The Earth in Context

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Introduction

- Earth: the topic of this course. We shall look into its
  - Structure, formation
  - History
  - Processes and condition
  - When did it all begin?

It began with a Big Bang

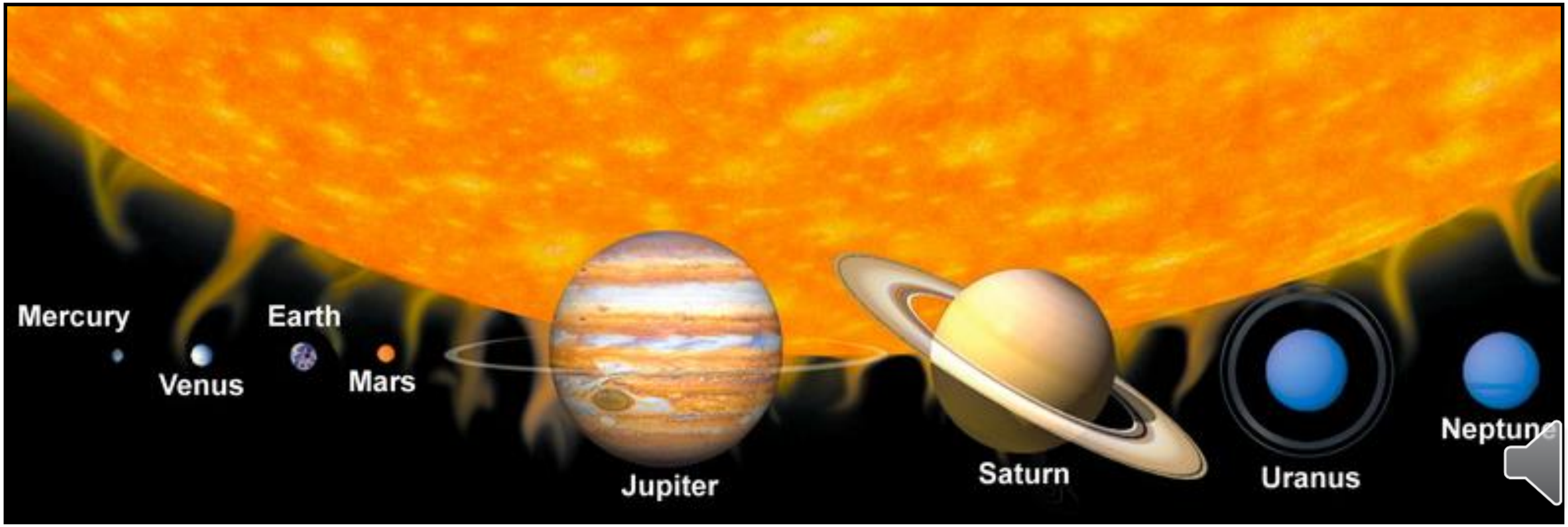
- We have good arguments for the origin of the Universe about 14 billion years ago.
- It seems to have started with a Big Bang that has exploded all the elements of the Universe that we see and the space in which we see them.
- Quickly (after about 100 million years) the earliest giant stars formed
- Then galaxies some of which assemble a trillion stars.

The Nature of Our Solar System

- **Our Sun is a member of the Milky Way galaxy. It is a medium-sized star, orbited by 8 planets.**
  - **The sun accounts for 99.8% of our solar system's mass.**
  - **Planets:**
    - **large formed bodies orbiting a star (the Sun). Our Earth is one of eight in orbit about our Sun.**
    - **Planets have a nearly spherical shape and have largely cleared their neighborhood of other objects (by gravity).**
  - **Moon: a body gravitationally locked in orbit around a planet**
  - **Millions of asteroids, trillions of icy bodies orbit the sun.**

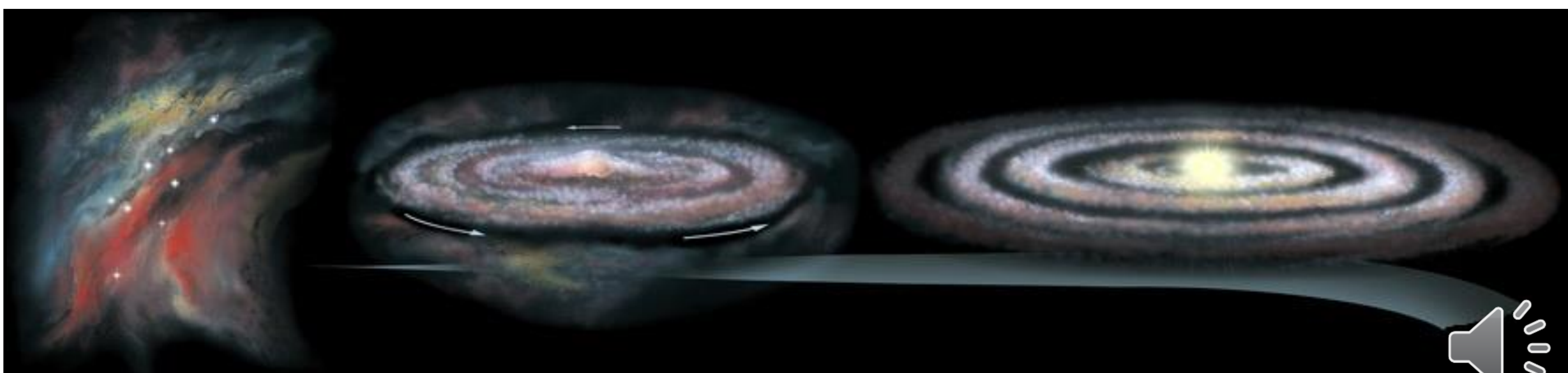
The Nature of Our Solar System

- **Two main groups of planets occur in the solar system.**
  - **Terrestrial Planets—small, dense, rocky planets**
    - **Mercury, Venus, Earth, and Mars**
  - **Giant Planets—large, low-density, gas and ice/water giants**
    - **Gas giants: Jupiter, Saturn (hydrogen and helium)**
    - **Ice giants: Uranus, Neptune (frozen water, ammonia, methane)**
  - **The Solar System is held together by gravity.**



Formation of the Solar System

- The Solar System formed from a concentration of gas and dusts released by earlier stars and supernova.
- Region where mass was concentrated began to pull in gas.
  - The region gained mass and density.
  - Mass compacted into a smaller region and began to rotate.
  - Rotation rate increased, developing a disk shape.
  - The central ball of the disk became hot enough to glow.
  - A protostar was born! Our Sun? ~ 4.6 Ga.
  - Planets formed within the rotating nebula

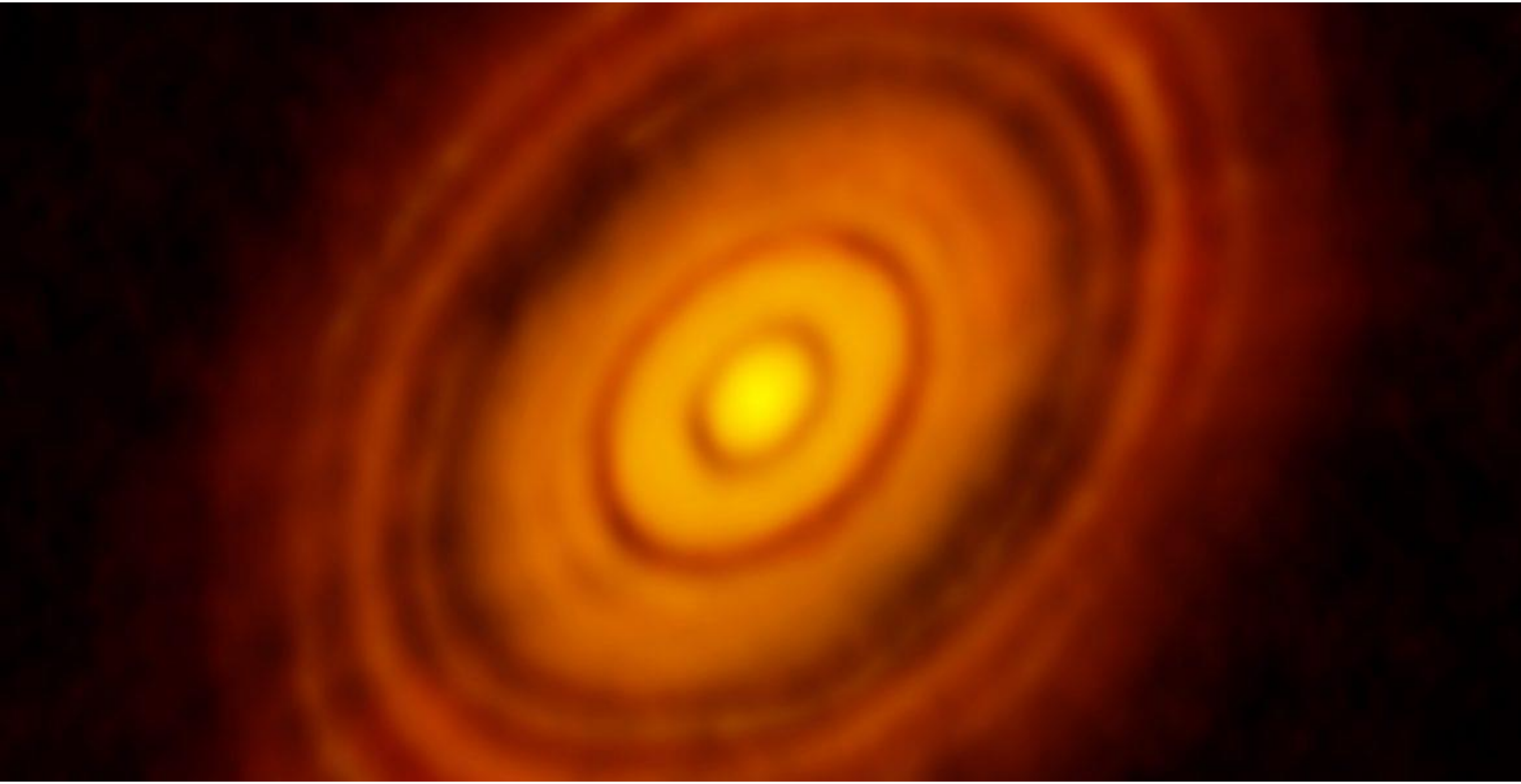


Where Do Elements Come From?

- The original Big Bang formed the lightest elements.
  - Atomic #s 1, 2, 3, 4, and 5 (H, He, Li, Be, and B)
- Heavier elements, #s 6–26 (C to Fe) are formed by fusion within the subsequent stars: *stellar nucleosynthesis*.
- The heaviest element (#s >26) form during fast neutron capture processes in *supernovae*.

Crab Nebula: a supernoval remnant

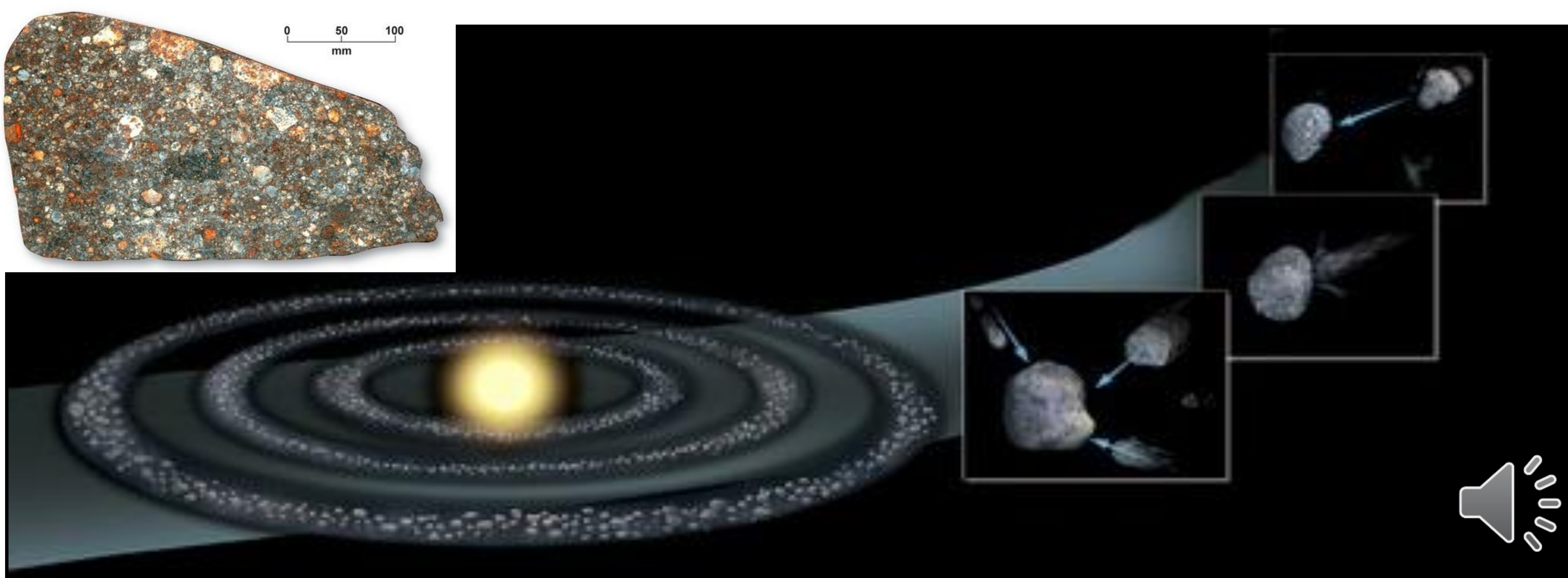
Protoplanetary disk



This is an actual image of a protoplanetary disk in formation as obtained by ALMA (Atacama Large Millimeter/submillimeter Array)

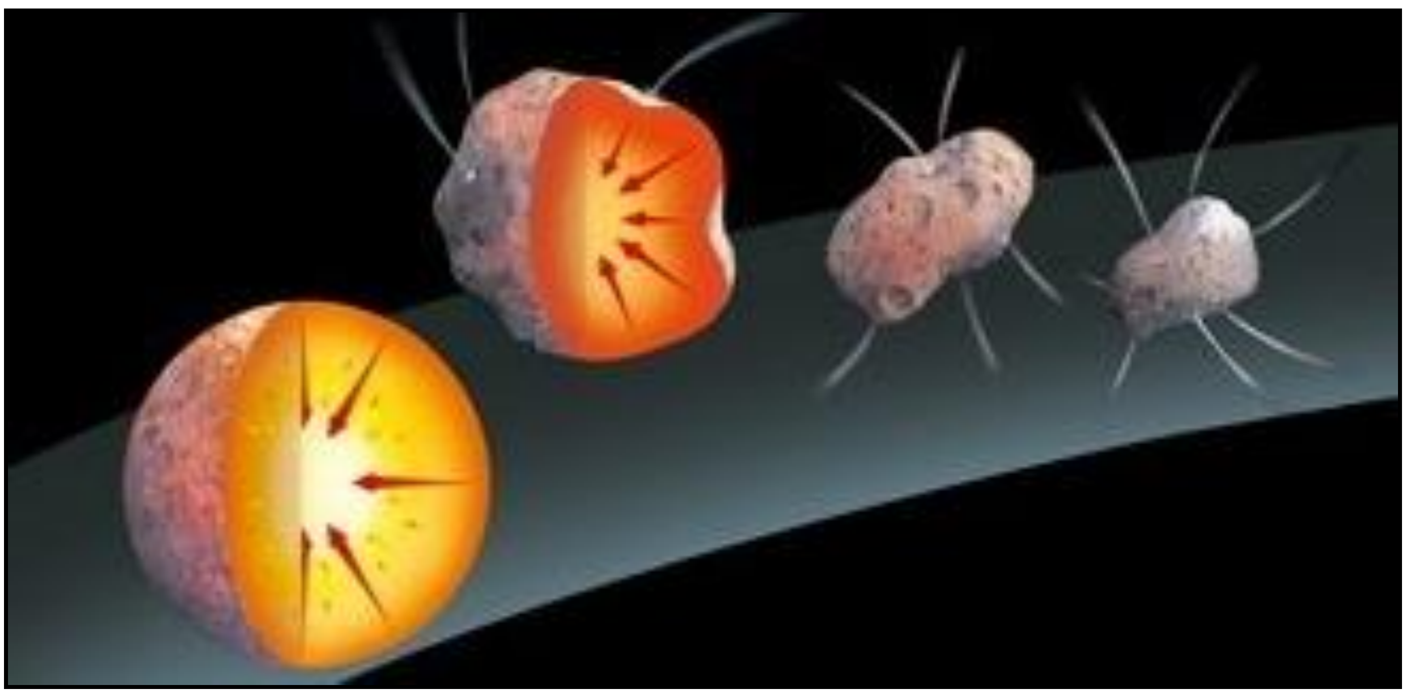
Solar System Formation

- The ball at the center grows dense and hot.
- Fusion reactions begin; our Sun is born ~ 4.6 billion years ago
- Dust in the rings condenses into mineral particles.
- Particles coalesce to form planetesimals.



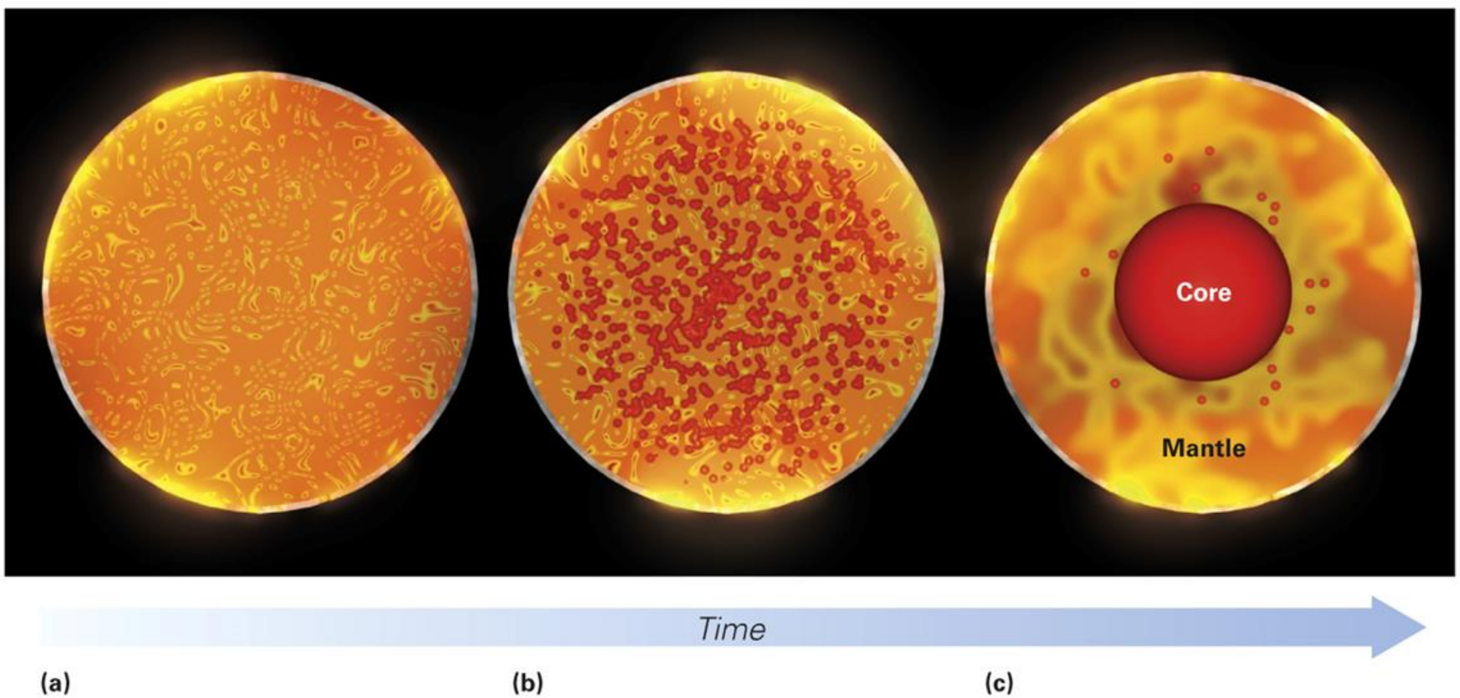
Formation and Differentiation of Earth

- Planetesimals clump into a lumpy protoplanet.
- The interior heats, softens, and gravity forms a sphere.
- The interior differentiates into:
  - A stony outer shell— the mantle
  - A central iron-rich core



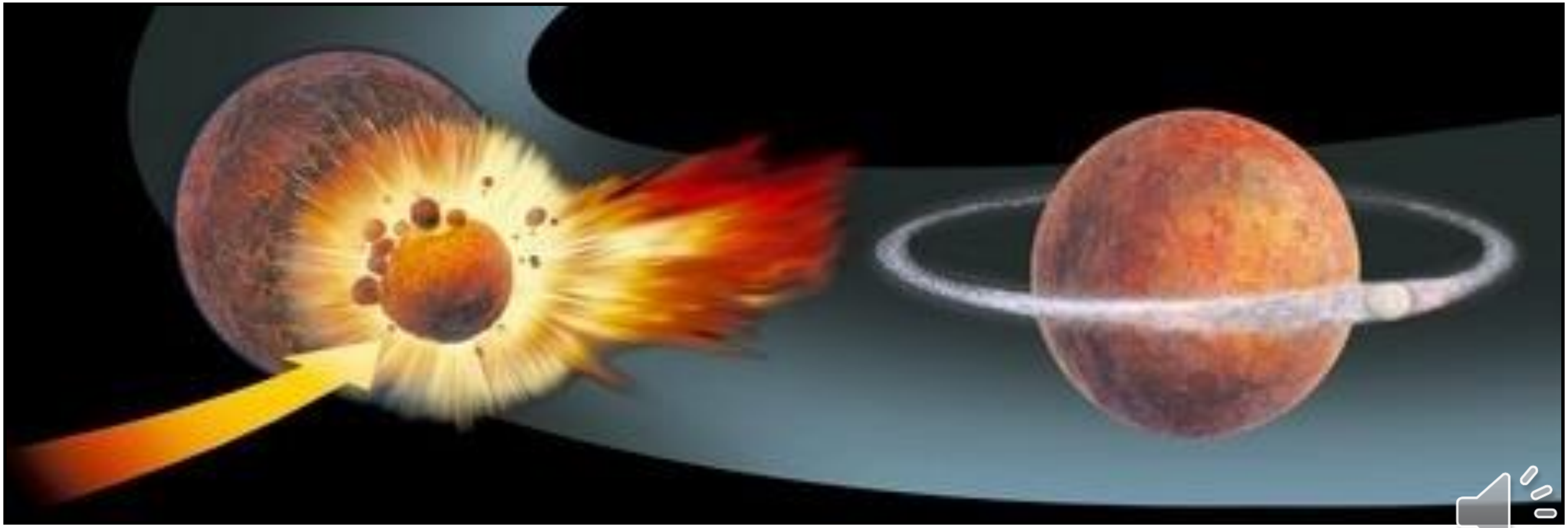
Formation and Differentiation of Earth

- Planetesimals clump into a lumpy protoplanet.
- The interior heats, softens, and gravity forms a sphere.
- The interior differentiates into:
  - A stony outer shell— the mantle.
  - A central iron-rich core, the outer shell of which is molten and the deepest interior solid.



