Engineering Geology

Lecture-6

Introduction to Structural Geology and Plate Tectonics

Why Study Structural Geology and Plate Tectonics

Structural Geology, **Tectonics** and **Geodynamics** make a coherent and interdependent group of sub-disciplines, the aim of which is the search for knowledge about how minerals, rocks & rock formations, and Earth systems (i.e., crust, lithosphere, asthenosphere ...) ***deform*** and via which processes.

Structural Geology

- Structural Geology aims to characterize deformation structures (***geometry***), to characterize flow paths followed by particles during deformation (***kinematics***), and to infer the direction and magnitude of the forces involved in driving deformation (***dynamics***).
- A field-based discipline, structural geology operates at scales ranging from 100 microns/micrometers to 100 meters (i.e. grain to outcrop).

Tectonics

- Tectonics (from Latin tectonicus; from Ancient Greek (tektonikos) 'pertaining to building') are the processes that control the structure and properties of the Earth's crust and its evolution through time.
- Discipline of Tectonics aims at finding the geological context in which deformation occurs. It involves the integration of structural geology data in maps, cross-sections and 3D block diagrams, as well as data from other Geoscience disciplines including sedimentology, petrology, geochronology, geochemistry and geophysics. Tectonics operates at scales ranging from 100 m to 1000 km, and focuses on processes such as continental rifting and basins formation, subduction, collisional processes and mountain building processes etc.

- ***Plate Tectonics is:*** *A theory explaining the structure of the earth's crust and many associated phenomena as resulting from the interaction of rigid lithospheric plates which move slowly over the underlying mantle*

Geodynamics

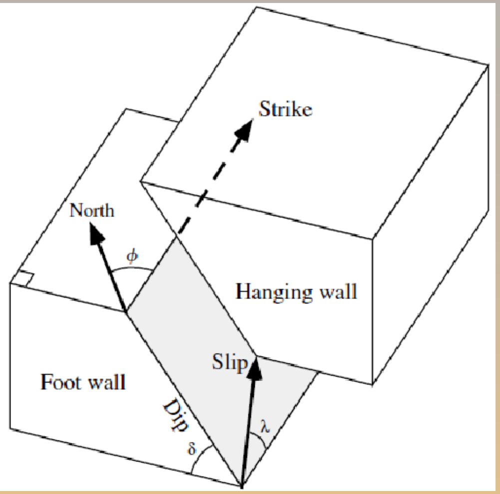
- Geodynamics focusses on the forces that drive mantle convection, plate motion and deformation of Earth's material. Geodynamics is concerned with deep mantle processes and their links to plate motion, including dynamic plate subsidence and uplift, and plate tectonic processes. Geodynamics involves working at scales > 100 km.

Structural Geology

- Structural geologists are concerned with features resulting from deformation. These include fractures, faults, folds, boudins, shear zones, cleavages (also knows as schistosities), foliations and lineations.

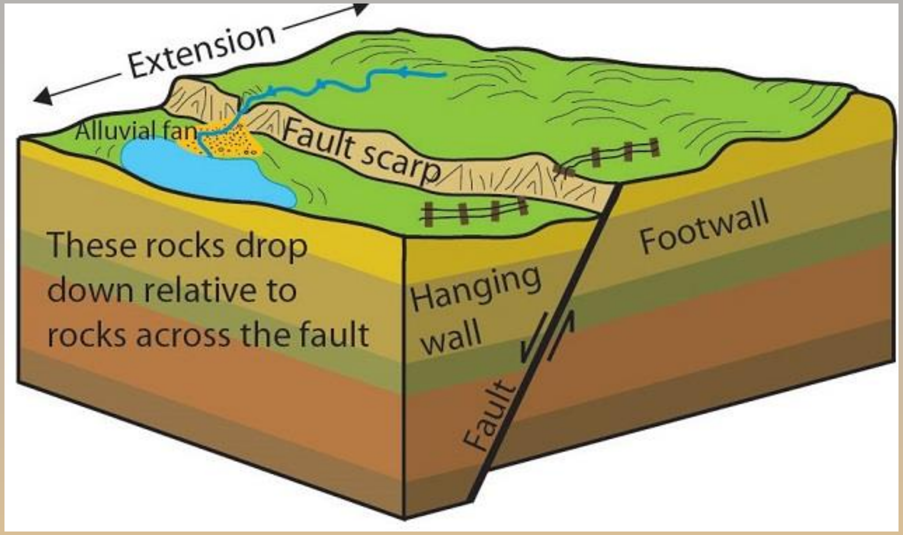
Fractures and Faults

- **Faults** are cracks in the earth's crust along which there is movement. These can be massive (the boundaries between the tectonic plates themselves) or very small. If tension builds up along a fault and then is suddenly released, the result is an earthquake.
- **Fractures** are simply cracks in the crust where there is no movement.
- Faults are classified according to the direction of relative movement along the fault. The terms **hanging wall** and **foot wall** refer to the relative position of the plates after movement.
- Economic minerals often grow along faults, and these terms come from where a miner would stand, and where they would hang their lantern.

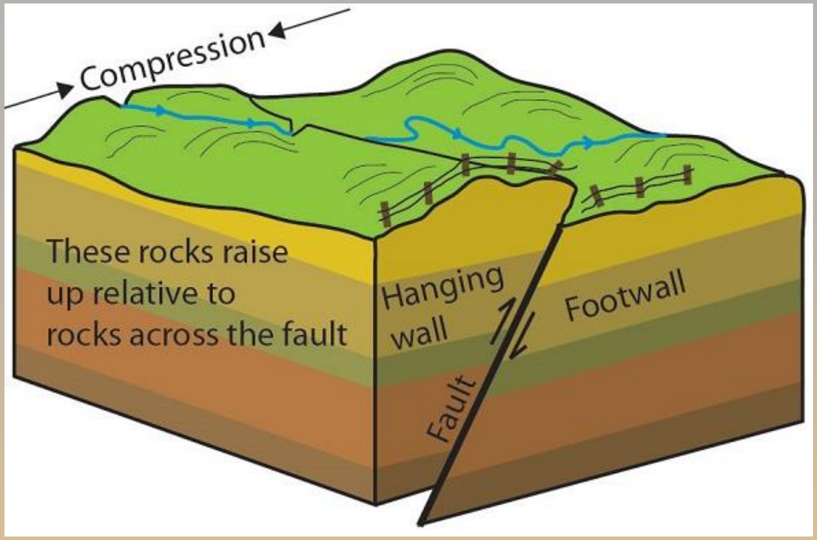


Faulting corresponds to the brittle failure of an un-deformed rock formation or, alternatively, involves frictional sliding on a pre-existing fault plane. Faulting occurs when the maximum differential stress (i.e., maximum stress σ_1 minus minimum stress σ_3) exceeds the shear strength of an intact rock formation, or the frictional strength of a pre-existing fault.

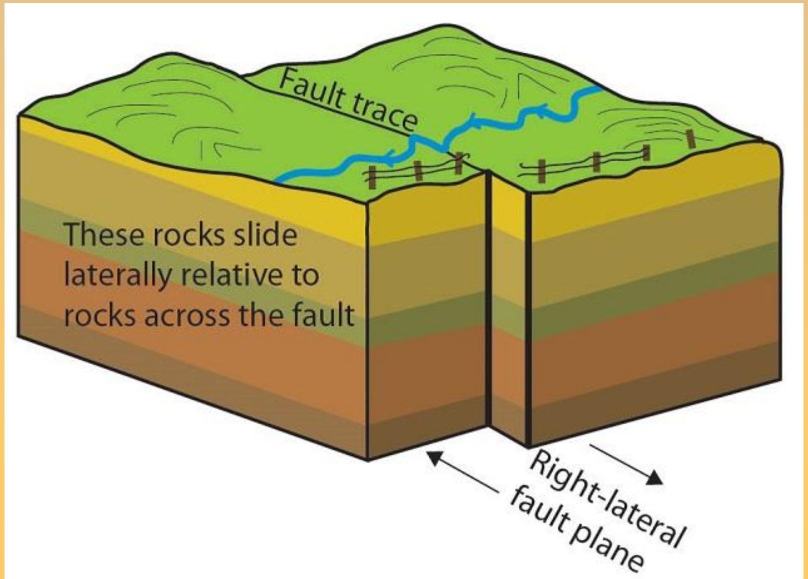
Normal Faulting



Reverse/Thrust Faulting



Strike-Slip Faulting

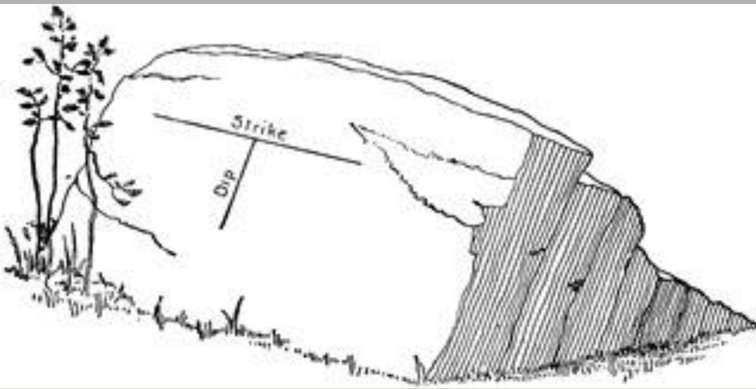


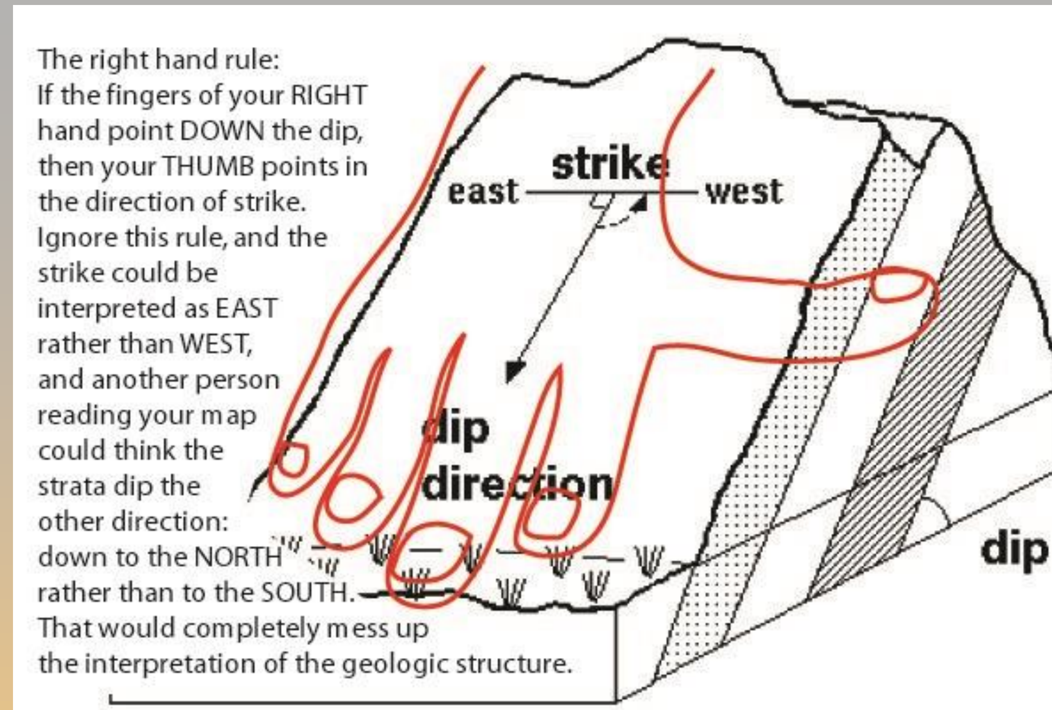
Strike and dip refer to the orientation or *attitude* of a geologic feature.

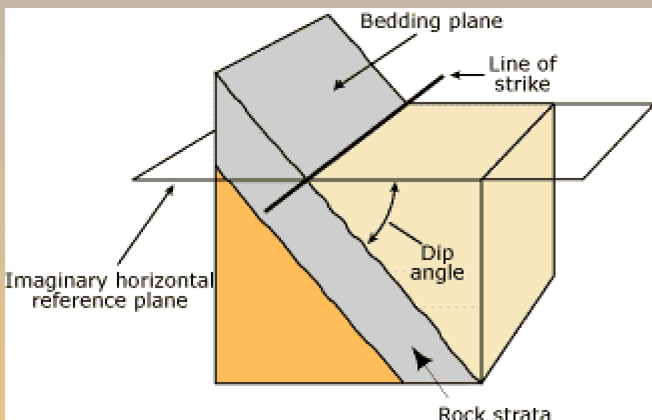
The ***strike*** *line* of a bed, fault, or other planar feature, is a line representing the intersection of that feature with a horizontal plane. On a geologic map, this is represented with a short straight line segment oriented parallel to the strike line.

