The Way Earth Works

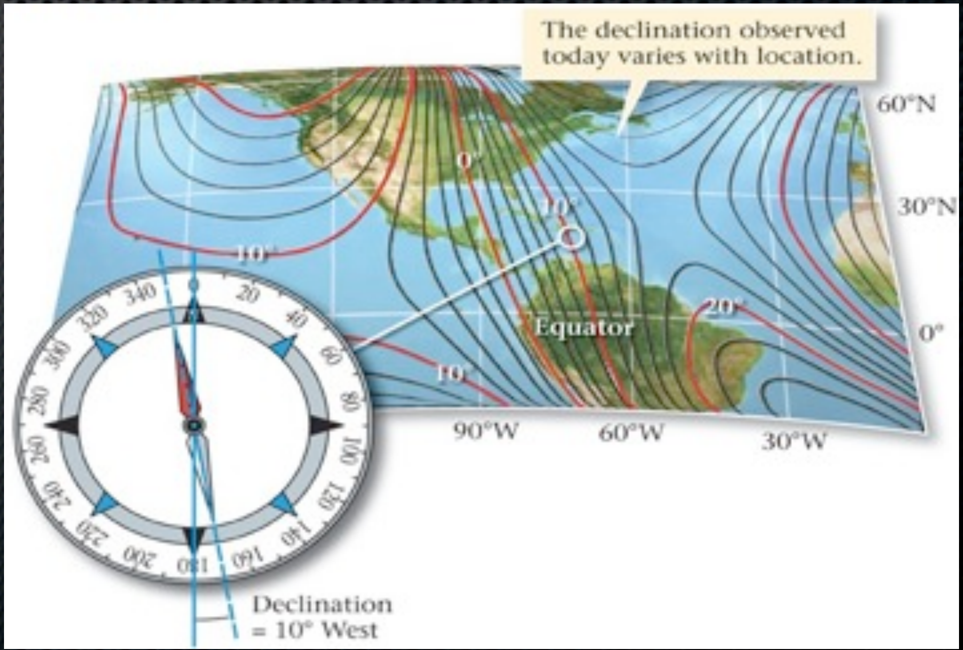
Plate Tectonics

Continental Drift

- Early hypothesis that continents are mobile.
- Proposed by German meteorologist Alfred Wegener.
  - ***The Origins of Oceans and Continents*** published in 1915.
  - Wegener hypothesized a former supercontinent, Pangaea.
  - Idea was founded on strong evidence.
    - “Fit” of continents.
    - Location of glaciations.
    - Fossil organisms.
    - Rock type and structural similarities.
    - Paleoclimates preserved in rocks.

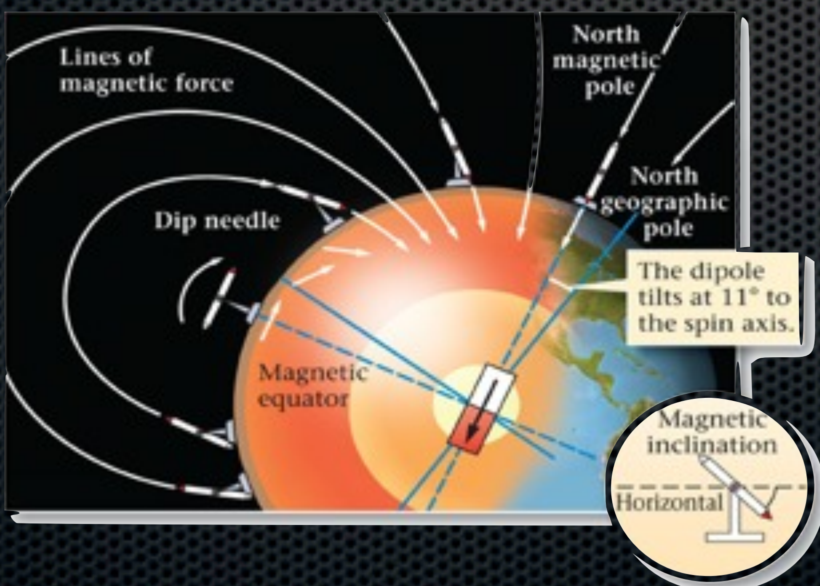
The Earth's Magnetic Field

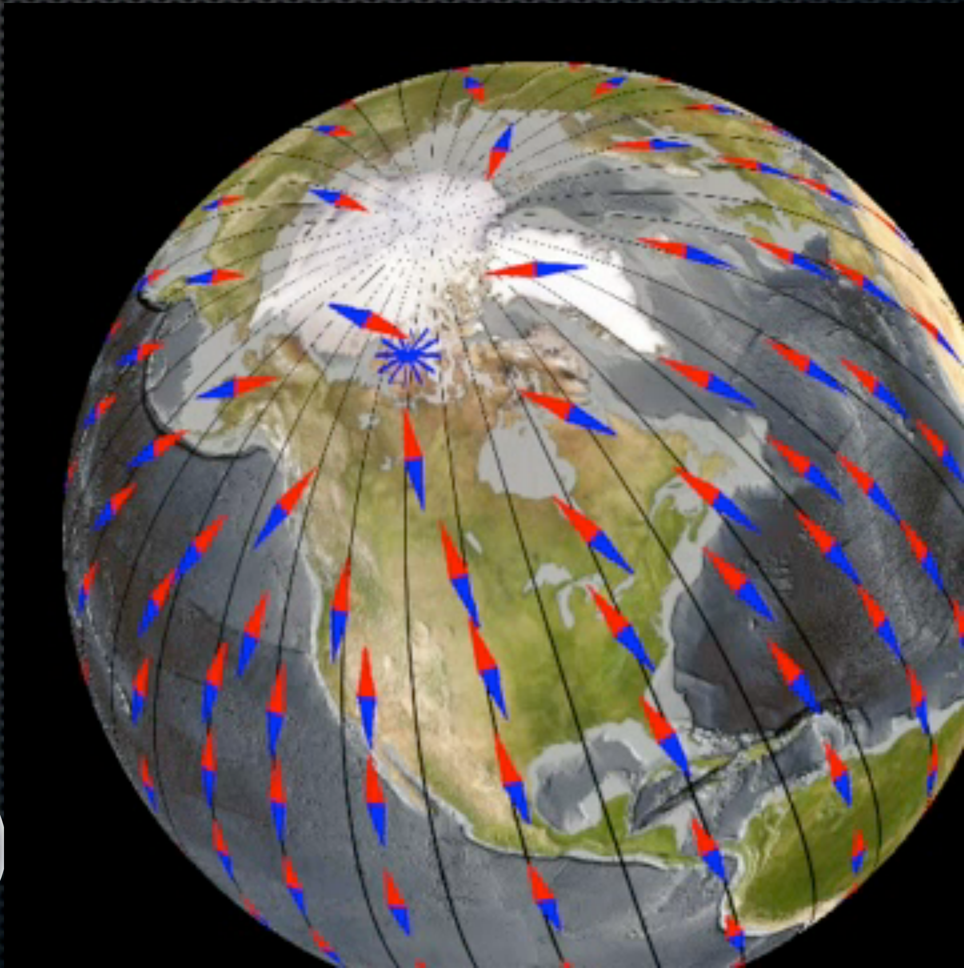
- Declination – Difference between magnetic north and geographic (true) north. Depends upon…
  - Longitude.
  - Absolute position of the two poles.
    - Geographic north.
    - Magnetic north.
  - Between the two poles declination can be 180°.



The Earth's Magnetic Field

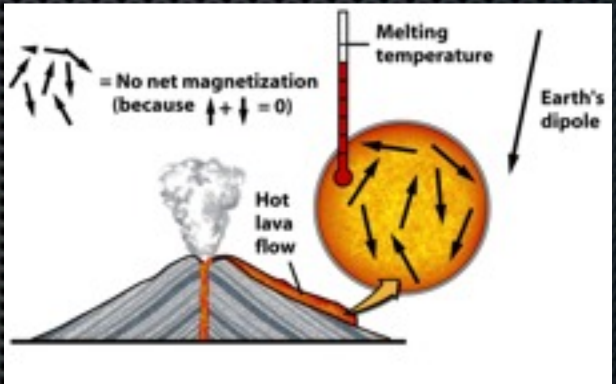
- Inclination – Tilt of a compass needle from the horizontal. Depends upon…
  - Normal or reverse polarity.
  - Latitude.

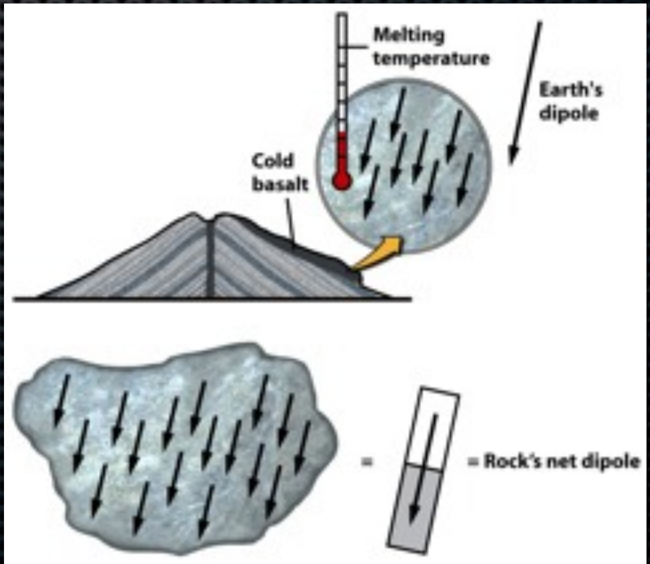




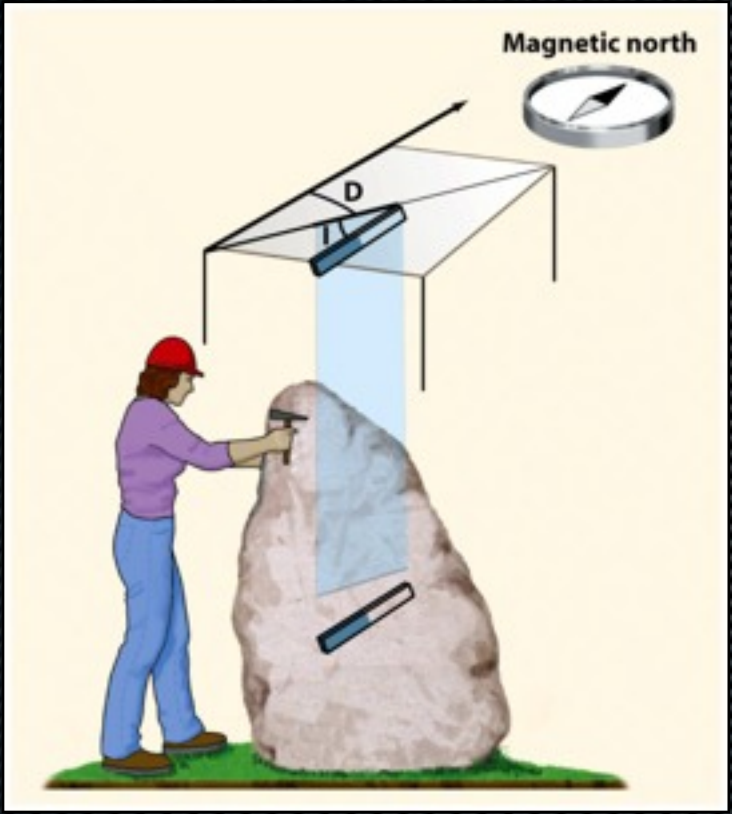
Magnetic Overprinting

- **Above 350-550°C.**
  - Thermal energy of atoms high.
  - Magnetic dipoles randomly oriented.
  - No magnetic signature.
- **Below 350-550°C**.
  - Thermal energy slows atoms.
  - Dipoles align with Earth’s field.
  - Material permanently magnetized.
- **Fe-minerals can lock in the Earth’s magnetic signal at the time formed.**
  - Preserves declination and inclination.
  - Can be used to determine lat / long.





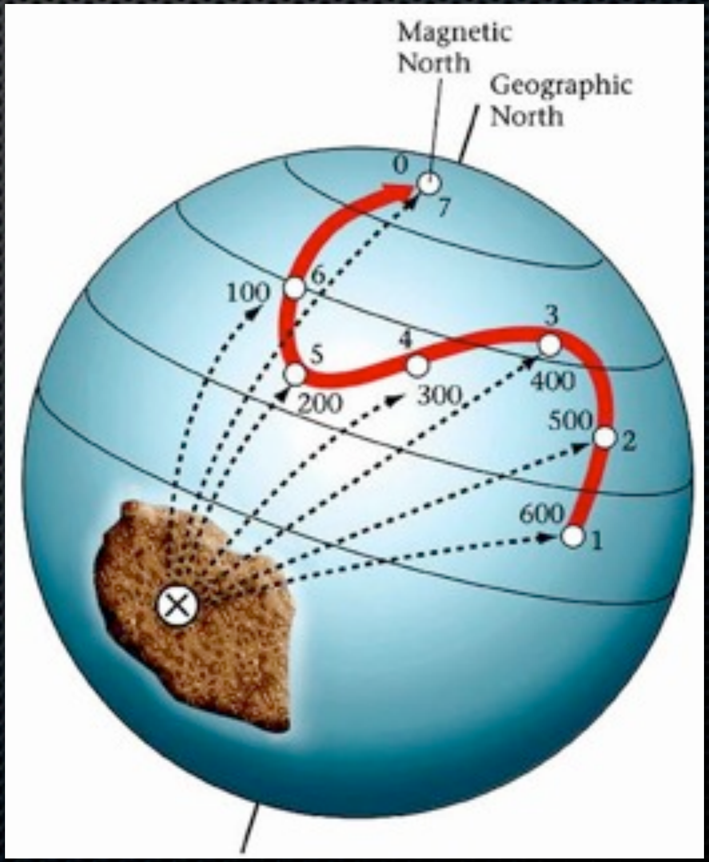
Paleomagnetism



- Rock magnetism can be measured in the laboratory.
- Study of fossil magnetism is called paleomagnetism.
- Ancient rocks reveal latitudes / longitudes unlike today.

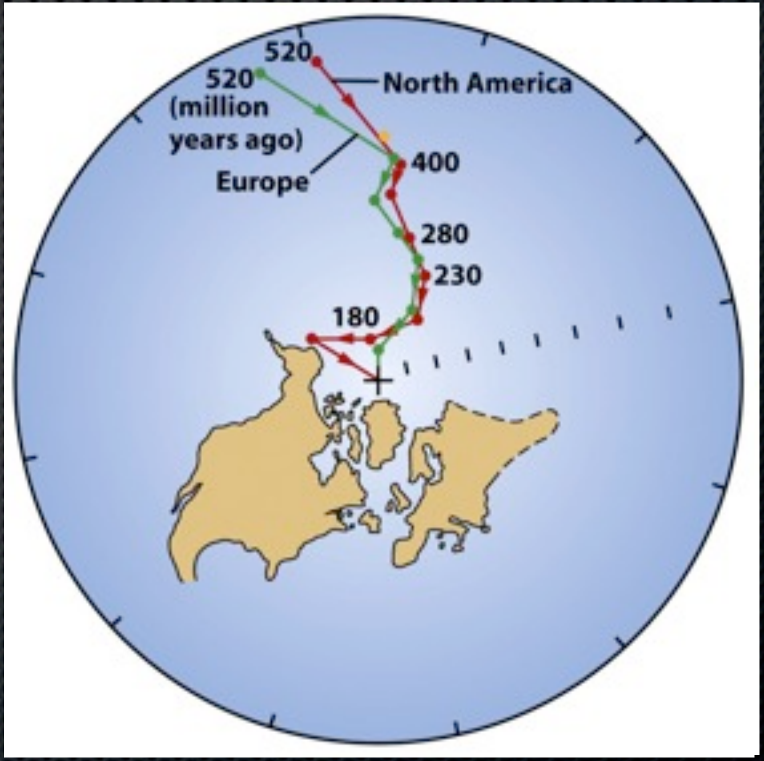
Polar Wander

- Paleomagnetism from ancient lavas didn't align with the present magnetic field.
- This lack of alignment indicates past magnetic polar wandering.



