydrolysis to clay minerals
Mafic minerals form clay minerals or oxidize to hematite
Quartz is hard some weathers to quartz grains
Clay minerals accumulate in soil or muddy environments
Quartz grains become quartz sand
15.03.b

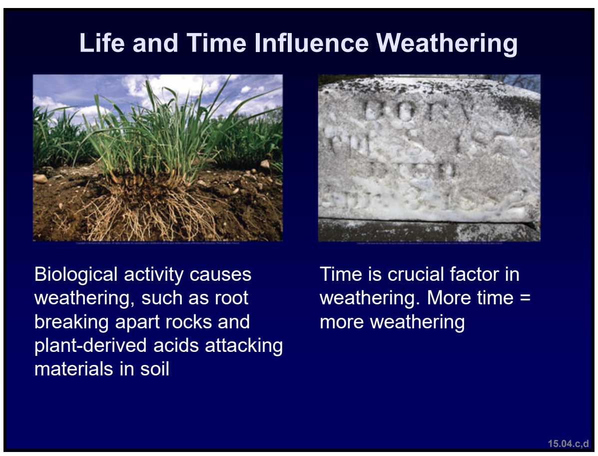


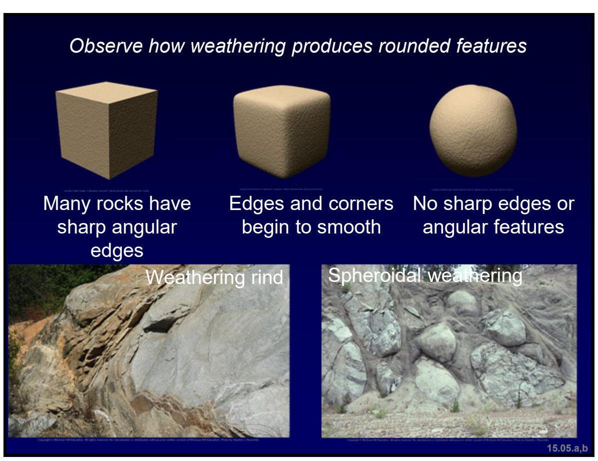
Factors that Influence Weathering
Composition
Discontinuities (fractures and bedding)
More easily weathered form recesses
Amount of surface area (fractures and pieces)
15.03.c1

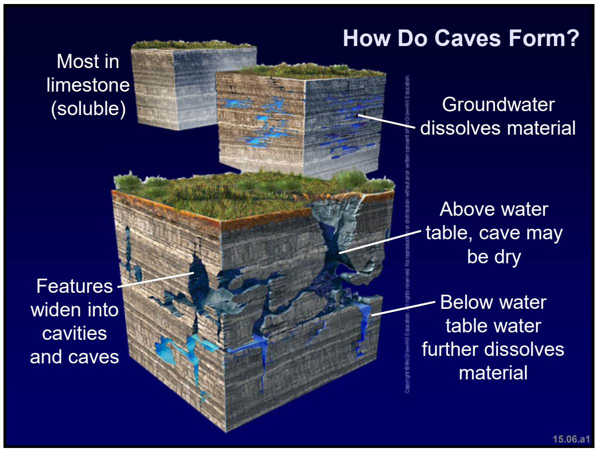


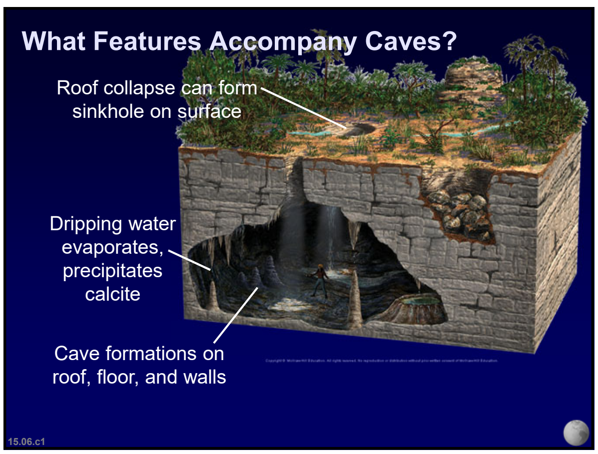
Role of Climate in Weathering
Tropical
Subtropical
Mid-Latitudes
Polar
Temperature
Precipitation
Depth of Weathering
Climate reflects temperature, precipitation, and seasonality, so influences weathering, plants, soil, etc.
15.04.a1