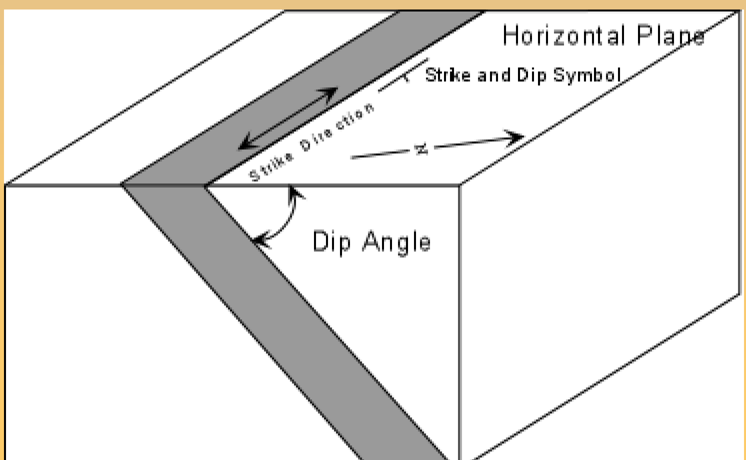
The ***dip*** gives the steepest angle of descent of a tilted bed or feature relative to a horizontal plane, and is given by the number (0°-90°) as well as a letter (N,S,E,W) with rough direction in which the bed is dipping downwards.

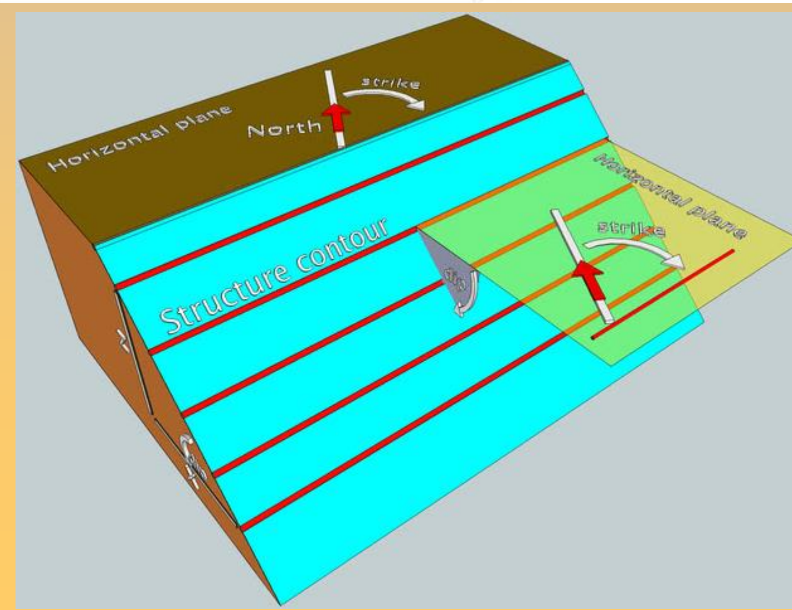
STRIKE AND DIP







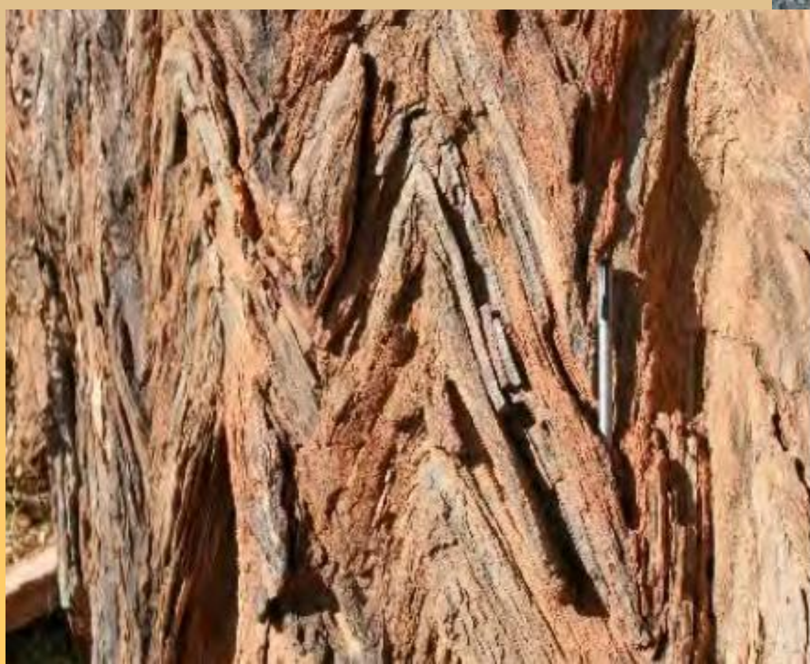




Folds

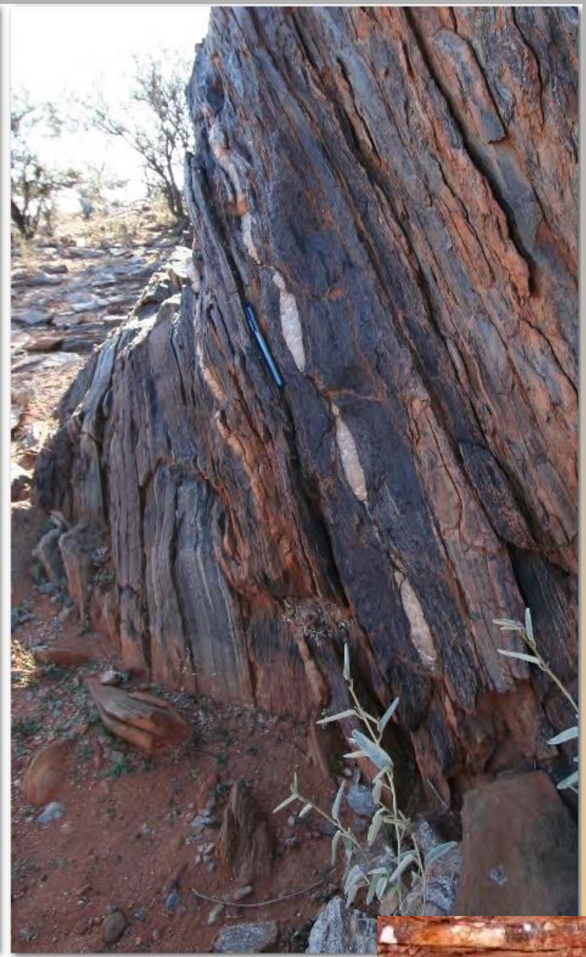
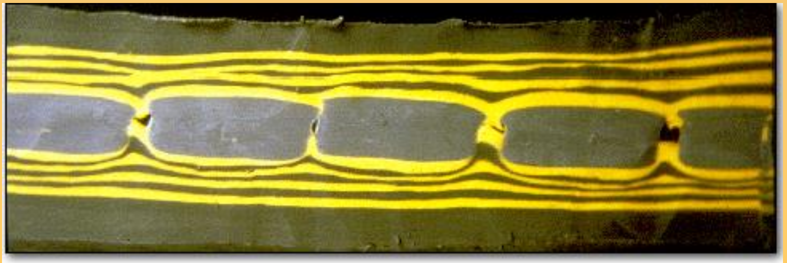
At depth, fracturing and faulting are inhibited by increasing confining pressure as well as increasing temperature which give rocks the ability to flow rather than break. At depth, rock formations organized into layered systems of alternating stronger and less strong layers, buckle under the action of stress to form **folds** and **fold systems**, or alternatively stretch to form **boudins**.


SW



Boudins and Boudinage

- Whereas folds are an expression of contractional deformation, boudins and boudinage result from extensional deformation applied to rock formations made of alternating stronger and less strong layers.
- Boudins form due to a process called boudinage. Boudins form when lengthening affects a layered rock formation involving competent layers embedded into a less competent, easily deformable, host rock.

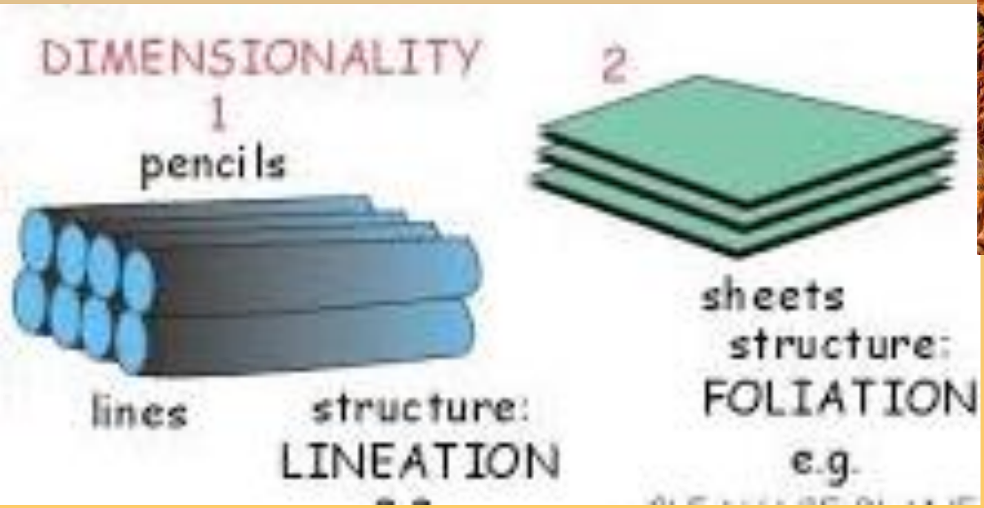
20 cm

Shear Zones

- Ductile shear zones develop as a results of slow, progressive deformation over long period of time. Deformation is typically continuous and develop without macro-scale fracturing.
- Deformation is said to be ductile as opposed to brittle. Zones are therefore different to brittle faults, which involve sudden mechanical instabilities that explain earthquakes. While faulting and fracturing typically develop at low temperatures (<250ºC), and/or high-strain rates, and/or high deviator stresses, ductile shearing is the mode of deformation at higher temperatures (>250ºC), low strain-rates, and low deviator stresses.