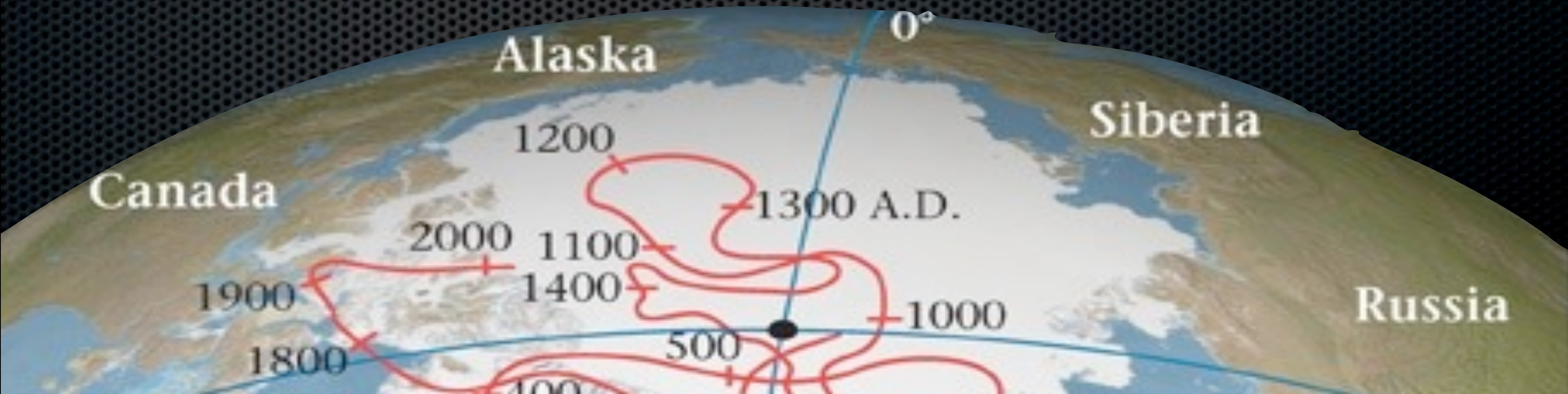
Polar Wander

- Each continent had a separate polar-wander path.
  - Either the location of the magnetic pole is not fixed, or…
  - The lava flows themselves have moved.
- These curves align when continents are assembled.



Magnetic Poles

- The poles of the magnetic field intersects Earth's surface.
  - Differs from geographic north pole (rotational axis).
  - The magnetic poles move constantly, but stay in the vicinity of the N and S geographic poles.

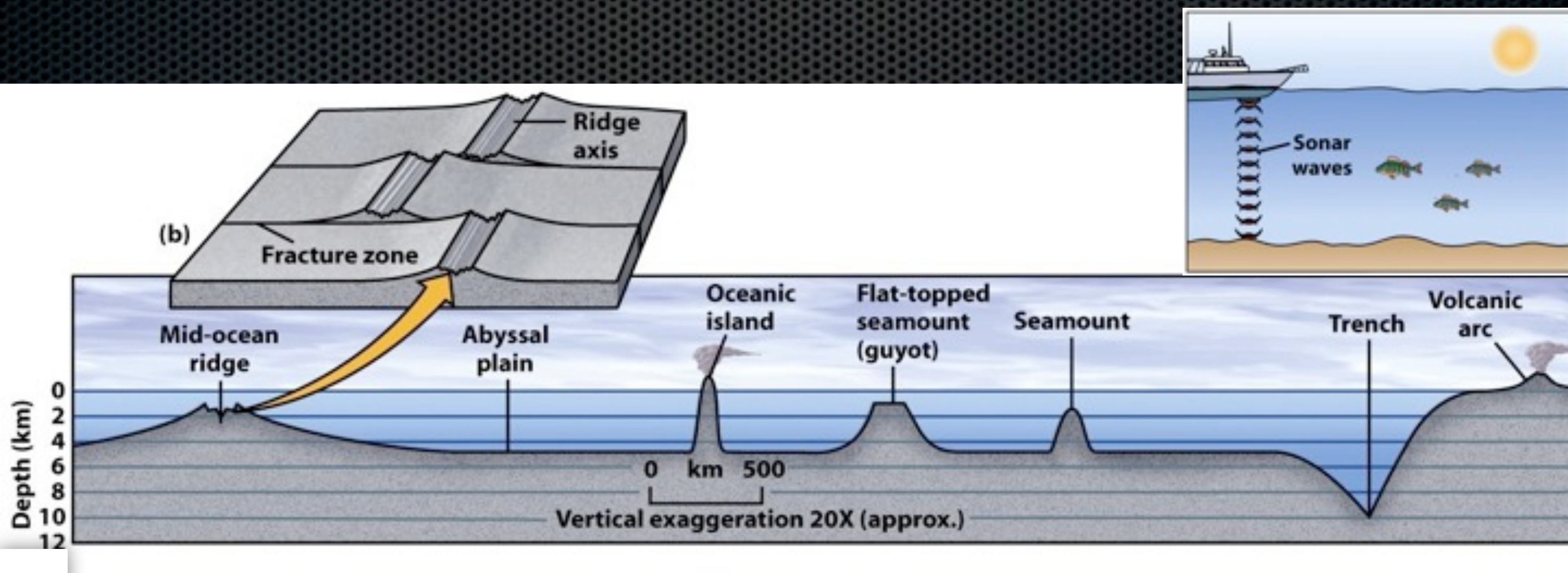


Apparent Polar Wander

- Polar wander is now known to be an artifact.
  - Not the signature of a wandering pole on a fixed continent.
  - The signature of a fixed pole on a wandering continent.
- Apparent polar wander is strong evidence for drift.

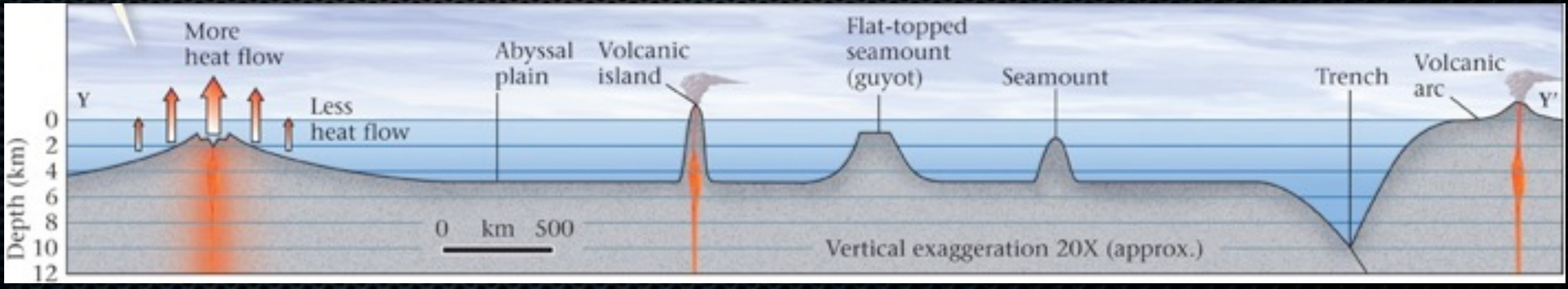
The Ocean Floor

- Sonar was used to map the ocean bathymetry.
  - The deepest parts of the ocean occur near land.
  - A mountain range runs through every ocean basin.
  - Submarine volcanoes form lines across ocean floors.



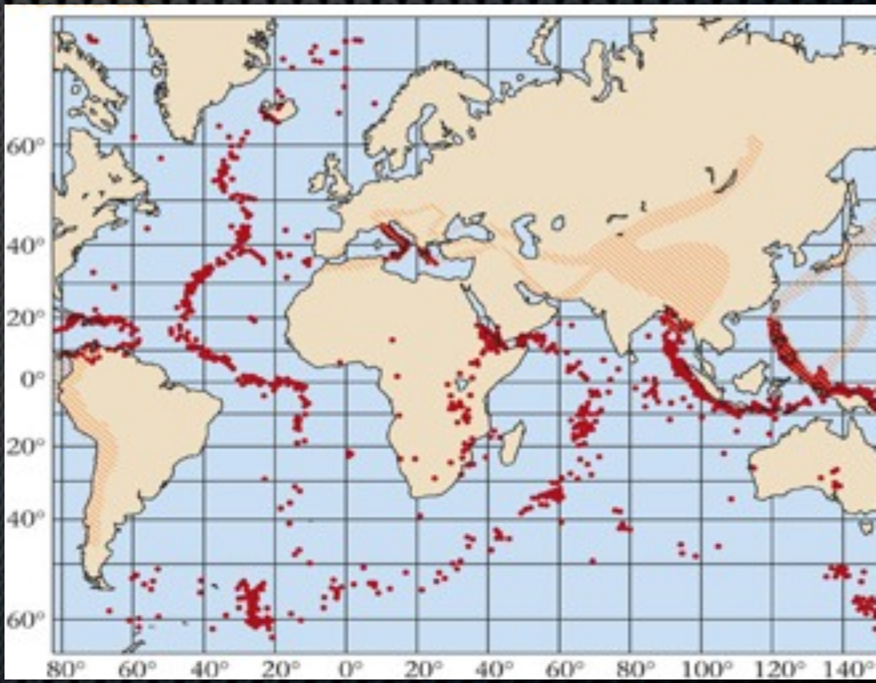
New Observations: Oceanic Crust

- By 1950, we had learned much about oceanic crust.
- Oceanic sediment is
  - Thickest near the continents.
  - Thinnest (or absent) at the mid-ocean ridge.
- Oceanic crust is mafic (basalt and gabbro).
  - No granitic rocks.
  - No metamorphic rocks.
- High heat flow characterizes the mid-ocean ridge.



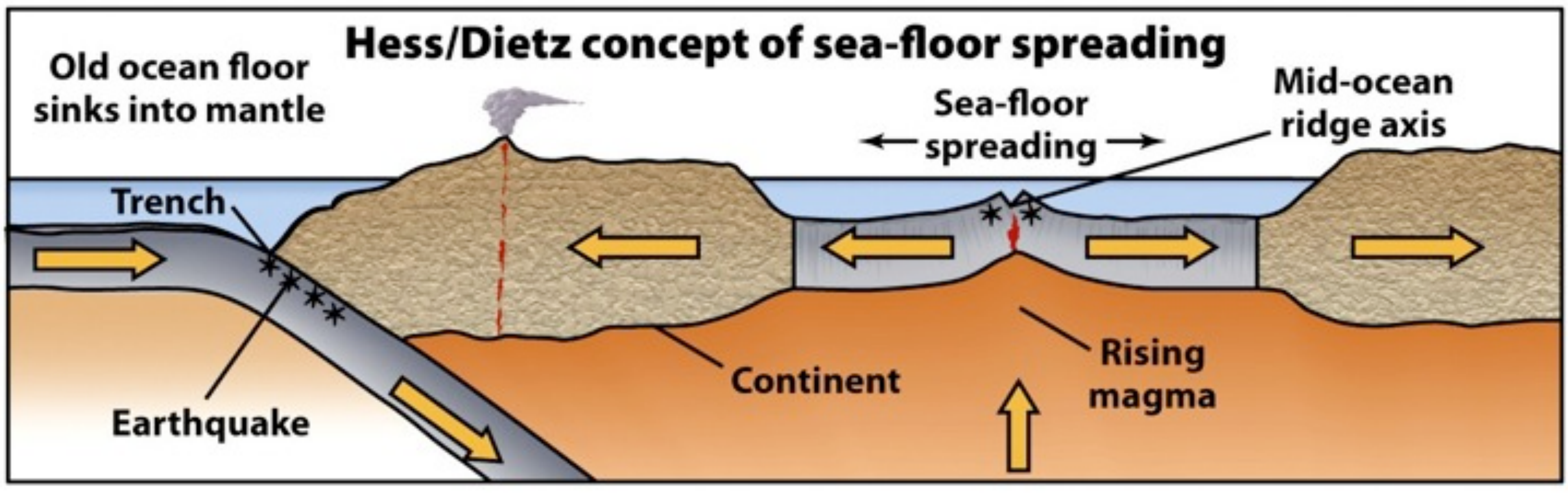
New Observations: Oceanic Crust

- Belts of concentrated subsea earthquakes were found.
- The earthquakes were surprising. They were limited to…
  - Parts of oceanic fracture zones.
  - Mid-ocean ridge axes.
  - Deep ocean trenches.



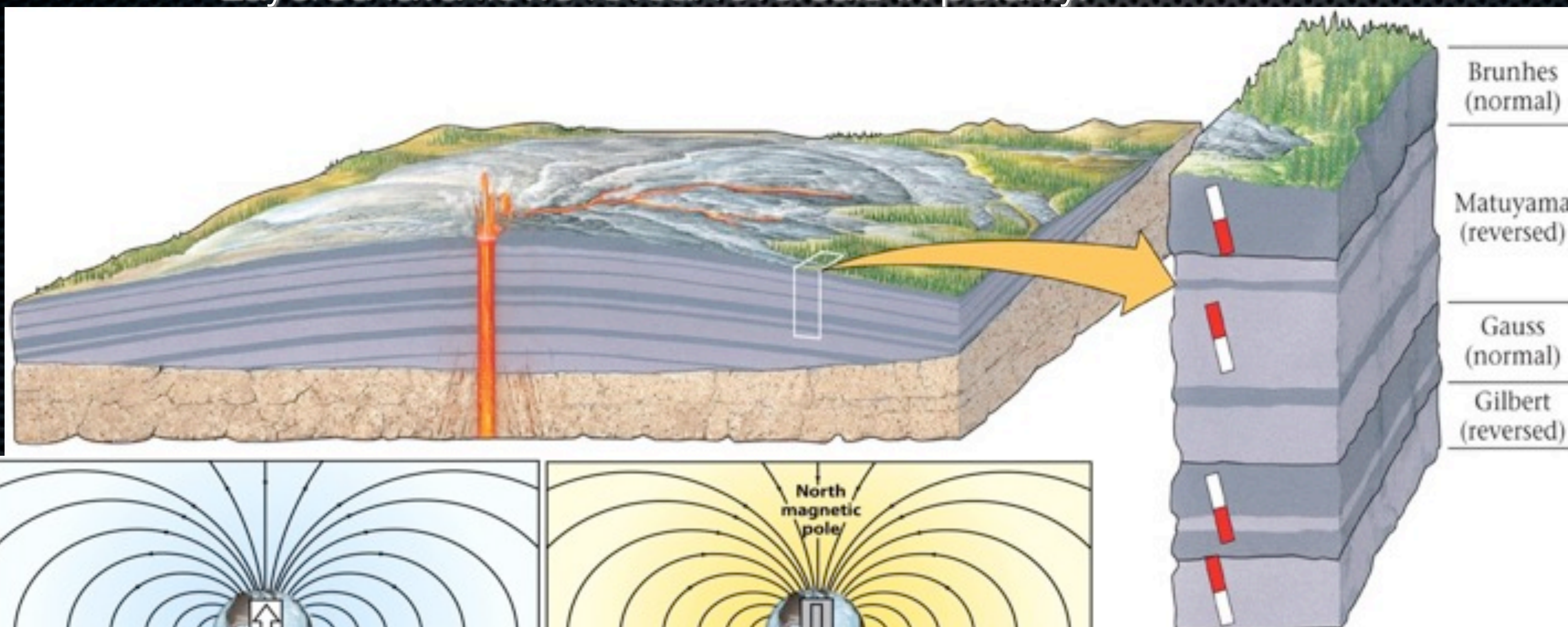
Sea-Floor Spreading

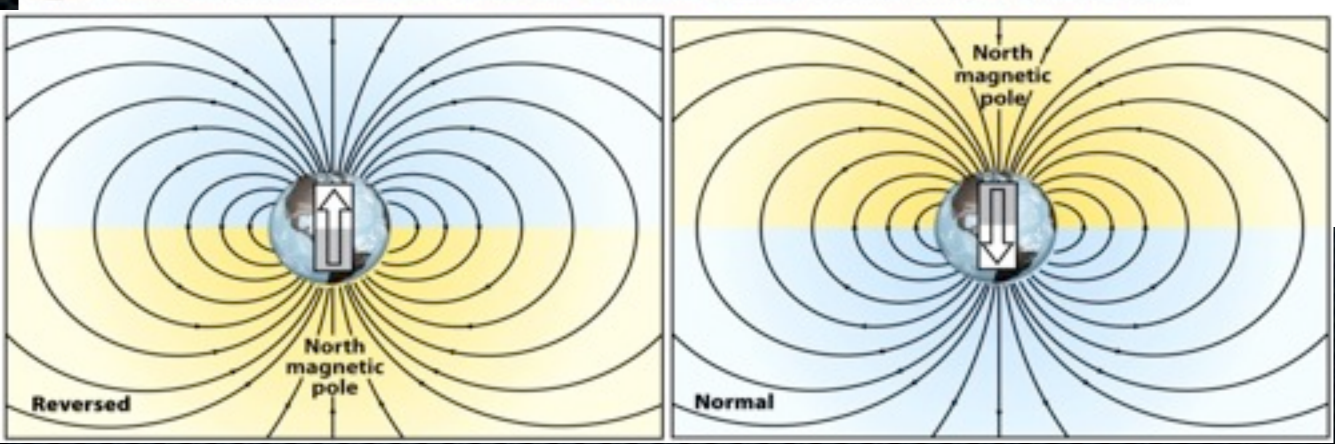
- In 1960, Harry Hess published his "Essay in Geopoetry."
- He called his theory "sea-floor spreading".
  - Upwelling mantle erupts at the mid-ocean ridges.