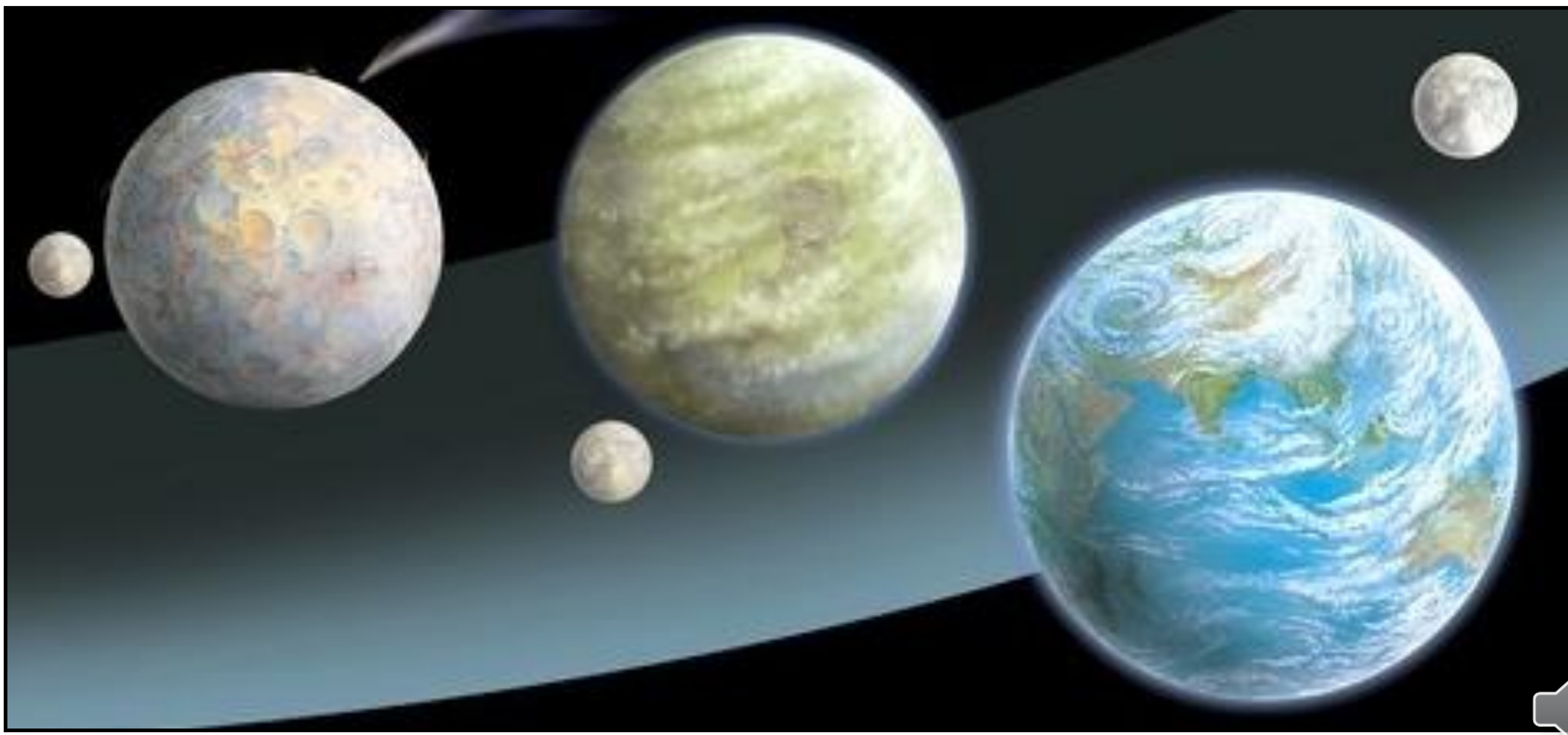
Formation of our Moon

- ~4.53 Ga, a Mars-sized protoplanet collides with Earth.
- The planet and a part of Earth's mantle are disintegrated.
- Collision debris forms a ring around Earth.
- The debris coalesces and forms the moon.
  - The moon has a composition similar to Earth's mantle.



The Atmosphere and Oceans

- Earth's atmosphere develops from volcanic gases.
- When Earth becomes cool enough:
  - Moisture condenses and accumulates.
  - The oceans come into existence.

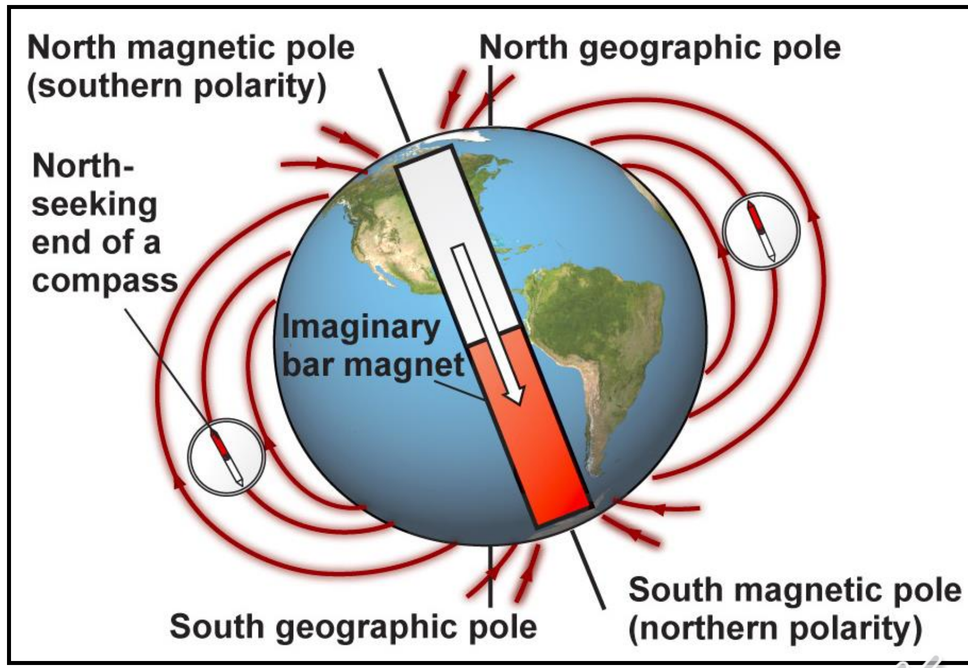


The Earth System

- Orbiting around Earth, space visitors would notice:
  - Atmosphere—the gaseous envelope.
  - Hydrosphere—the blue liquid water.
  - Biosphere—the wealth of life.
  - Lithosphere—the solid outer, rocky shell of Earth.
- Interaction of these components comprises the *Earth System*.
- Heat from radioactive decay fuels internal processes.
- Sunlight powers atmosphere, biosphere, and hydrosphere.

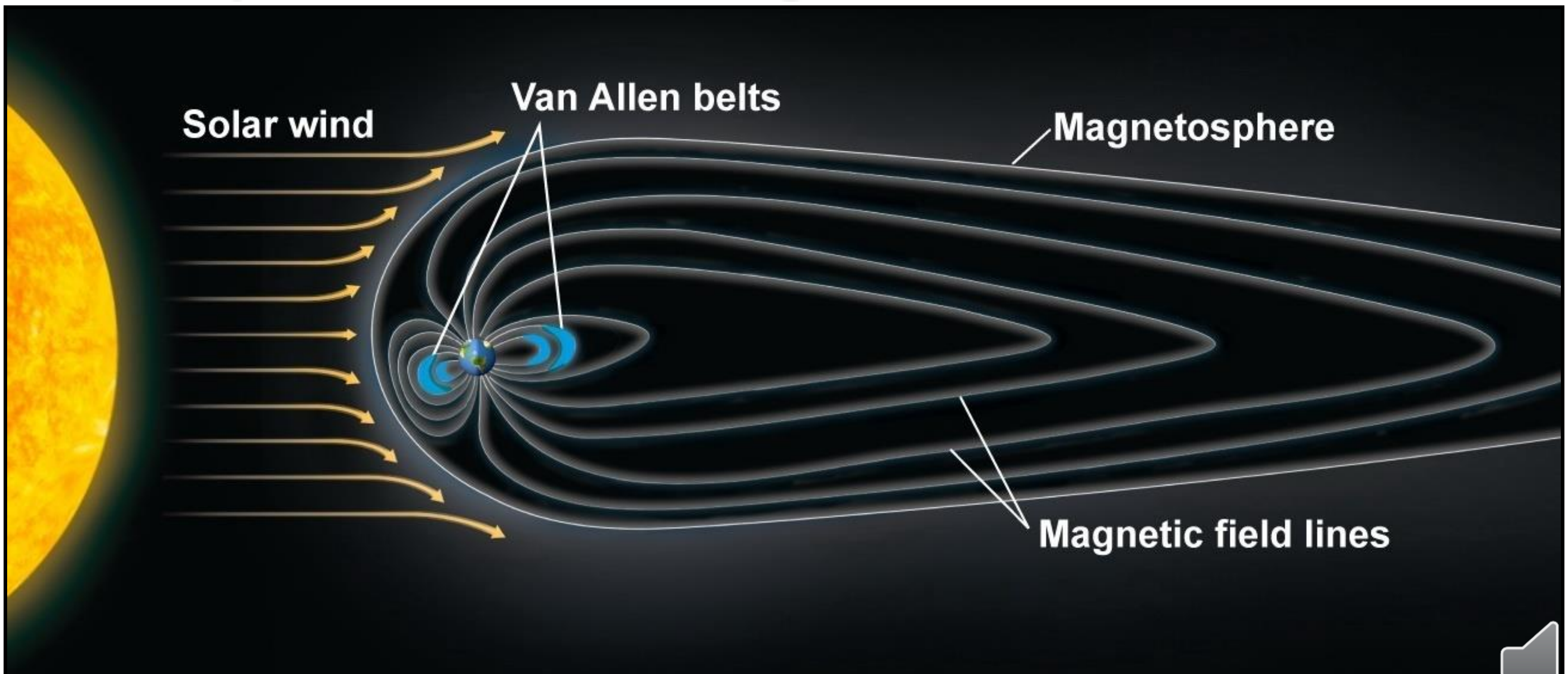
Magnetic Field

- Earth's magnetic field is generated by fluid circulation in the liquid outer layer of the core.
- The N pole of the field is near Earth's geographic S pole!
  - A compass needle aligns with the field lines.
  - The N compass arrow points to the geomagnetic S pole.
    - Opposites attract.
- Magnetic field lines:
  - Extend into space.
  - Weaken with distance.
  - Form a shield around Earth (magnetosphere).
  - The magnetosphere protects us from cosmic radiation and solar wind



Magnetic Field

- The solar wind distorts the magnetosphere.
  - Shaped like a teardrop
  - Deflects most of the solar wind, protecting Earth
- The strong magnetic field of the Van Allen belts intercepts and collects dangerous cosmic radiation.



Magnetic Field

- The magnetic field is revealed by spectacular aurorae.
  - Some charged particles make it past the Van Allen belts.
  - These are channeled along magnetic field lines.
  - They cause atmospheric gases in polar regions to glow.
- Northern lights: aurora borealis
- Southern lights: aurora australis

The Atmosphere

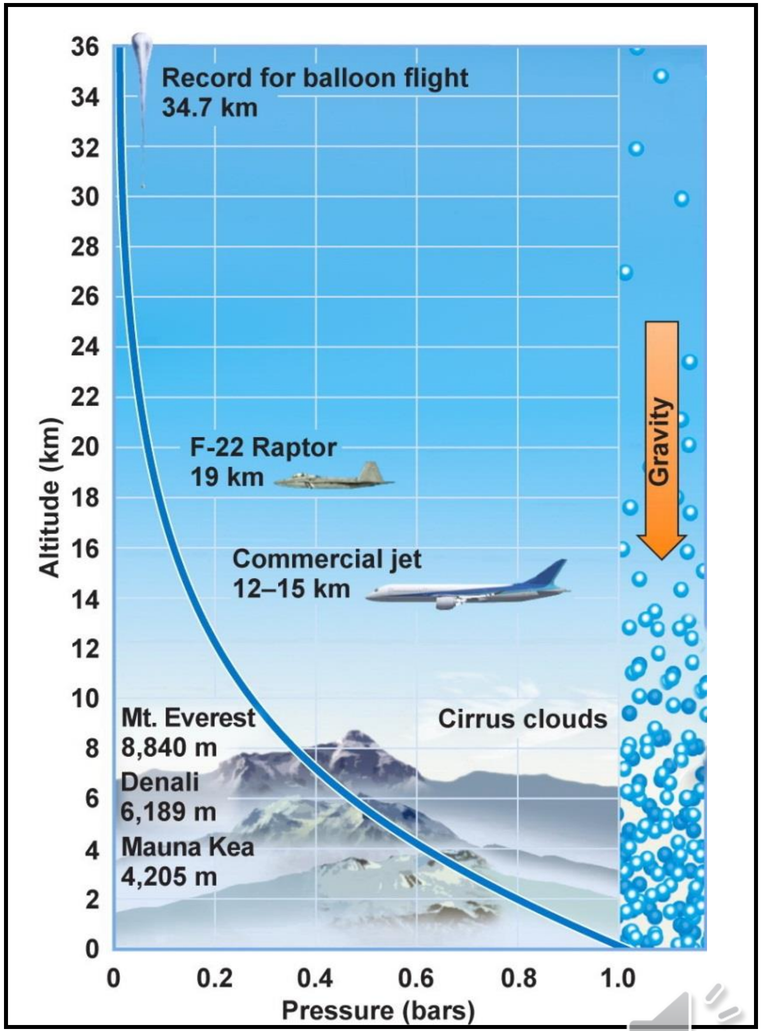
- Our atmosphere is mostly nitrogen (N_2 78%) and oxygen (O_2 21%)
- The remaining gases (totaling less than 1%) include:
  - Argon (0.93%), carbon dioxide (now 0.0415% and increasing), neon (0.0018%) and variable water vapour.
  - Other, less common gases (helium, methane, krypton).
- The atmosphere thins and dries away from the surface.
- Atmospheric layers have distinct characteristics.
  - Pressure, temperature, density, moisture composition

The Atmosphere

- The atmosphere is more dense closer to Earth.

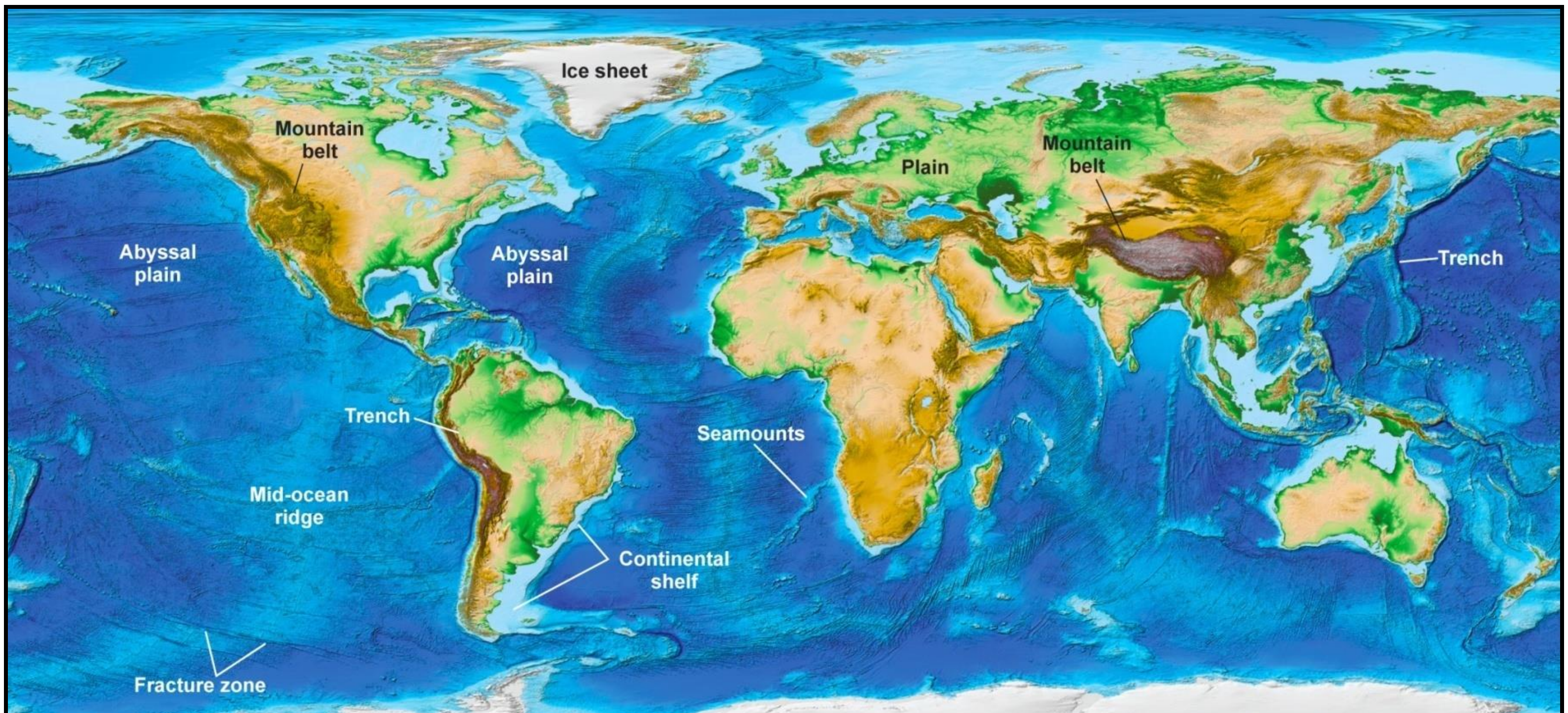
- Sea-level atmospheric pressure:
  - 14.7 pounds per square inch (psi)
  - 101.3 kPa (kilo Pascal); 1Pa = 1N/m^2
  - 1 bar
  - Half of the mass of the atmosphere is contained below 5800m elevation

- With increasing elevation:
  - Pressure decreases.
  - Density decreases.
  - Oxygen content decreases.



Earth's Surface

- Land (30%) by area and water (70%) are the most prominent surface features.
- Topography (land) defines plains, mountains, and valleys.
- Bathymetry (sea-floor variations) defines mid-ocean ridges, abyssal plains, and deep-ocean trenches.



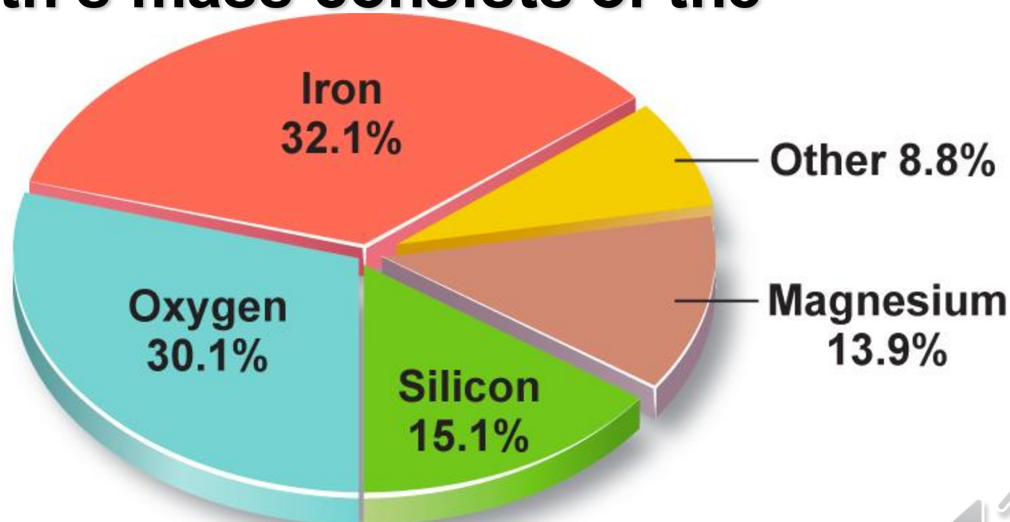
What is Earth Made Of?