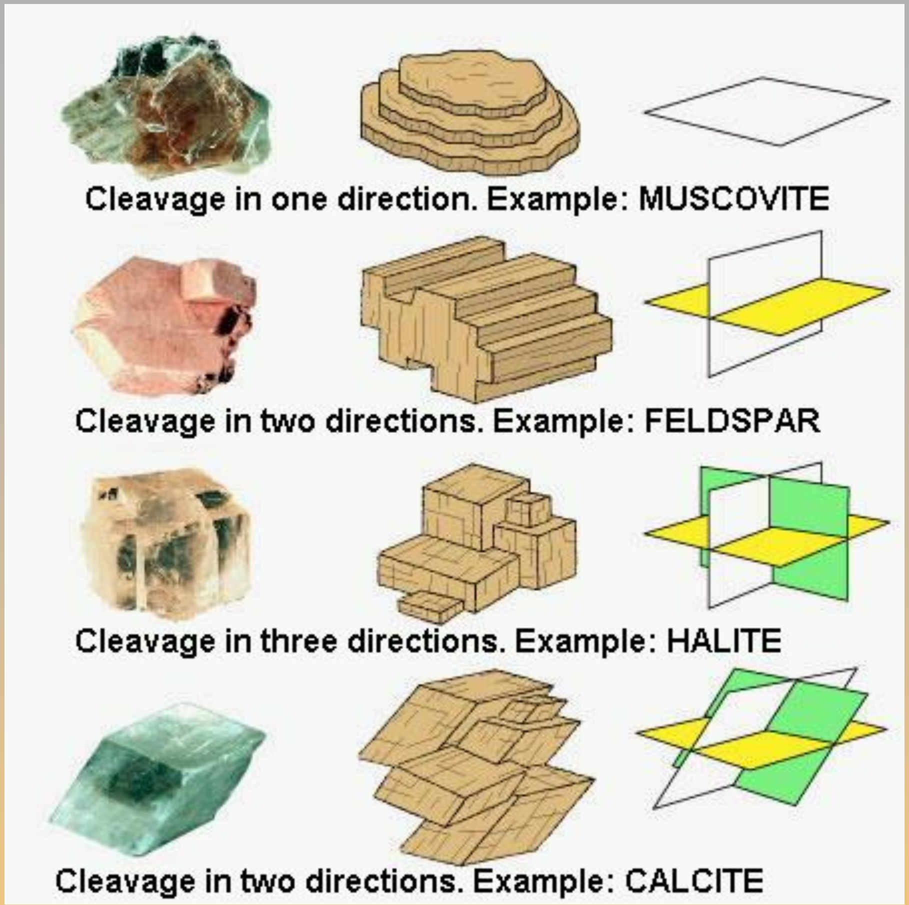
Foliations and Lineations

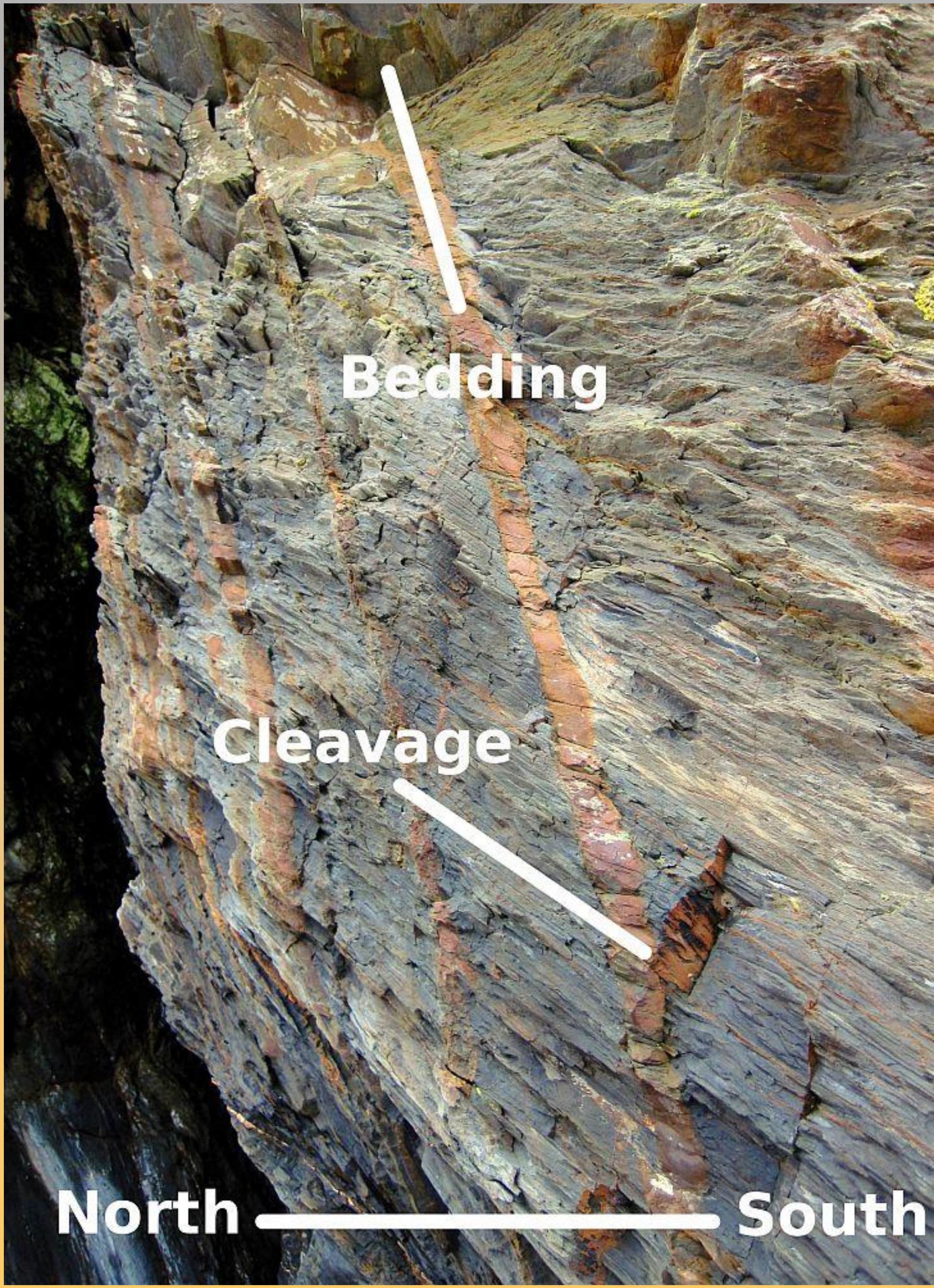
During deformation, rock forming grains and minerals change their orientation and shape, giving deformed rocks organized planar and linear structures called fabrics. Foliation (the result of flattening) and lineation (most of the time the result of elongation) are planar and linear fabrics respectively


DIMENSIONALITY
1
pencils
lines
structure:
LINEATION
2
sheets
structure:
FOLIATION
e.g.

Cleavage

- Cleavage, in structural geology and petrology, describes a type of planar rock feature that develops as a result.
- Cleavage is a type of rock foliation, a fabric element that describes the way planar features develop in a rock. Foliation is separated into two groups: primary and secondary. Primary deals with igneous and sedimentary rocks while secondary deals with rocks that undergo metamorphism as a result of deformation. Cleavage is a type of secondary foliation associated with fine grained rocks. For coarser grained rocks, schistosity is used to describe secondary foliation.


Cleavage in one direction. Example: MUSCOVITE
Cleavage in two directions. Example: FELDSPAR
Cleavage in three directions. Example: HALITE
Cleavage in two directions. Example: CALCITE


Bedding
Cleavage
North
South

Who needs Structural Geology?

- Structural geology is at the core of hydrocarbon and mineral exploration, as structures control the migration, trapping and escape of hydrocarbon fluids.
- Structural geology is the first stage to any regional geophysical and geochemical surveys aiming at identifying new mineralized provinces.
- It is also critical for the interpretation of geophysical, geochemical, and geochronological data.
- At the mine camp scale, structural geology guide the mining process.
- Structural geology is at the core of geotechnical site assessment for bridges, dams, tunnels, nuclear reactors, waste disposals etc.
- Because of the obvious relationship between faults and earthquake, structural geology is the core of earthquake prevention and earthquake seismology.
- Structural geology is central to any study of past and present mountain belts and sedimentary basins. No geological, geochemical or geophysical study can be done without the input of structural geology

Plate Tectonics: The Beginning

Background

❖ At the beginning of the 20th Century, scientists realized that that they could not explain many of the Earth's structures and processes with a single theory. Many scientific hypotheses were developed to try and support the conflicting observations. One hypotheses was ***continental drift***, which was proposed by Alfred Wegener in a series of papers from 1910 to 1928.

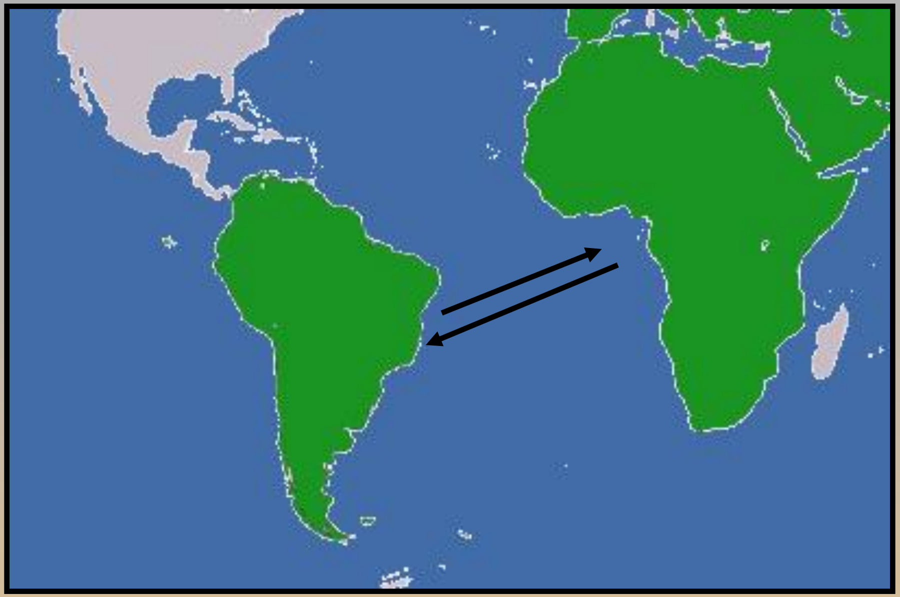
❖ The principal thought of continental drift theory is that the continents are situated on slabs of rock, or plates, and they have drifted across the surface of the Earth over time; however, originally, they were all joined together as a huge super-continent at one time.

❖ In the 1960's, the theory of continental drift was combined with the theory of sea-floor spreading to create the theory of plate tectonics.

Alfred Lothar Wegener (1880-1930)

(Photograph courtesy of the Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany.)

Plate Tectonics: The Beginning



The “fit” of two continents.

❖ The idea for Wegener's theory was sparked by his observation of the nearly perfect **“fit”** of the South American and African continents.

Additional evidence supporting the continental drift theory:

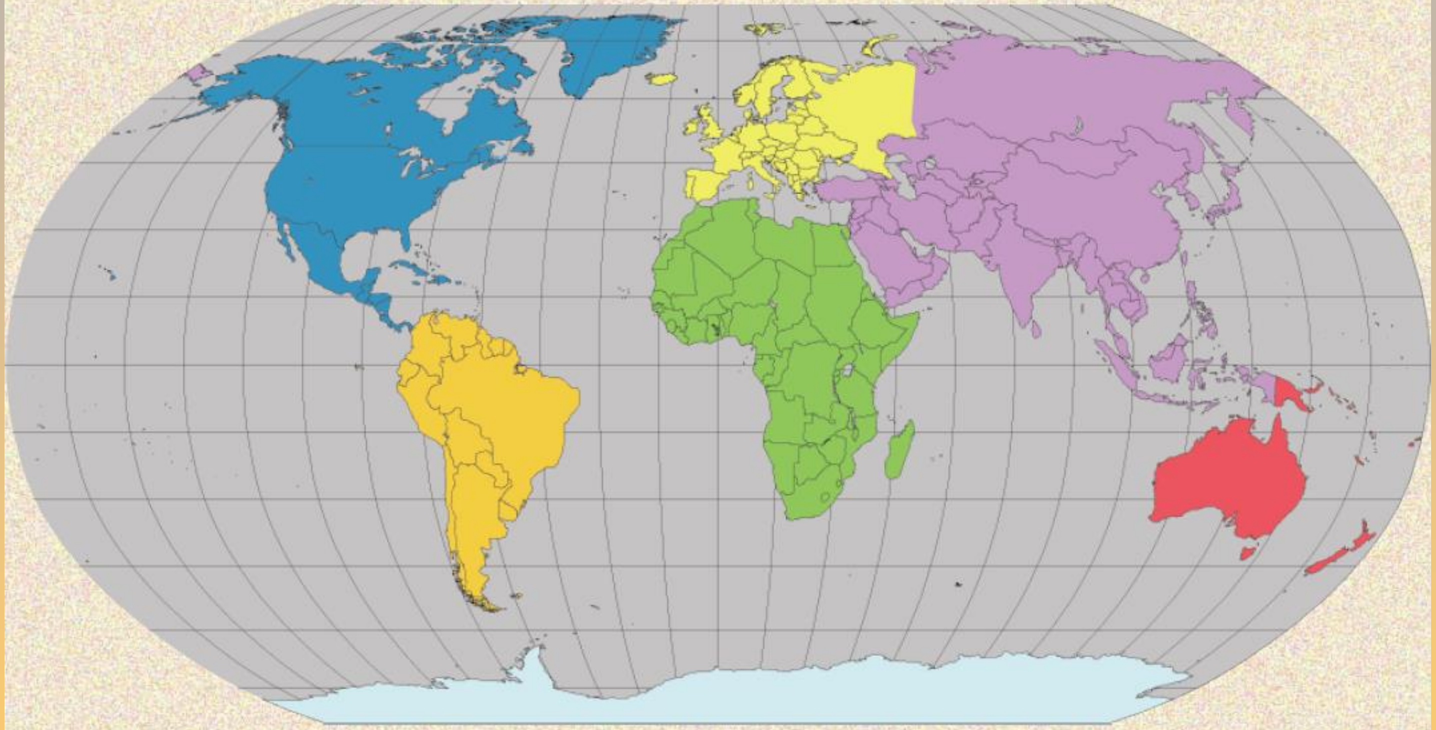
1. Fossils of the same plant (Glossopteris) found in Australia, India, Antarctica and South America.

2. Fossils of same reptile (Mesosaurus) found in Africa and South America. This animal could not have swum across the existing Atlantic Ocean!

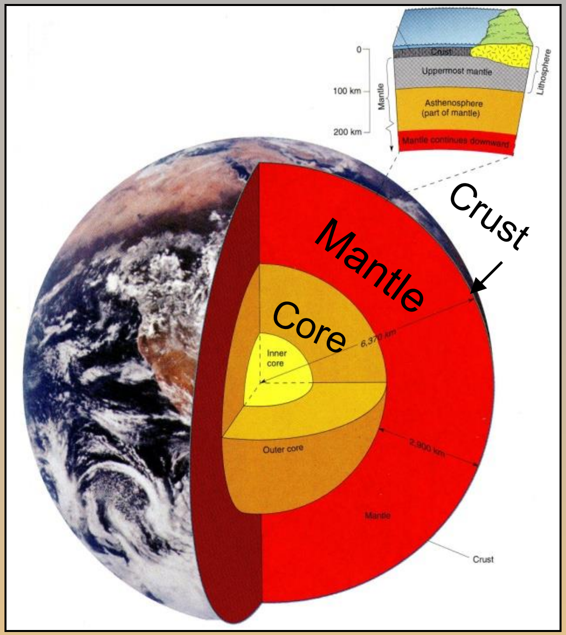
3. Glacial deposits found in current warm climates and warm climate plant fossils found in what is now the Arctic.

4. Nearly identical rock formations found on the east coast of U.S. and the west coast of Europe and eastern South America and western Africa.

- If you look at a map of the world, you may notice that some of the continents could fit together like pieces of a puzzle.



What are Tectonic Plates?



The layers of the earth.

The Earth is made up of three main layers:

1. The **<u>Core</u>** is at the center of the Earth. It is divided into an inner and outer core.
2. The **<u>Mantle</u>** is the layer surrounding the core. The upper mantle is partially molten and called the asthenosphere.
3. The **<u>Crust</u>**, or lithosphere, is the rigid outer-most layer. Thick continental crust underlies continents, and thin, very dense oceanic crust underlies oceans.