Magnetic Reversals

- Layered lava flows reveal reversals in polarity.

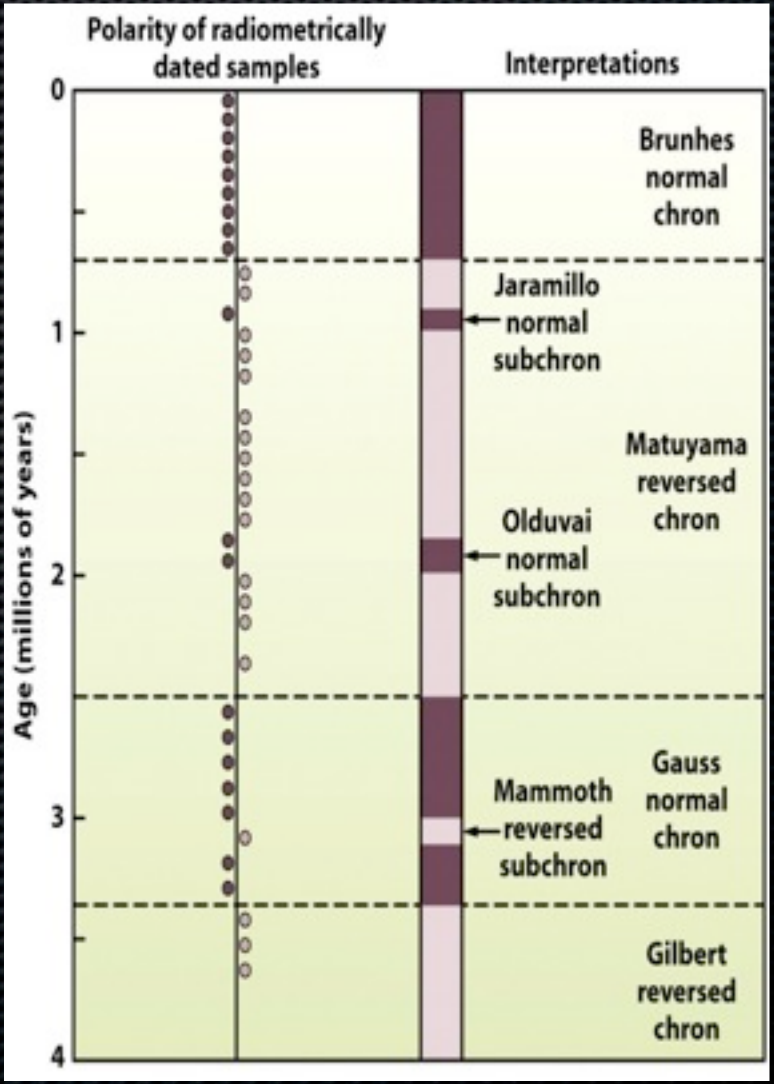




Magnetic Reversals

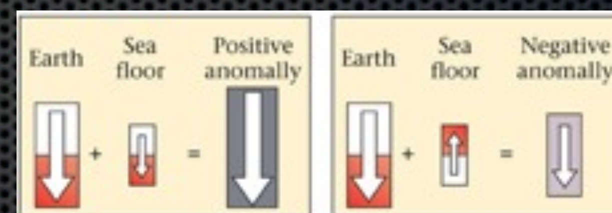
- Radioactivity permits rock absolute age-dating.
- Reversals occur every 500-700 ka (chrons).
- Shorter durations (~200 ka)

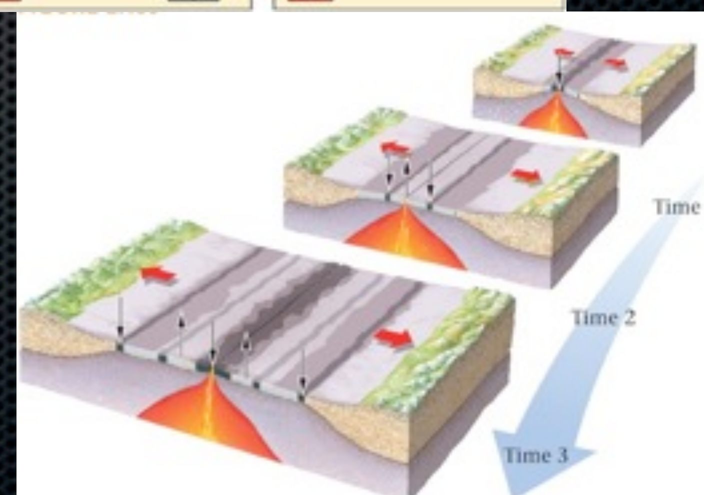
= subchrons.



Sea-Floor Spreading: Proof

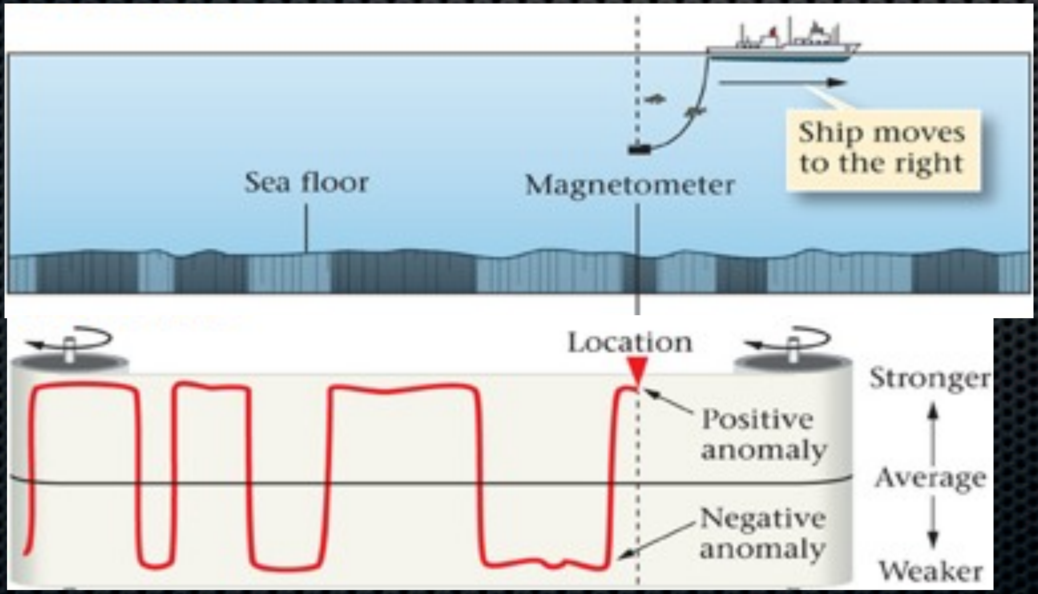
- Reversals in polarity explain magnetic anomalies.
- Magnetic anomalies are symmetric across a mid-ocean ridge.



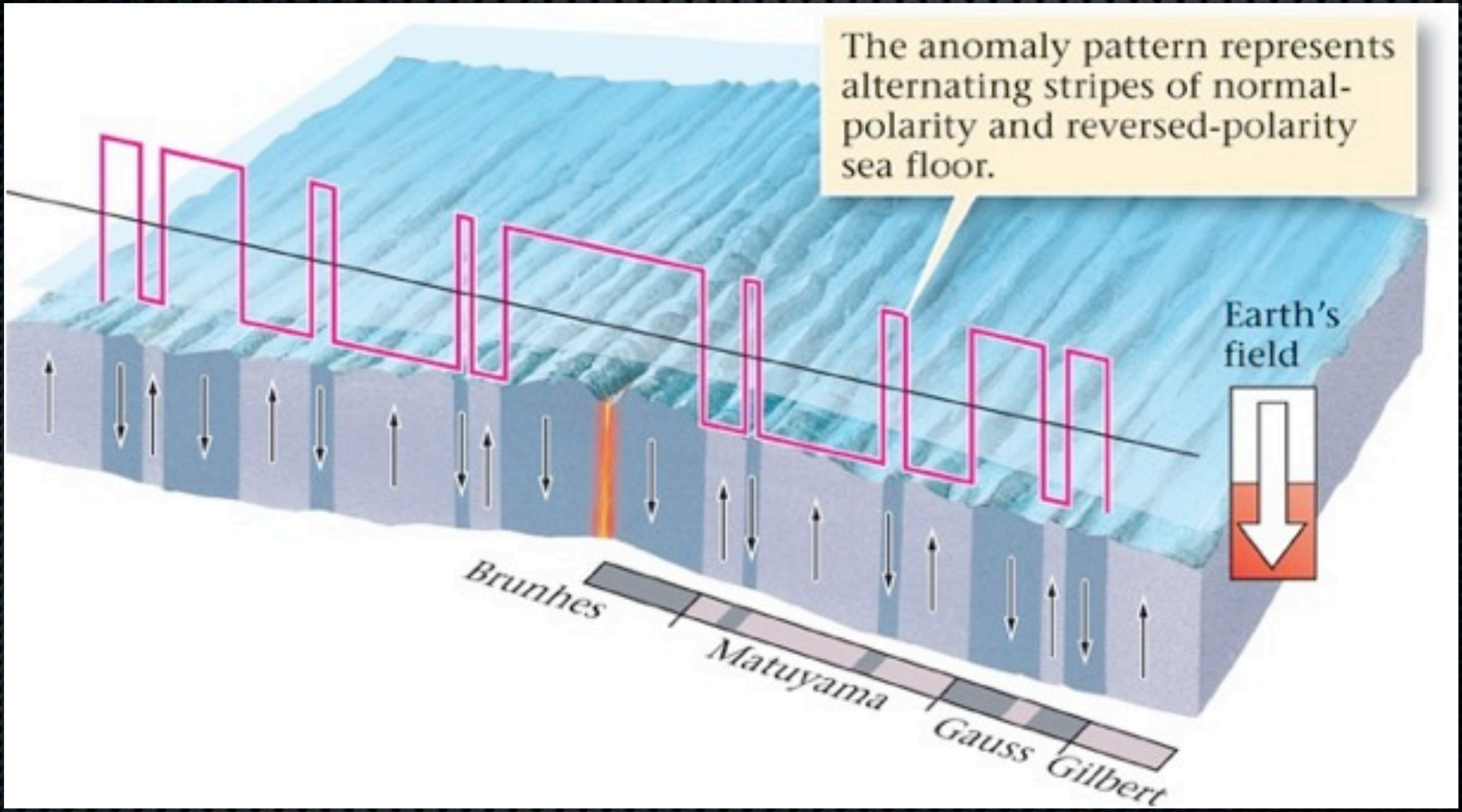


Magnetic Anomalies

- Towed magnetometers measure paleomagnetism within ocean crust.
- These variations are + and - magnetic anomalies.
- Anomalies are linear belts that parallel MO ridges.



Sea-Floor Spreading: Proof



Sea-Floor Spreading

- Drilling in the late 1960s recovered crust samples.
  - Ages increase away from the mid-ocean ridge.
  - Ages are “mirror images” across the mid-ocean ridge.
- Strong supporting evidence for sea-floor spreading.

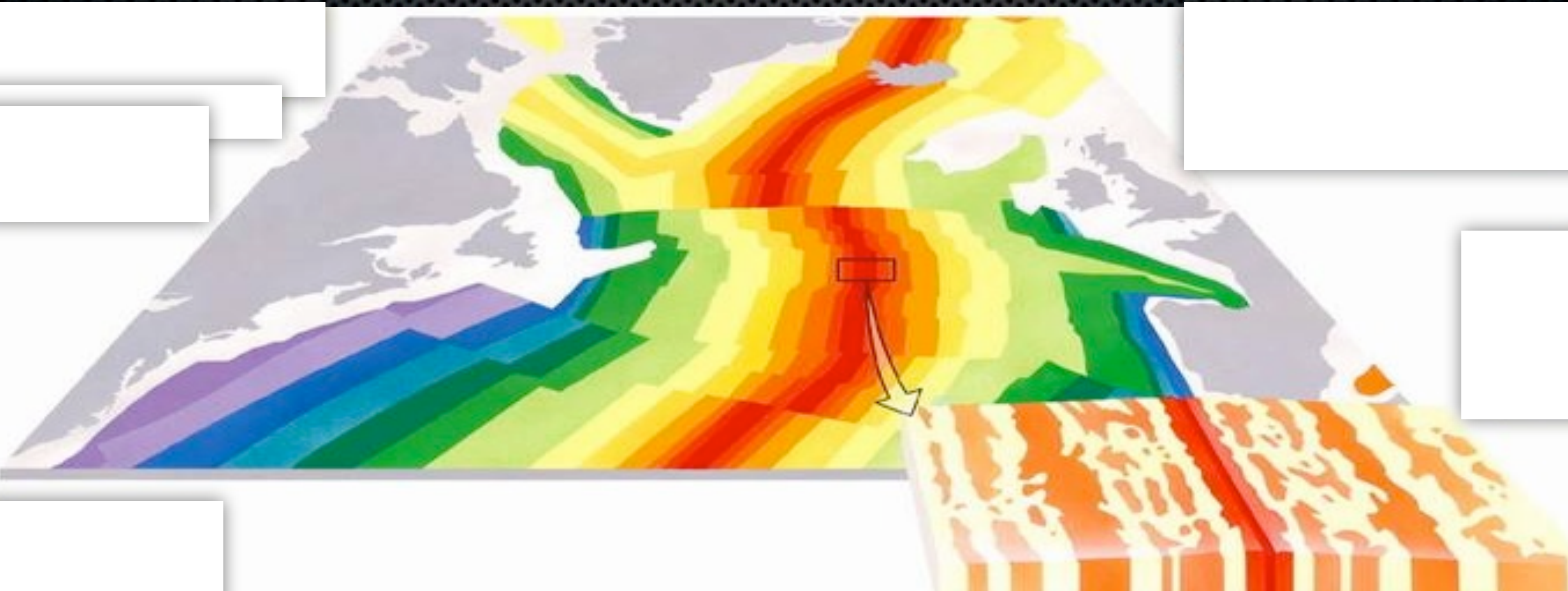


Plate Tectonics

- Tectonic theory evolved in the 1960s.
- Previous research provided a strong foundation.
  - Wegener (1915) – Evidence supporting continental drift
  - Hess / Dietz (1960) – The sea-floor spreading hypothesis.
- By 1968, evidence for tectonics was overwhelming.
  - This evidence changed the view of most geologists.
  - Even reluctant scientists were eventually won over.