- **91% of Earth's mass comprises just four elements:**
  - **Iron (Fe)—32.1%**
  - **Oxygen (O)—30.1%**
  - **Silicon (Si)—15.1%**
  - **Magnesium (Mg)—13.9%**

These 4 elements *could* combine to form **olivine**: **$(Mg,Fe)_2SiO_4$**

- **The remaining 9% of Earth's mass consists of the remaining 88 elements.**

- **These elements form the minerals, fluids and volatiles of the Earth.**

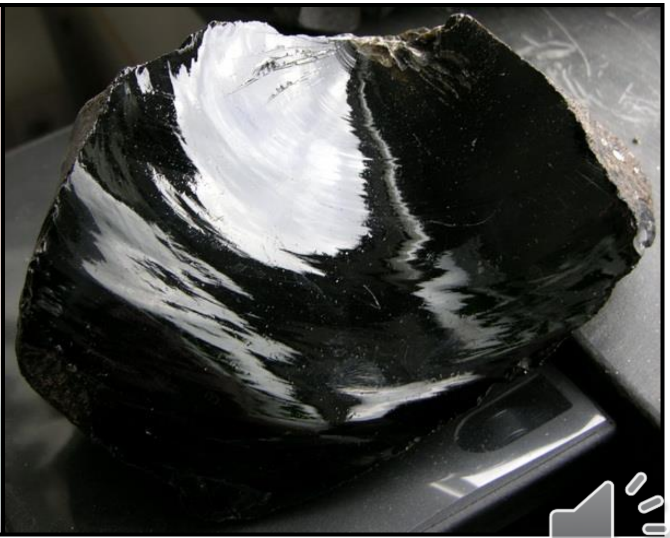


Earth Materials

- Elements combine into a variety of Earth materials.
  - Organic chemicals – carbon-containing compounds.
    - Most are residue from once-living creatures.
    - These include wood, peat, lignite, coal, and oil.

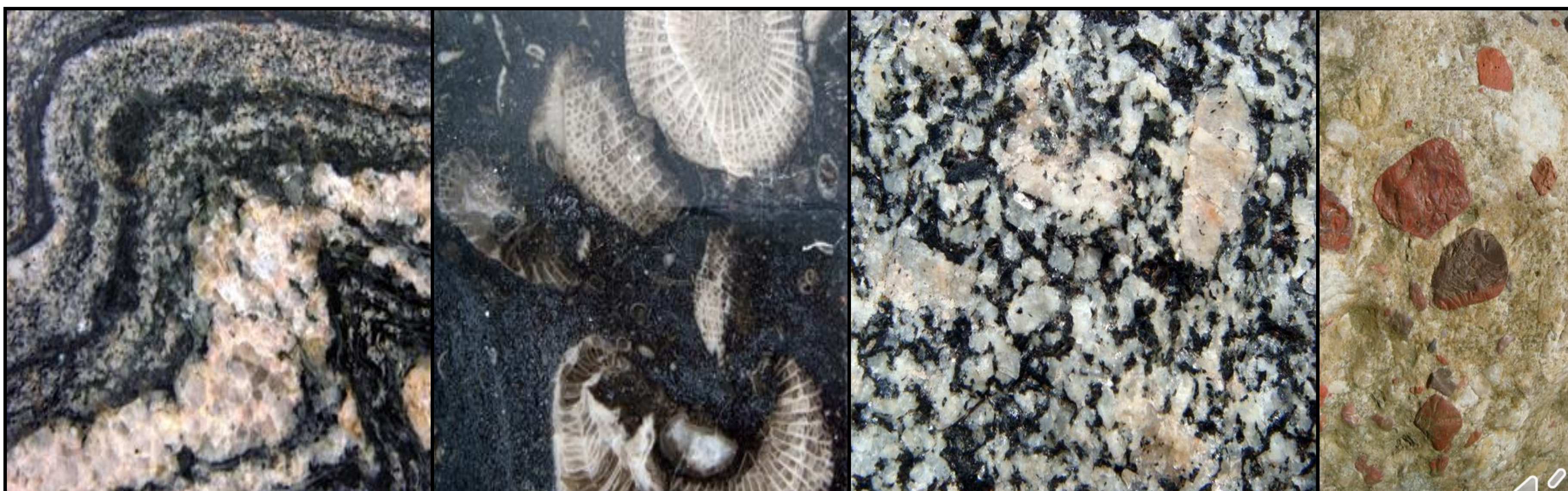
Earth Materials

- Elements combine into a variety of Earth materials.
  - Minerals—naturally-occurring crystalline solids
    - Crystal—a single coherent mineral with geometric faces
    - Grain—an irregularly shaped fragment of a larger crystal
    - Minerals comprise rocks and, therefore, most of the earth.
  - Glasses—noncrystalline solids
    - Glasses form by rapid cooling—too fast for crystal growth.



Earth Materials

- Minerals combine into a variety of Earth materials.
  - Rocks—aggregates of minerals, grains, and/or glass
    - Igneous—cooled from a liquid (melt)
    - Sedimentary—debris cemented from preexisting rock.
    - Metamorphic—rock altered by pressure and temperature
  - Rocks may be made of a single mineral (eg. Limestone).



Earth Materials

- **Sediment—an accumulation of loose mineral grains**
  - **Weathered and eroded from preexisting rocks**
  - **Precipitated from evaporating water, may cement into rock**
- **Metals—solids composed of metal atoms (Al, Fe, Cu, Sn).**
  - **Metals have high density, are shiny, and conduct electricity.**
  - **An alloy contains more than one type of metal atom.**



Earth Materials

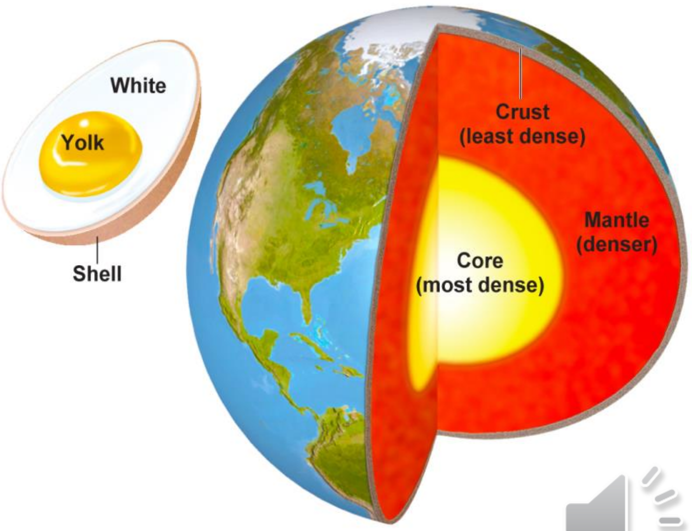
- Melts—rocks that have been heated to a liquid
  - Magma—molten rock beneath the surface
  - Lava—molten (or once molten) rock at the surface
- Volatiles—materials that turn into gas at the surface
  - Commonly H_2O, CO_2, and SO_2
  - Volatiles are released from volcanic eruptions.

Earth Materials

- **Most rocks on Earth are silicates (based on Si and O).**
- **There are four classes of igneous silicate rocks.**
  - **Based on proportion of Silica to Iron + Magnesium,**
  - **as proportion of silica (SiO_2) increases, density decreases.**
    - **Felsic (most Si-rich)**
      - **Granite (coarse-grained)**
      - **Rhyolite (fine-grained)**
    - **Intermediate**
      - **Diorite (coarse-grained)**
      - **Andesite (fine-grained)**
    - **Mafic**
      - **Gabbro (coarse-grained)**
      - **Basalt (fine grained)**
    - **Ultra-mafic (most Fe+Mg–rich)**
      - **Peridotite (coarse-grained, typically subcrustal)**
      - **Composition like that of the mineral olivine ($Fe_{0.2}Mg_{1.8}SiO_4$)**

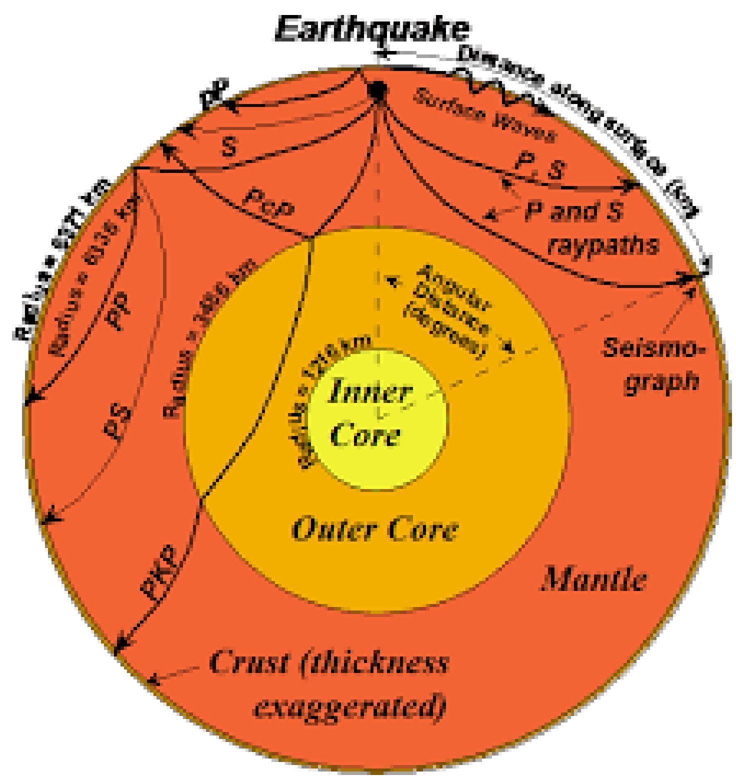
A Layered Earth

- The first key to understanding Earth's interior: density!
  - When scientists first determined Earth's mass they realized:
    - Average density of Earth >> average density of surface rocks.
    - Deduced that denser metals must be concentrated in Earth's center.
  - These ideas led to a layered model:
    - Earth is like an egg.
      - Thin, light brittle crust (eggshell)
      - Thicker, more dense, rocky mantle (eggwhite); plastic
      - Innermost, very dense metallic core (yolk); liquid layer + solid innerpart



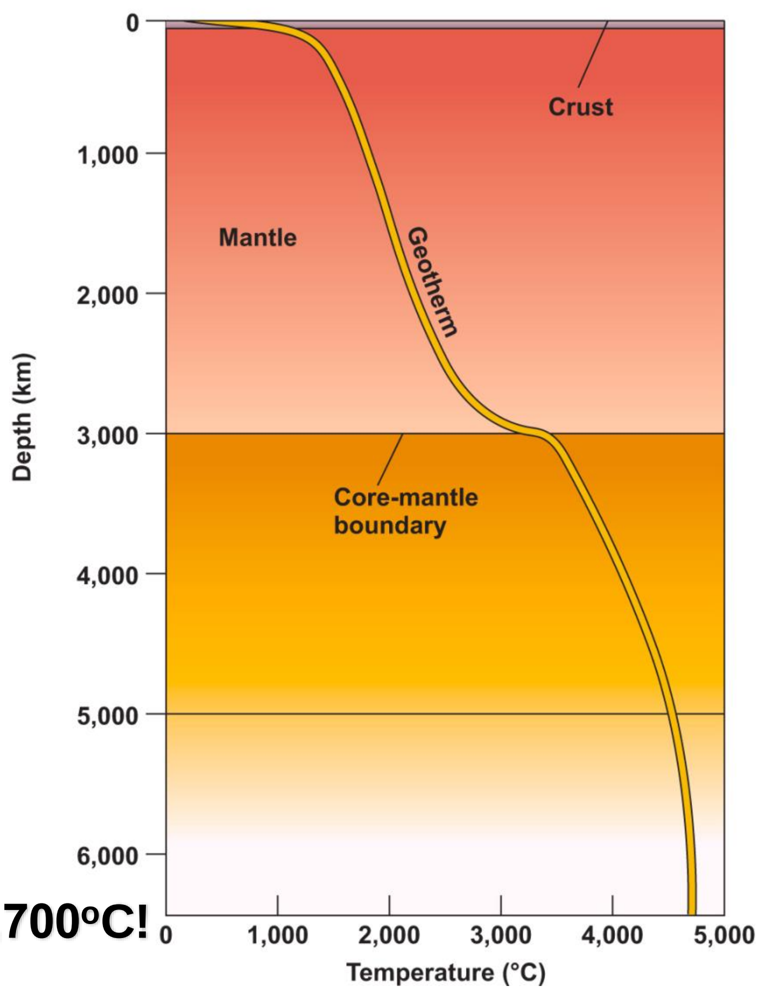
Mapping the Layers

- Earthquakes: seismic energy from fault motion generate
  - Seismic waves which bounce around in Earth's interior.
    - Seismic wave velocities change with density, rock strength.
    - We can determine the depth of seismic velocity changes.
    - Hence, we can tell where physical properties change in Earth's interior.



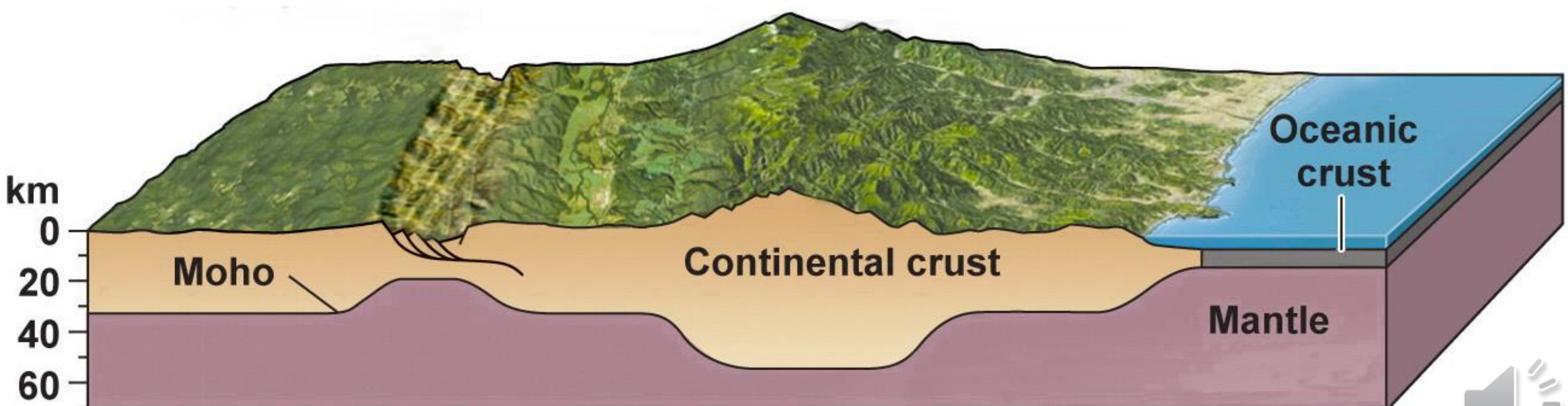
The Layered Earth

- **Changes with depth?**
  - **Pressure (P)**
    - **The weight of overlying rock increases with depth.**
  - **Temperature (T)**
    - **Heat is generated in Earth's interior.**
    - **T increases with depth.**
- **Geothermal gradient**
  - **The rate of T changes with depth.**
  - **The geothermal gradient varies.**
    - **~ 20-30° C per km in crust**
    - **< 1°C per km at greater depths**
    - **Earth's center may reach more than 4,700°C!**



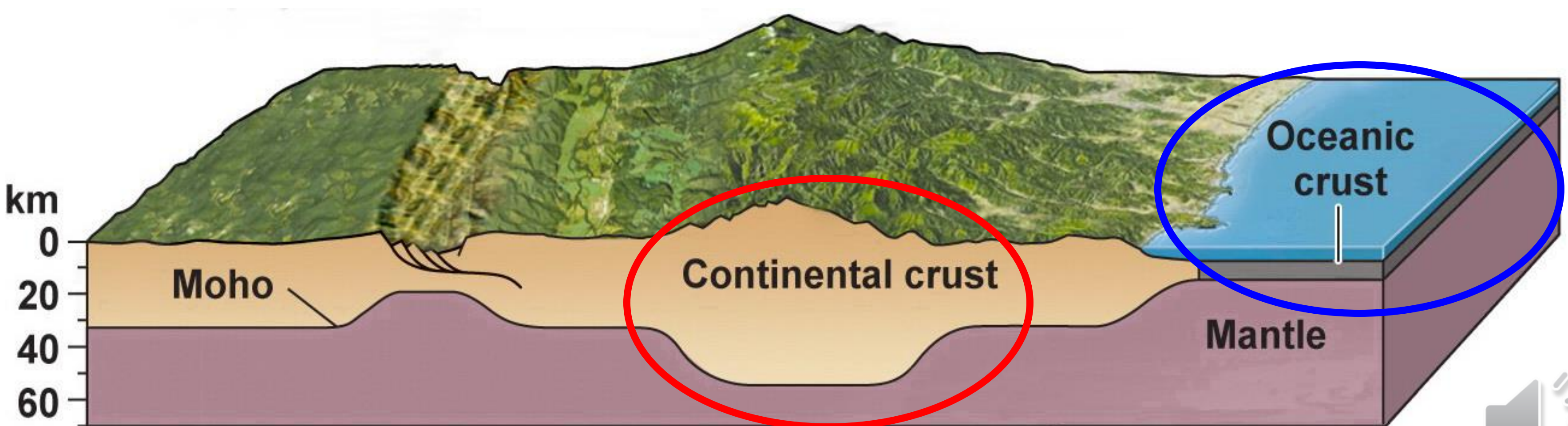
The Crust

- The outermost "skin" of our planet is highly variable.
  - Thickest under mountain ranges (70 km)
  - Thinner under ocean (0-7 km)
- Relatively as thick as the membrane of a toy balloon
- The Mohorovičić discontinuity (Moho) is the base.
  - Seismic velocity change between crust and upper mantle
  - The crust is the upper part of a tectonic plate.