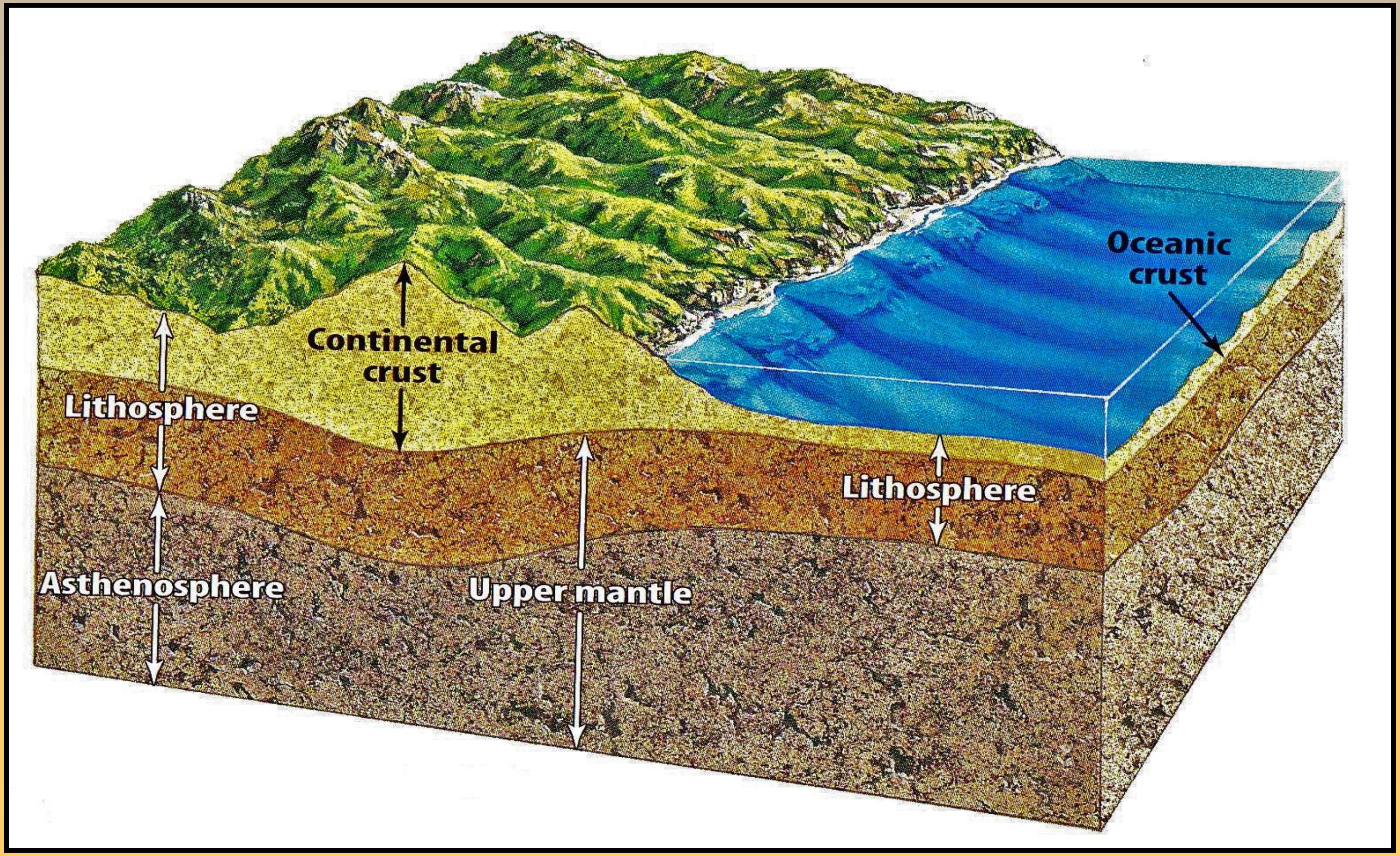
	Inner Core	**Outer Core**	**Mantle**	**Crust**
Thickness	1,216 km	2,270 km	2,900 km	Continental 35-90 km Oceanic 7-8 km
Physical Properties	Solid Iron; extremely dense (17 g/cm^3)	Molten Iron, very dense (12 g/cm^3)	Made mostly of silicates of magnesium and iron; moderately dense. Behaves like melted plastic in upper-most section (5.5 g/cm^3)	Made of silicate rocks and oxides; slightly dense; rigid. (2.67-3.3 g/cm^3)
Percentage of Earths' Mass	30%		65%	5%

What are Tectonic Plates? (continued)

Earth's Sublayers

❖ **Lithosphere**: This layer combines the rigid crust plus the upper-most mantle. (Greek: Rock)

❖ **Asthenosphere**: Partially molten part of upper mantle (Greek: weak). Tectonic plates are able to move about on top of the softer, partially molten asthenosphere.



The outer-most layers of the earth.

McGraw Hill/ Glencoe, 1st ed., pg. 142.

What are Tectonic Plates? (continued)

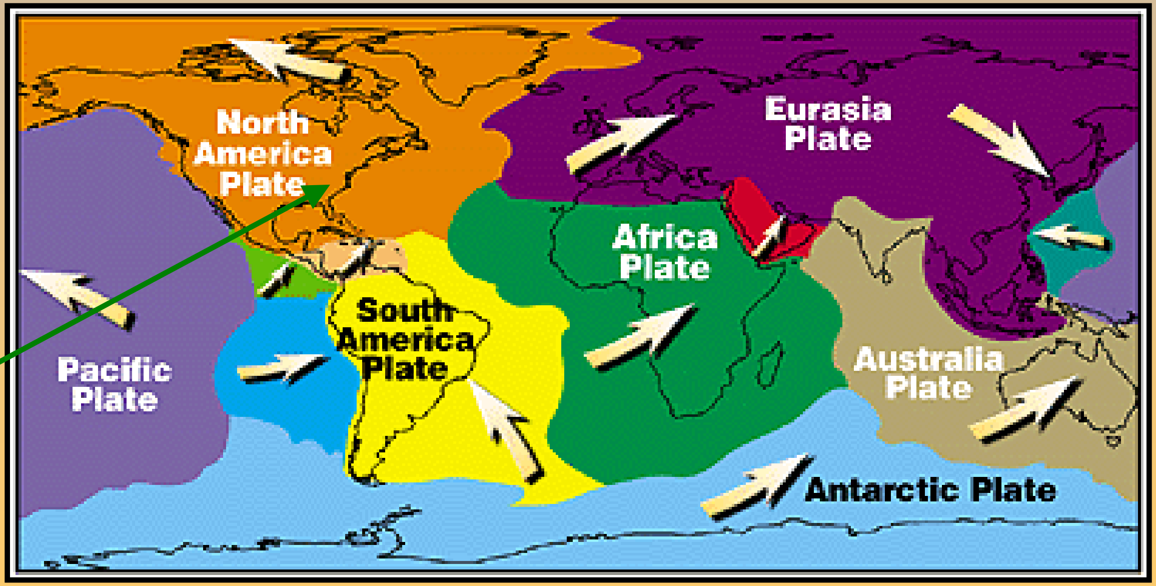
❖ The Earth's crust consists of about a dozen large slabs of rock, or **PLATES**, that the continents and oceans rest on. These tectonic plates can move centimeters per year— about as fast as your fingernails grow up to 15cm/yr in some places.

❖ Tectonic plates are also called **lithospheric plates** because the crust and the upper-most mantle make up a sub-layer of the earth called the lithosphere. The plates can move about because the uppermost mantle, or the asthenosphere, is partially molten and possesses a physical property called plasticity, allowing the strong, rigid plates of the crust to move over the weaker, softer asthenosphere.

Plates and relative plate motion.

Modified after NOAA

South Carolina is located on the North American plate



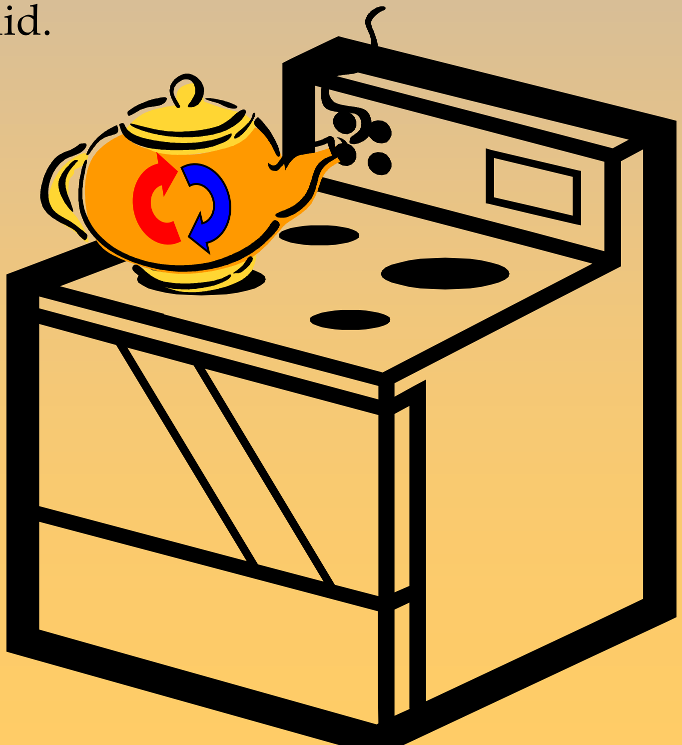
❖ The word TECTONICS is of Greek origin and it means "to build." The word "tectonism" refers to the deformation of the lithosphere. This deformation most notably includes mountain building.

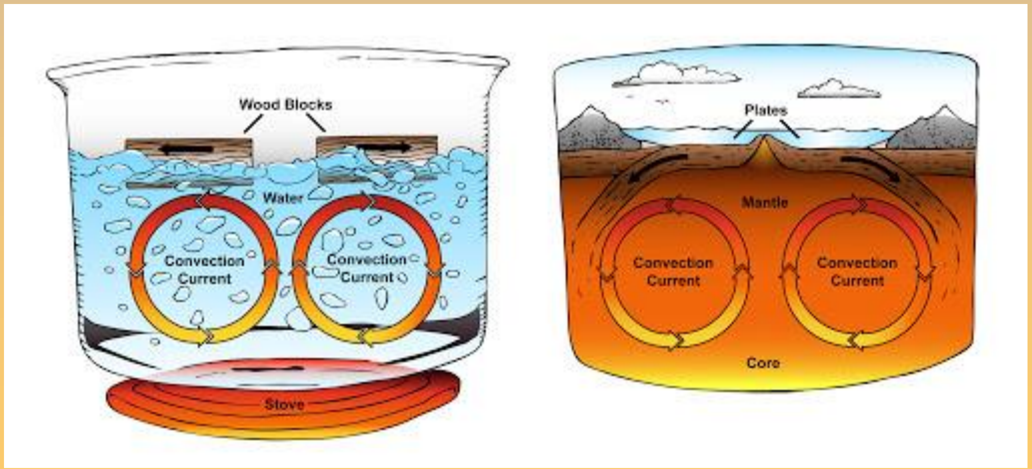
What are Tectonic Plates? (continued)

❖ Tectonic plates, or lithospheric plates, are constantly moving, being created, and consumed simultaneously. The motion sometimes results in earthquakes, volcanoes, and mountain ranges at the plate boundaries.

❖ Plate motion is driven by heat escaping from the mantle. The constant movement of heat in the mantle leads to circular convection currents. These hot convective cells are similar to the rolling boil that occurs when water is heated on a stovetop. The flowing mantle has also been compared to a “conveyor belt,” moving the rigid plates in different directions.

❖ Fundamentally, convection occurs due to uneven heating and different densities within the liquid.



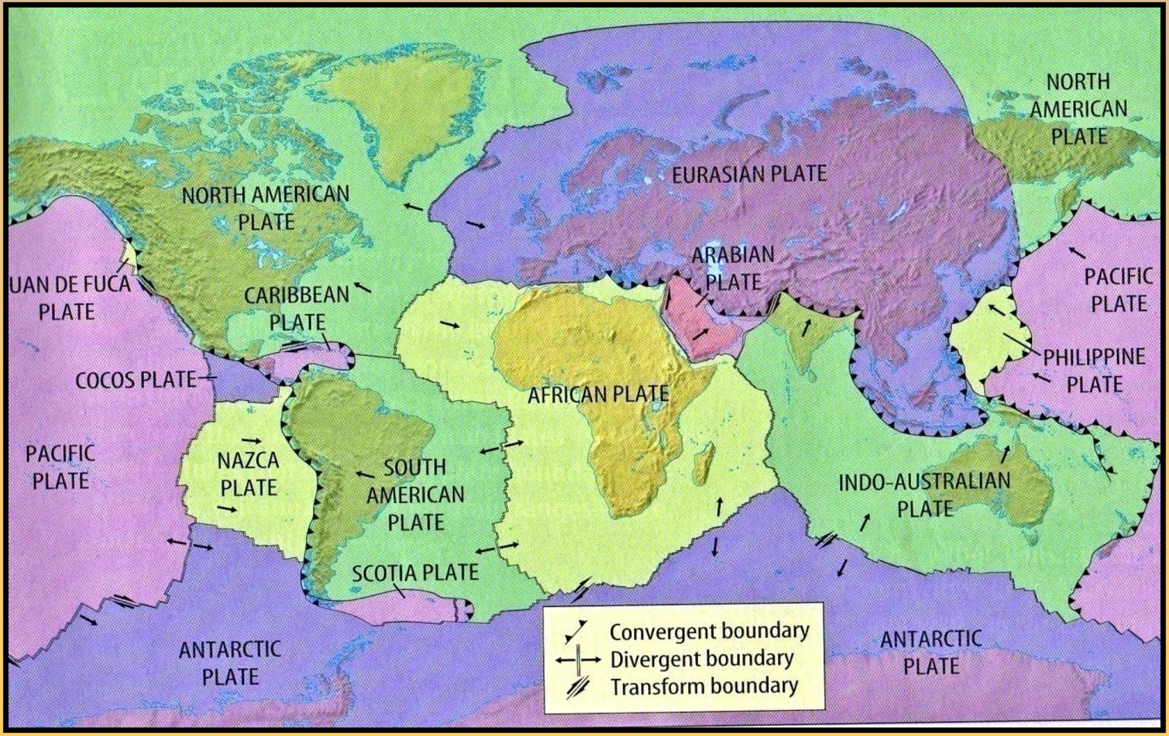


Convection currents within the mantle.