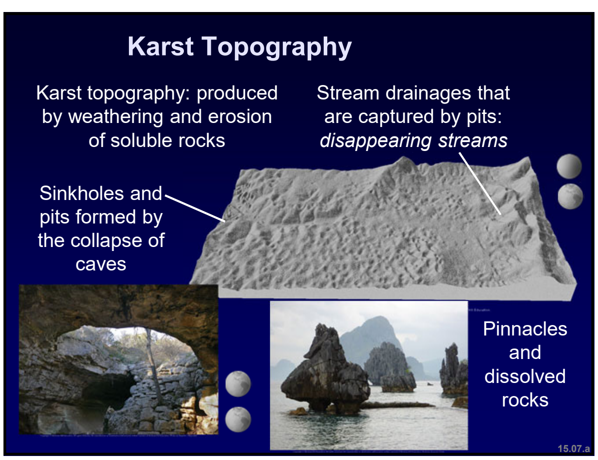

How Slope Influences Weathering
Which way a slope faces (slope aspect)
Sunny slopes have less soil, plants, and chemical weathering
Windward slopes receive more precipitation (orographic effect)
Shaded slopes have more soil and plants
N
Gentle slopes retain soil and moisture and accumulate material from higher
15.04.b1


Life and Time Influence Weathering
Biological activity causes weathering, such as root breaking apart rocks and plant-derived acids attacking materials in soil
Time is crucial factor in weathering. More time = more weathering
15.04.c,d

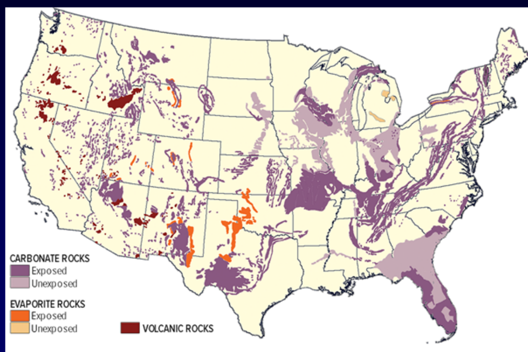

Observe how weathering produces rounded features
Many rocks have sharp angular edges
Edges and corners begin to smooth
No sharp edges or angular features
Weathering rind
Spheroidal weathering
15.05.a,b


How Do Caves Form?
Most in limestone (soluble)
Groundwater dissolves material
Above water table, cave may be dry
Features widen into cavities and caves
Below water table water further dissolves material
15.06.a1


What Features Accompany Caves?
Roof collapse can form sinkhole on surface
Dripping water evaporates, precipitates calcite
Cave formations on roof, floor, and walls
15.06.c1


Karst Topography
Karst topography: produced by weathering and erosion of soluble rocks
Stream drainages that are captured by pits: *disappearing streams*
Sinkholes and pits formed by the collapse of caves
Pinnacles and dissolved rocks
15.07.a

Spatial Distribution of Karst in U.S.



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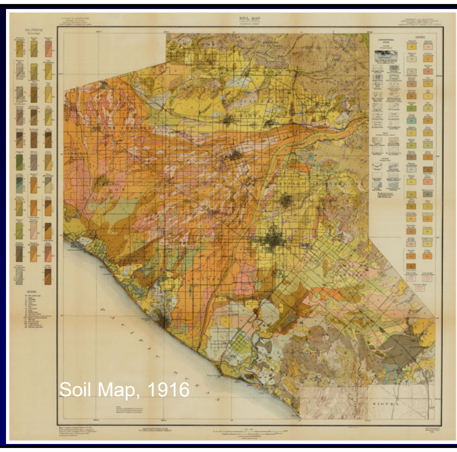
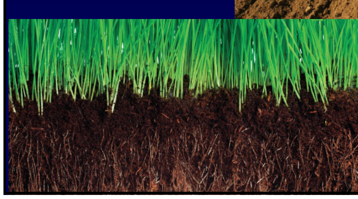
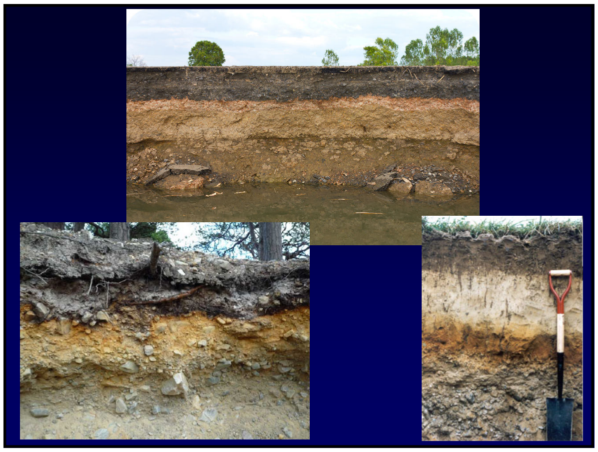
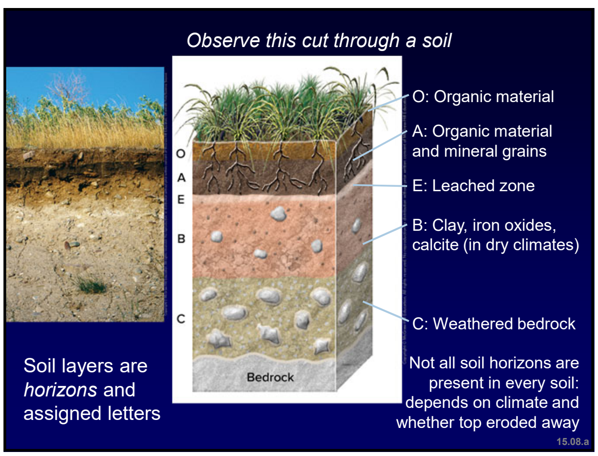
12.07.b2