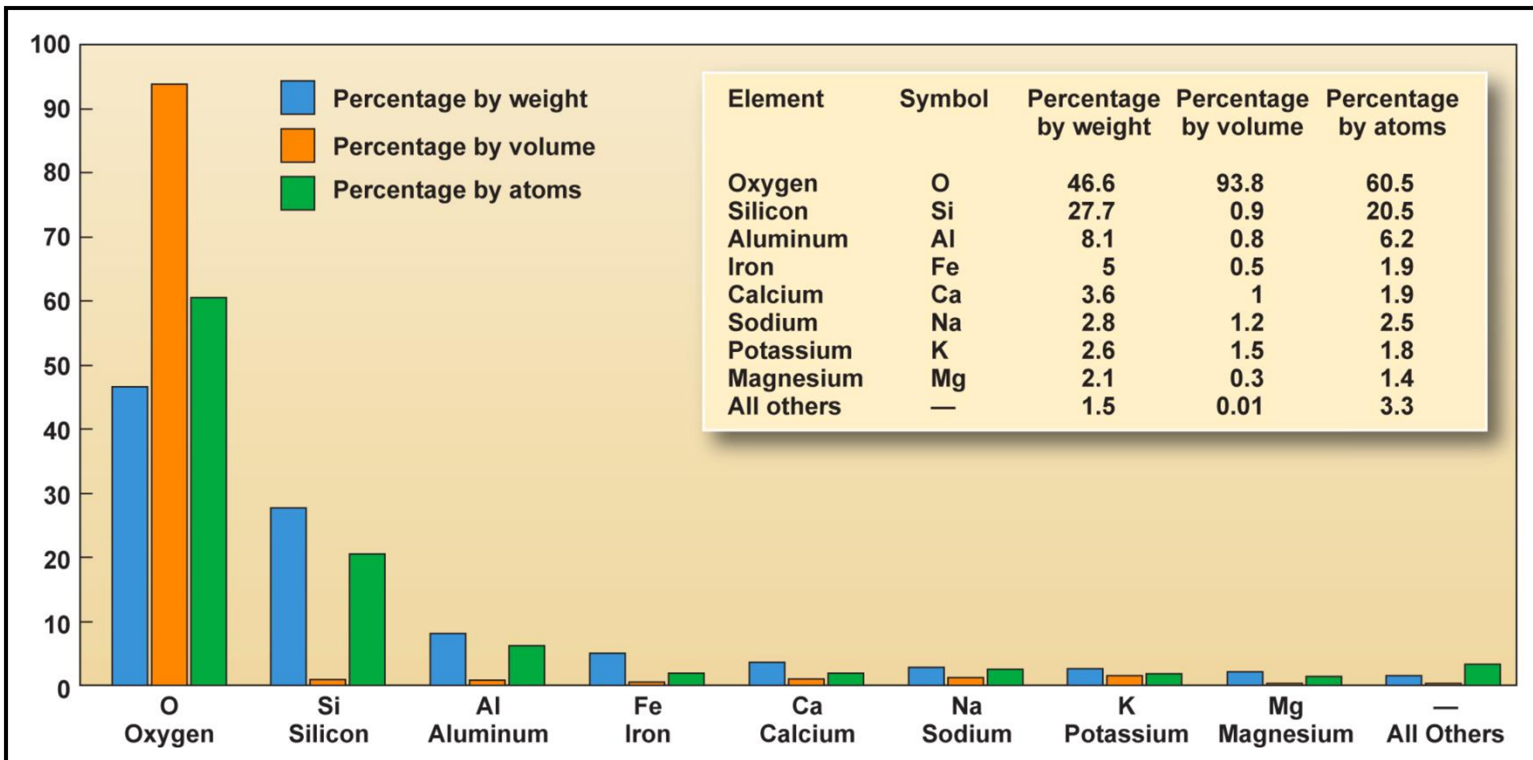
The Crust

- There are two kinds of crust: *continental* and *oceanic*.
  - Continental crust underlies the continents.
    - Average thickness 35–40 km
    - Felsic (granite) to intermediate in composition
  - Oceanic crust underlies the ocean basins.
    - Average thickness 7–10 km
    - Mafic (basalt and gabbro) in composition
    - More dense than continental crust



Crustal Composition

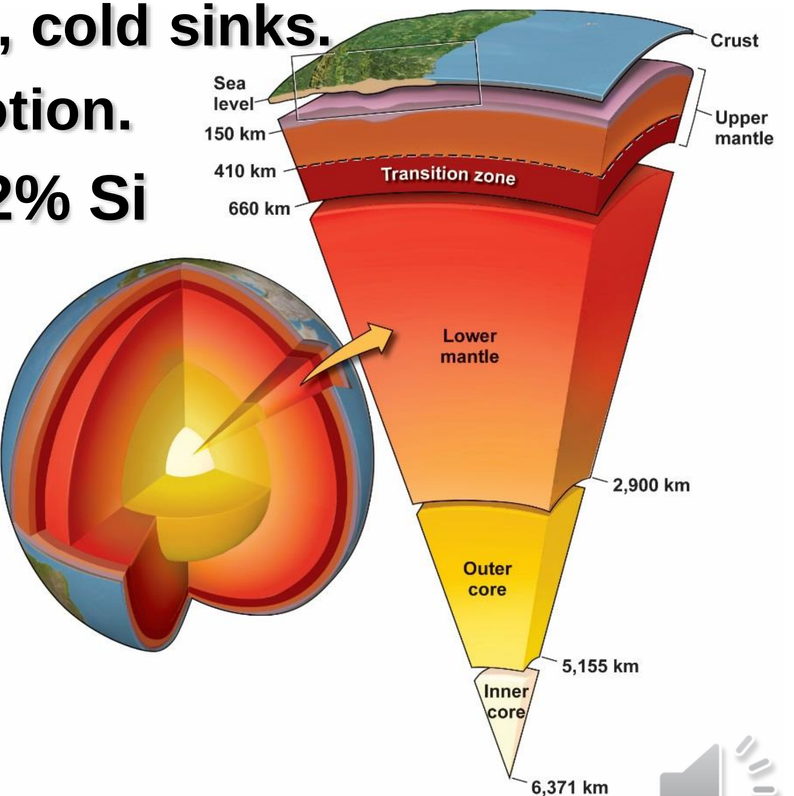
- **98.5% of the crust is composed of just eight elements.**
- **Oxygen is the most abundant element in the crust.**
  - **This reflects the importance of silicate (SiO_4) minerals.**
  - **Oxygen is abundant. It account for ~ 47% of crustal mass**



Element	Symbol	Percentage by weight	Percentage by volume	Percentage by atoms
Oxygen	O	46.6	93.8	60.5
Silicon	Si	27.7	0.9	20.5
Aluminum	Al	8.1	0.8	6.2
Iron	Fe	5	0.5	1.9
Calcium	Ca	3.6	1	1.9
Sodium	Na	2.8	1.2	2.5
Potassium	K	2.6	1.5	1.8
Magnesium	Mg	2.1	0.3	1.4
All others	—	1.5	0.01	3.3

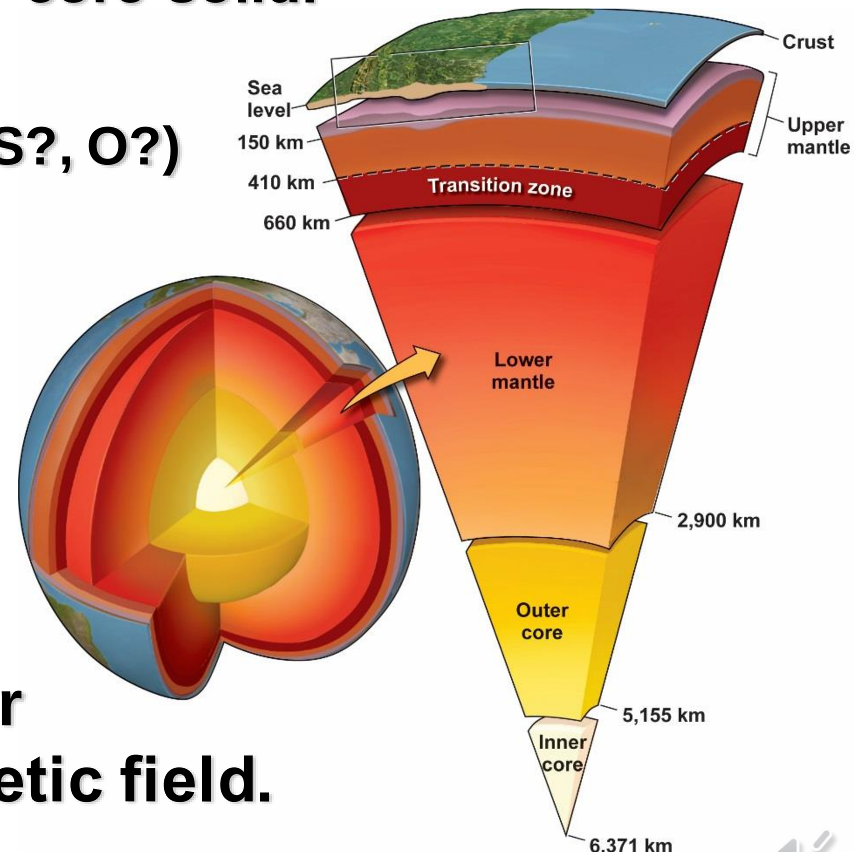
The Mantle

- Solid rock, 2,885 km thick, 82% of Earth's volume
- The mantle is entirely the ultra-mafic rock peridotite and largely bridgemanite by mineral; it is plastic!
- Convection below ~ 100 km mixes the mantle.
  - Like oatmeal on a stove: hot rises, cold sinks.
  - Convection aids tectonic plate motion.
- Composition? 45% O, 23% Mg, 22% Si and 6% Fe, with a little Ca, Al, Na
- Divided into two sub-layers:
  - Upper Mantle
  - Transitional zone
  - Lower Mantle



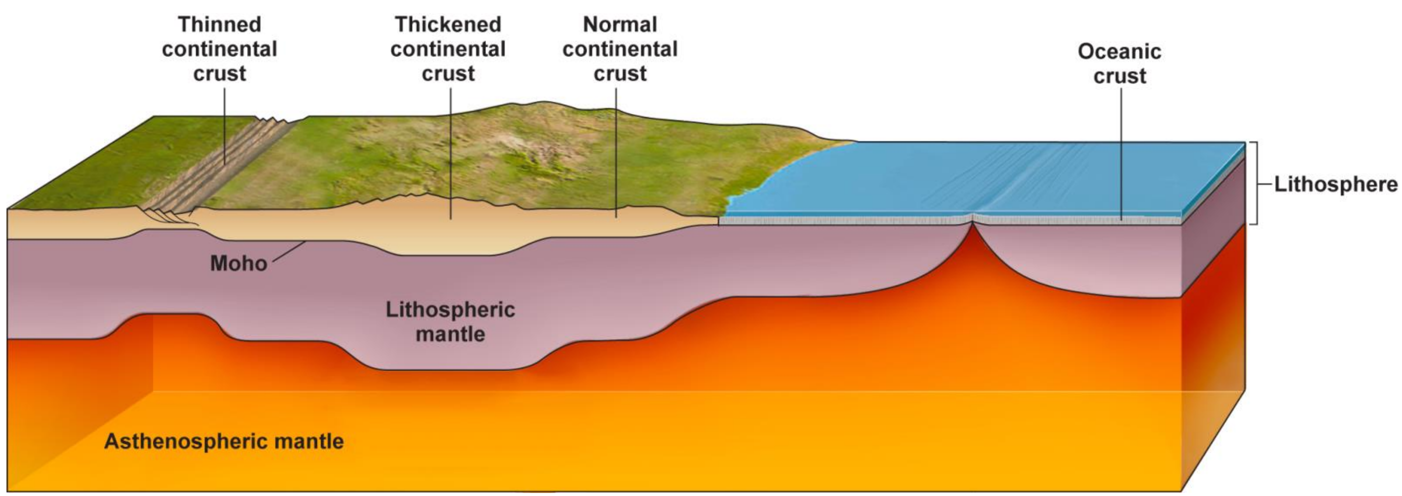
The Core

- An iron-rich sphere with a radius of 3,471 km
- Seismic waves segregate two radically different parts.
  - The outer core is liquid; inner core solid.
  - Outer core
    - Liquid iron alloy (Fe, Ni, Co, S?, O?)
    - 2,255 km thick
    - Liquid cirdulates easily
  - Inner core
    - Solid iron-nickel alloy
    - Radius of 1,220 km
    - Pressure keeps it solid
- Flow of the liquids in the outer core generates Earth's magnetic field.

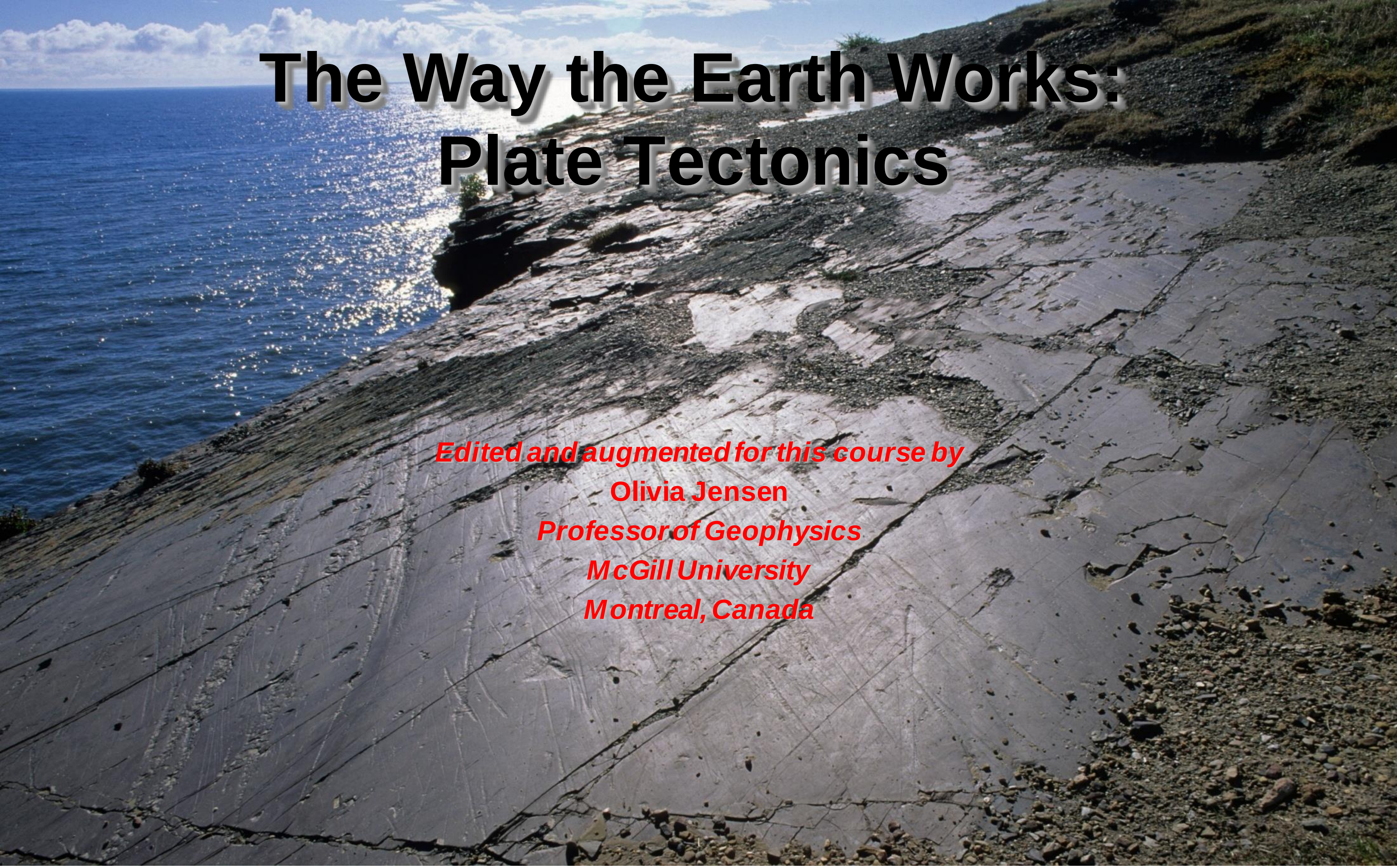


Lithosphere-Asthenosphere

- We can also regard layering based on rock strength.
  - Lithosphere—the outermost 100–150 km of Earth
    - Behaves rigidly, as a non-flowing material
    - Composed of two components: crust and upper mantle
    - This is the layer that makes up tectonic plates.
  - Asthenosphere—upper mantle *below* the lithosphere
    - Shallow under oceanic lithosphere; deeper under continental
    - Flows as a soft plastic solid.



The Way the Earth Works: Plate Tectonics



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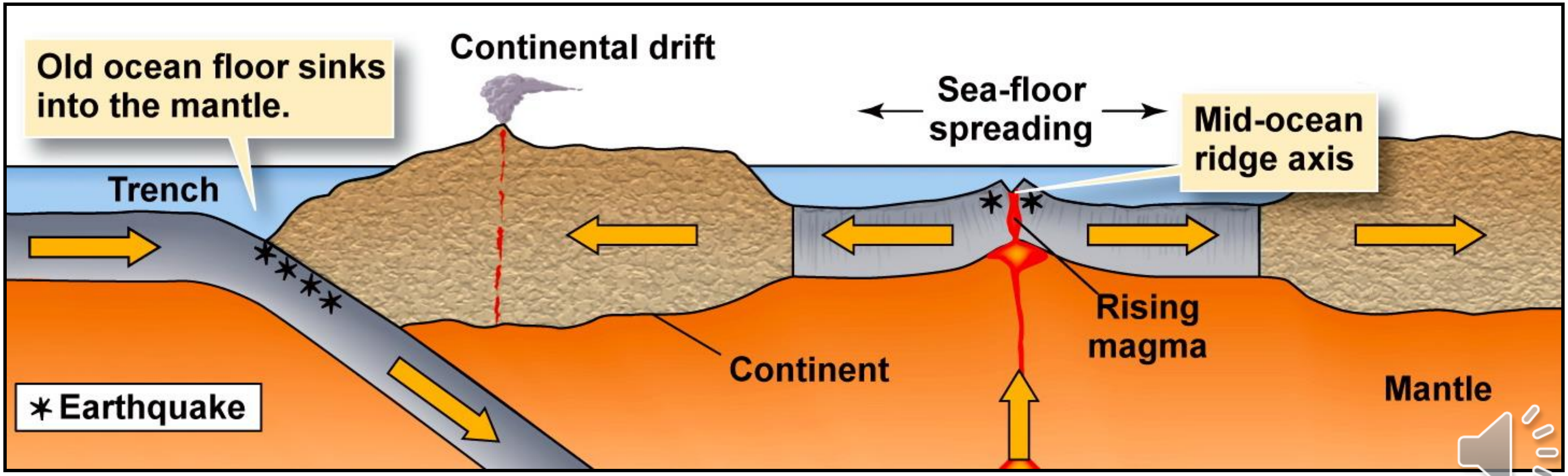
Alfred Wegener

- German meteorologist and polar explorer.
- Wrote *The Origins of the Continents and Oceans* in 1915.
  - He hypothesized a former supercontinent, Pangaea.
  - He suggested that land masses slowly move (continental drift).
  - These were based on strong evidence.
    - "Fit" of the continents
    - Glacial deposits far from polar regions
    - Paleoclimatic belts
    - Distribution of fossils
    - Matching geologic units

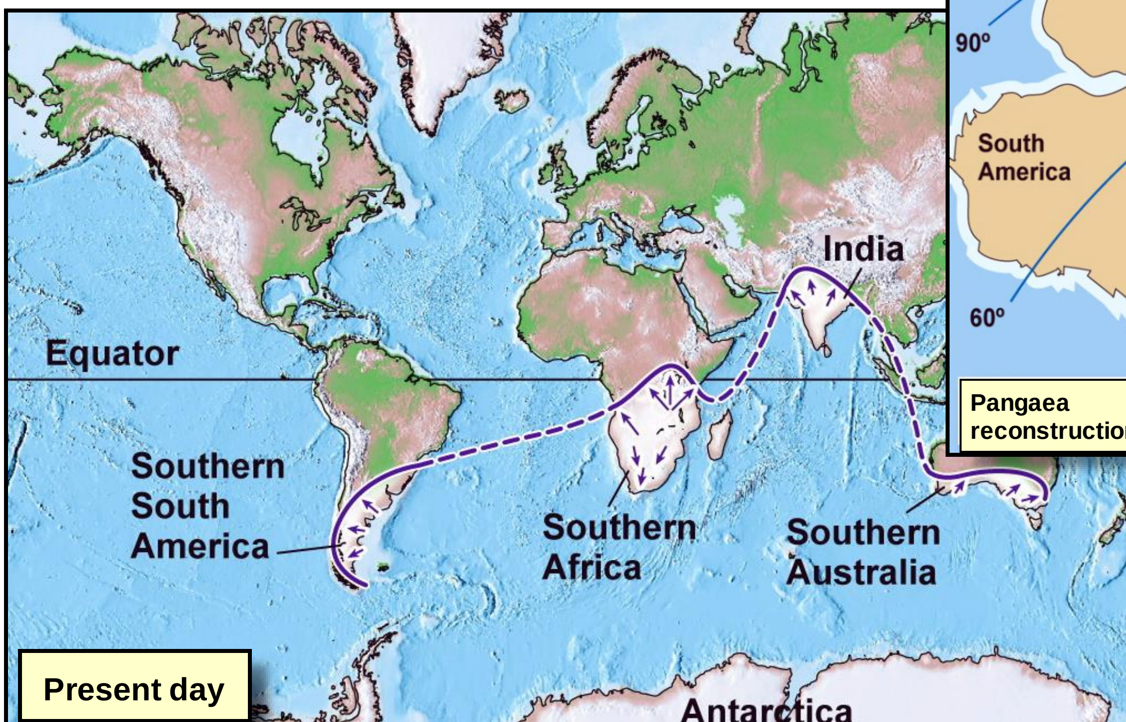
Plate Tectonics

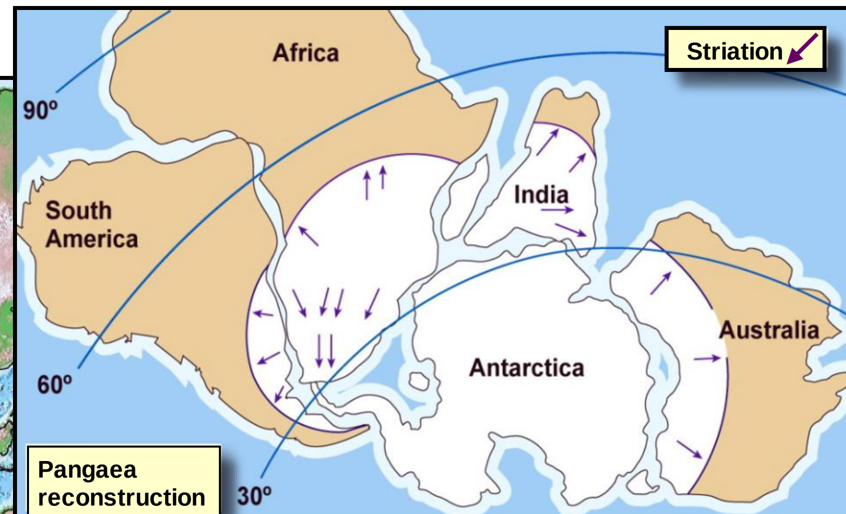
- The scientific revolution confirming Wegener's hypothesis began in 1960.
  - Harry Hess (Princeton) proposed sea-floor spreading.
    - As continents drift apart, new ocean floor forms between.
    - Continents converge when ocean floor sinks into the interior.
- By 1968, a complete model had been developed.
  - Continental drift, sea-floor spreading, and subduction.



Glacial Evidence

- Evidence of Late Paleozoic (circa 500 million years ago) glaciers found on five continents.
- Some of this evidence is now far from the poles.
- These glaciers could not be explained unless the continents had moved.