Plate Boundaries

There are three basic ways that plates interact with one another. Each of these plate boundaries has the potential to create different geological features.

1. When plates **collide** with each other **= Convergent boundary**
2. When plates **separate** from each other **= Divergent boundary**
3. When plates **slide** along side each other **= Transform boundary**

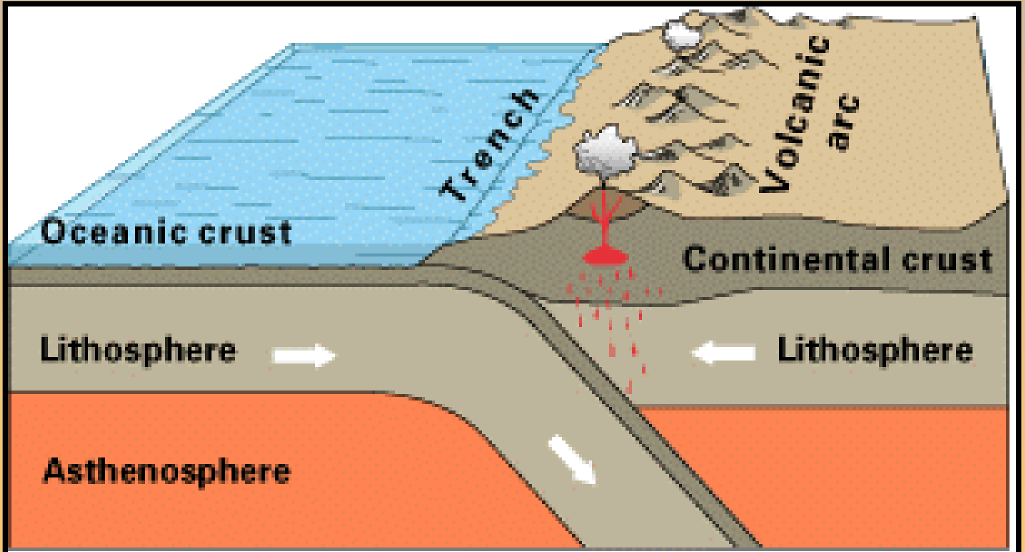


The tectonic plates and plate boundaries.

1. Convergent Boundary:
Ocean-Continent Collision

❖ Because the oceanic crust is more dense than continental crust, when these two collide, the continental crust rides up over the oceanic crust and the oceanic crust is bent down and subducted beneath the continental crust. This is called a subduction zone.

Figure depicting oceanic crust subducting beneath continental crust, creating volcanoes on the land surface above, and a deep-sea trench off of the coast.



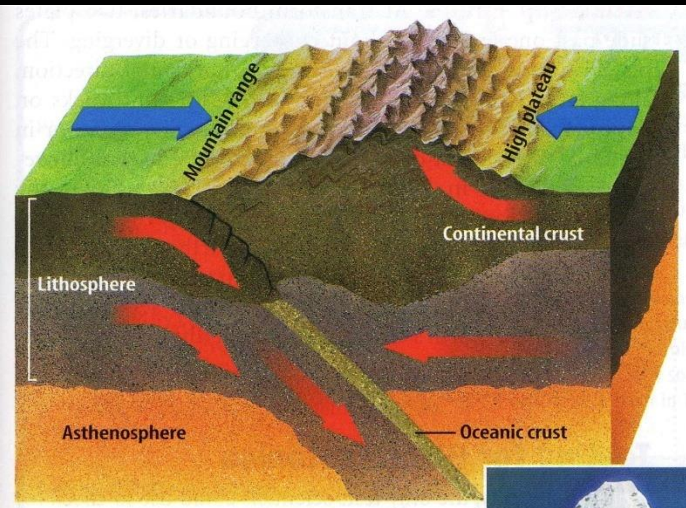
Oceanic-continental convergence

Convergent Boundary:
Continent-Continent Collision

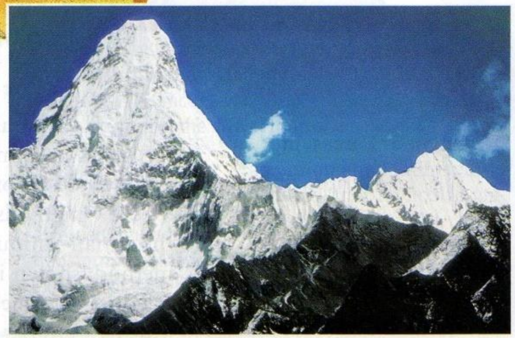
❖ If two continental plates collide, mountain building usually takes place because they are both relatively low in density.

❖ Earthquake activity at these boundaries is common; however, because igneous activity is different from ocean-continent collisions, volcanoes are rare.

❖ Examples: The Himalayan and the Appalachian mountain chains.



Constructive mountain building during continent-continent collision.



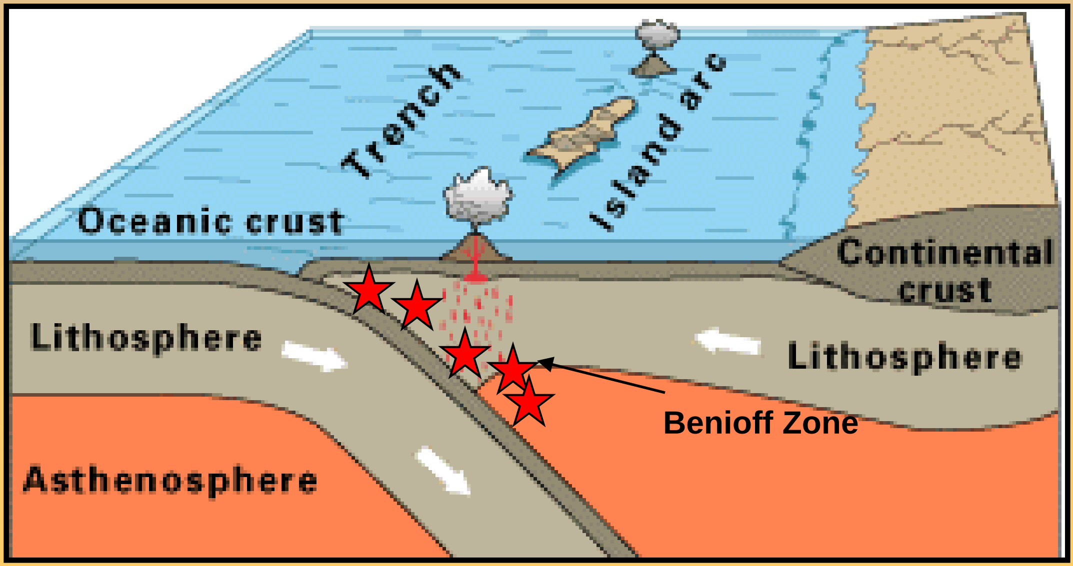
The Himalaya mountains are still forming today as the Ind-Australian Plate collides with the Eurasian Plate

Convergent Boundary: Ocean-Ocean Collision

❖ If 2 oceanic plates collide, the older, denser one is subducted downward into the mantle and a chain of volcanic islands can form, called a volcanic arc.

❖ Example: Mariana Islands (Mariana Trench). It is deeper than the earth's tallest mountain is tall. Mariana Trench: 11,000 meters deep. Mt. Everest: 8850 meters high.

❖ The interaction of the descending oceanic plate causes incredible amounts of stress between the plates. This usually causes frequent earthquakes along the top of the descending plate known as the "Benioff Zone." The focii of Benioff earthquakes can be as deep as 700 km below sea level.



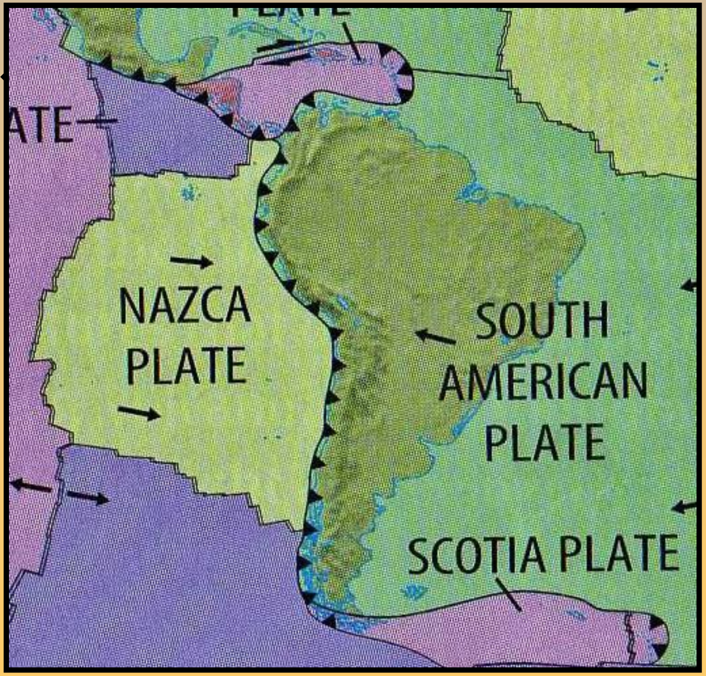
Oceanic/oceanic collision resulting in a chain of island arcs.

Credit: U.S. Geological Survey Department of the Interior/USGS

Convergent Boundary: Volcanism

❖ Most volcanoes form above subduction zones because as one slab is subducted beneath the other, the interaction of fluids and geothermal heat form new magma. The new magma then rises upward through the overlying plate to create volcanoes at the surface.

❖ The Andes Mountains are home to many volcanoes that were formed at the convergent boundary of the Nazca and South American Plates.



<u>Left:</u> Image of the Nazca Plate subducting beneath the South American Plate.

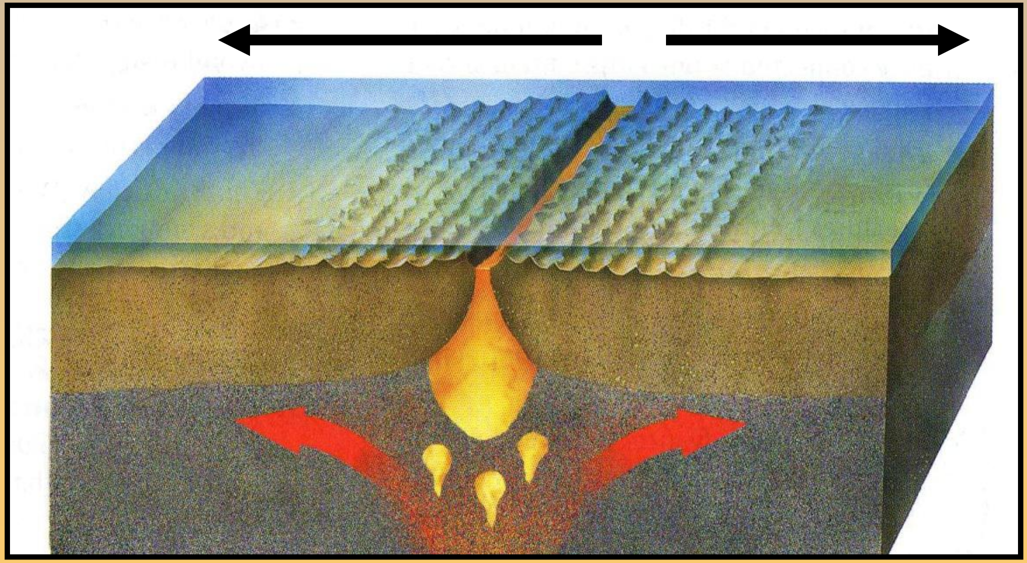
Modified after McGraw Hill/Glencoe, 1st ed., pg. 143

<u>Right:</u> Red dots indicate general locations of volcanoes along western coast of South America.

2. Divergent Boundary: Sea-floor Spreading

❖ At a divergent boundary, two oceanic plates pull apart from each other through a process called **<u>sea-floor spreading</u>**.

❖ Sea-floor spreading was proposed by Harry Hess in the early 1960's. Hess proposed that hot magma rises from the asthenosphere and up into existing ocean crust through fractures. The crust spreads apart making room for new magma to flow up through it. The magma cools, forming new sea floor and resulting in a build-up of basaltic rock around the crack, which is called a mid-ocean ridge.