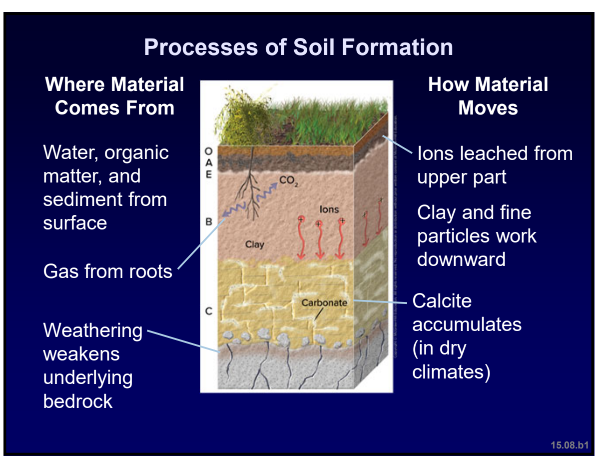


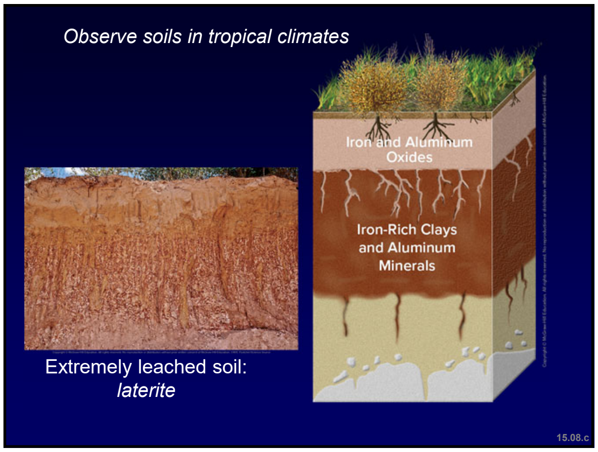
Soil Map, 1916

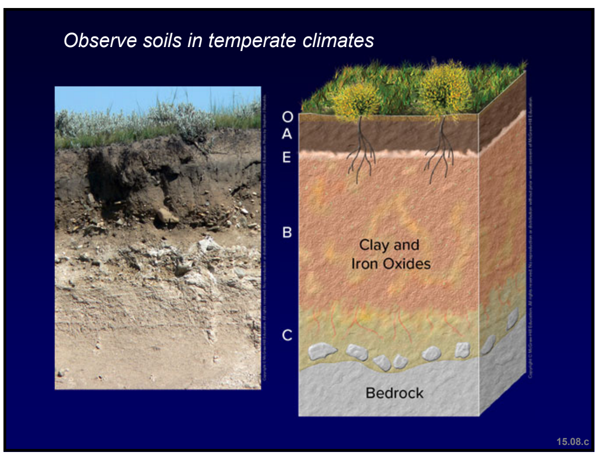


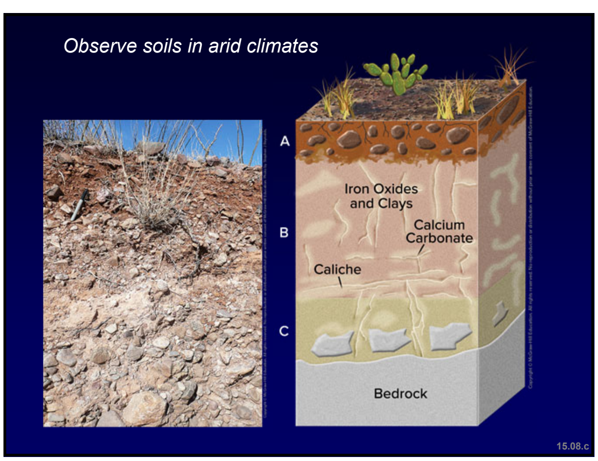


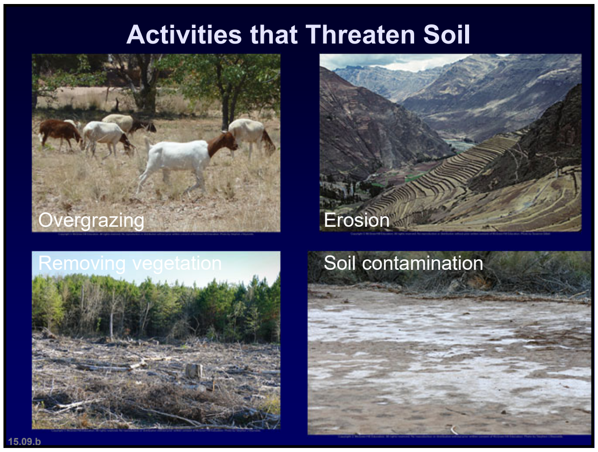

Observe this cut through a soil
O
A
E
B
C
Bedrock
O: Organic material
A: Organic material and mineral grains
E: Leached zone
B: Clay, iron oxides, calcite (in dry climates)
C: Weathered bedrock
Soil layers are *horizons* and assigned letters
Not all soil horizons are present in every soil: depends on climate and whether top eroded away
15.08.a

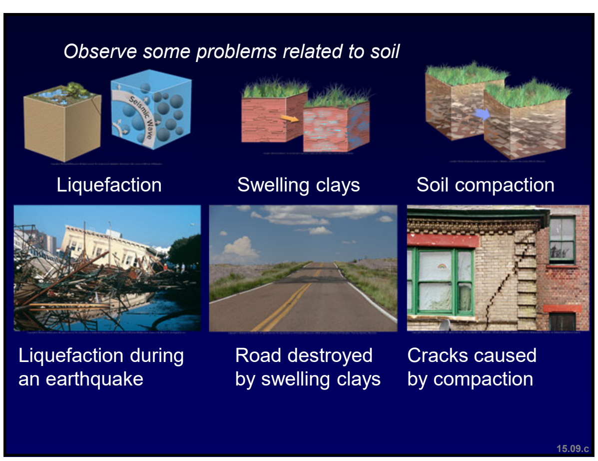