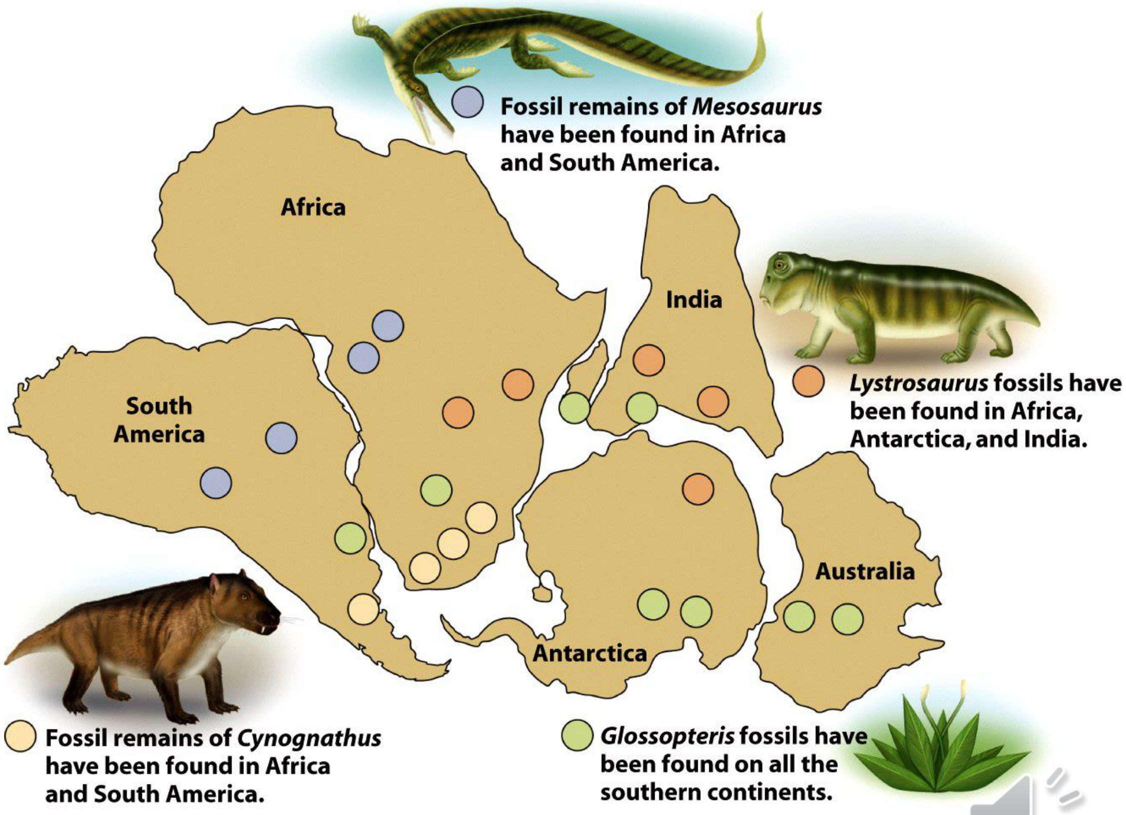


Paleoclimatic Evidence

- Placing Pangaea over the Late Paleozoic South Pole:
- Wegener predicted rocks defining Pangea climate belts.
  - Tropical coals
  - Tropical reefs
  - Subtropical deserts
  - Subtropical evaporites

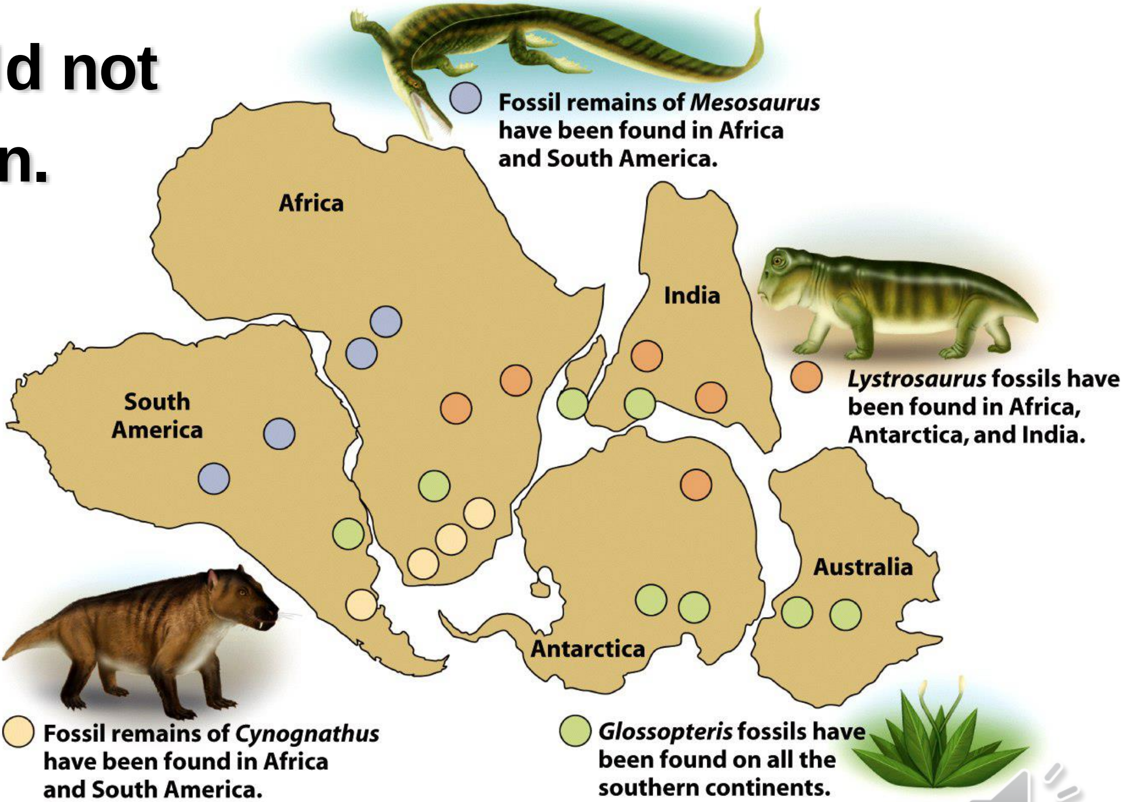
Fossil Evidence

- Identical fossils found on widely separated land masses.
  - *Mesosaurus*—a freshwater reptile
  - *Glossopteris*—a subpolar plant with heavy seeds



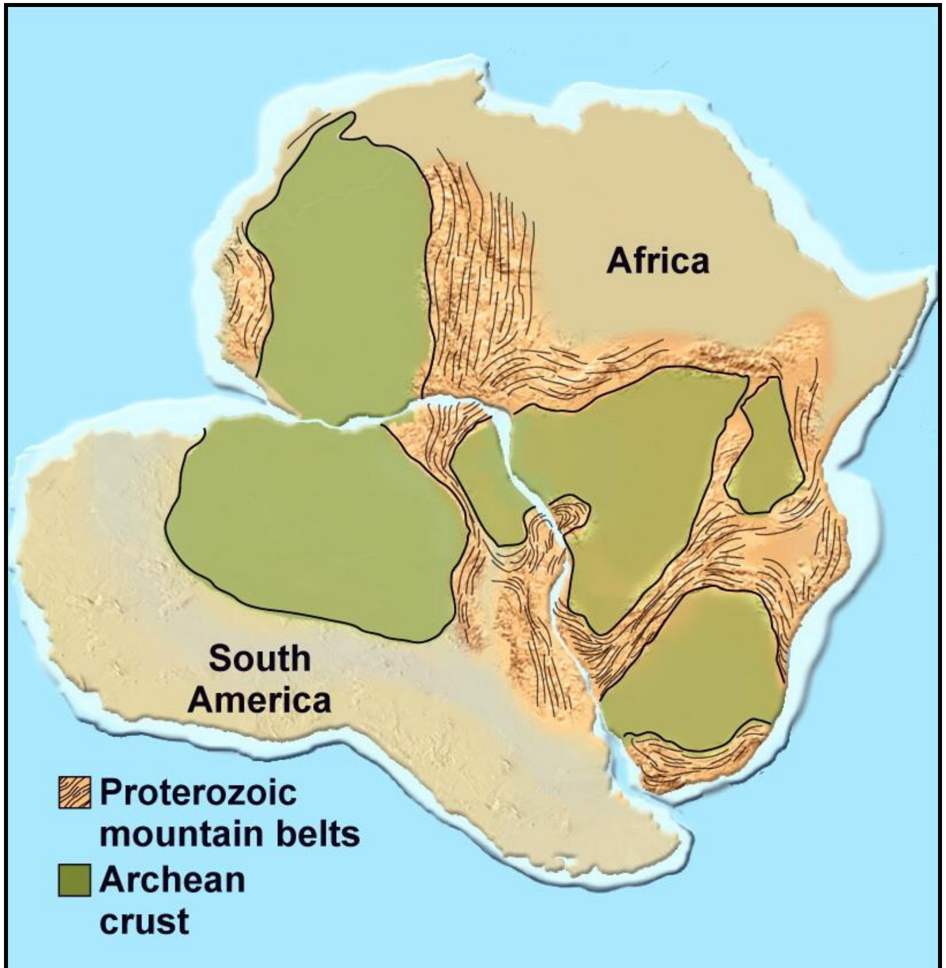
Fossil Evidence

- **Identical fossils found on widely separated land.**
  - ***Lystrosaurus*—A non-swimming, land-dwelling reptile.**
  - ***Cynognathus*—A non-swimming, land-dwelling mammal-like reptile.**
- **These organisms could not have crossed an ocean.**
- **Pangaea explains the distribution.**



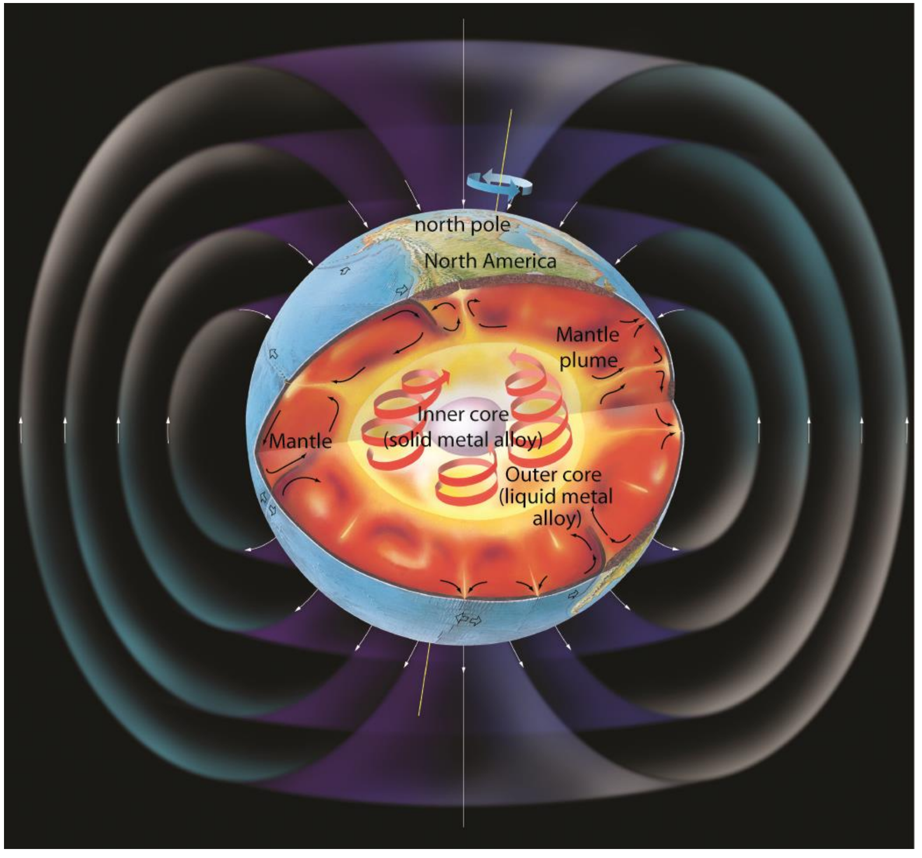
Matching Geologic Units

- Distinctive rock assemblages and mountain belts match across the Atlantic.



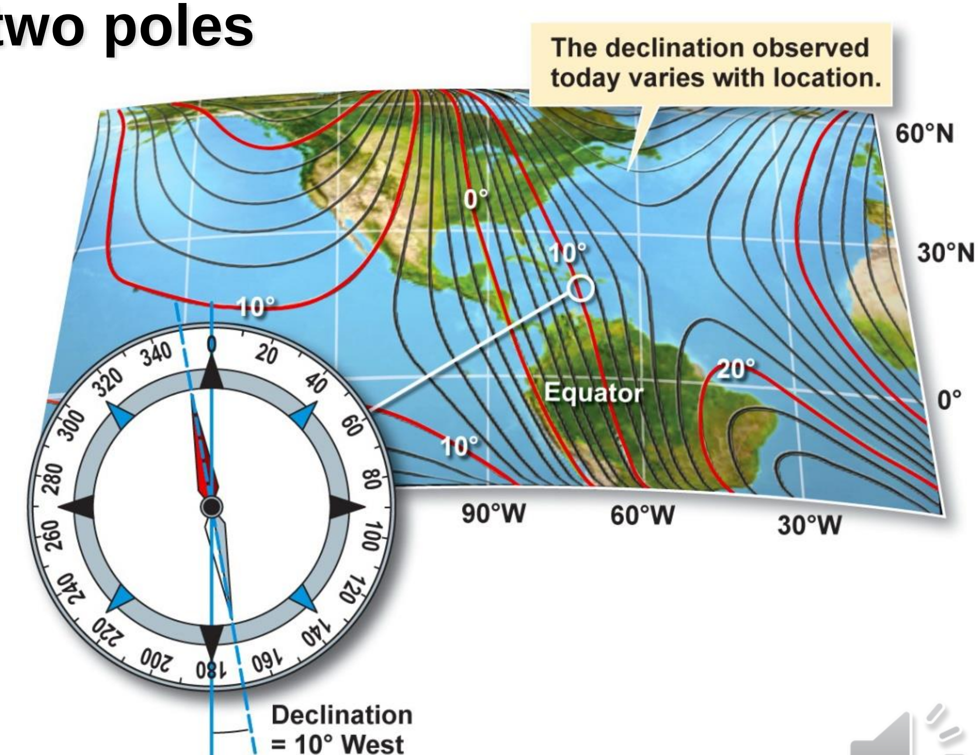
Earth's Magnetic Field

- Recall that flow in the liquid outer core creates the magnetic field.
  - It is similar to the field produced by a bar magnet.
  - The magnetic pole is tilted ~11.5° from the axis of rotation.



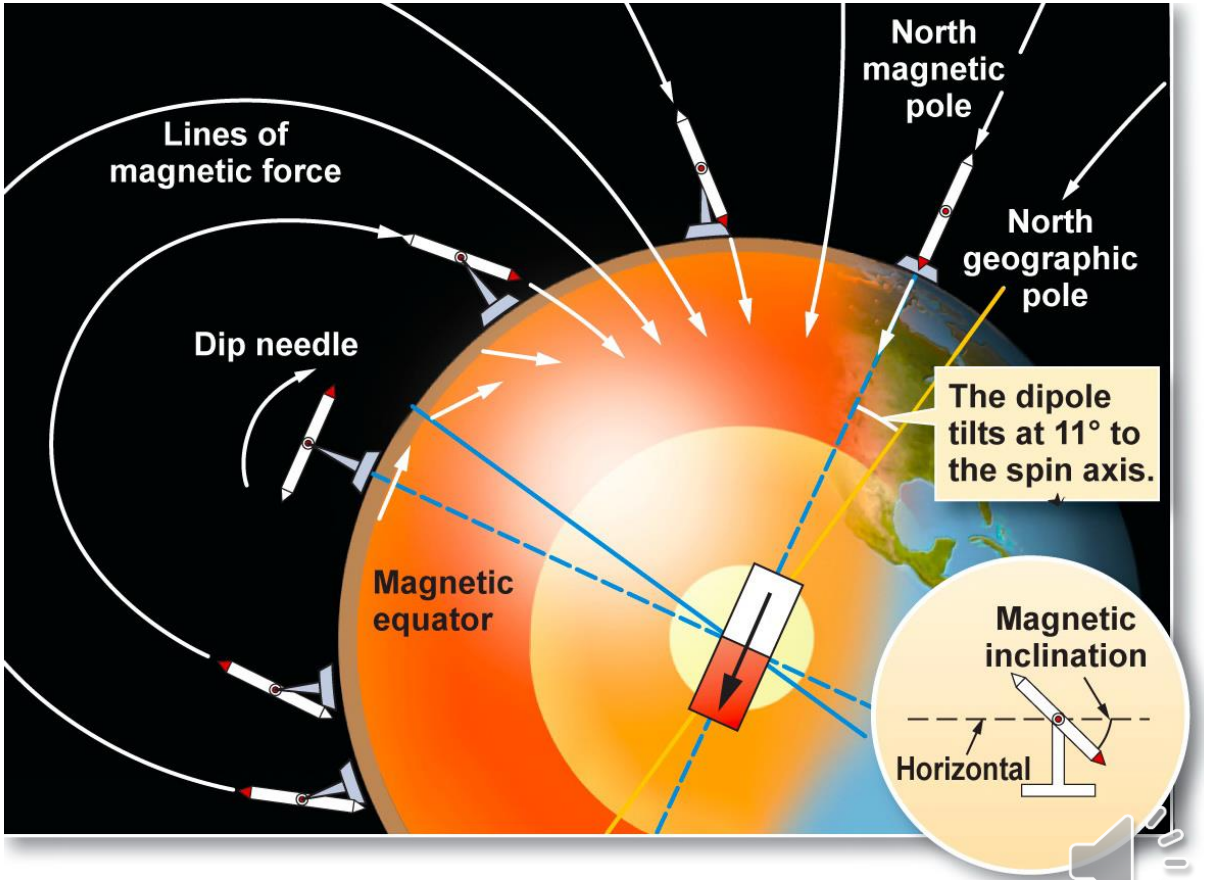
The Earth's Magnetic Field

- Geographic and magnetic poles are not coincident.
- A compass points to magnetic N, not geographic N.
- The difference between geographic N and magnetic N is called *declination*. It depends on:
  - Absolute position of the two poles
    - Geographic north
    - Magnetic north
  - Longitude



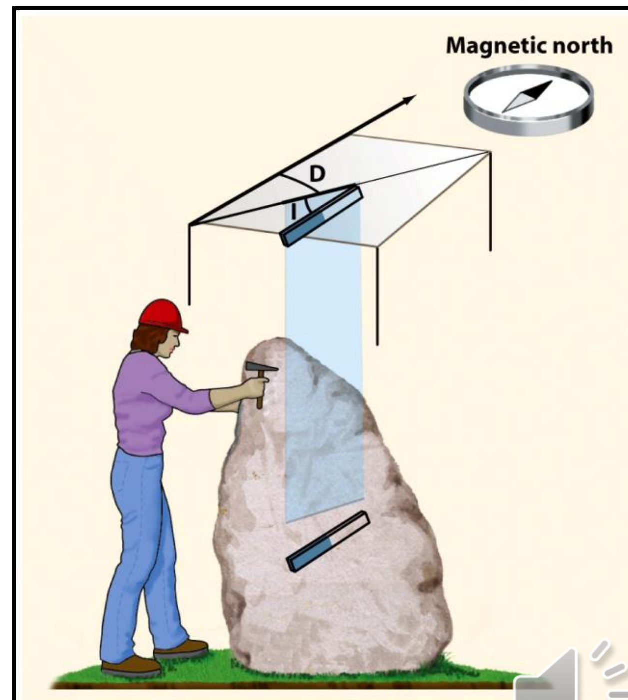
The Earth's Magnetic Field

- Curved field lines cause a magnetic needle to tilt.
- Angle between magnetic field line and surface of the Earth is called *inclination*. It depends on:
  - Latitude (geo-magnetic)



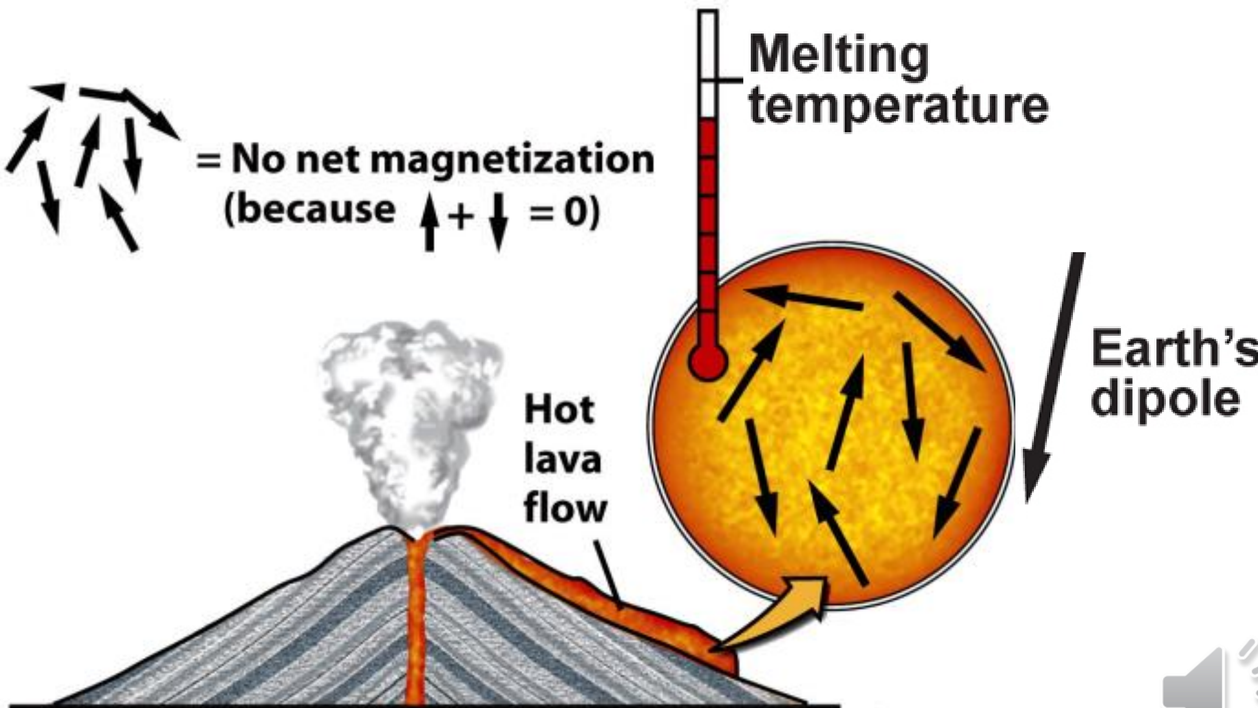
Paleomagnetism

- Rock magnetism can be measured in the laboratory.
- The study of fossil magnetism is called paleomagnetism.
- Iron (Fe) minerals in rock preserve information about the magnetic field at the time the rocks formed.
  - Declination and inclination preserved in rocks often vary from present latitude / longitude.
  - Instruments used in paleomagnetism record changes in position.
  - These data are used to trace continental drift.