Sea-floor spreading at an oceanic divergent boundary.

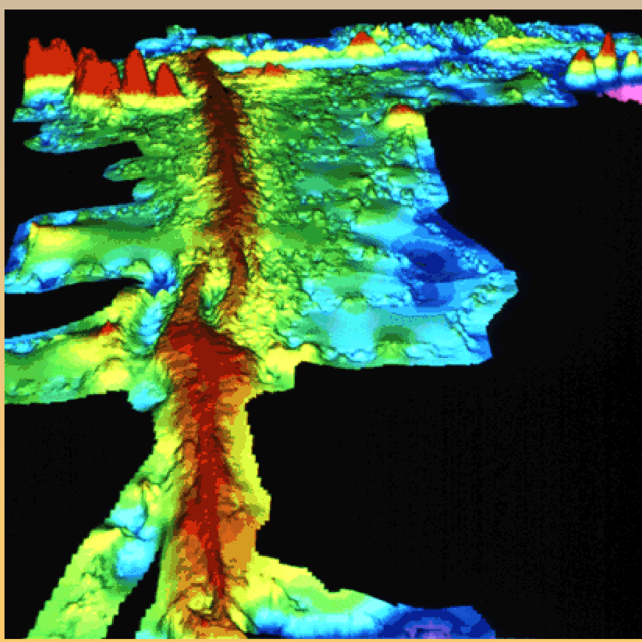
Modified after McGraw Hill/ Glencoe, 1st ed., pg. 138 (with permission)

❖ New material is constantly being created. This is the opposite of a convergent boundary, where material is constantly being destroyed.

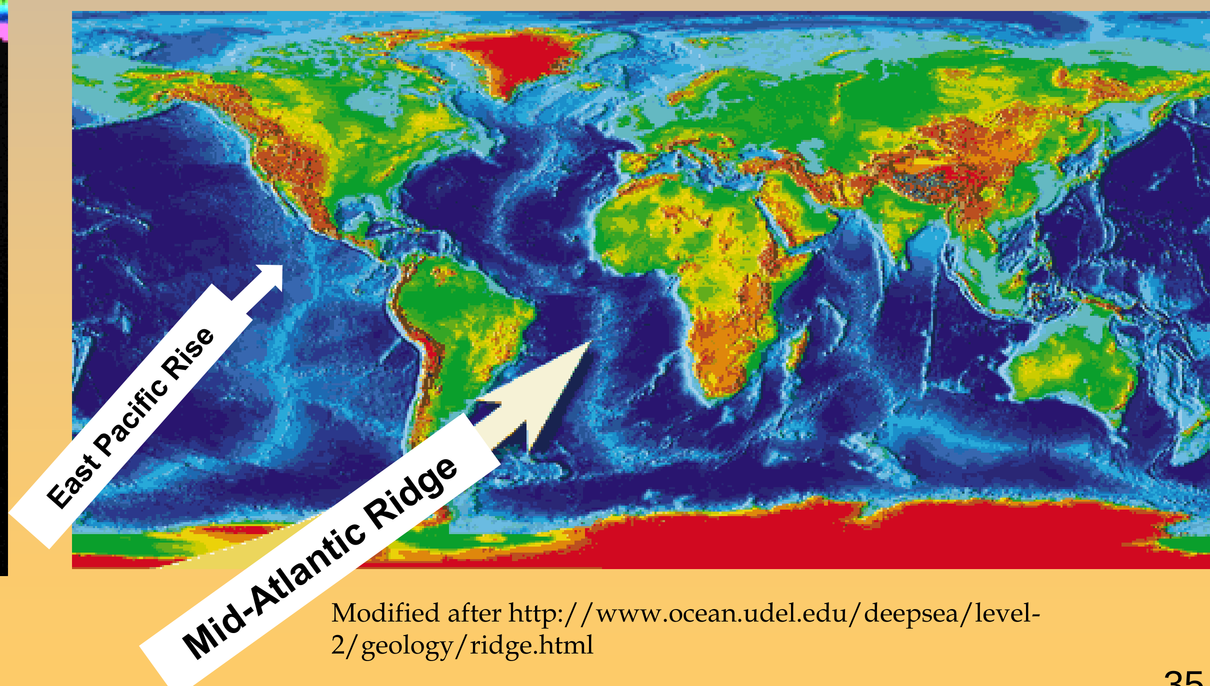
Divergent Boundary: Mid-Atlantic Ridge

❖ The world's longest mountain chain is underwater. It is 56,000 km long and is called the Mid-Atlantic Ridge.

❖When a divergent boundary occurs beneath oceanic lithosphere, the rising convection current below lifts the lithosphere, producing a mid-ocean ridge.



Satellite bathymetry of the East Pacific Rise spreading ridge. *Credit: U.S. Geological Survey Department of the Interior/USGS*

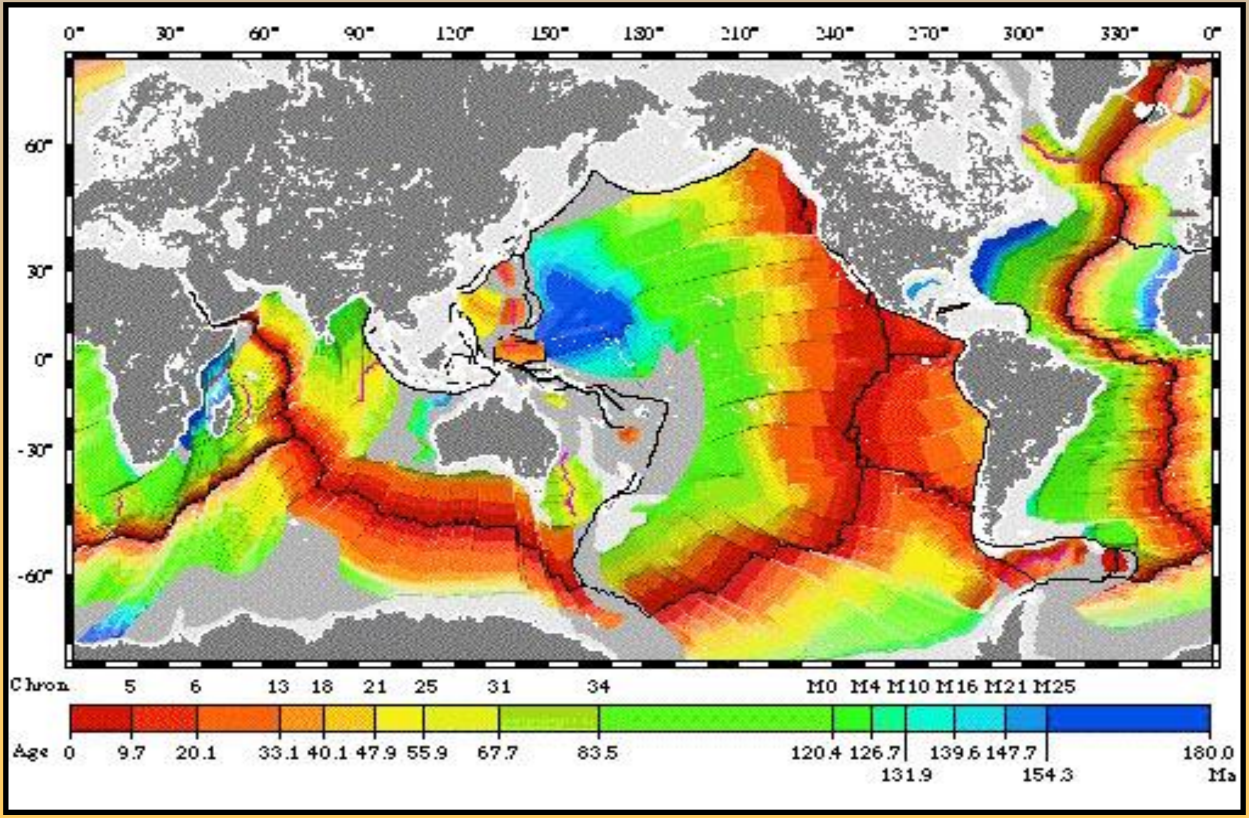


Modified after http://www.ocean.udel.edu/deepsea/level-2/geology/ridge.html

Sea-floor Exploration: Age-dating

❖ The oldest oceanic crust found is ~ 180 million years old.

❖ Because the age of the earth is ~4,600 million years, we know that oceanic crust is continually being formed at spreading ridges and being destroyed at subduction zones. The ocean floor is constantly changing shape and size through the processes of sea-floor spreading and subduction.



❖ Because no older ocean crust has been found, recycling of the ocean crust takes place about every 180 million years.

The relative ages of the ocean floor.

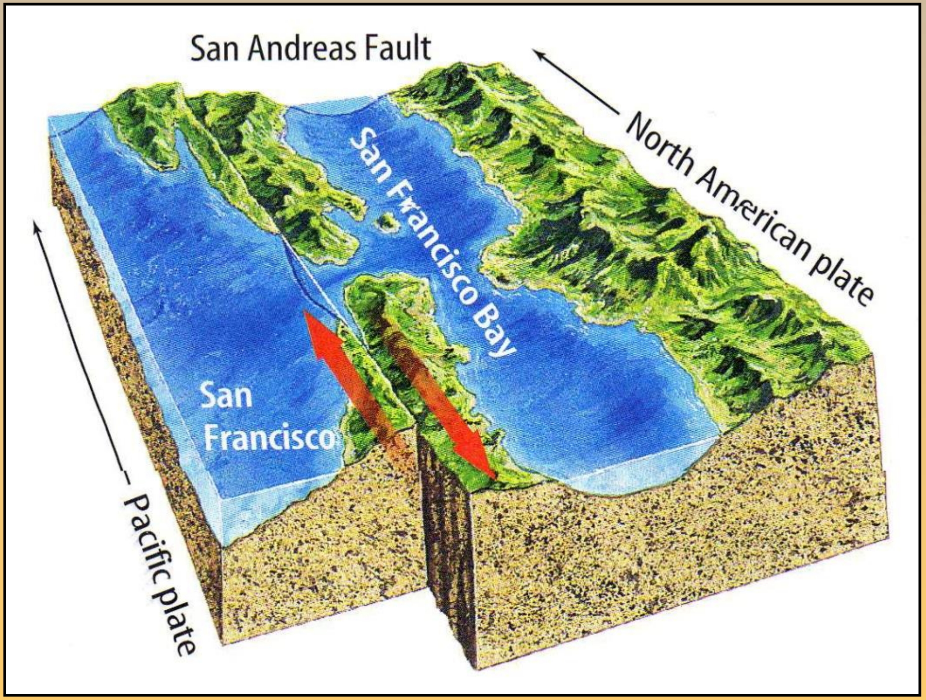
Credit: Nova.

3. Transform Boundary

❖ When two plates slide past each other moving in different directions or the same direction, it is termed a transform boundary and is characterized by a transform fault and earthquake activity.

❖ An example of a transform fault is the San Andreas Fault in California. Here the North American Plate joins the Pacific Plate. The difference in plate motion along the contact (fault) leads to a buildup of strain energy that sometimes slips releasing a huge amount of energy and causing an earthquake.

An aerial photo of the San Andreas fault line



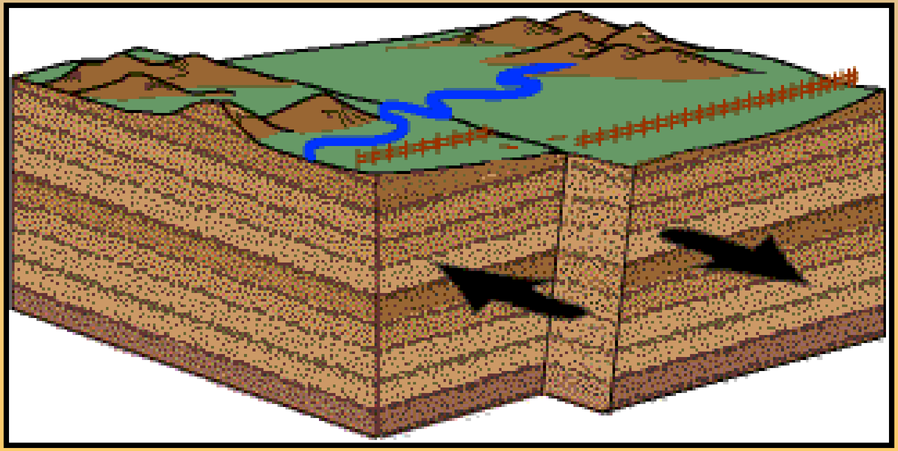
Movement between the 2 plates at the San Andreas Transform Fault. *McGraw Hill/Glencoe, 1st ed., pg. 146 (with permission).*

Mountain building processes, faults and folds

❖ Plate tectonics cause many of the physical features that we see on earth today like volcanoes and earthquakes, but also many other geological features like faults. **Faults** are planar rock fractures along which movement has occurred.

❖ A transform fault occurs at a transform plate boundary like the San Andreas Fault in California. It connects two of the other plate boundaries.

❖ Similar in movement, a strike-slip fault occurs through **shearing** when two blocks move in horizontal but opposite directions of each other. Depending on the direction of offset, it can be a "right-lateral offset" or a "left-lateral offset."