Processes of Soil Formation
Where Material Comes From
Water, organic matter, and sediment from surface
Gas from roots
Weathering weakens underlying bedrock
O
A
E
B
C
CO_2
Ions
Clay
Carbonate
How Material Moves
Ions leached from upper part
Clay and fine particles work downward
Calcite accumulates (in dry climates)
15.08.b1

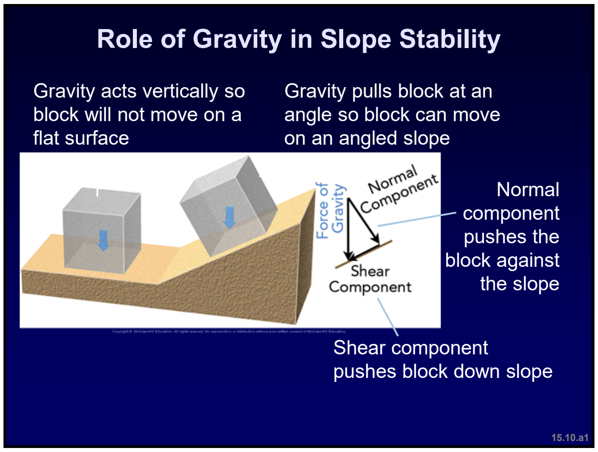

Observe soils in tropical climates
Extremely leached soil: *laterite*
Iron and Aluminum Oxides
Iron-Rich Clays and Aluminum Minerals
15.08.c

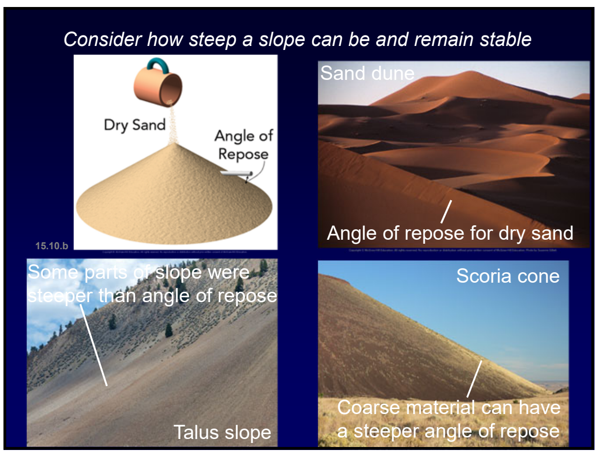

Observe soils in temperate climates
O
A
E
B
C
Clay and Iron Oxides
Bedrock
15.08.c