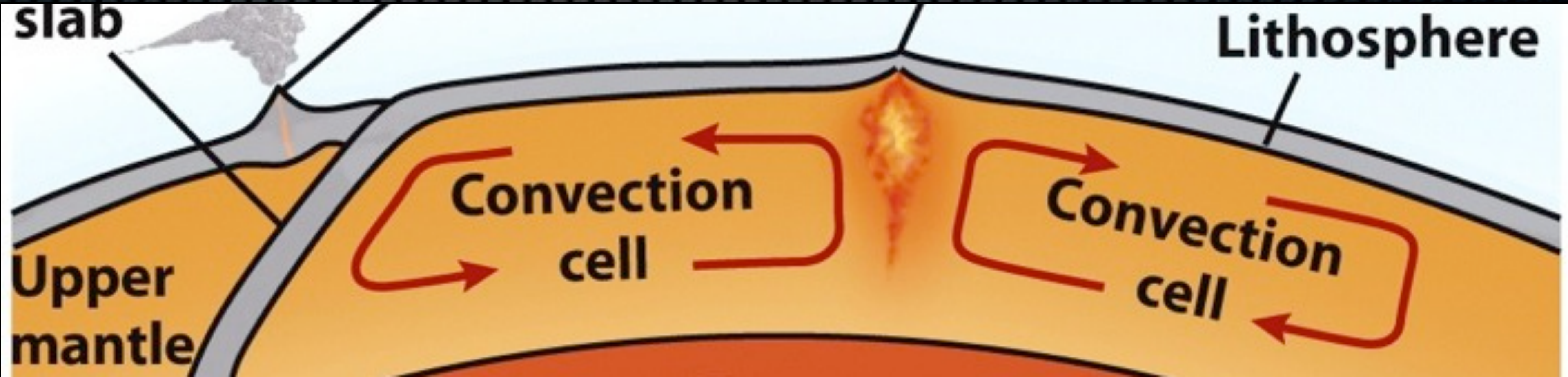
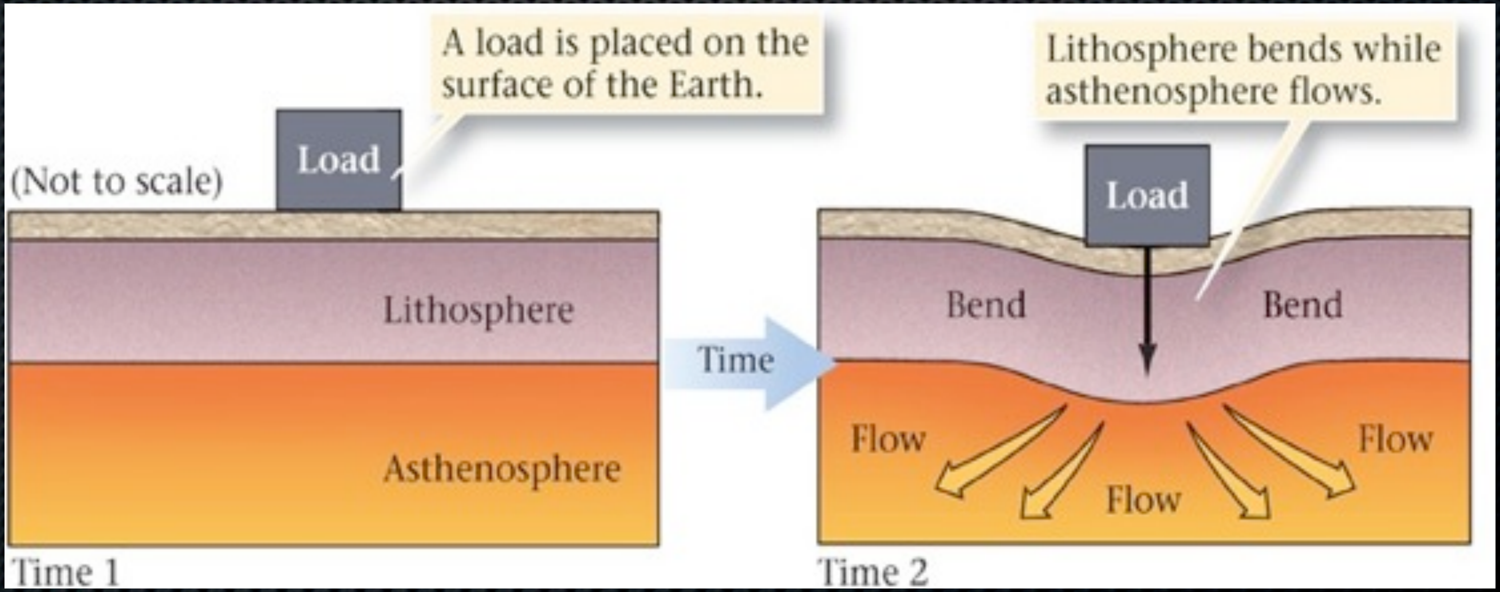


Plate Tectonics

- Provides a unified mechanism explaining:
  - Igneous, sedimentary and metamorphic rocks.
  - The distribution of earthquakes and volcanoes.
  - The origin of continents and ocean basins.
  - The distribution of fossil plants and animals.
  - The genesis and destruction of mountain chains.
  - Continental drift.

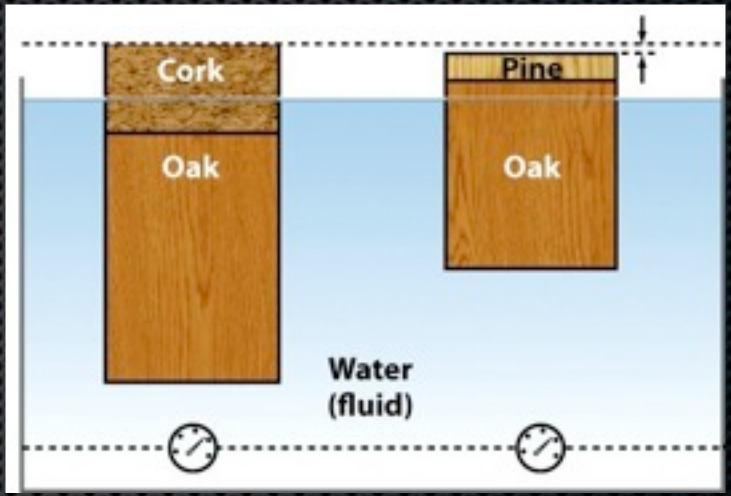
Lithosphere

- Tectonic plates are fragments of lithosphere.
  - Lithosphere is made of both crust and the upper mantle.
  - The lithosphere is in motion over the asthenosphere.
- Lithosphere bends elastically when loaded.
- Asthenosphere flows plastically when loaded.



Two Types of Lithosphere

- Continental ~ 150 km thick.
  - Granitic crust.
    - 35-40 km thick.
    - Lighter (less dense) .
    - More buoyant – Floats higher.
- Oceanic ~ 7 to 100 km thick.
  - Basaltic crust.
    - 7-10 km thick.
    - Heavier (more dense).
    - Less buoyant – Sinks lower.



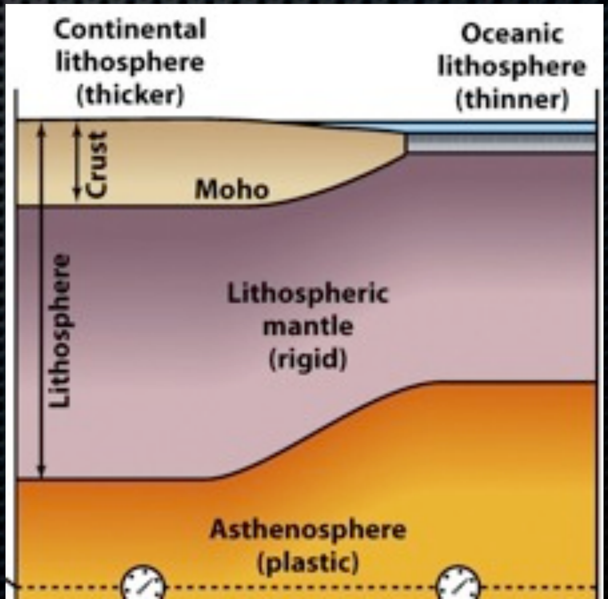


Plate Boundaries

- Lithosphere is fragmented into ~ 20 tectonic plates.
- Plates move continuously at a rate of 1 to 15 cm/yr.
  - Slow on a human time scale; extremely rapid geologically.
- Plates interact along their boundaries.

Plate Boundaries

- Locations on Earth where tectonic plates meet.
  - Identified by concentrations of earthquakes.
  - Associated with many other dynamic phenomena.
- Plate interiors are almost earthquake free.

Continental Margins

- Where land meets the ocean.
  - Margins near plate boundaries are "active."
  - Margins far from a plate boundaries are "passive."
- Passive margin continental crust thins seaward.
  - Transitions into oceanic crust.
  - Traps eroded sediment.
  - Develops into the continental shelf.

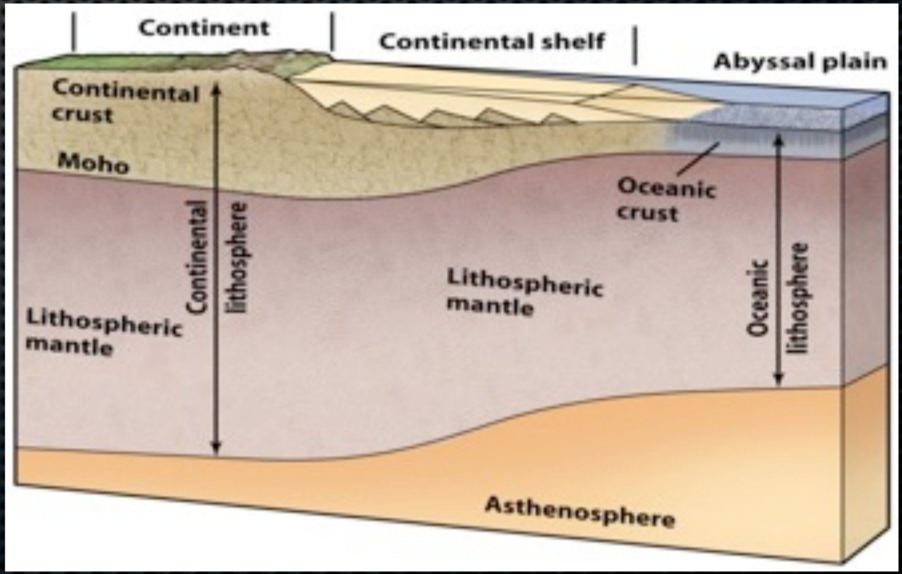


Plate Boundaries: Three Types

- Divergent – Tectonic plates move apart.
  - Lithosphere thickens away from the ridge axis.

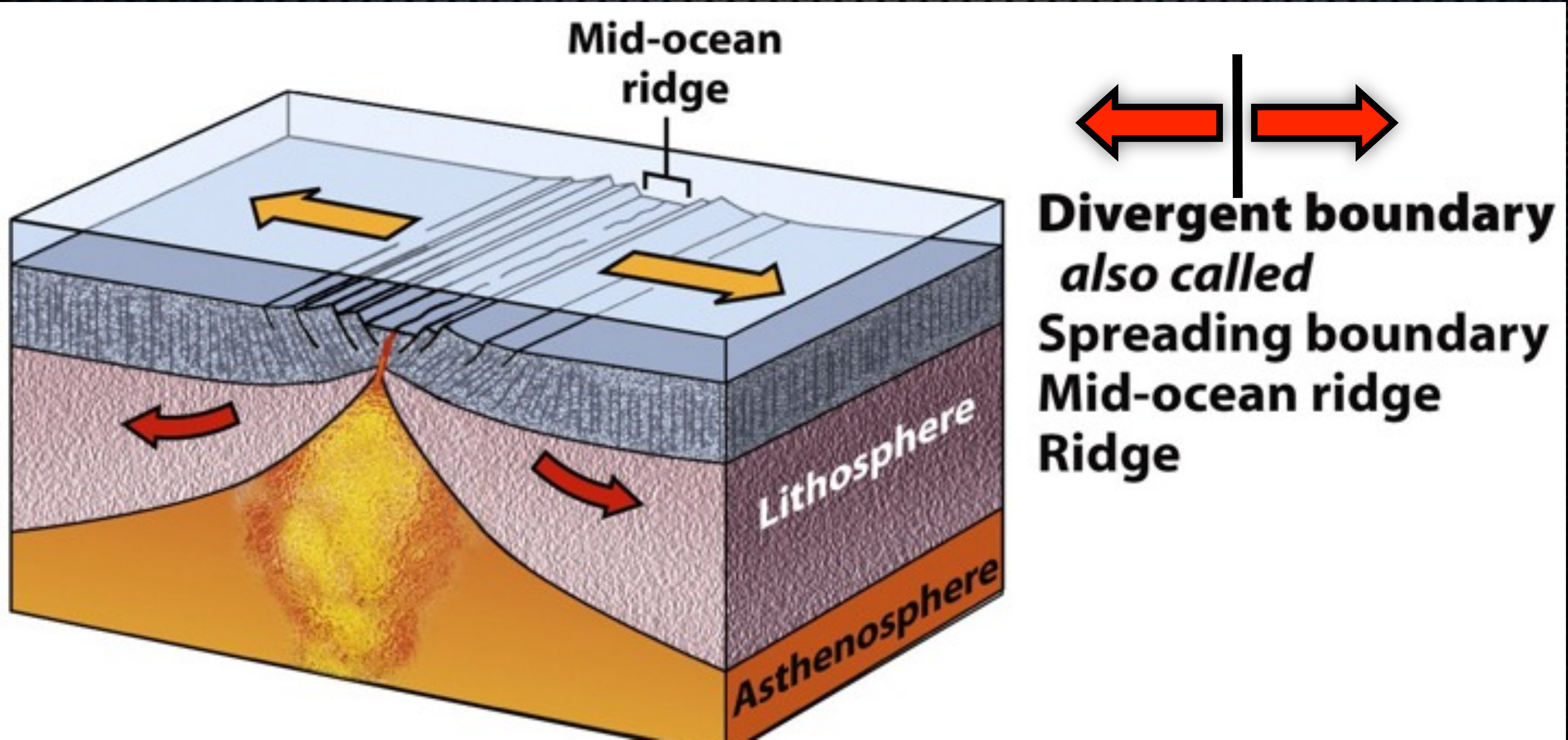


Plate Boundaries: Three Types

- Convergent – Tectonic plates move together.
  - The process of plate consumption is called subduction.