In the example above, it is obvious that the fence has been offset to the right, therefore it is called a right lateral strike-slip fault *(Credit: U.S. Geological Survey Department of the Interior/USGS)*

The photograph above displays a light-colored pegmatite vein offset to the right in a schistose matrix. *Photo courtesy of K. McCarney-Castle.*

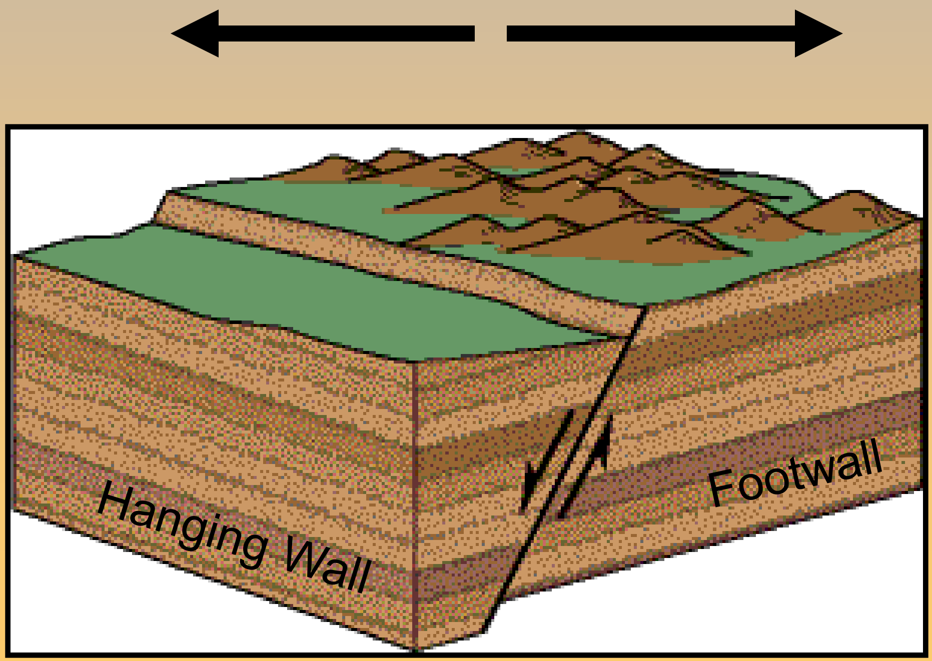
Faults: Normal Faults

❖ Faults caused by blocks of crust pulling apart under the forces of tension are called **normal faults.** Entire mountain ranges can form through these processes and are known as fault block mountains (examples: Basin and Range Province, Tetons).

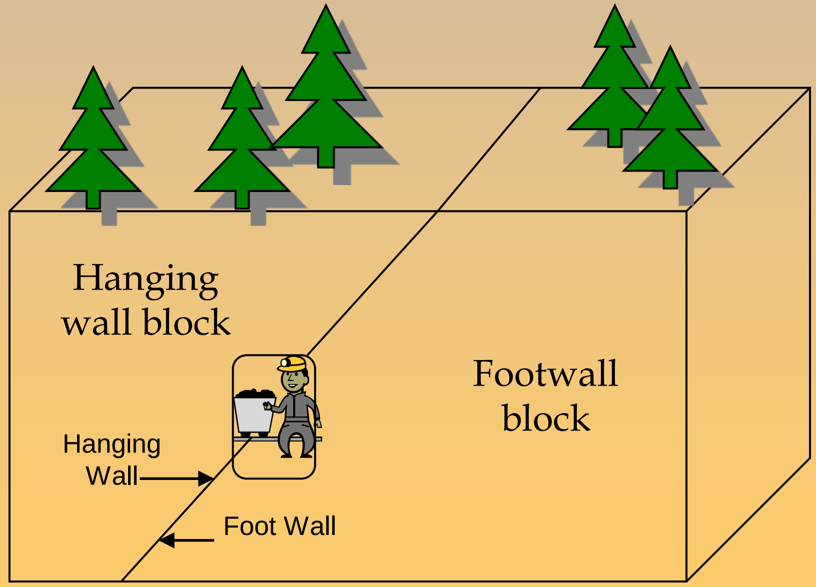
❖ In a normal fault, the hanging-wall block moves down relative to the foot-wall block.

❖ The footwall is the underlying surface of an inclined fault plane.

❖ The hanging wall is the overlying surface of an inclined fault plane.



Relative movement of two blocks indicating a normal fault. *(Credit: Modified after U.S. Geological Survey Department of the Interior/USGS)*



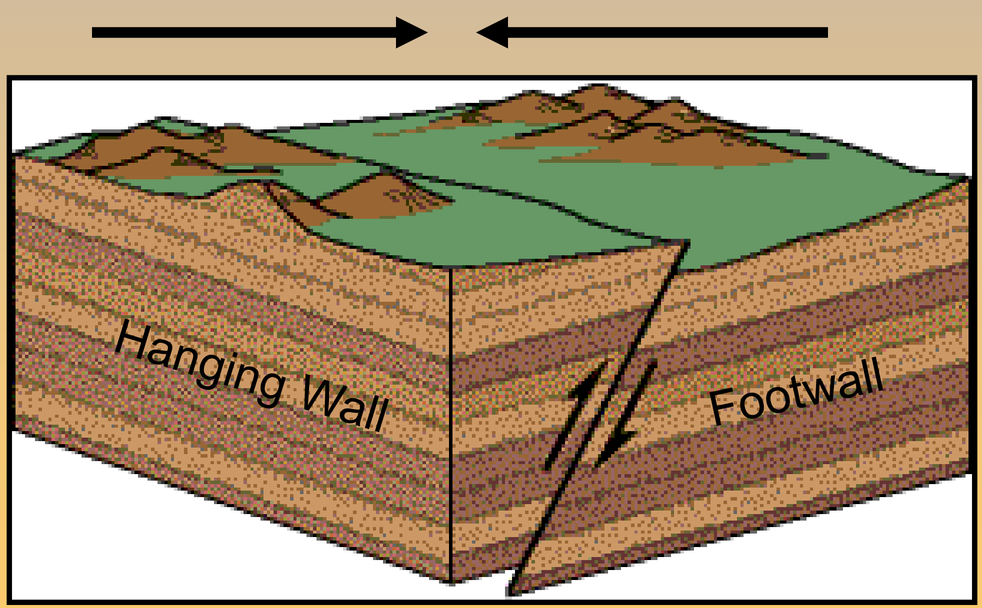
Diagrammatic sketch of the two types of blocks used in identifying normal faults.

Faults: Reverse Faults

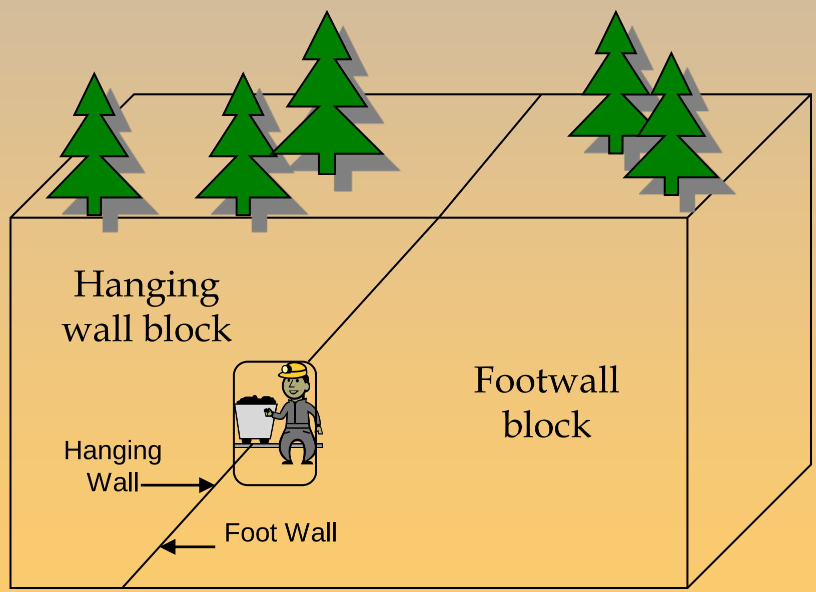
❖ Faults caused by blocks of crust colliding under the forces of compression are called reverse faults.

❖ Reverse faults form during continent-continent collision. Usually, there is also accompanying folding of rocks.

❖ During reverse faulting, the hanging wall block moves upward (and over) relative to the footwall block.



Relative movement of two blocks indicating a reverse fault. *(Credit: U.S. Geological Survey Department of the Interior/USGS)*



Diagrammatic sketch of the two types of blocks used in identifying reverse faults.

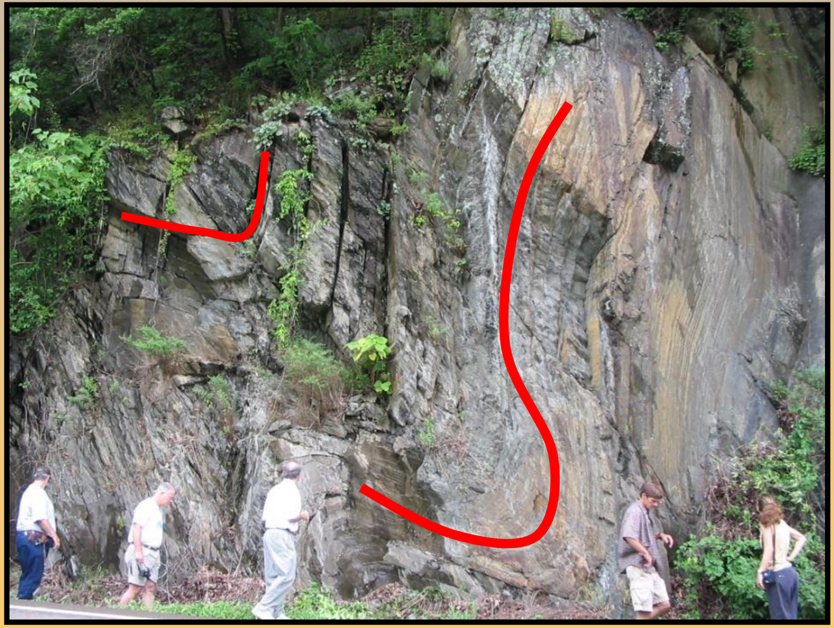
Folding

❖ During mountain building processes, rocks can undergo folding as well as faulting.

❖ Sometimes rocks deform ductilely, particularly if they are subjected to heat and pressure. At elevated temperature and pressure within the crust, folds can form from compressional forces.

❖ Entire mountain rages, like the Appalachians, have extensive fold systems.

Z-fold in schist with white felsic dike (hammer for scale). Near Lake Murray, South Carolina.
Photo courtesy of K. McCarney-Castle



Large fold in outcrop (geologists for scale). Near Oakridge, Tennessee, Appalachian Mtns. *Photo courtesy of K. McCarney-Castle.*

Just for Knowledge

Plate Movement Over Geologic Time

Just for Knowledge

Plate Movement Over Geologic Time

❖ Alfred Wegener proposed that all of the continents once formed a "supercontinent" called Pangaea.

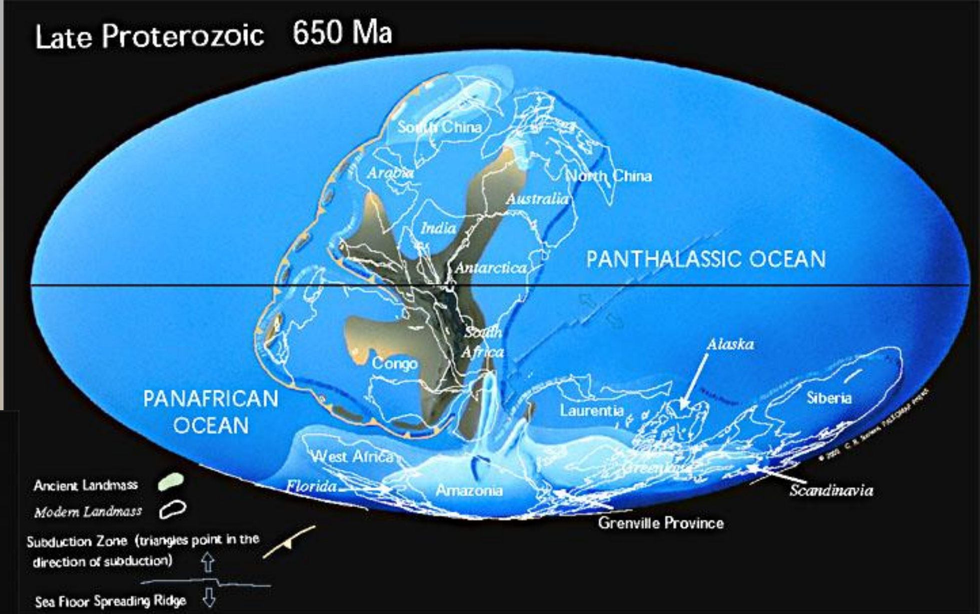
❖ From the Greek language, '*pan*' meaning ALL and '*gaea*' meaning EARTH. It was thought to have come together and formed approximately 200 million years ago.