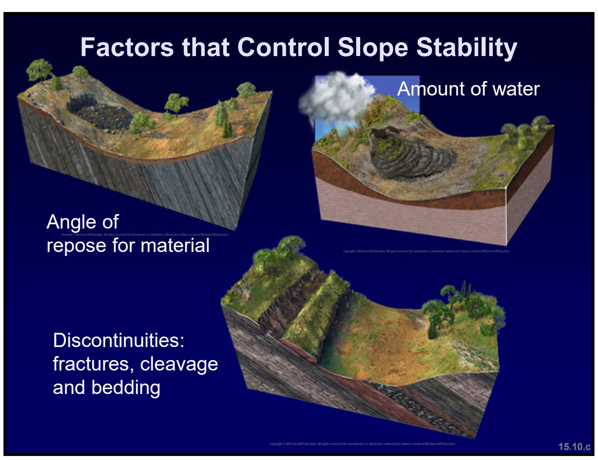

Observe soils in arid climates
A
B
C
Iron Oxides and Clays
Calcium Carbonate
Caliche
Bedrock
15.08.c

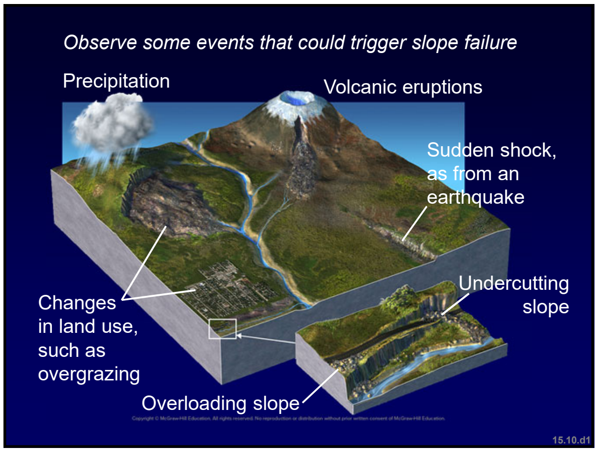

Activities that Threaten Soil
Overgrazing
Erosion
Removing vegetation
Soil contamination
15.09.b


Observe some problems related to soil
Liquefaction
Swelling clays
Soil compaction
Liquefaction during an earthquake
Road destroyed by swelling clays
Cracks caused by compaction
15.09.c

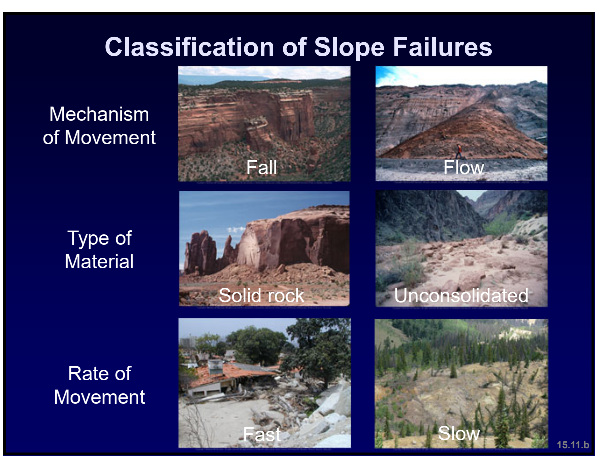

Role of Gravity in Slope Stability
Gravity acts vertically so block will not move on a flat surface
Gravity pulls block at an angle so block can move on an angled slope
Force of Gravity
Normal Component
Shear Component
Normal component pushes the block against the slope
Shear component pushes block down slope
15.10.a1


Consider how steep a slope can be and remain stable
Dry Sand
Angle of Repose
15.10.b
Sand dune
Angle of repose for dry sand
Some parts of slope were steeper than angle of repose
Talus slope
Scoria cone
Coarse material can have a steeper angle of repose

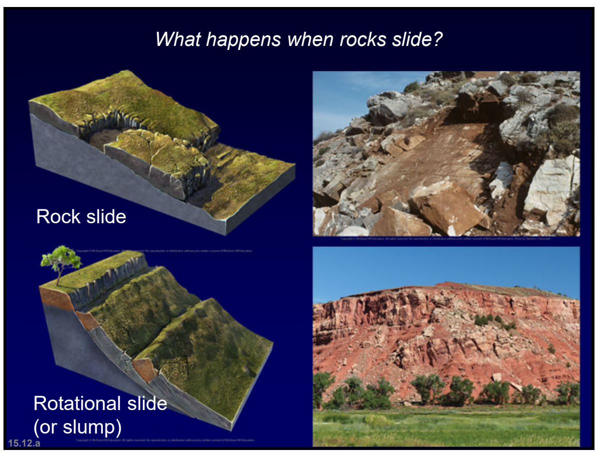

Factors that Control Slope Stability
Amount of water
Angle of repose for material
Discontinuities: fractures, cleavage and bedding
15.10.c