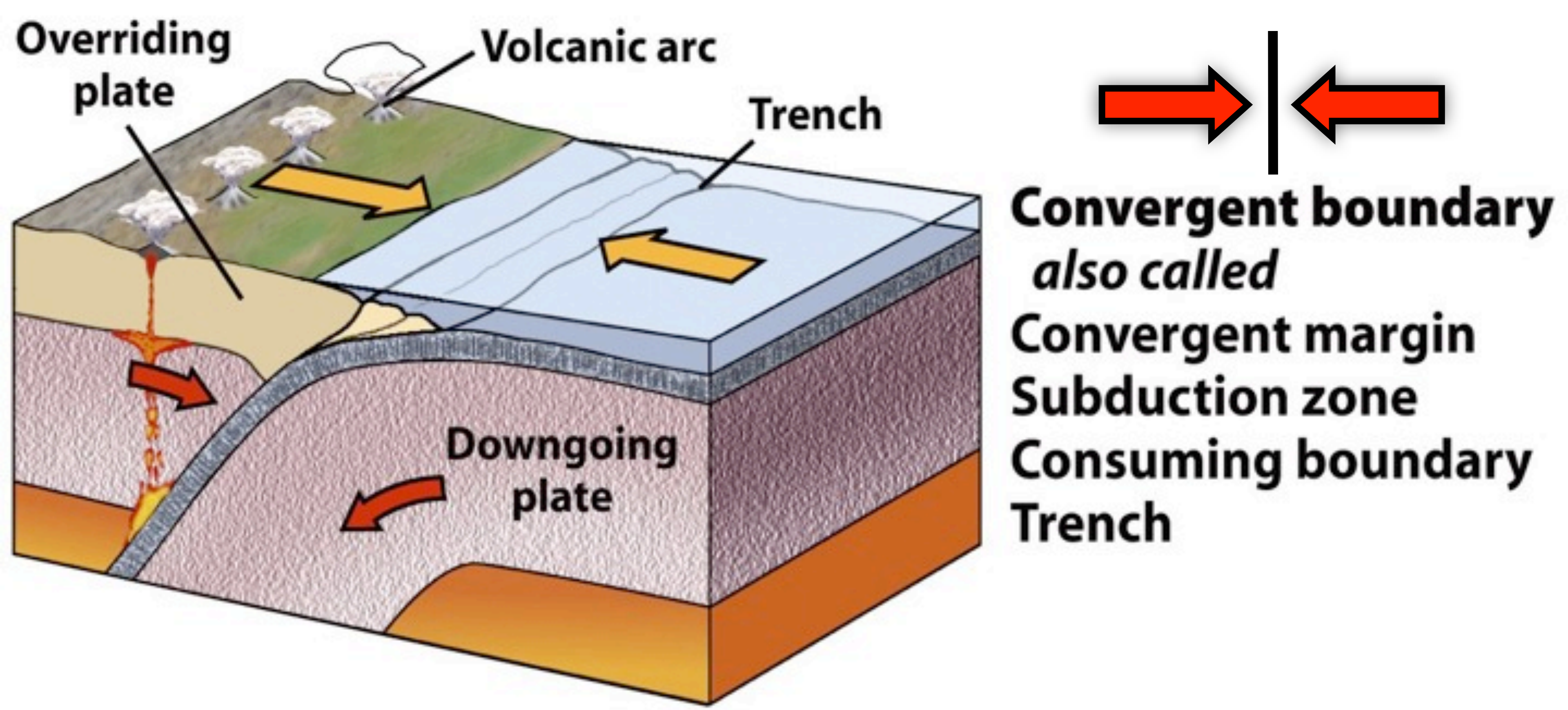
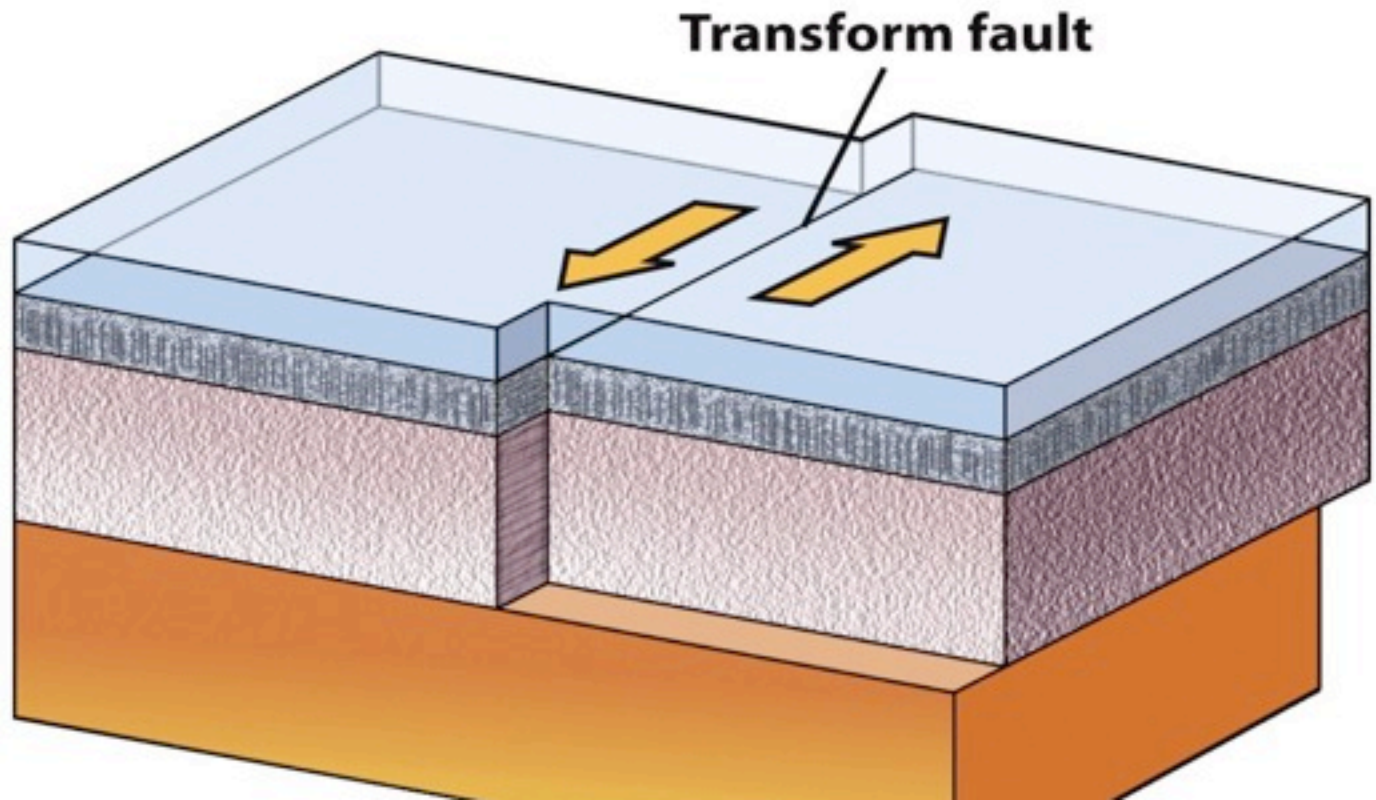
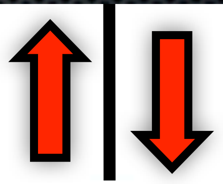


Plate Boundaries: Three Types

- Transform – Tectonic plates slide sideways.
  - Plate material is neither created, nor destroyed.

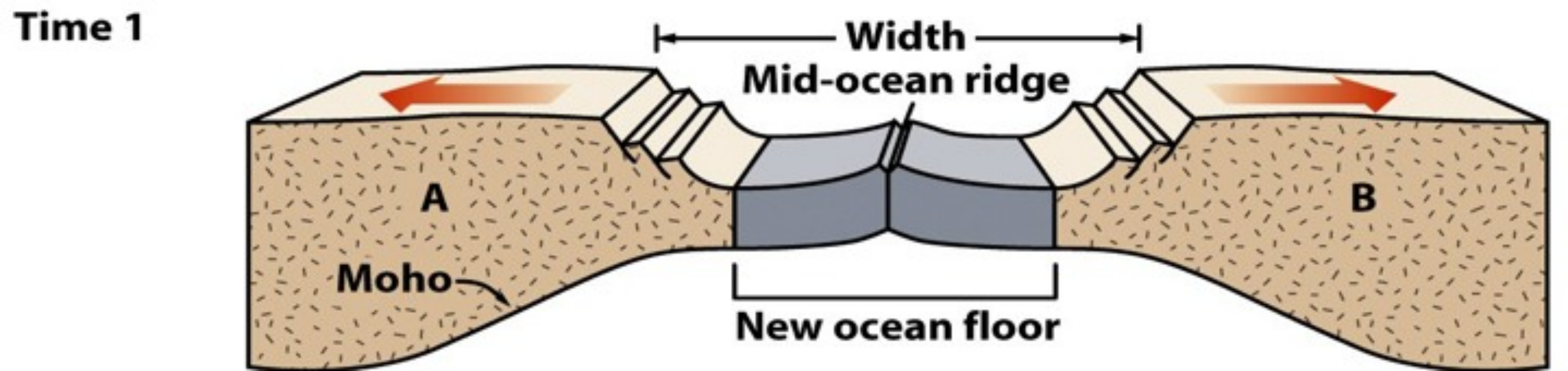




Transform boundary
also called
Transform fault
Transform

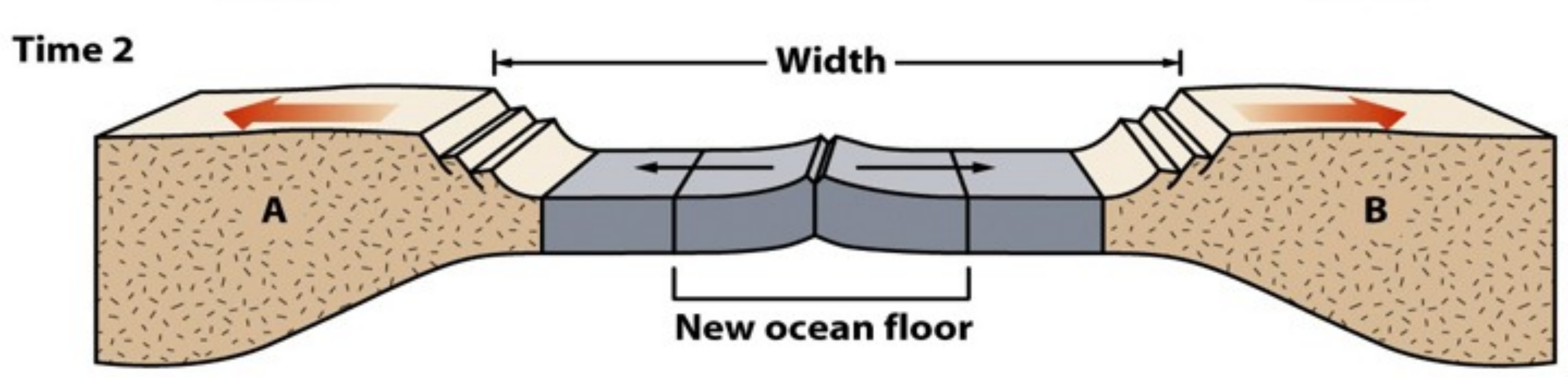
Divergent Boundaries

- Sea-floor spreading progression.
  - Early stage
    - Forms a long, thin ocean basin with young oceanic crust.
  - Example: The Red Sea



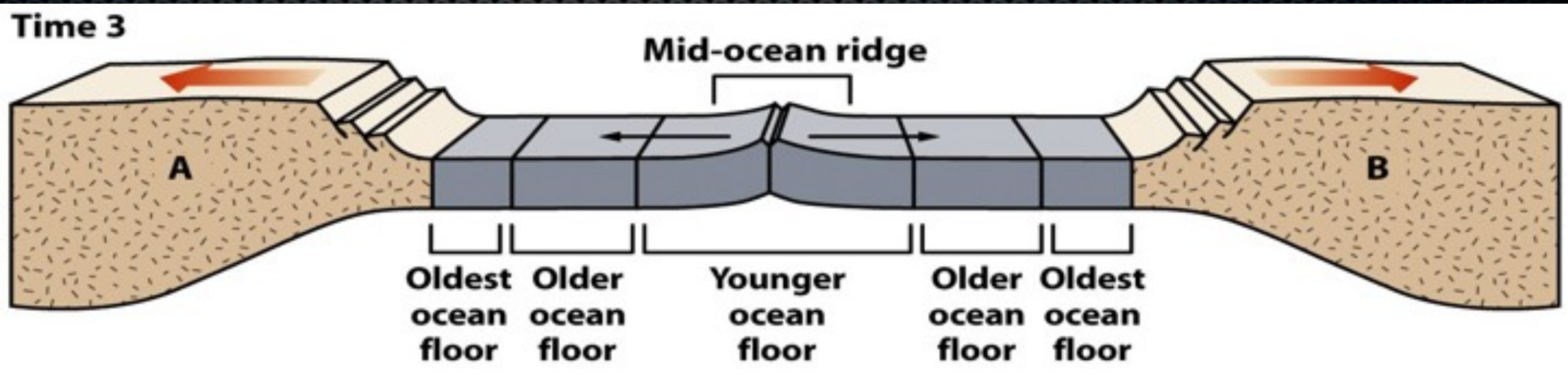
Divergent Boundaries

- Sea-floor spreading progression.
  - Mid-stage
    - Ocean begins to widen.
    - New seafloor is added at the Mid-Ocean Ridge.
    - Continents move farther apart.
  - Example: Greenland and the North Atlantic.



Divergent Boundaries

- Sea-floor spreading progression.
  - Late Stage
    - Mature, wide ocean basin.
    - Linear increase in age with distance from central ridge.
    - Edge of ocean basin - oldest; ridge proximal - youngest.
  - Example: The Atlantic Ocean

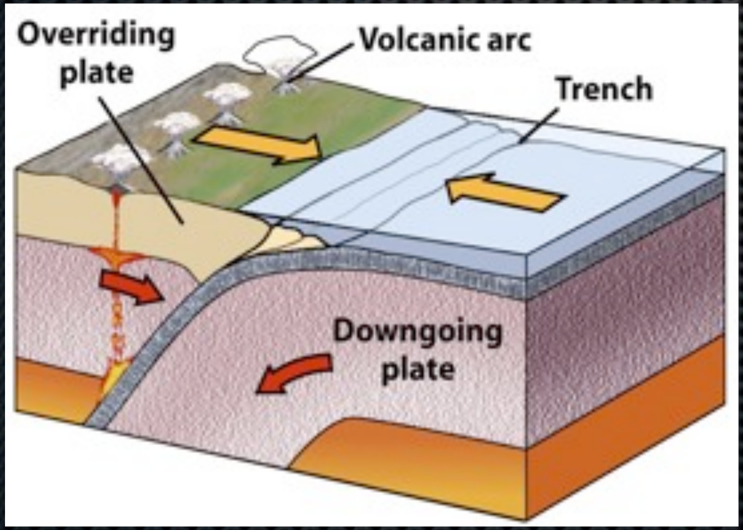


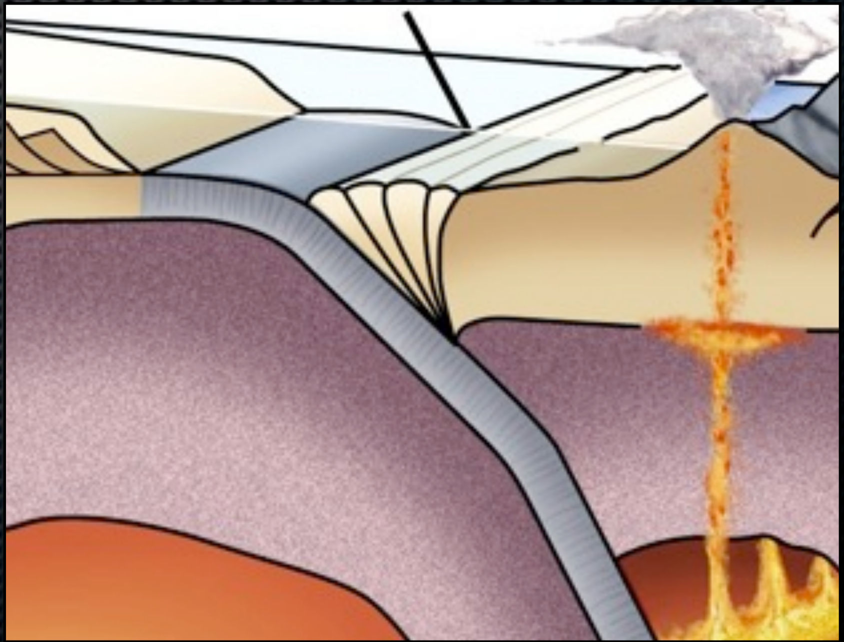
Mid-Ocean Ridges

- "Black smokers" are found at some MORs.
  - Water entering fractured rock is heated by magma.
  - Hot water dissolves minerals and cycles back out of rock.
  - When water reaches the sea, minerals precipitate quickly.

Convergent Boundaries

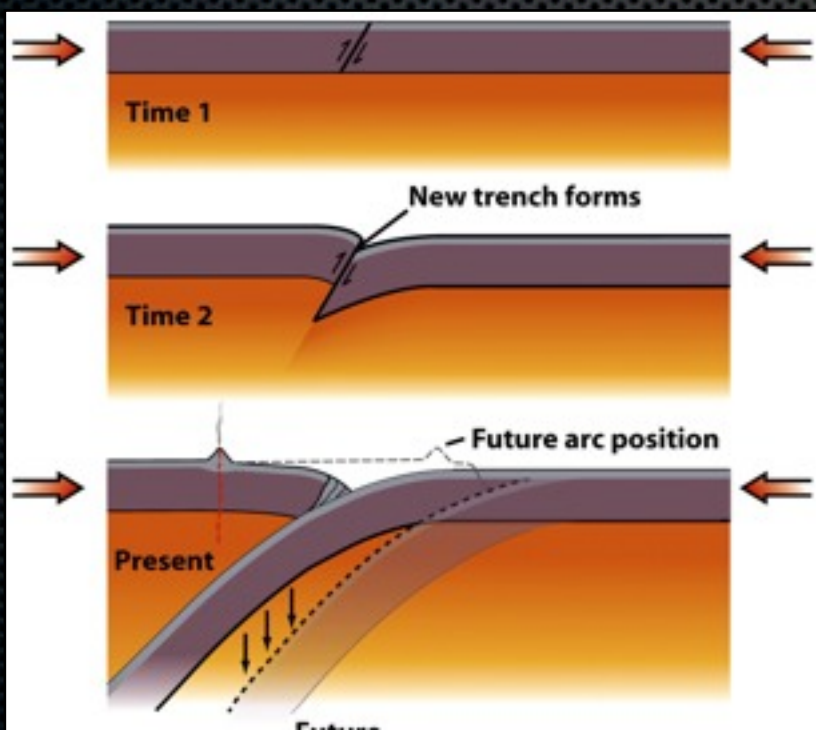
- Lithospheric plates move toward one another.
- One plate dives back into the mantle (subduction).
- The subducting plate is always oceanic lithosphere.