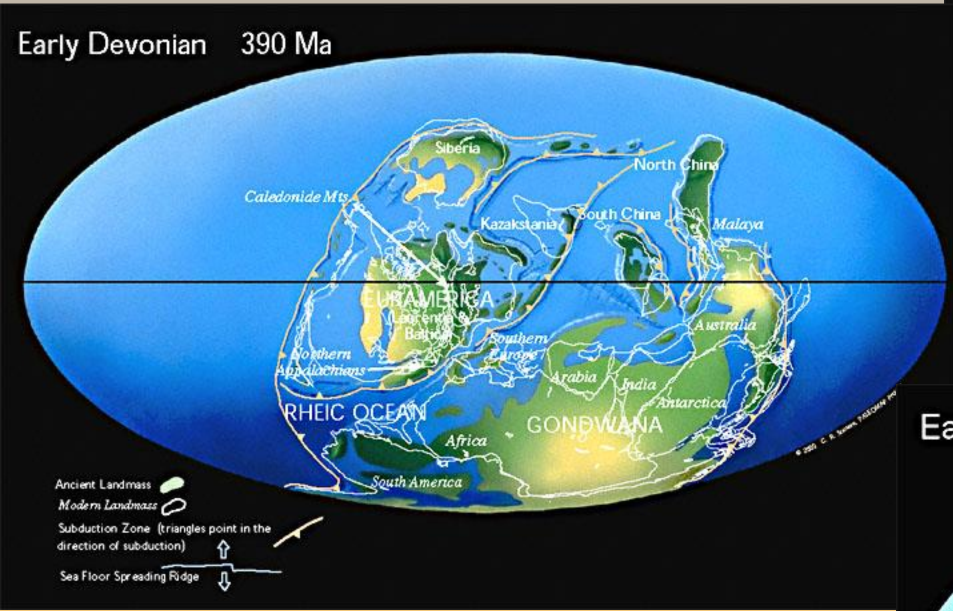
❖ Evidence for a supercontinent included:

1. Fossils of the same plant (Glossopteris) found in Australia, India, Antarctica, and South America.
2. Fossils of same reptile (Mesosaurus) found in Africa and South America. This animal could not have swum across the existing Atlantic Ocean!
3. Glacial deposits found in current warm climates and warm-climate plant fossils found in what is now the Arctic.
4. Nearly identical rock formations found on the east coast of U.S. and the west coast of Europe and on eastern South America and western Africa.

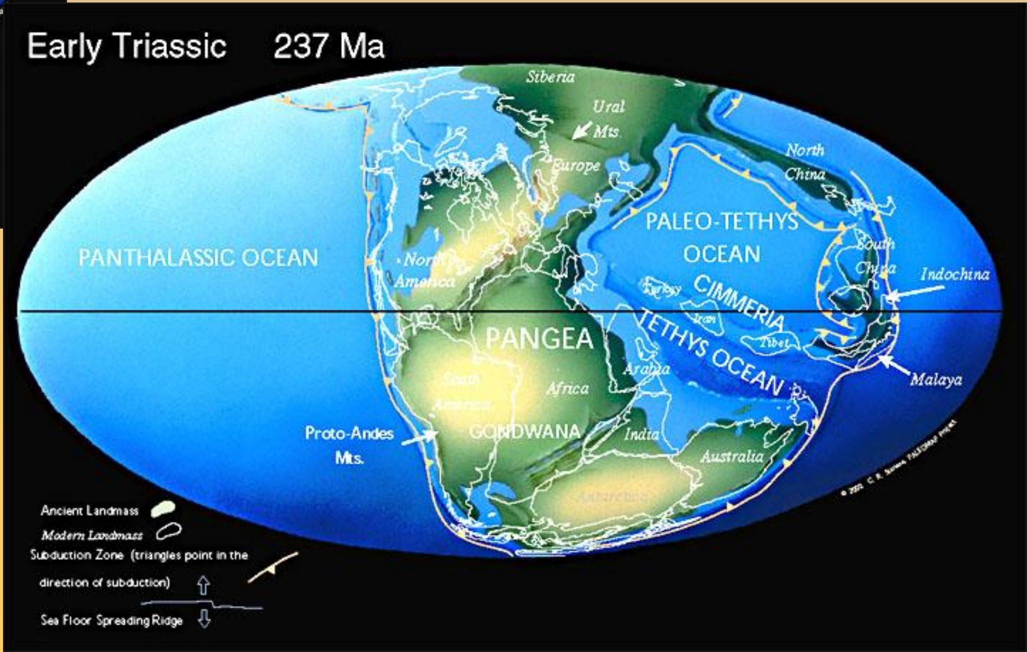
1. About 1,100 million years ago, a super-continent called Rodinia existed (pre-Cambrian).

2. Rodinia broke apart, and about 400 million years ago, the oceans began to close up to form a pre-Pangea (early Devonian).





3. Pangea formed around 250 million years ago and animals could migrate from the north to the south pole (Early Triassic).



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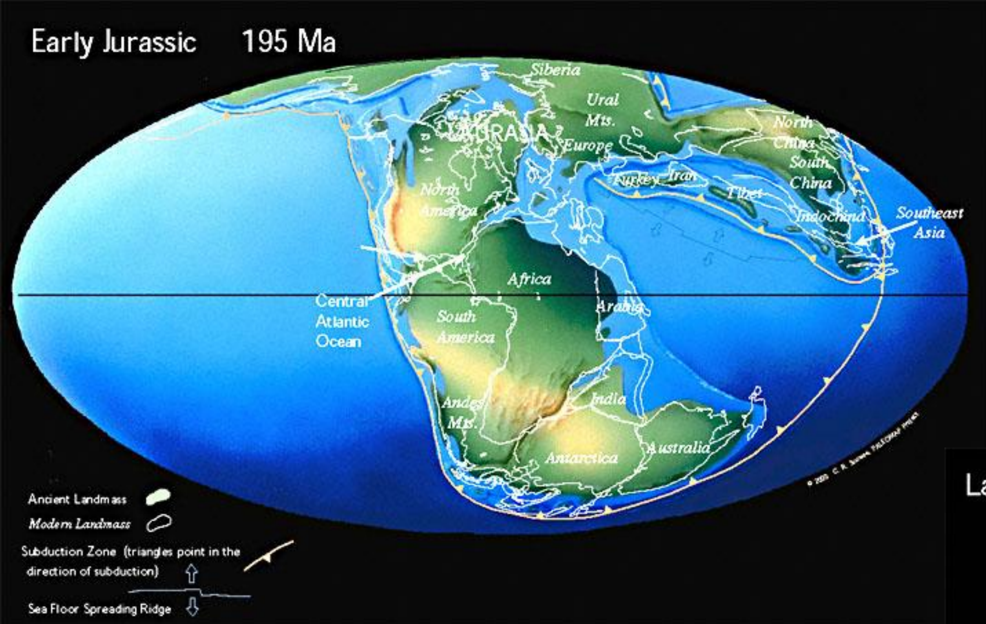
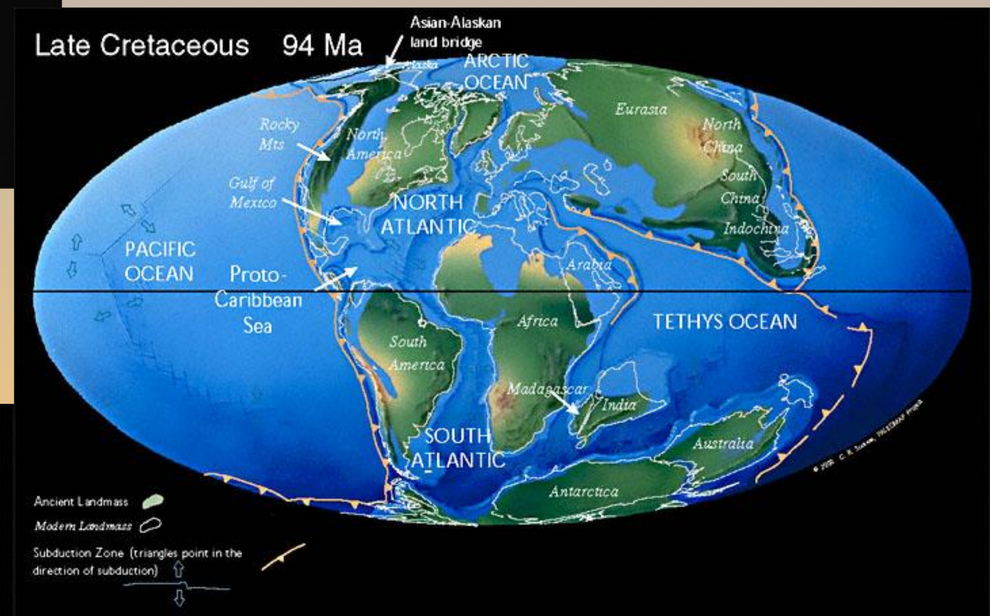
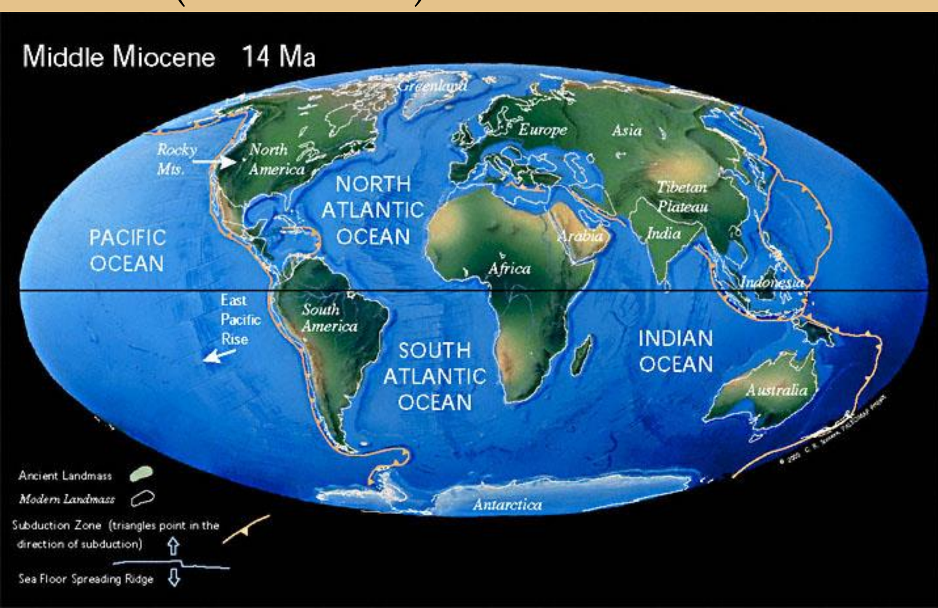


4. Pangaea began to break apart into 2 halves approximately 200 million years ago (Early Jurassic). The northern half is called Laurasia and the southern half is called Gondwanaland. These two huge continents were separated by a body of water called the Tethys Sea.

5. Gondwananland split to form Africa, South America, Antarctica, Australia and India. Laurasia split to form North America, Eurasia (minus India) and Greenland.





6. Around 15 million years ago, the continents finally looked like they do today

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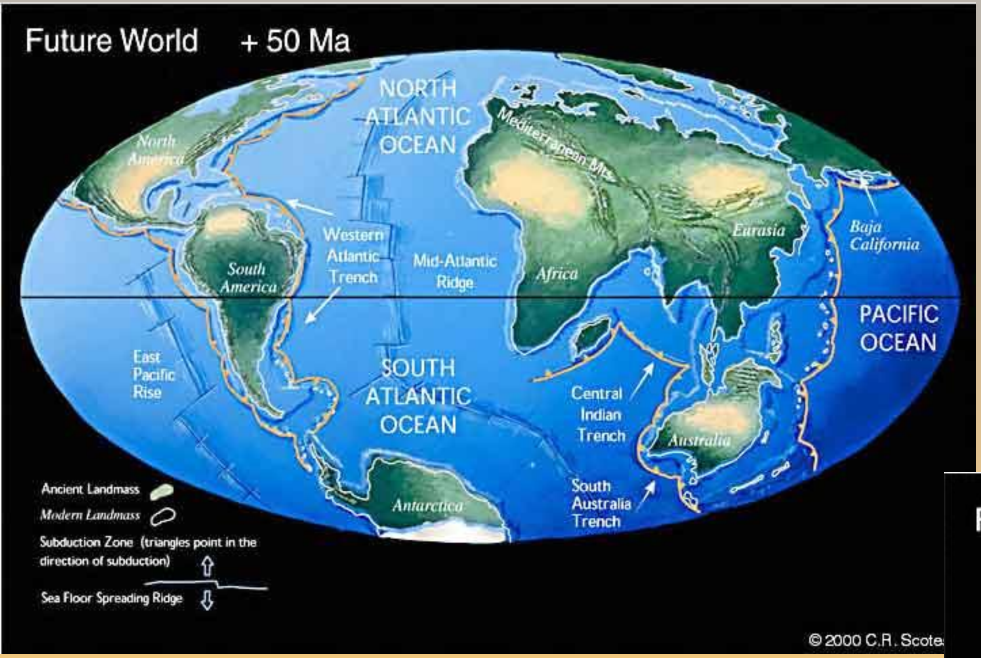
Continents in the future?



In 50 million years, it is possible that the Mediterranean could close due to the collision of Africa with Europe. Australia may eventually join Asia.

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It is though that in another 250 million years, another Pangea will form.