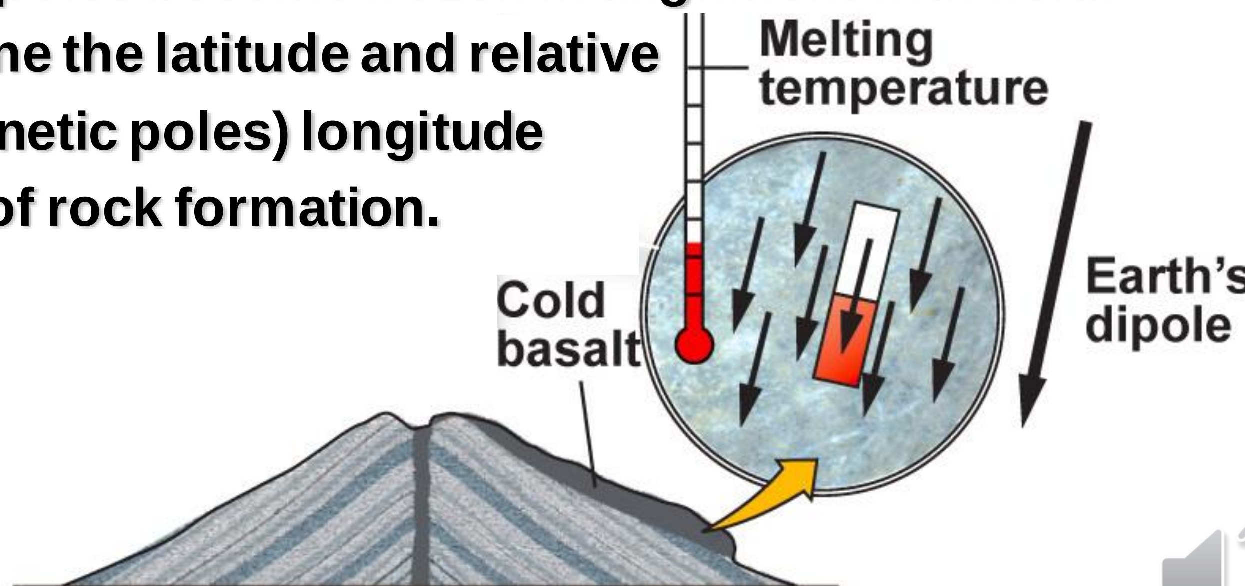
Paleomagnetism

- Iron minerals archive the magnetic signal at formation.
- Hot magma
  - High Temp—no magnetization
    - Thermal energy of atoms is very high.
    - Magnetic dipoles are randomly oriented.



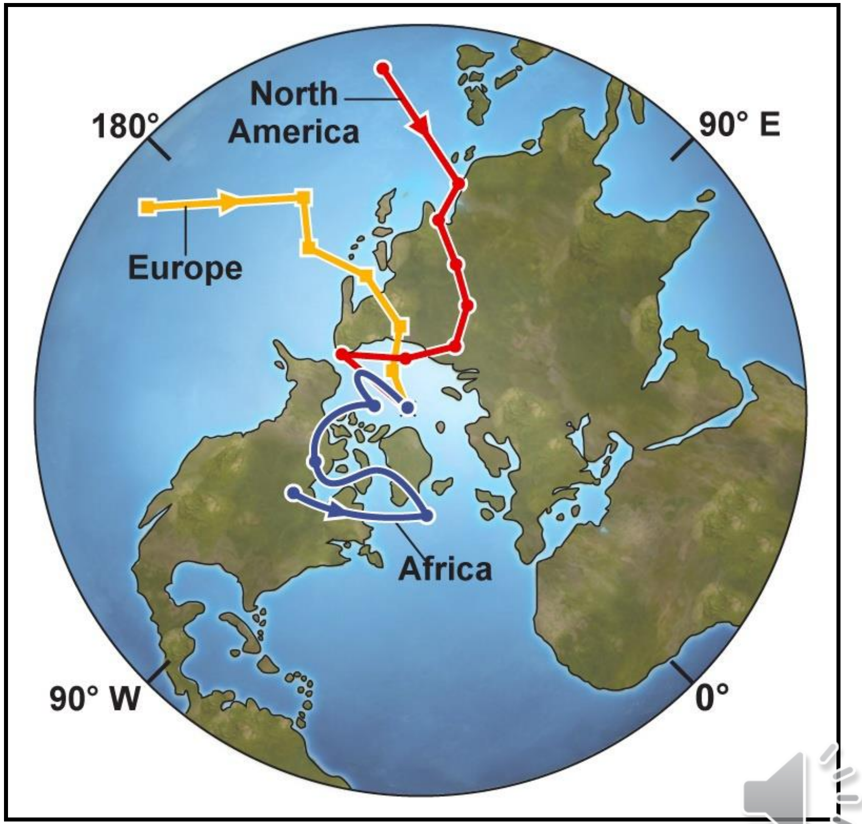
Paleomagnetism

- Iron minerals archive the magnetic signal at formation.
- Cooled magma
  - Low Temp, below the *Curie* temperature, permanent magnetization
    - Thermal energy of atoms slows.
    - Dipoles align with Earth's magnetic field.
    - Magnetic dipoles become frozen in alignment with field.
    - We determine the latitude and relative (to the magnetic poles) longitude at the time of rock formation.



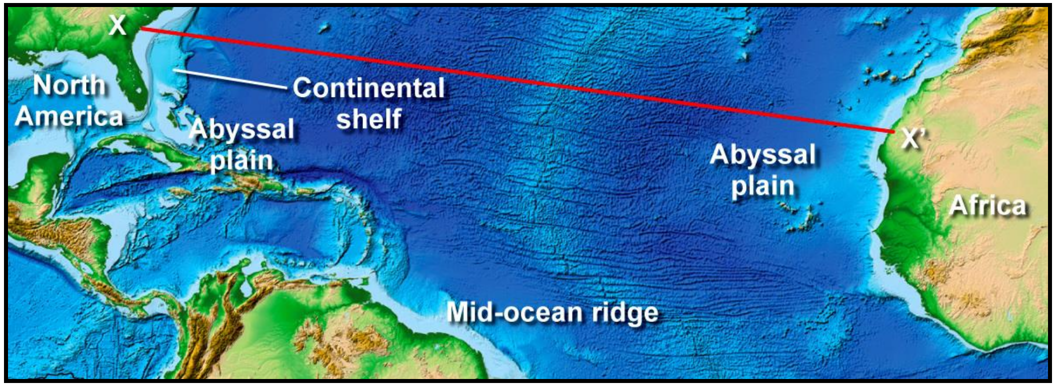
Polar Wandering

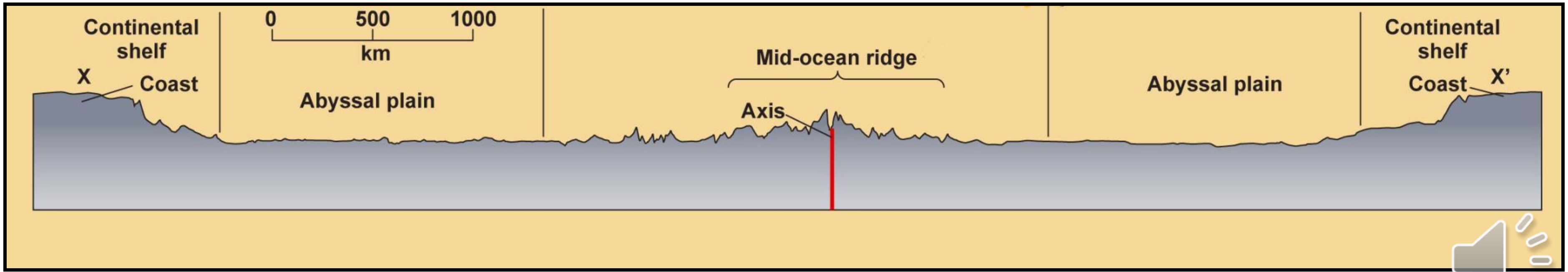
- Rocks on each of the continents show a separate polar wandering path in past time. It is now understood that:
  - The location of the magnetic pole is fixed.
  - The continents themselves have moved.
- These curves align when continents are reassembled.
- Ted Irving of the Geological Survey of Canada is usually credited with this discovery (OJ).



The Ocean Floor

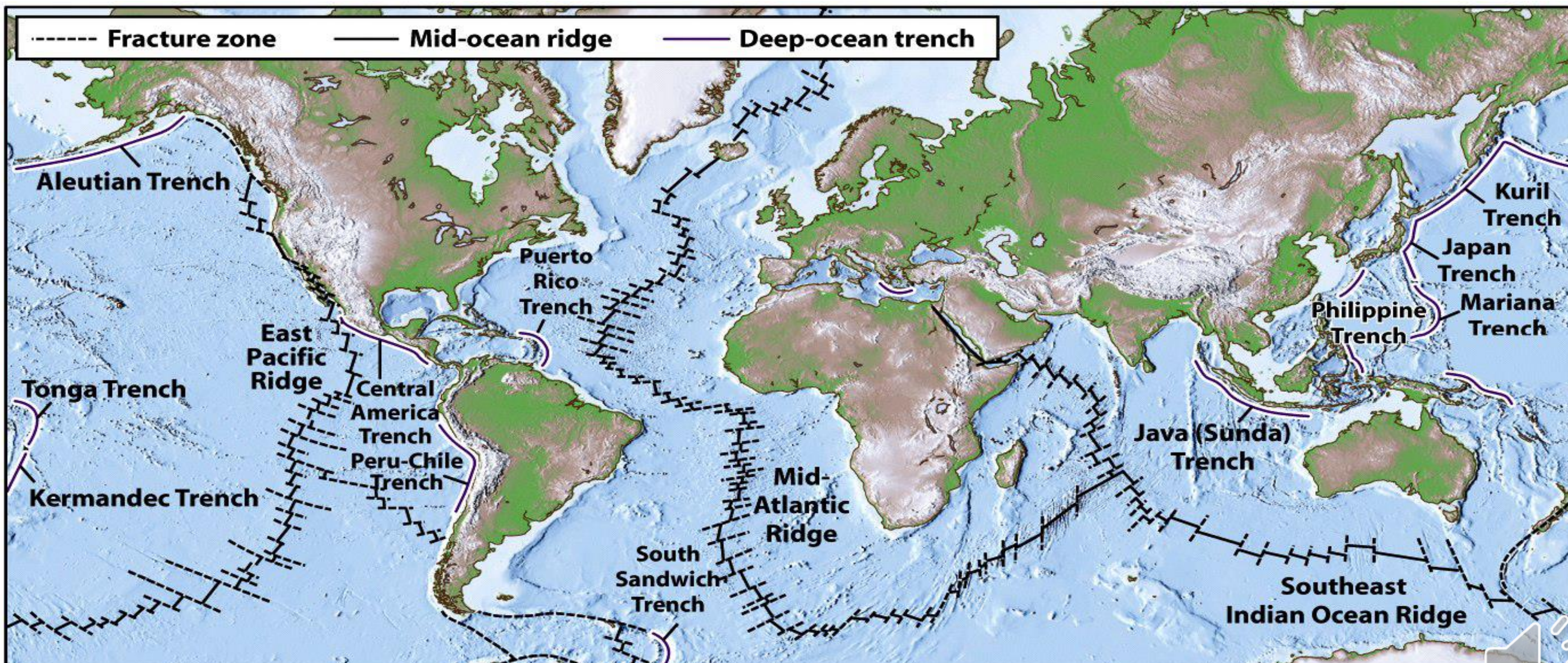
- Oceanographers were surprised to discover that:
  - A mid-ocean mountain range runs through every ocean.
  - Deep-ocean trenches occur near volcanic island chains.
  - Submarine volcanoes poke up from the ocean floor.
  - Huge fracture zones segment the mid-ocean ridge.
- These observations are all explained by *plate tectonics*.





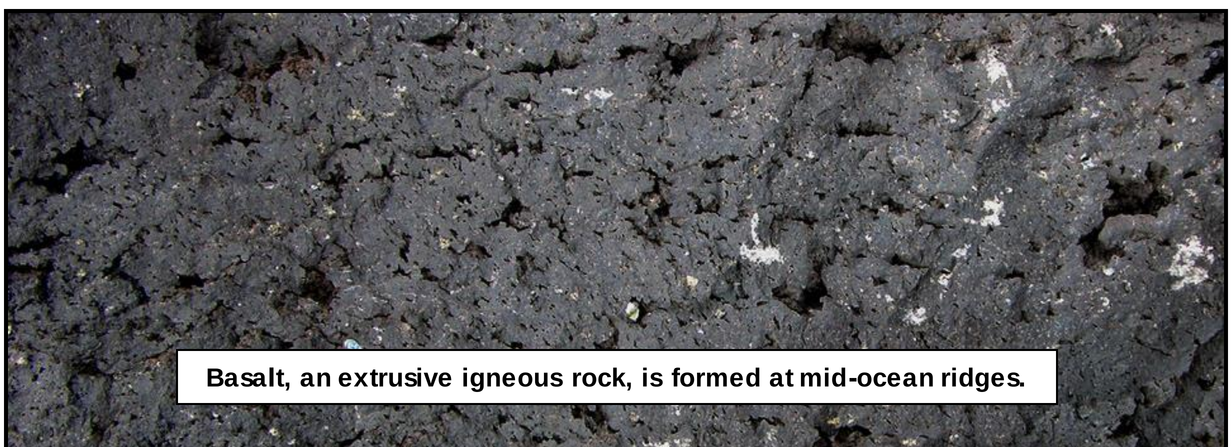
The Ocean Floor

- Today's view of the ocean floor reveals the location of:
  - Mid-ocean ridges
  - Deep-ocean trenches
  - Oceanic fracture zones



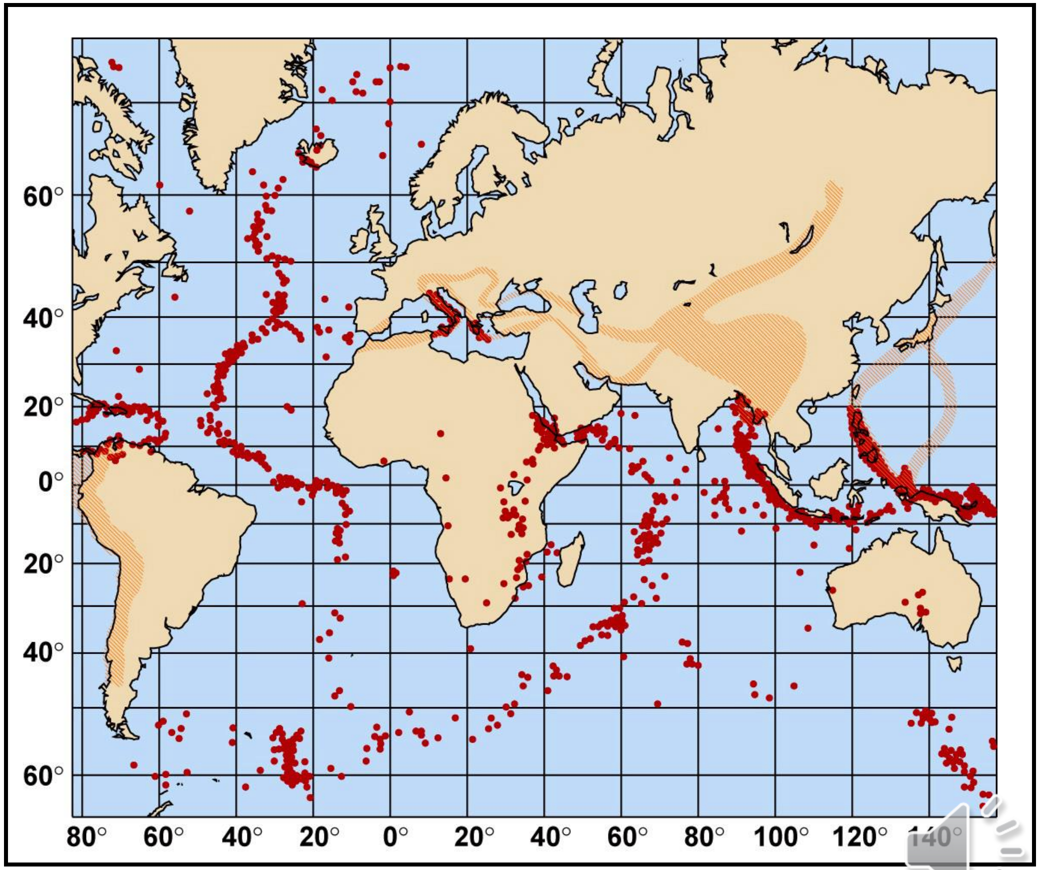
The Oceanic Crust

- By 1950, we had learned much about oceanic crust.
- Oceanic crust is covered by sediment.
  - Thickest near the continents
  - Thinnest (or absent) at the mid-ocean ridge
- Oceanic crust consists primarily of basalt.
  - Lacks variety of continental rock types
  - No metamorphic rocks
- Heat flow is much greater at the mid-ocean ridges.


Basalt, an extrusive igneous rock, is formed at mid-ocean ridges.

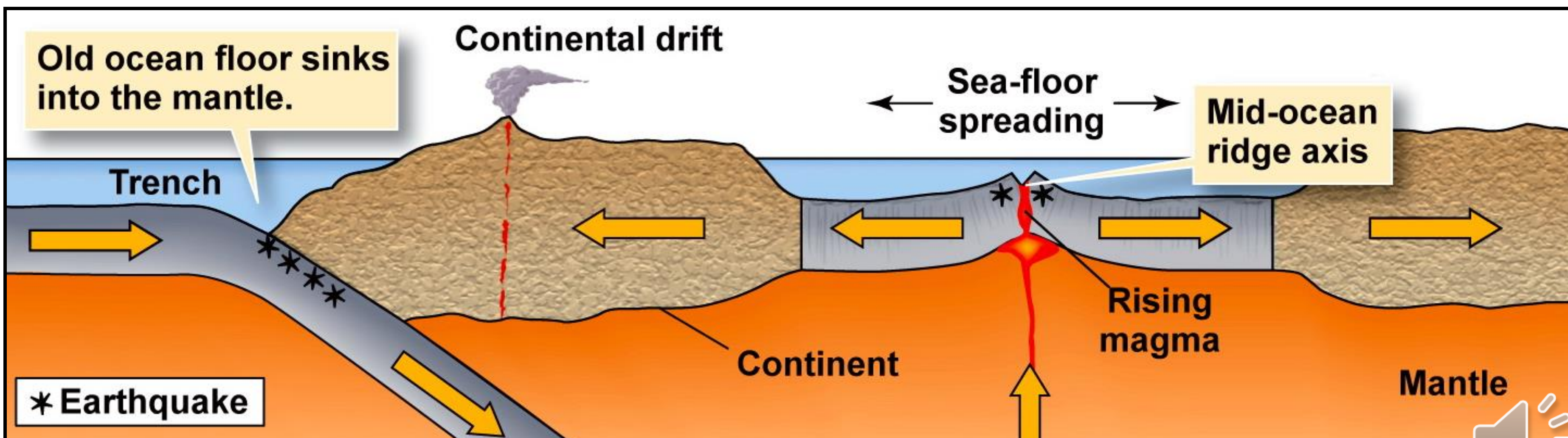
The Oceanic Crust

- Earthquakes occur in distinct belts in oceanic regions.
- The earthquakes were limited to:
  - Parts of oceanic fracture zones
  - Mid-ocean ridge axes
  - Deep ocean trenches
- Geologists realized that earthquakes defined zones of movement and boundaries of the tectonic plates.