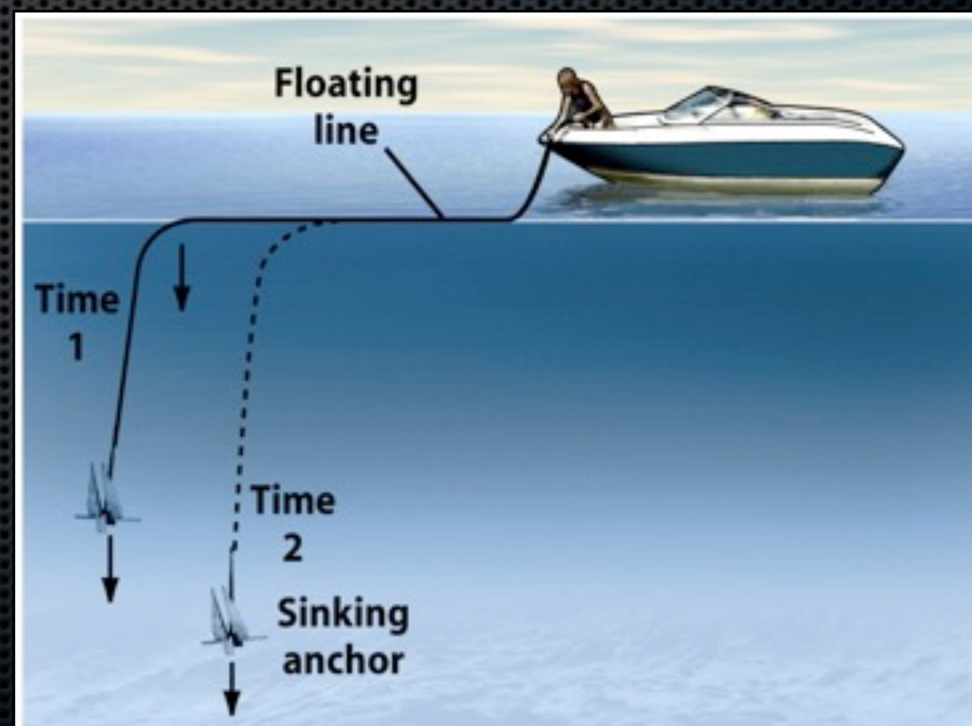




Subduction

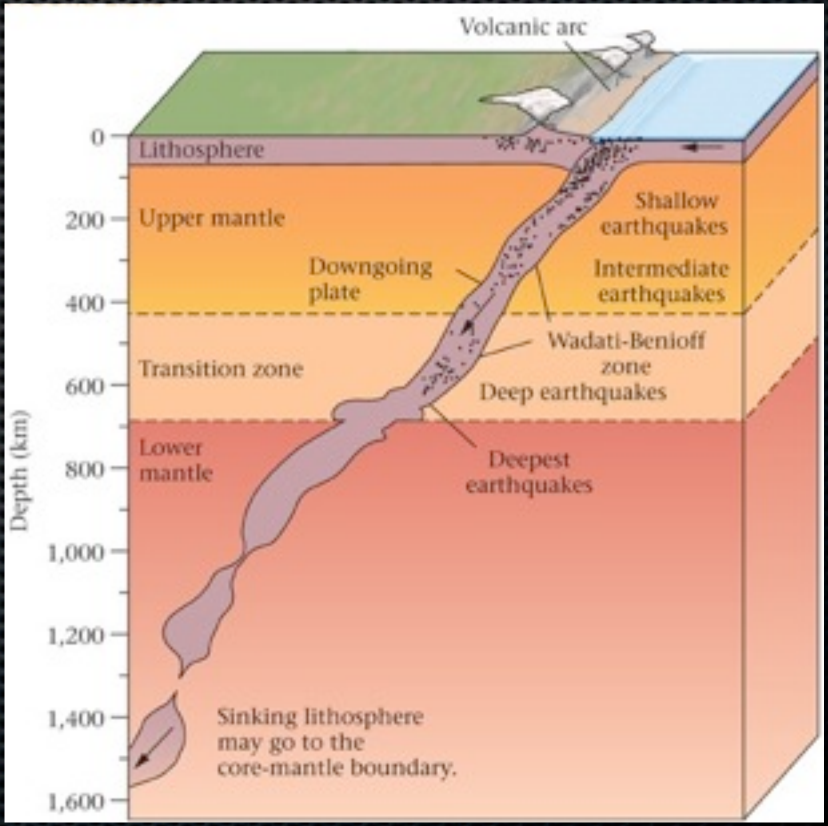
- Old oceanic lithosphere is more dense than mantle.
- A flat-lying oceanic plate doesn't subduct easily.
- Once bent downward, however, the leading edge sinks like an anchor rope.





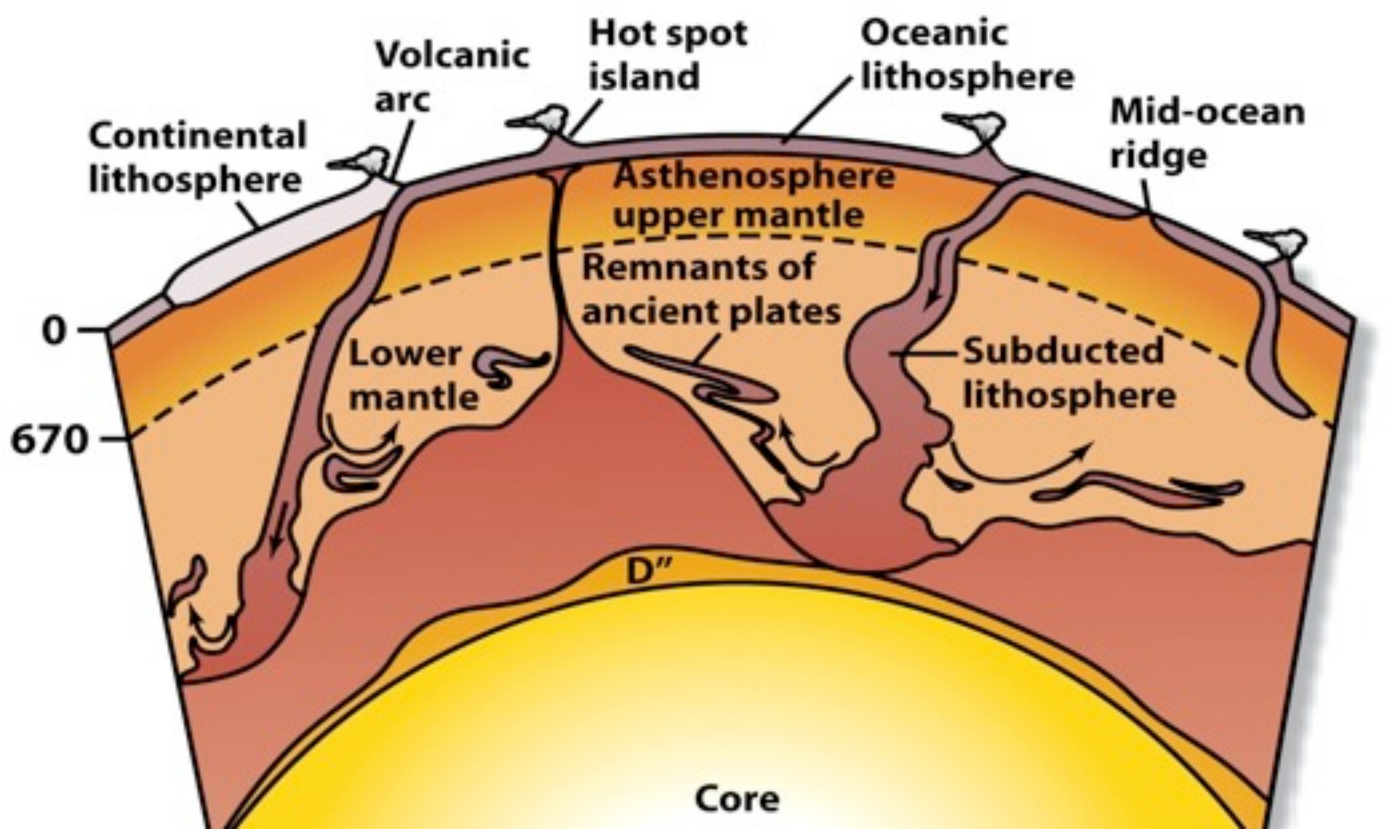
Convergent Boundaries

- The subducting plate descends at an average of 45°
  - Plate descent is revealed by Wadati-Benioff earthquakes.
    - Mark frictional contact and mineral transformations.
    - Earthquakes deepen away from trench.
- Quakes cease below 660 km.



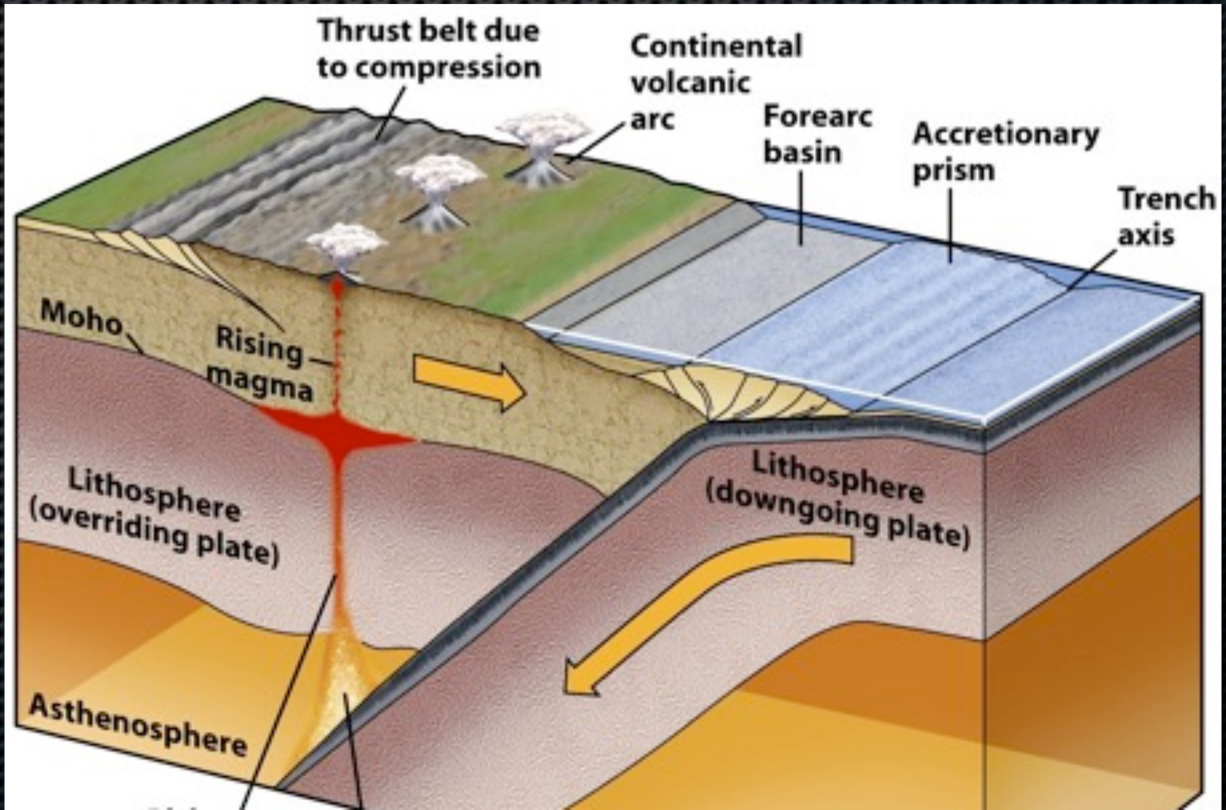
Fate of Subducted Plates?

- Plate descent may continue past the earthquake limit.
- The lower mantle may be a "plate graveyard."



Subduction Features

- Subduction is associated with unique features.
  - Accretionary prisms.
  - Volcanic arcs.
  - Back-arc basins.

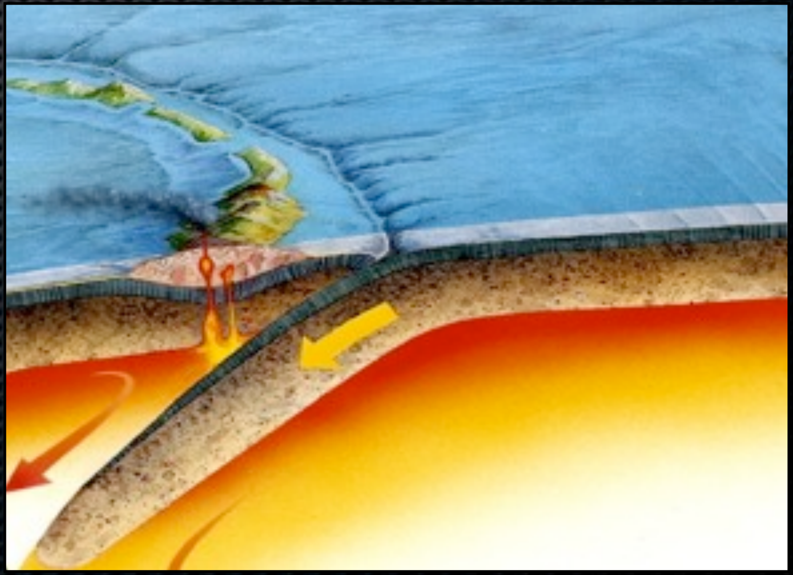


Convergent Boundaries

- **Accretionary Prism** – A deformed sediment wedge.
  - Sediments are scraped off of subducting plates.
  - This thrusts them onto the overriding plate.
  - Contorted prism sediments can be pushed above sea-level.

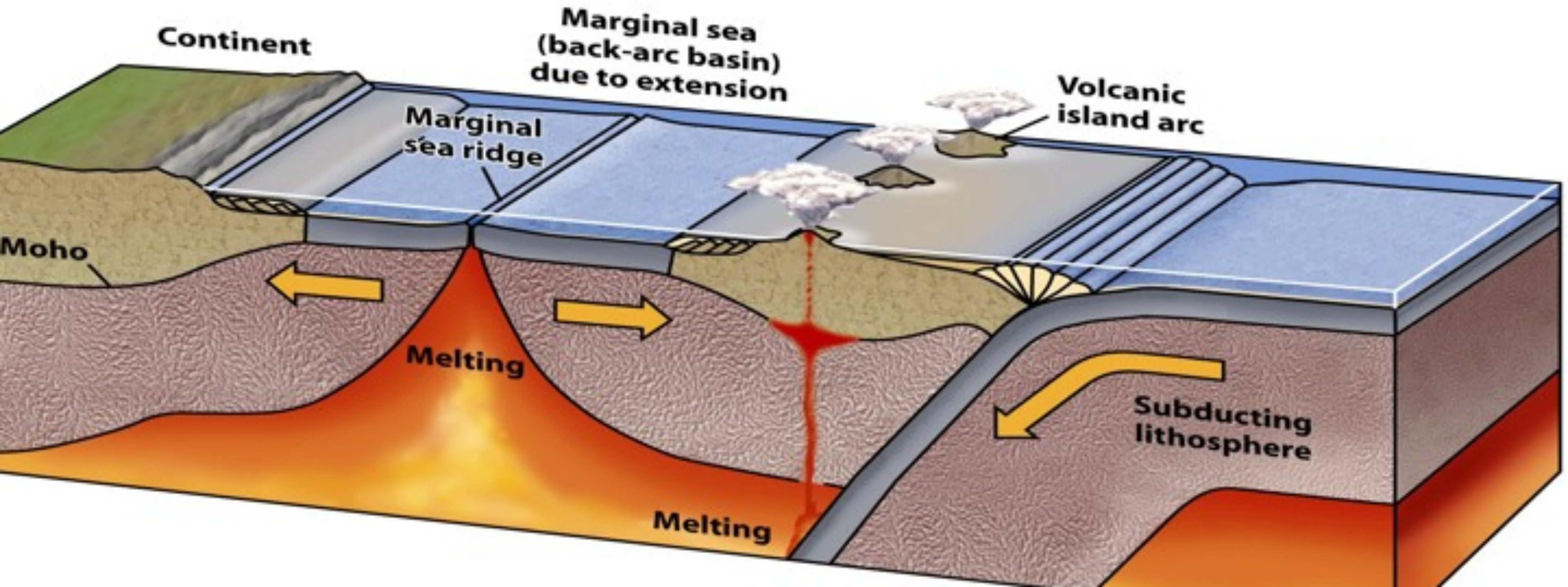
Convergent Boundaries

- **Volcanic Arc** – A chain of volcanoes on overriding plate.
  - The descending plate partially melts at ~ 150 km depth.
  - Magmas burn through overriding plate.
  - Volcanic arcs are curved because the Earth is a sphere.
- Arc type depends upon the overriding plate.
  - Continental crust – **Continental Arc**.
  - Oceanic – **Island Arc**.