Observe some events that could trigger slope failure
Precipitation
Volcanic eruptions
Sudden shock, as from an earthquake
Undercutting slope
Changes in land use, such as overgrazing
Overloading slope
15.10.d1

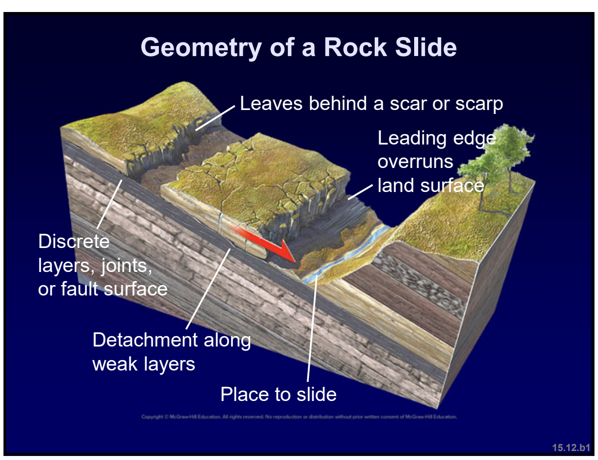

Observe some ways that slopes fail
Undercut cliff
Earthquake activity
Too steep a slope
Landslide
Undercut slope
15.11.a


Classification of Slope Failures
Mechanism of Movement
Fall
Flow
Type of Material
Solid rock
Unconsolidated
Rate of Movement
Fast
Slow
15.11.b

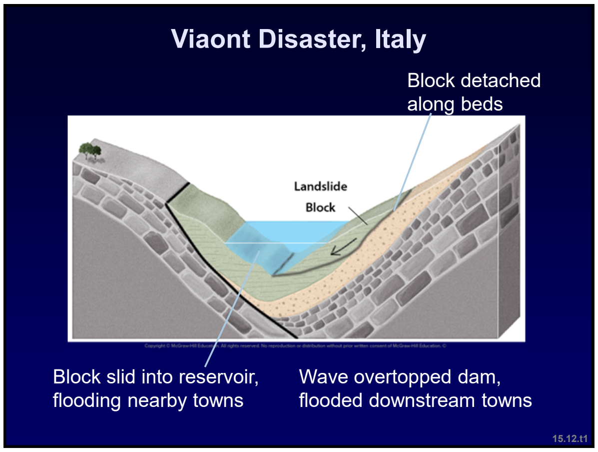
What happens when rock or debris falls?
Rock fall
or debris fall
15.12.a

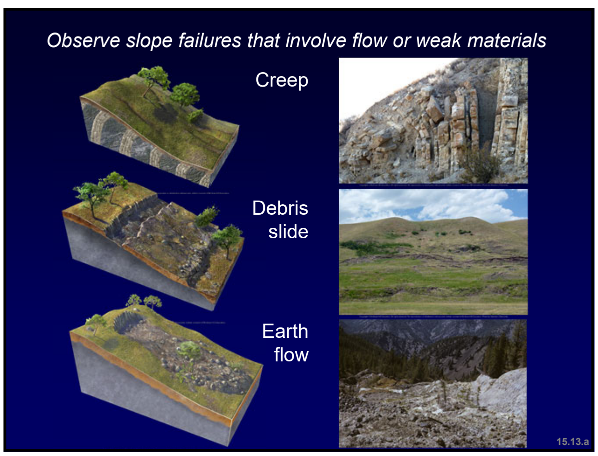


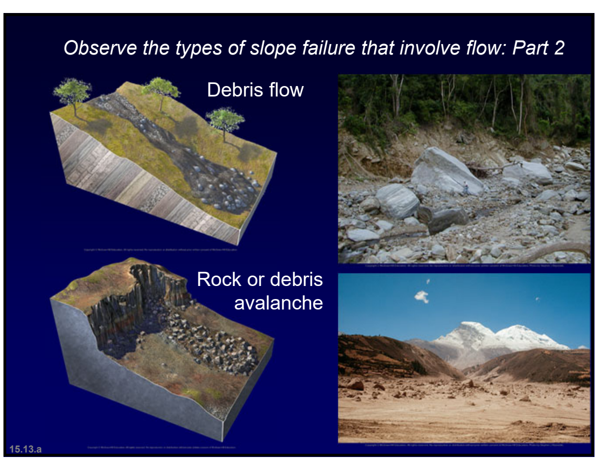
What happens when rocks slide?
Rock slide
Rotational slide
(or slump)
15.12.a



Geometry of a Rock Slide
Leaves behind a scar or scarp
Leading edge
overruns
land surface
Discrete
layers, joints,
or fault surface
Detachment along
weak layers
Place to slide
15.12.b1