Sea-Floor Spreading

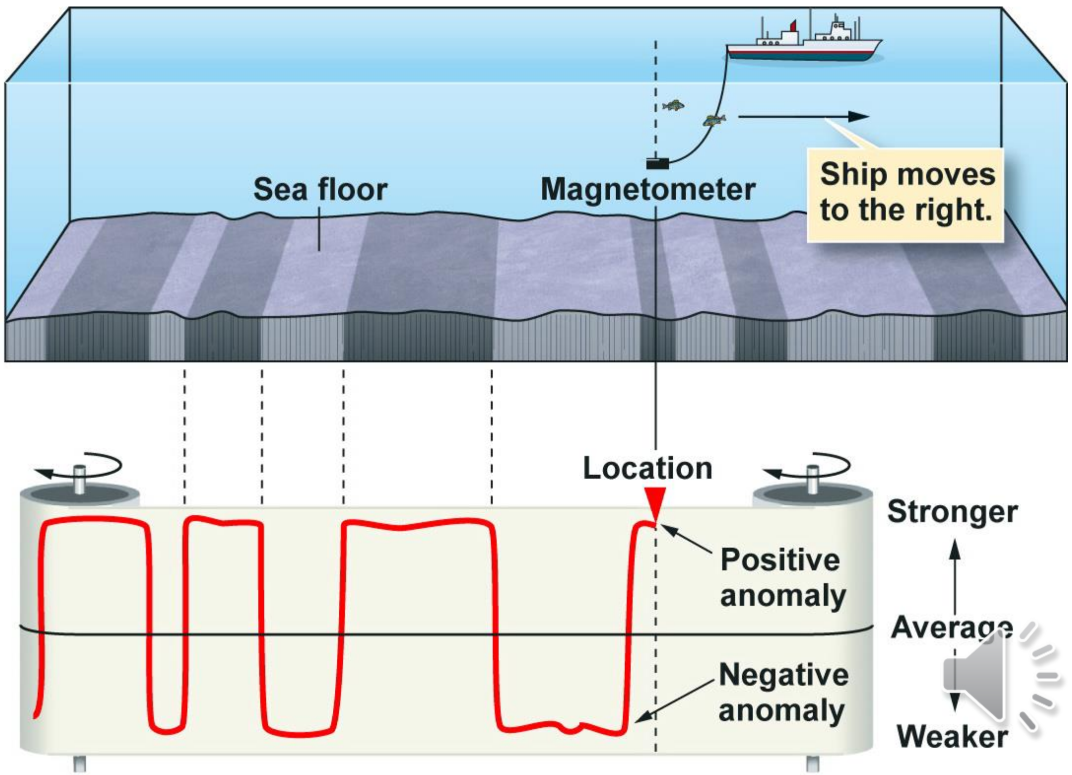
- In 1960, Harry Hess published his "Essay in Geopoetry."
  - Sediment thickens away from ridges.
  - Earthquakes at mid-ocean ridges indicate cracking.
    - Cracked crust splits apart.
    - High heat flow from molten rock rises into the cracked crust.
  - New ocean floor forming at mid-ocean ridges.
  - Old ocean floor is consumed into the mantle at subduction.



Evidence of Sea-Floor Spreading

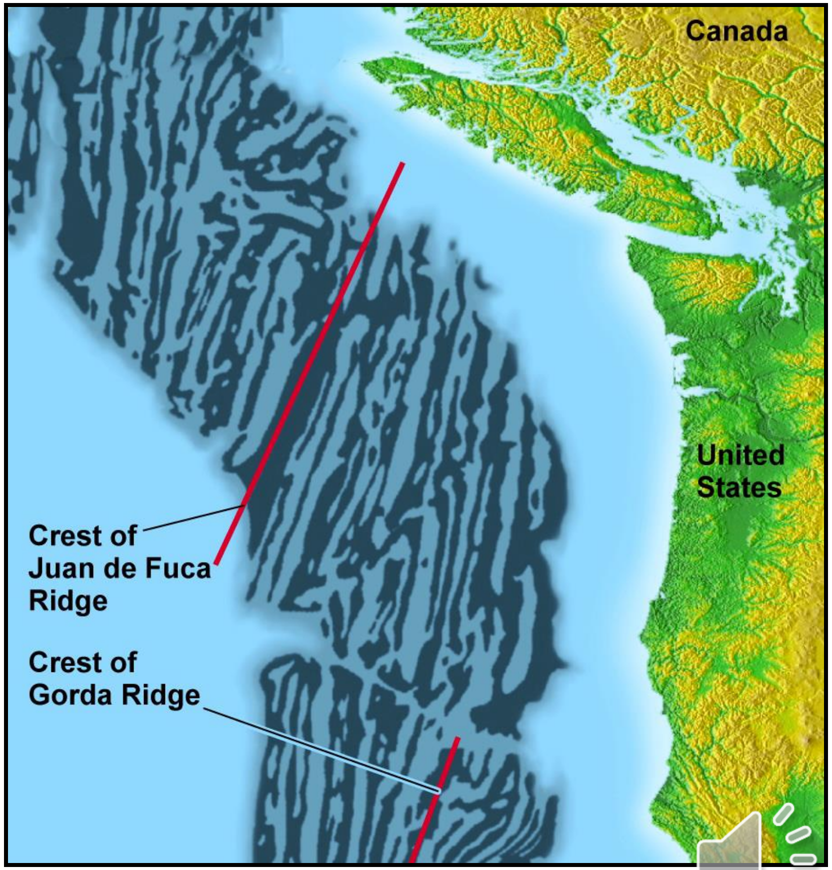
- Magnetism in sea-floor rocks varies farther from MOR. Oceanic crustal rocks form on the ridges.
  - Stripes of normal (S pole in N hemisphere) and reverse (N pole in the N hemisphere) magnetic field

Recorded in sea-floor basalts



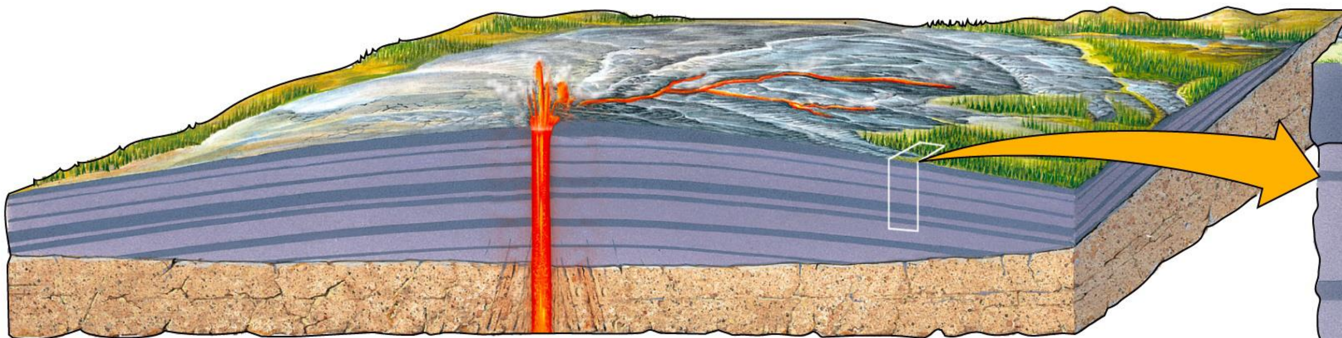
Evidence of Sea-Floor Spreading

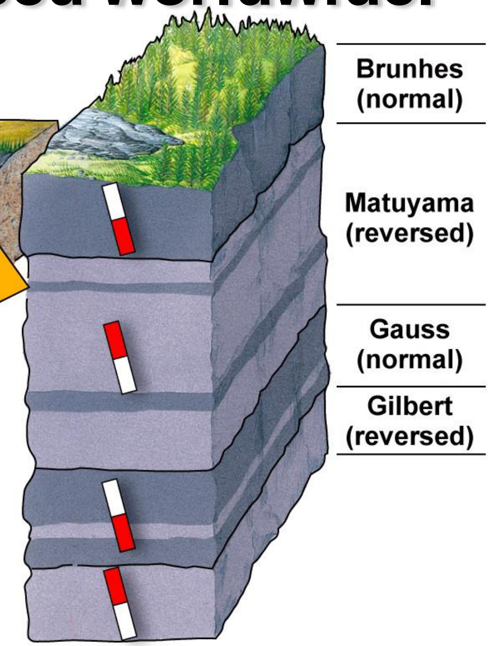
- Magnetic anomalies map as stripes of positive and negative polarity.
- Magnetic stripes form a pattern.
- The pattern is symmetric on either side of the MOR.
- Vine and Matthews (1963) are usually credited with the proof of sea-floor spreading though the precedent discovery by Morley and Larochelle (1964) is now often acknowledged (OJ).

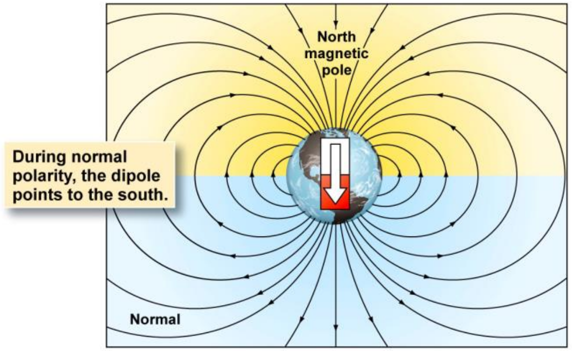


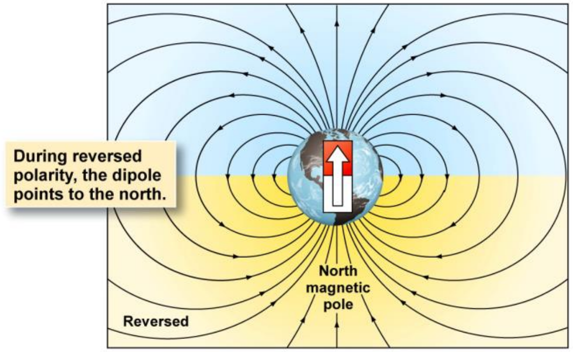
Why Striping? Magnetic Reversals!

- Layered lava flows reveal reversals in magnetic polarity.
  - The magnetic field sometimes “flips”; we don’t know why.
  - A reversed N magnetic pole is near the S geographic pole.
- Reversals are geologically rapid, expressed worldwide.
- Can be used as time markers.









Sea-floor Spreading

In the early 1960s, geophysicists such as J.T. Wilson had been brought to accept the fact of relative motions of the continents upon learning of the work of Ted Irving of the Earth Physics Branch of the Geological Survey of Canada on paleomagnetic pole positions and then by that of [L. Morley and A. Larochelle] who, in 1962, recognized that a pattern of magnetic striping on the ocean floor southwest of Vancouver Island implied sea-floor spreading.

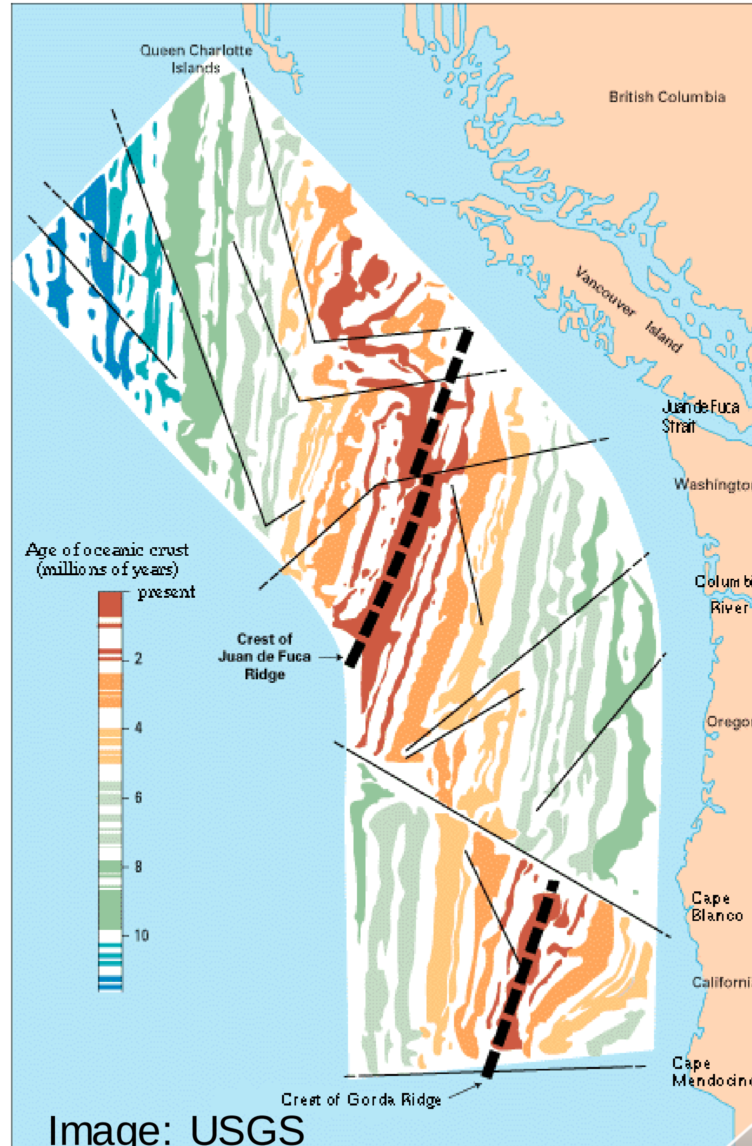
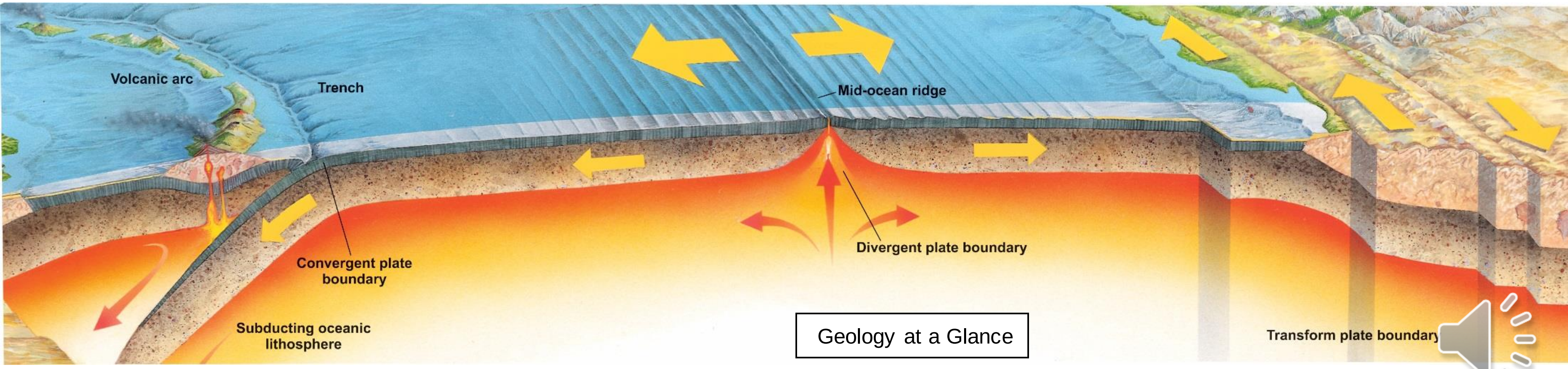


Plate Tectonics

- Plate tectonics: the explanation of "how Earth works."
  - Earth's outer shell is broken into rigid plates that move.
  - Plate motion defines three types of plate boundaries
- It provides a unified mechanism explaining:
  - The distribution of earthquakes and volcanoes.
  - Changes in past positions of continents and ocean basins.
  - The origins of mountain belts and seamount chains.
  - The origin and ages of ocean basins



Geology at a Glance

Two Types of Lithosphere

- **Continental: ~150 - ~400 km thick.**
  - **Felsic to intermediate crustal rocks**
    - **25–70 km thick.**
    - **Lighter (less dense).**
    - **More buoyant—floats higher.**
- **Oceanic: ~100 km thick.**
  - **Mafic crust: basalt & gabbro**
    - **7–10 km thick.**
    - **Heavier (more dense).**
    - **Less buoyant—sinks lower.**

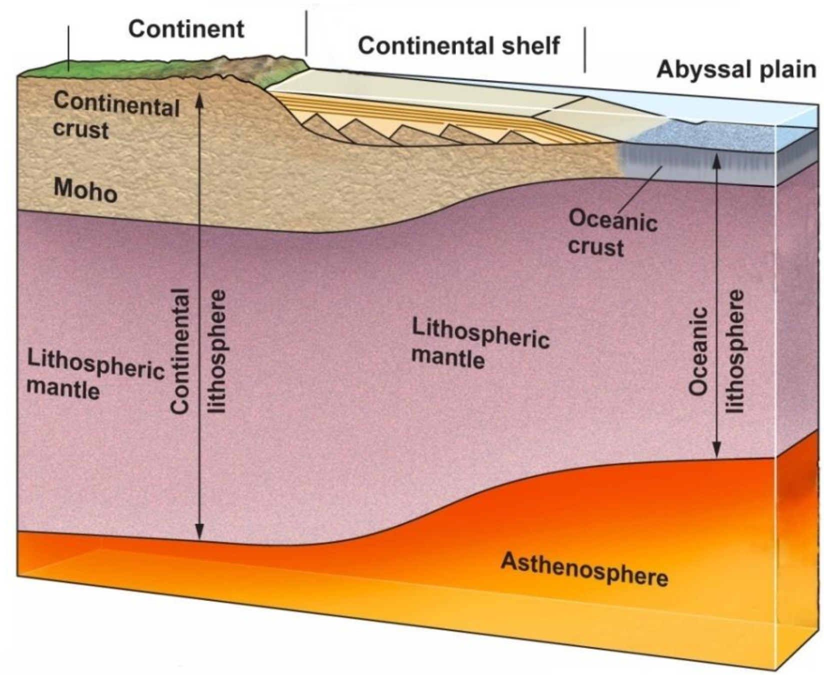


Plate Boundaries

- Lithosphere is fragmented into ~12 major tectonic plates.
- Plates move continuously at a rate of 1–15 cm/year.
  - Slow on a human time scale; extremely rapid geologically.
- Plates interact along their boundaries.

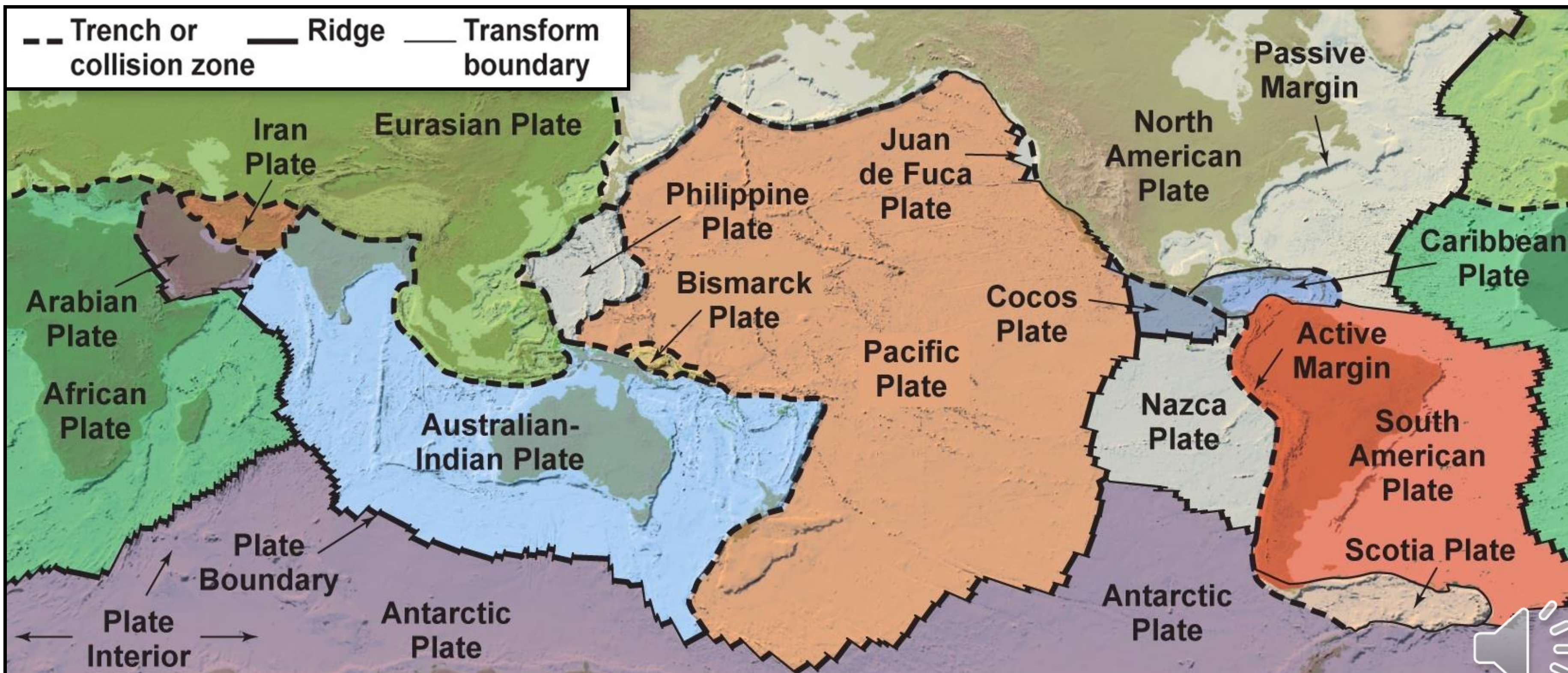
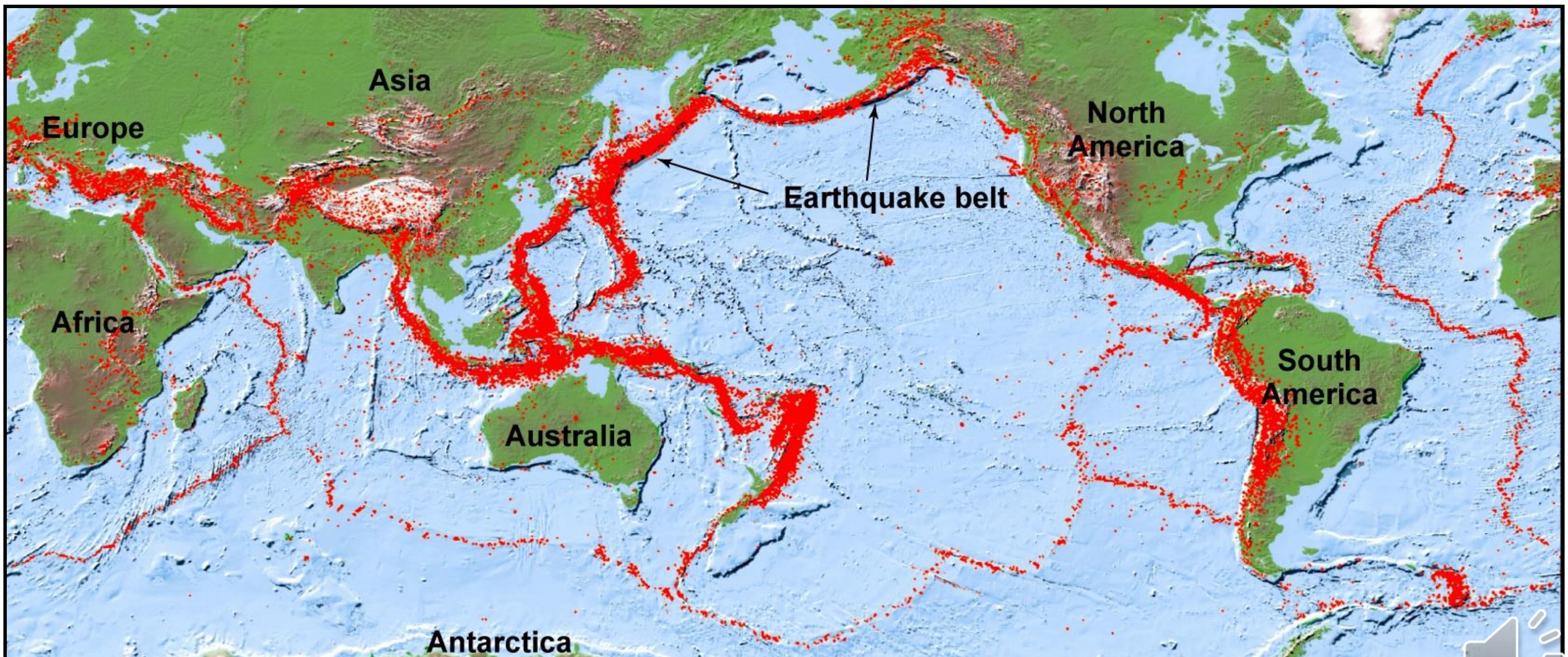