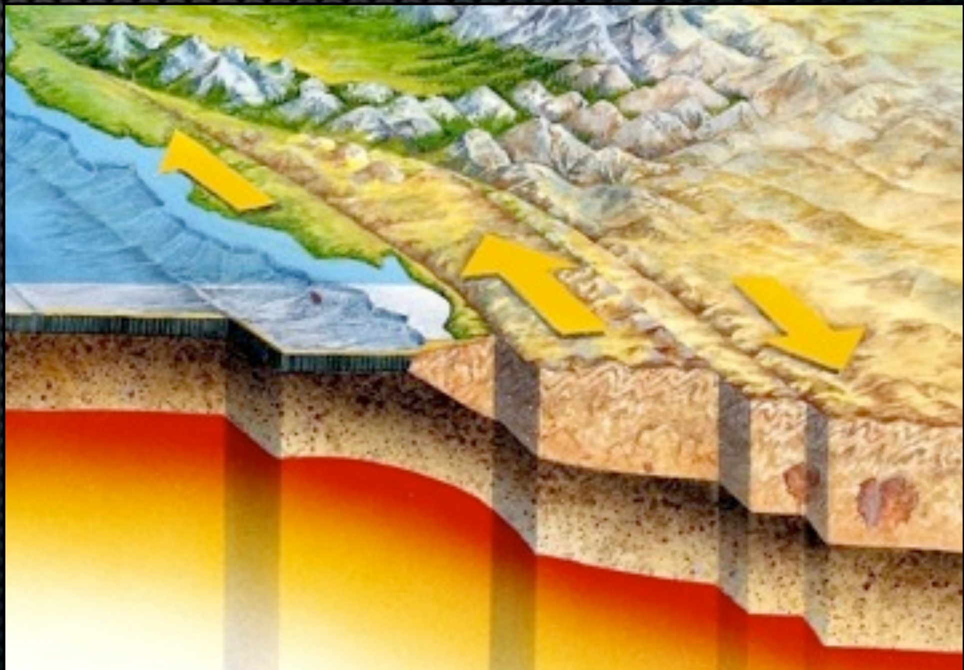
Convergent Boundaries

- **Back-arc basin** – A marginal sea behind an arc.
  - Forms between an island arc and a continent.
  - Offshore subduction traps a piece of oceanic crust, or…
  - Stretching births a new spreading ridge.



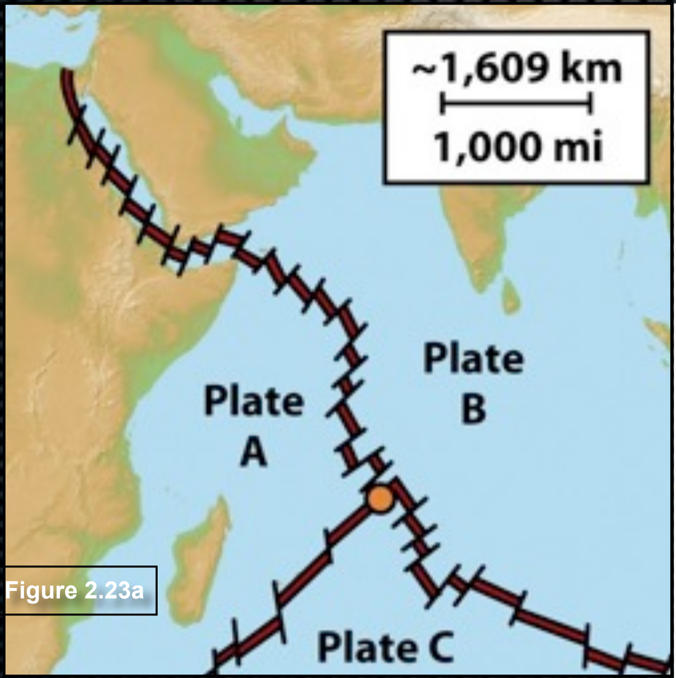
Transform Boundaries

- Lithosphere slides past; not created or destroyed.
  - Many transforms offset spreading ridge segments.
  - Some transforms cut through continental crust.
- Characterized by…
  - Earthquakes.
  - Absence of volcanism.



Oceanic Transforms

- The Mid-Ocean Ridge axis is offset by transform faults.
  - A geometric necessity for a line spreading on a sphere.
  - Transforms bear strong evidence of sea-floor spreading.



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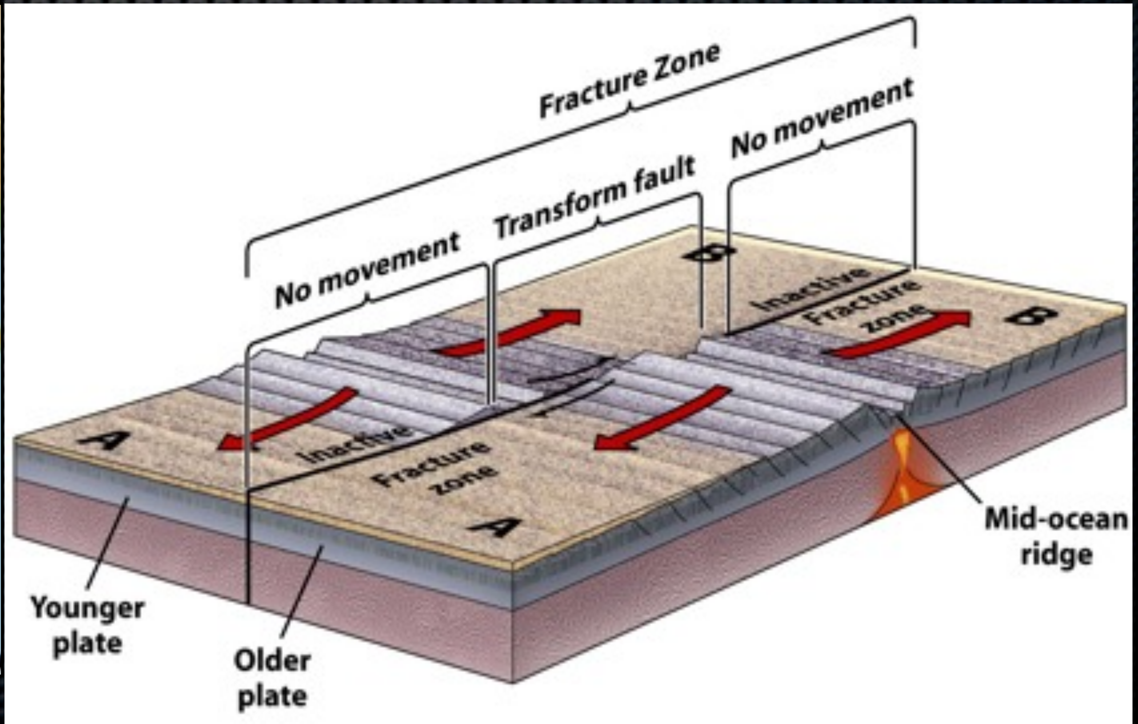
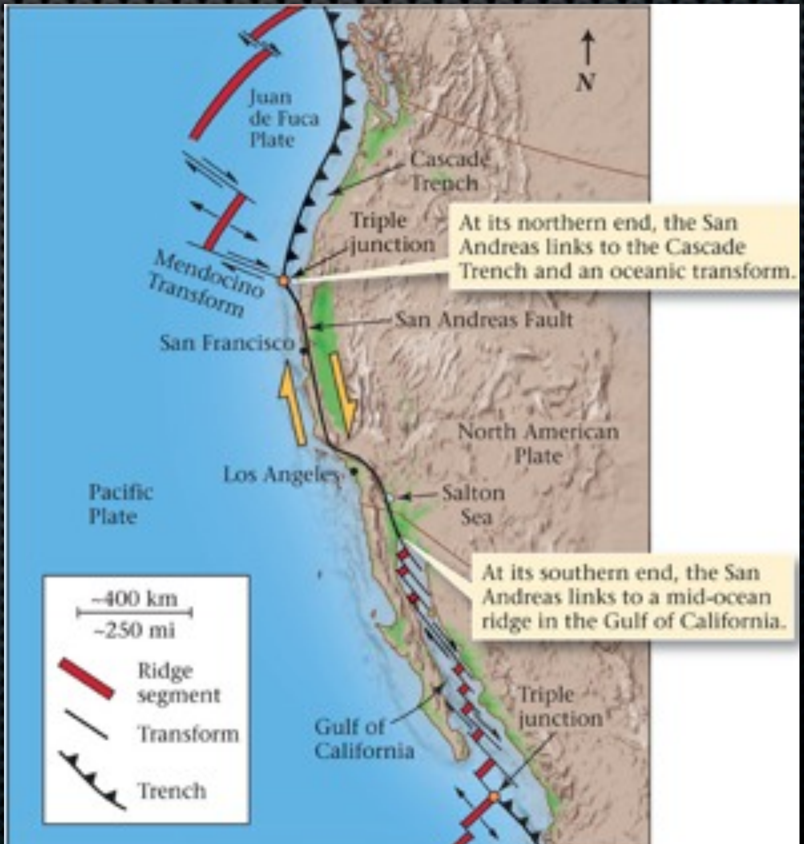


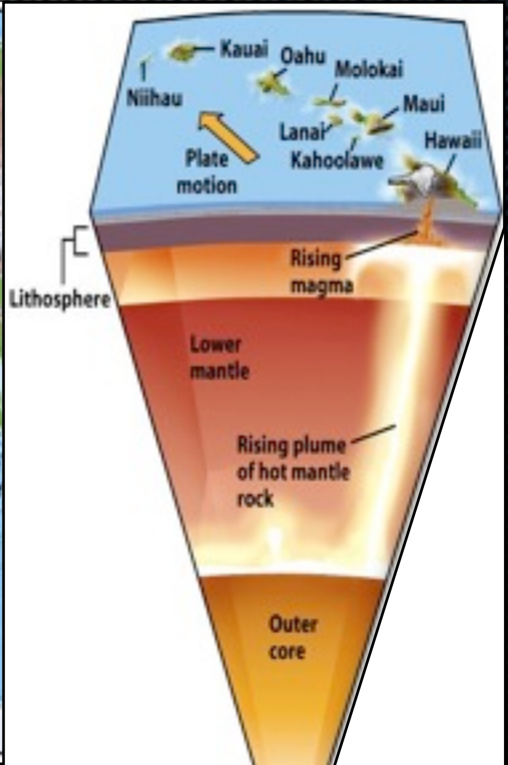
Transform Boundaries

- Continental transforms – Chop continental crust.
  - Example: The San Andreas Fault.



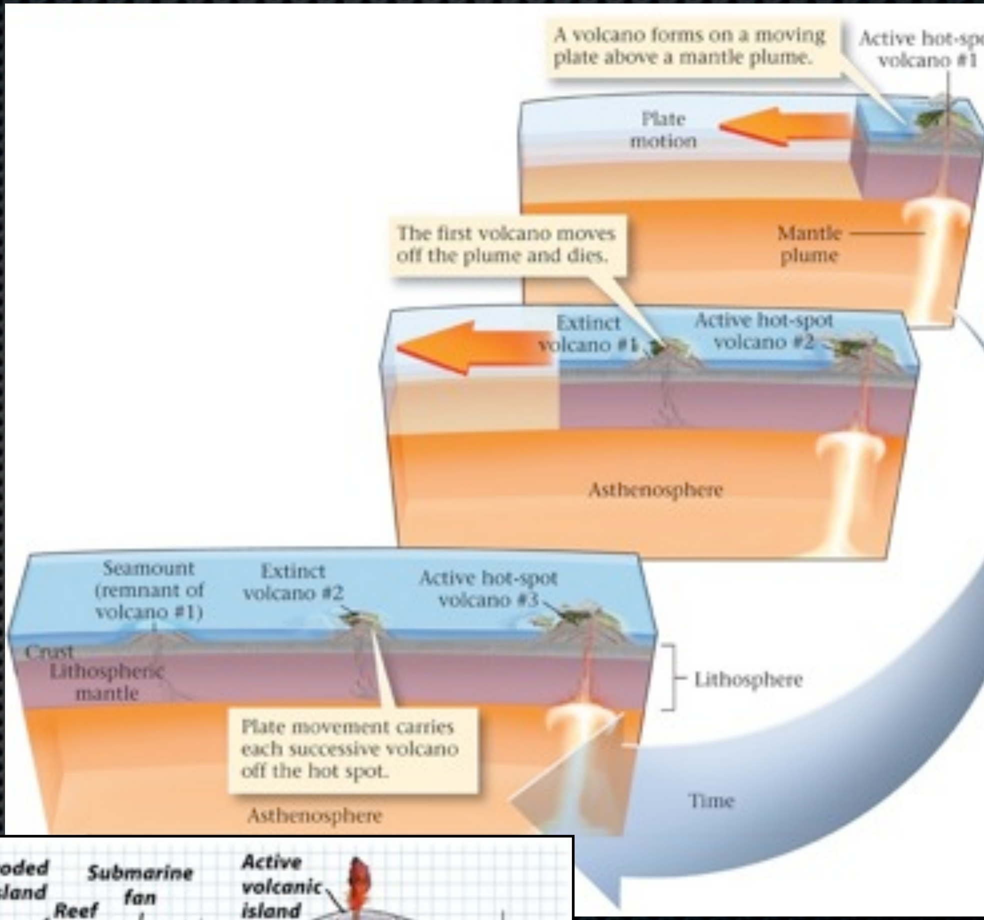
Hot Spots

- Volcanic plumes independent of tectonic plates.
  - Most are located far from plate boundaries.
  - Comprised of mafic magmas from the lower mantle.
  - Tattoo overriding plates with volcanoes.



Hot Spots

- Hot spot perforates overriding plate.
- Volcano builds above sea level.
- Plate motion pulls volcano off plume.
  - Volcano goes extinct and erodes.
  - Subsidence creates a guyot.



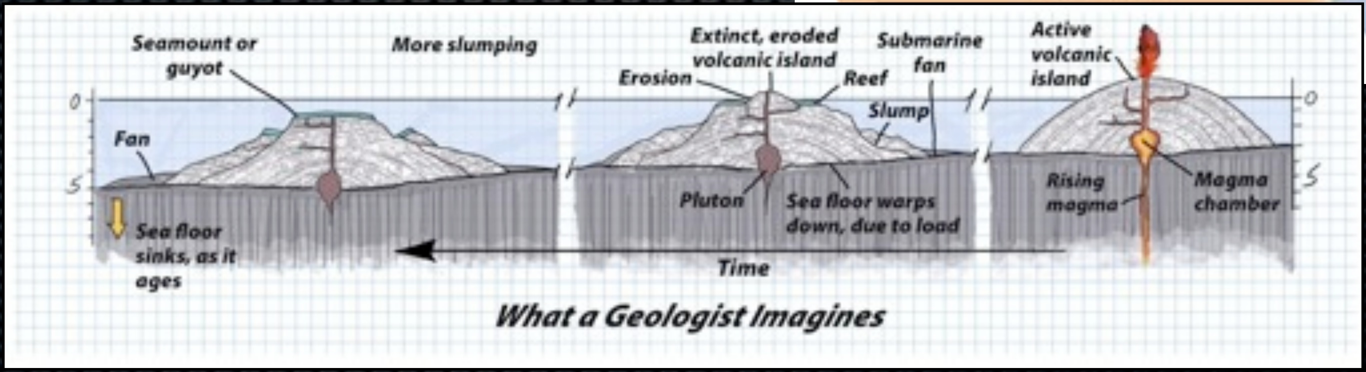


Plate Collision

- Subduction consumes ocean basins.
- Ocean closure ends in continental collision.
  - Buoyant continental crust will not subduct.
  - Subduction ceases and mountains are uplifted.