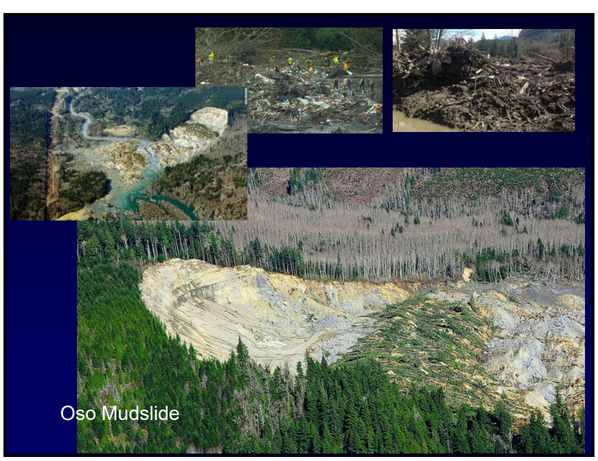

Viaont Disaster, Italy
Block detached along beds
Landslide Block
Block slid into reservoir, flooding nearby towns
Wave overtopped dam, flooded downstream towns
15.12.t1

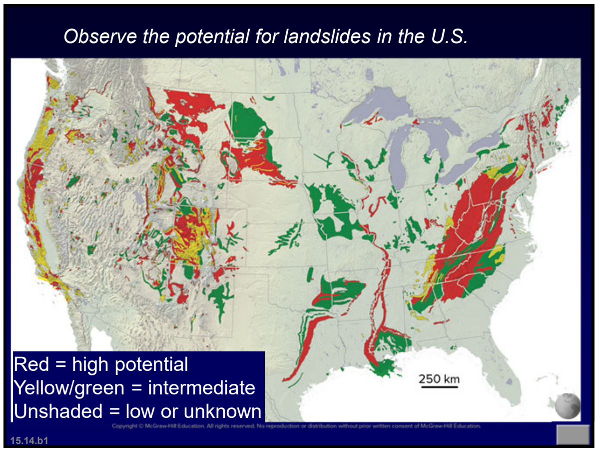

Observe slope failures that involve flow or weak materials
Creep
Debris slide
Earth flow
15.13.a

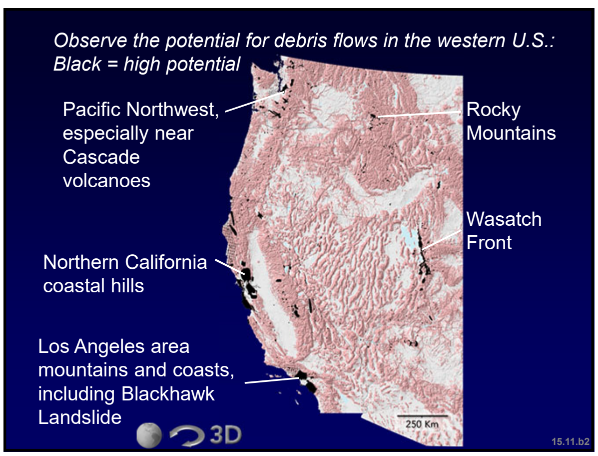

Observe the types of slope failure that involve flow: Part 2
Debris flow
Rock or debris avalanche
15.13.a

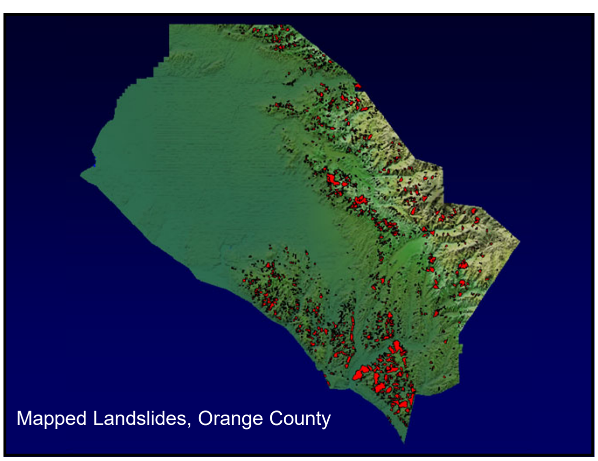

Slope Failures in the U.S.
Debris avalanche - Alaska
Earth flow - New York
Rock slide - Wyoming
Landslide - Utah
15.14.a


Landslides and La Conchita
15.10.mtb
1995
2005


Oso Mudslide

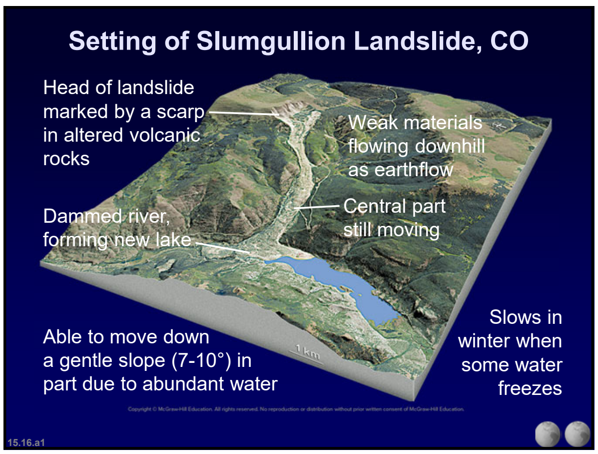

Observe the potential for landslides in the U.S.
Red = high potential
Yellow/green = intermediate
Unshaded = low or unknown
250 km
15.14.b1

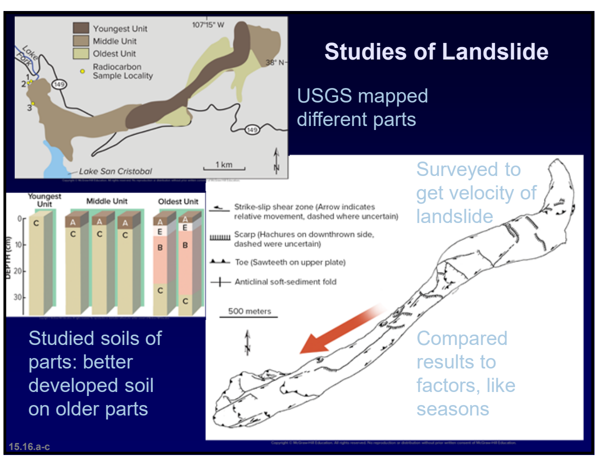

Observe the potential for debris flows in the western U.S.:
Black = high potential
Pacific Northwest, especially near Cascade volcanoes
Rocky Mountains
Wasatch Front
Northern California coastal hills
Los Angeles area mountains and coasts, including Blackhawk Landslide
250 Km
3D
15.11.b2


Mapped Landslides, Orange County

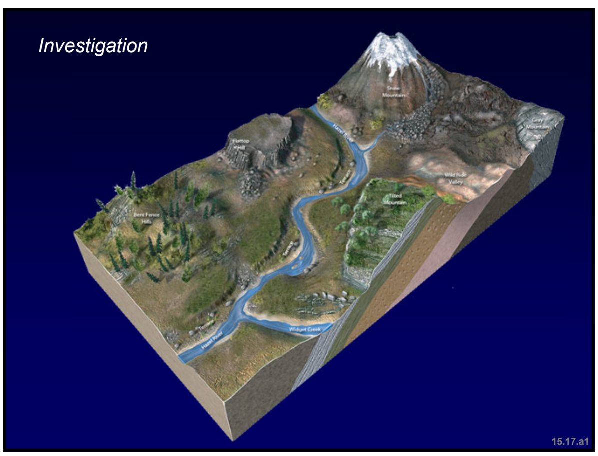

Recognizing Prehistoric Slope Failures
Hummocky topography
Prehistoric deposits
Broken, angular rocks
Rock types that do not belong
15.15.b


Assessing Potential for Slope Failure
Past failures
Known problems
Steep slopes
Changes in slope
Conditions of material
Potential triggers
15.15.c


Setting of Slumgullion Landslide, CO
Head of landslide marked by a scarp in altered volcanic rocks
Weak materials flowing downhill as earthflow
Dammed river, forming new lake
Central part still moving
Able to move down a gentle slope (7-10°) in part due to abundant water
1 km
Slows in winter when some water freezes
15.16.a1


Studies of Landslide
Youngest Unit
Middle Unit
Oldest Unit
Radiocarbon Sample Locality
107°15' W
38° N
Lake Fork
149
Lake San Cristobal
1 km
USGS mapped different parts
Youngest Unit
Middle Unit
Oldest Unit
DEPTH (cm)
Strike-slip shear zone (Arrow indicates relative movement, dashed where uncertain)
Scarp (Hachures on downthrown side, dashed were uncertain)
Toe (Sawteeth on upper plate)
Anticlinal soft-sediment fold
500 meters
Surveyed to get velocity of landslide
Studied soils of parts: better developed soil on older parts
Compared results to factors, like seasons
15.16.a-c

Investigation: Which Areas Have Highest Risk of Slope Failure?
Snow Mountain: occasional steam from crater; huge blocks of andesite on flanks
Rock Valley: hummocky with huge angular blocks
Flattop Hill: Basalt over weak clay; scar on side
Gray Mountain: granite with fractures
Bent Fence Hills: leaning trees
Wild Ride Valley: cracked and bumpy roads
Hazel River: large blocks of volcanic rocks on terrace
Tilted Mountain: tilted limestone cut by fissures; shale layer at base
15.17.a1



Investigation
15.17.a1