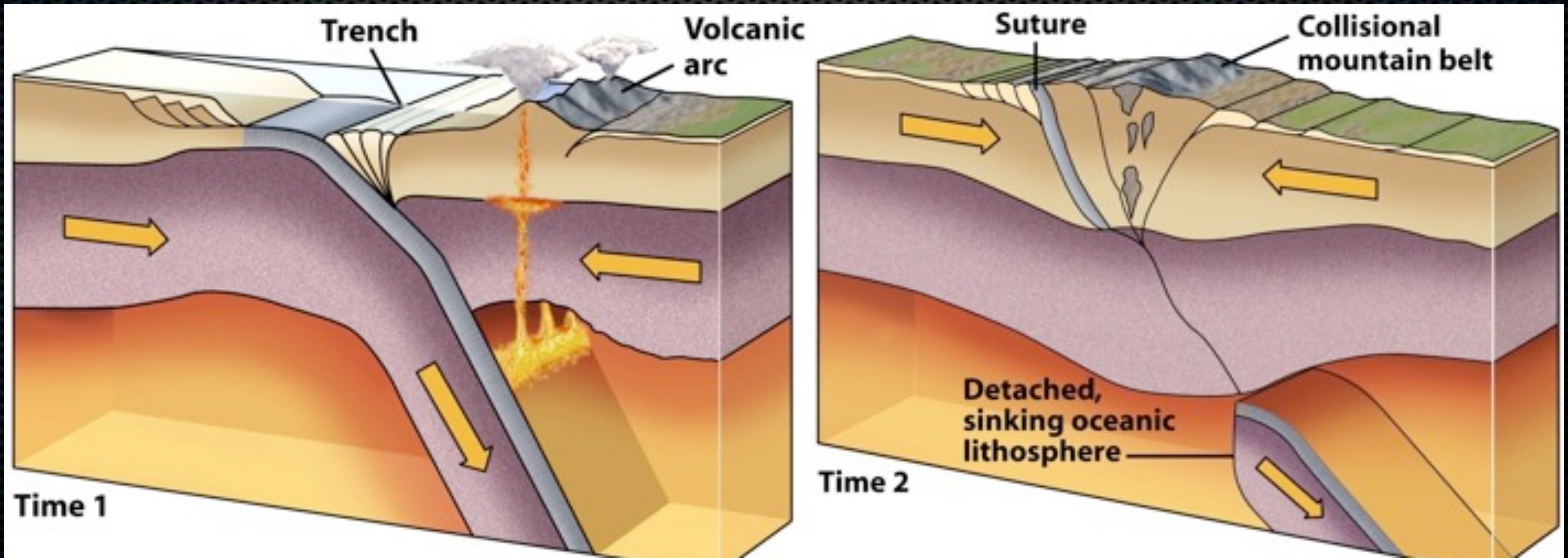
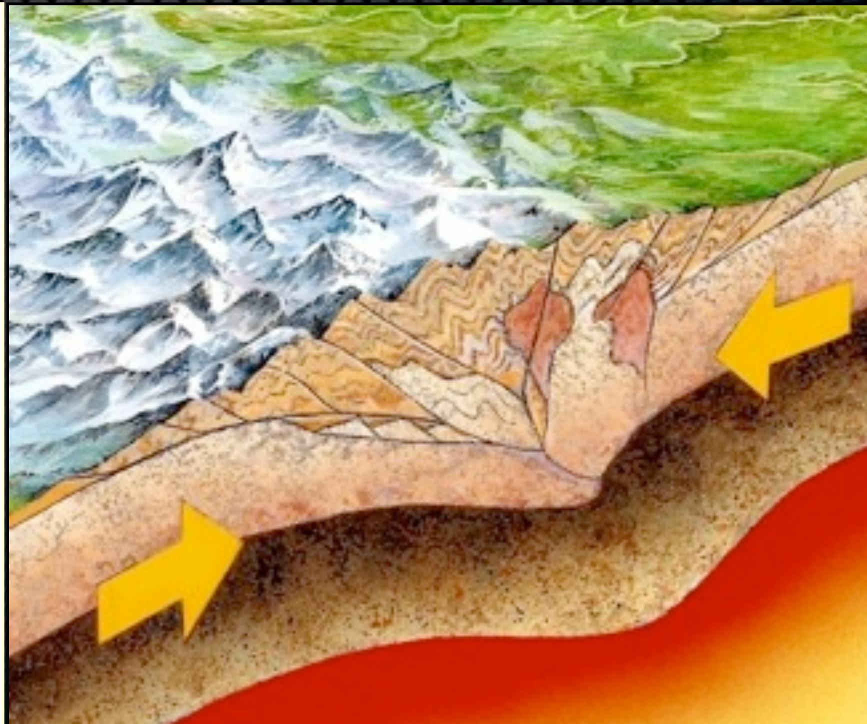


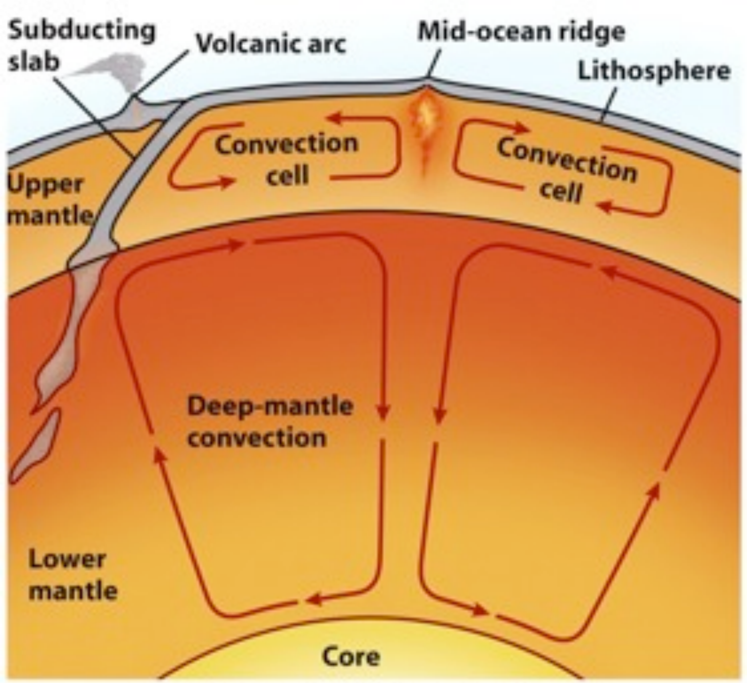
Plate Collision

- Plate tectonic collision may involve…
  - Two continents.
  - A continent and an island arc.
- Collision "sutures" the convergent plate boundary.



Driving Mechanisms

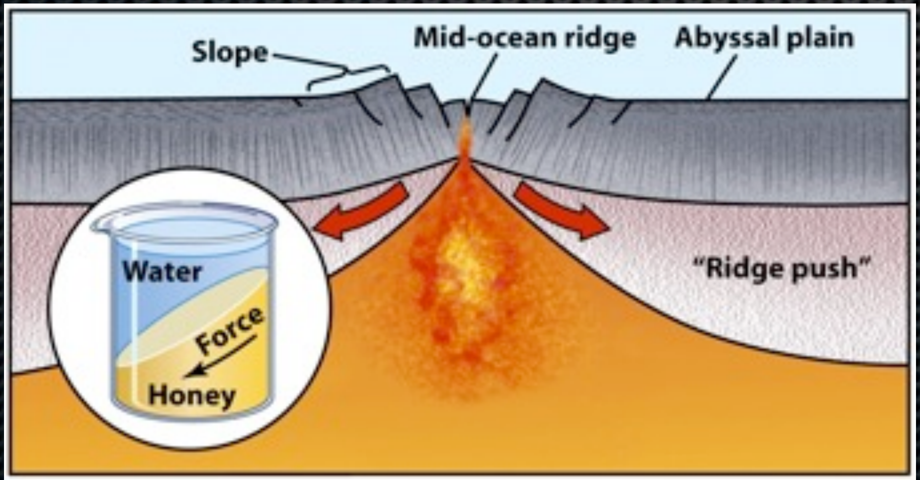
- What drives plate motion?
  - Old idea: Plates are dragged atop a convecting mantle.
    - Plate motions are much too complex.
    - Convection does occur.
      - It is not the prime driving mechanism.



Old Convection Model (two-layer)

Driving Mechanisms

- Modern thinking: Two other forces drive plate motions.
  - **Ridge-push** – Elevated MOR pushes lithosphere away.
  - **Slab-pull** – Gravity pulls a subducting plate downward.
  - Convection in the asthenosphere adds or subtracts.



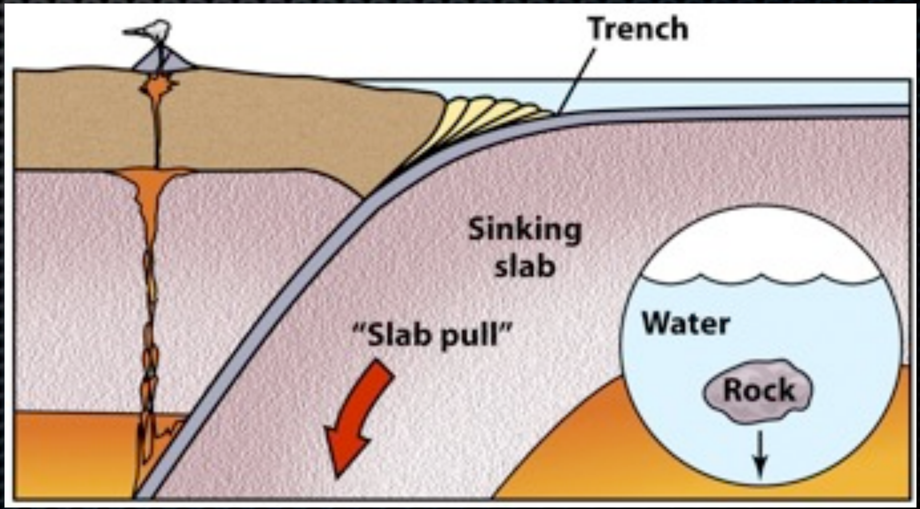


Plate Velocities

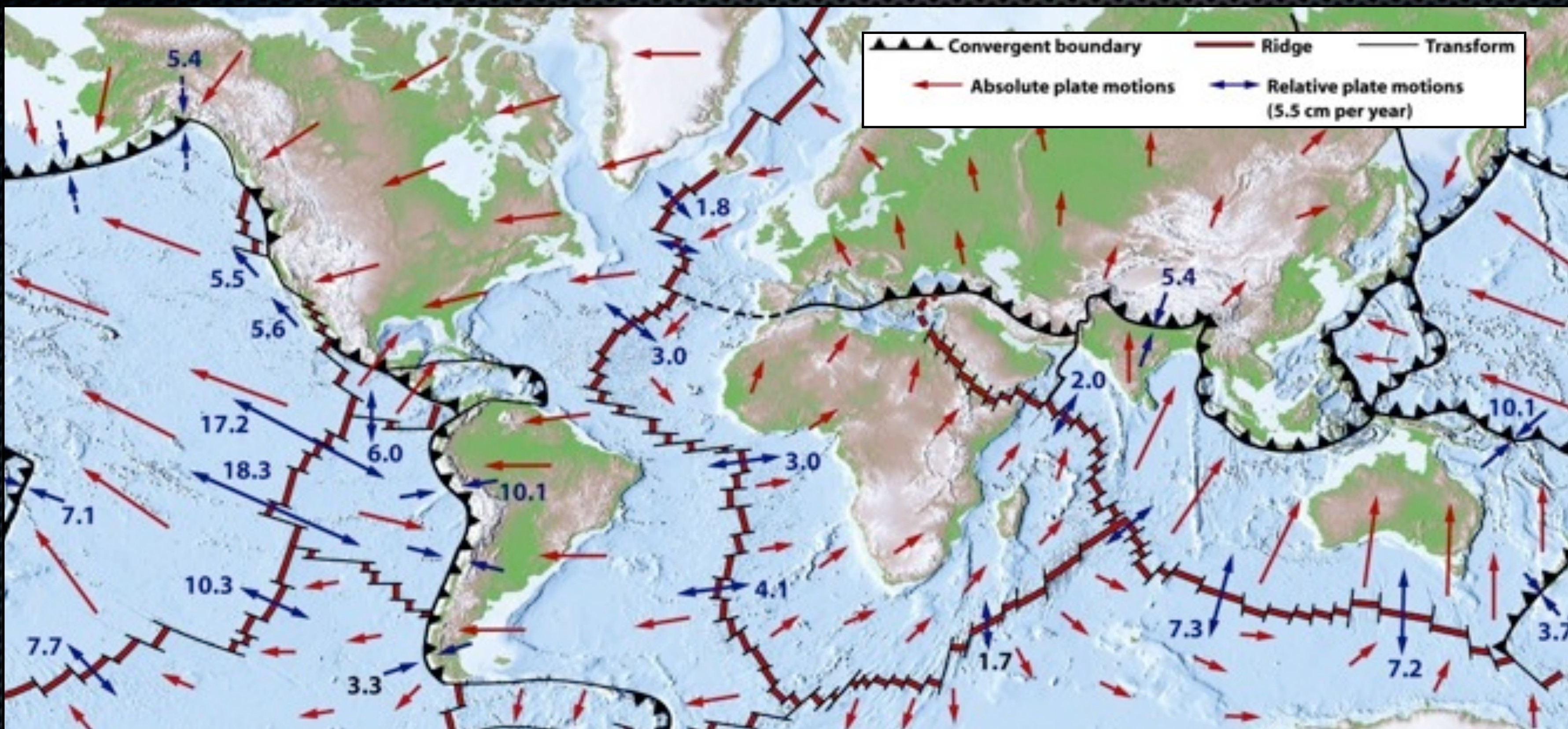
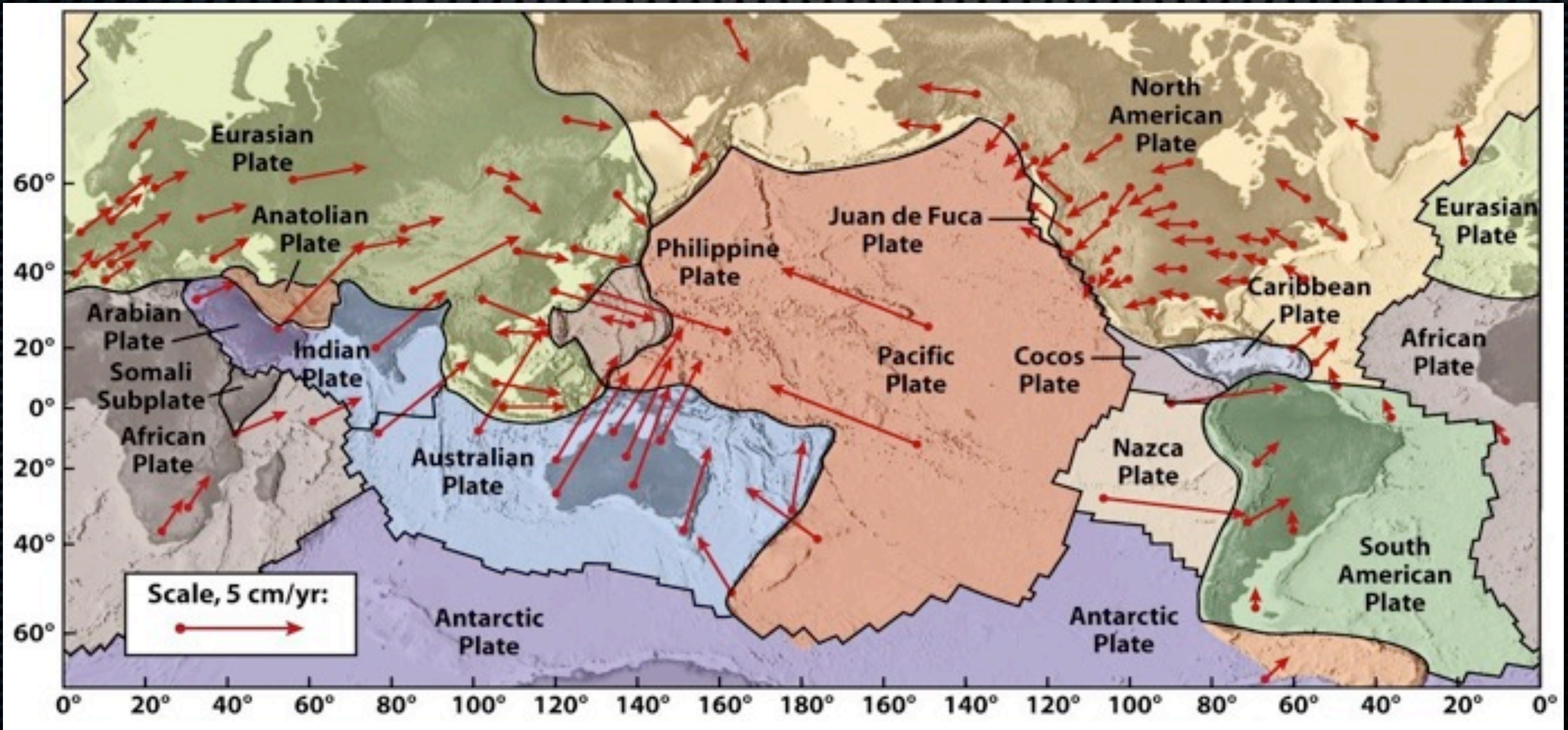


Plate Velocities

- Plate vectors are determined GPS measurements.
  - Global Positioning System (GPS) uses satellites.
  - Knowledge of plate motion is now accurate and precise.



The Dynamic Planet

- Earth's surface changes continuously.
  - These changes appear slow to us.
  - Geologically, change is rapid.
- Earth looked very different in the past.
- Earth will look very different in the future.