Plate Boundaries

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



Lithosphere at Continental Margins

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

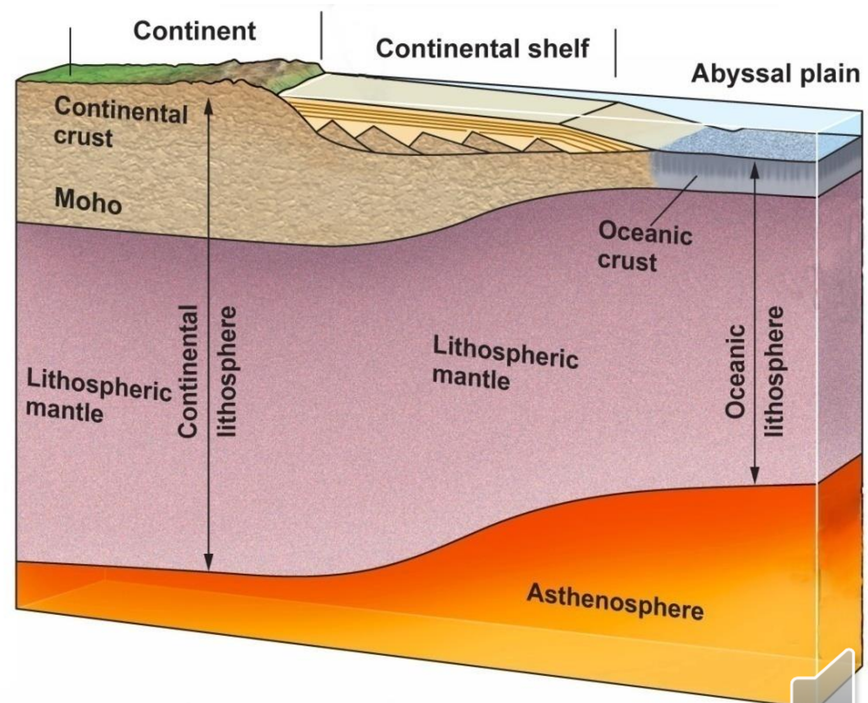
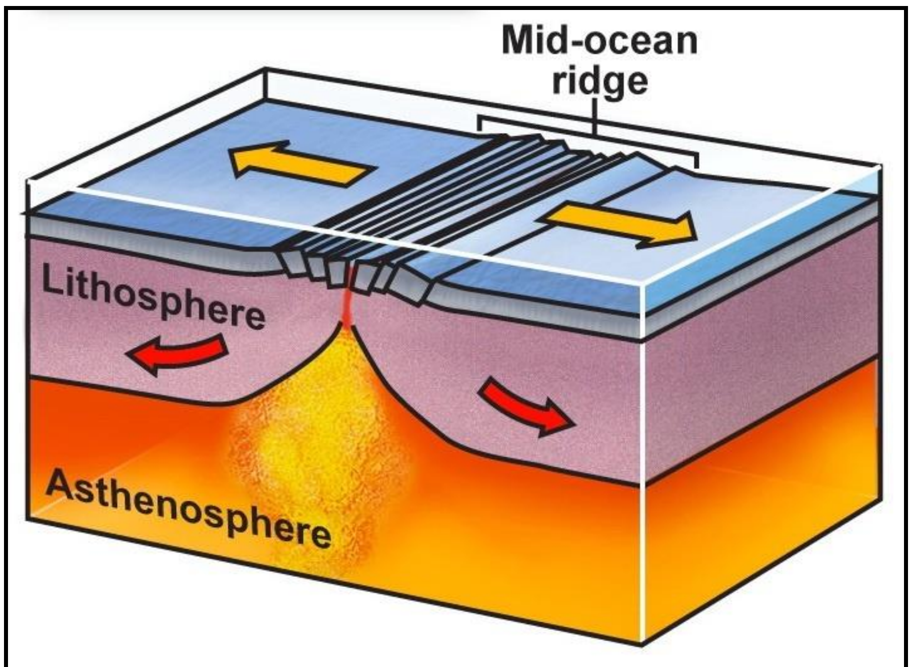


Plate Boundaries: Three Types

- Divergent boundary—tectonic plates move apart.
  - Lithosphere thickens away from the ridge axis.
  - New lithosphere created at divergent boundary
  - Also called: mid-ocean ridge, or just ridge.
  - Ocean depth increases with distance from the ridge.



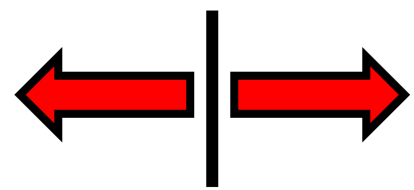
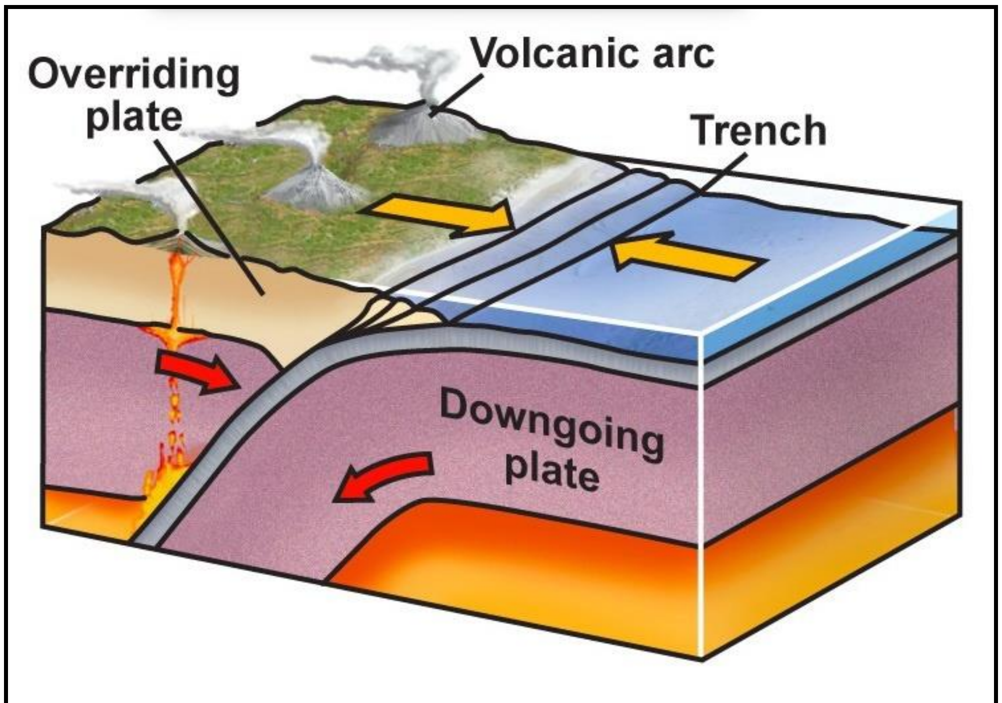


Plate Boundaries: Three Types

- **Convergent boundary—tectonic plates move together.**
  - **The process of plate consumption is called subduction.**
  - **Also called: convergent margin, subduction zone, trench.**
  - **Trenches are the deepest parts of the oceans.**



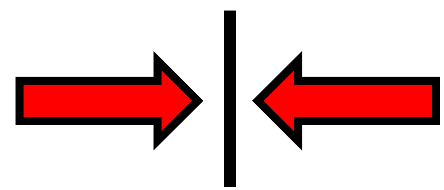
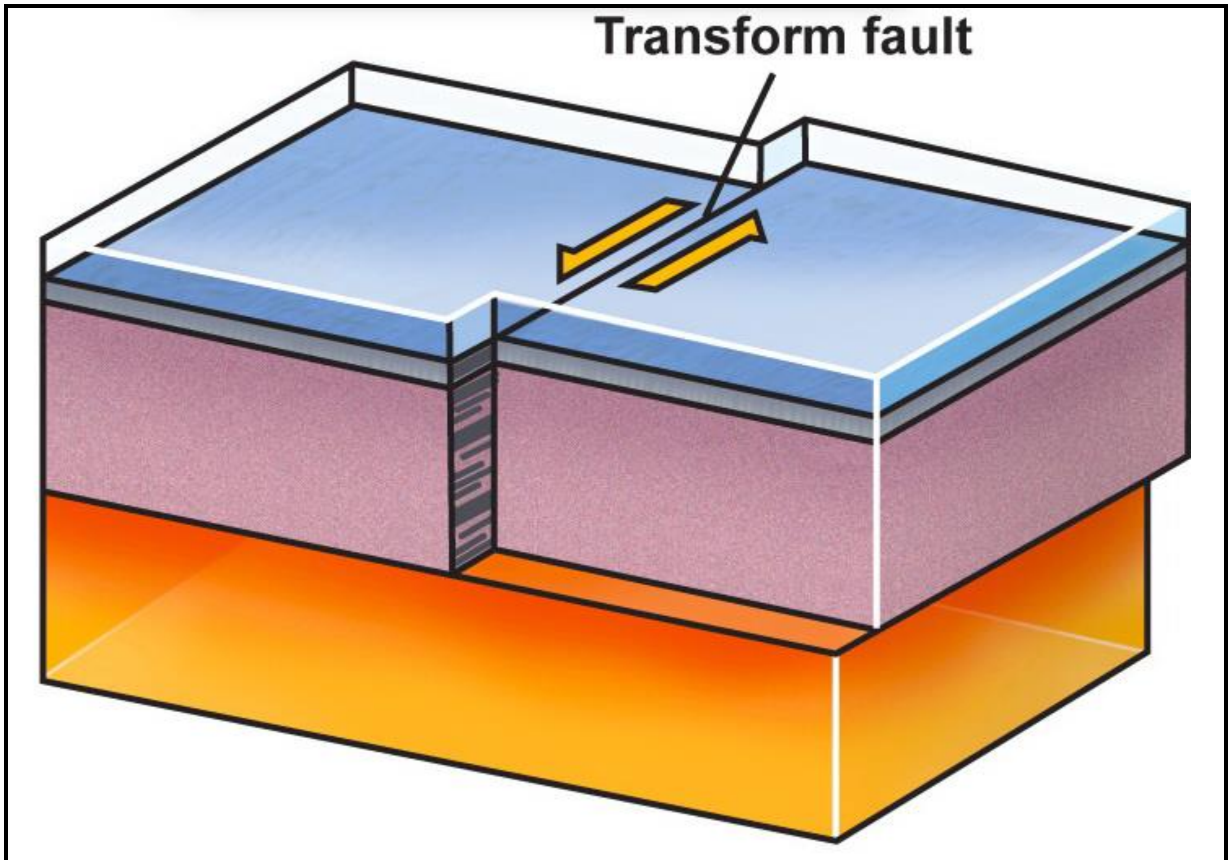
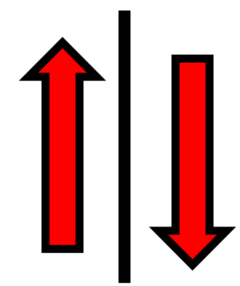


Plate Boundaries: Three Types

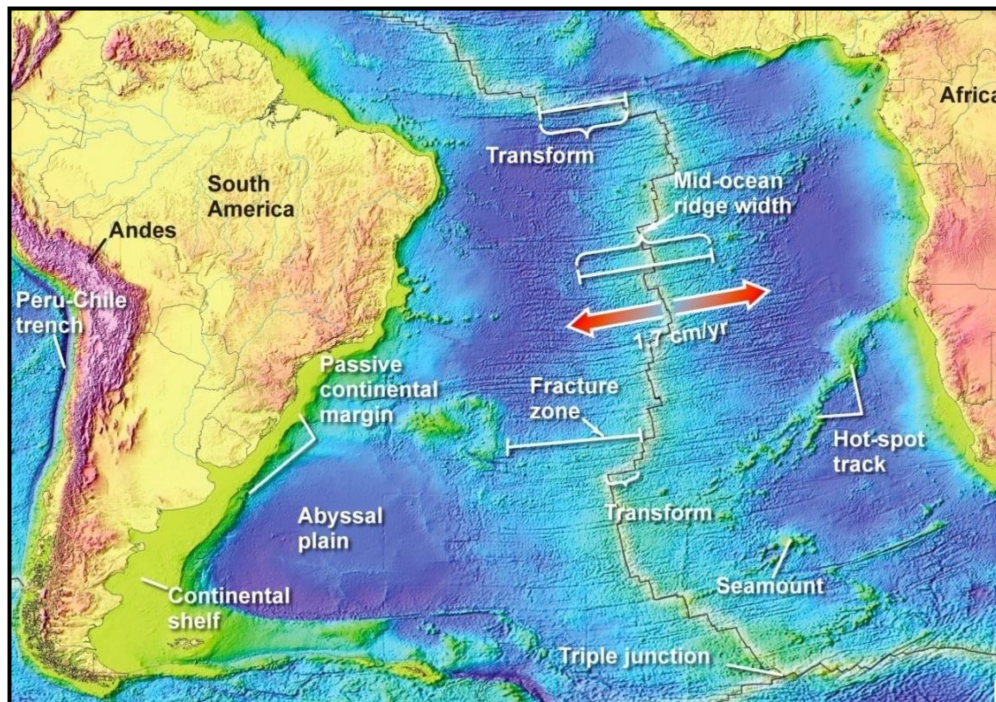
- **Transform boundary—tectonic plates slide sideways.**
  - **Plate material is neither created nor destroyed.**
  - **Also called: transform fault, transform.**





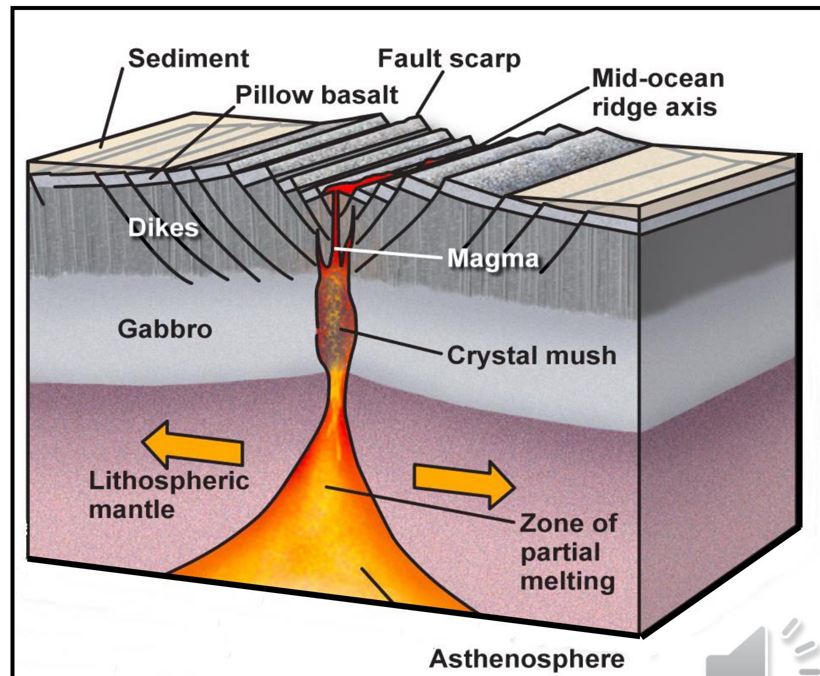
Divergent: Mid-Ocean Ridges

- Linear mountain ranges in Earth's ocean basins.
- Example: The Mid-Atlantic Ridge
  - Snakes N–S through the entire Atlantic Ocean.
  - Elevated ridge (1,500 km wide) 2 km above abyssal plains.
  - New sea floor created only along axis of the ridge
  - Symmetrical



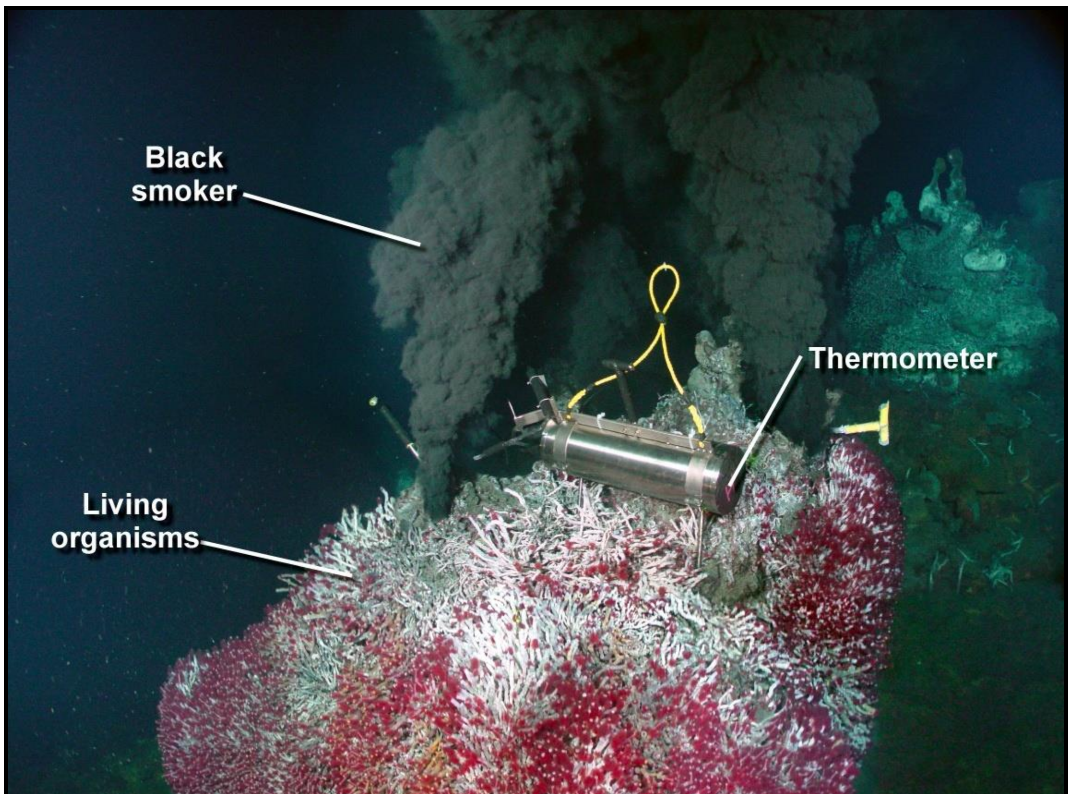
Mid-Ocean Ridges

- Sea-floor spreading opens the axial rift valley.
- Rising asthenosphere melts, forming mafic magma.
- Pooled magma solidifies into oceanic crustal rock.
  - Pillow basalt—magma quenched at the sea-floor.
  - Dikes—preserved magma conduits.
  - Gabbro rock -- deeper
  - Basalt -- shallower



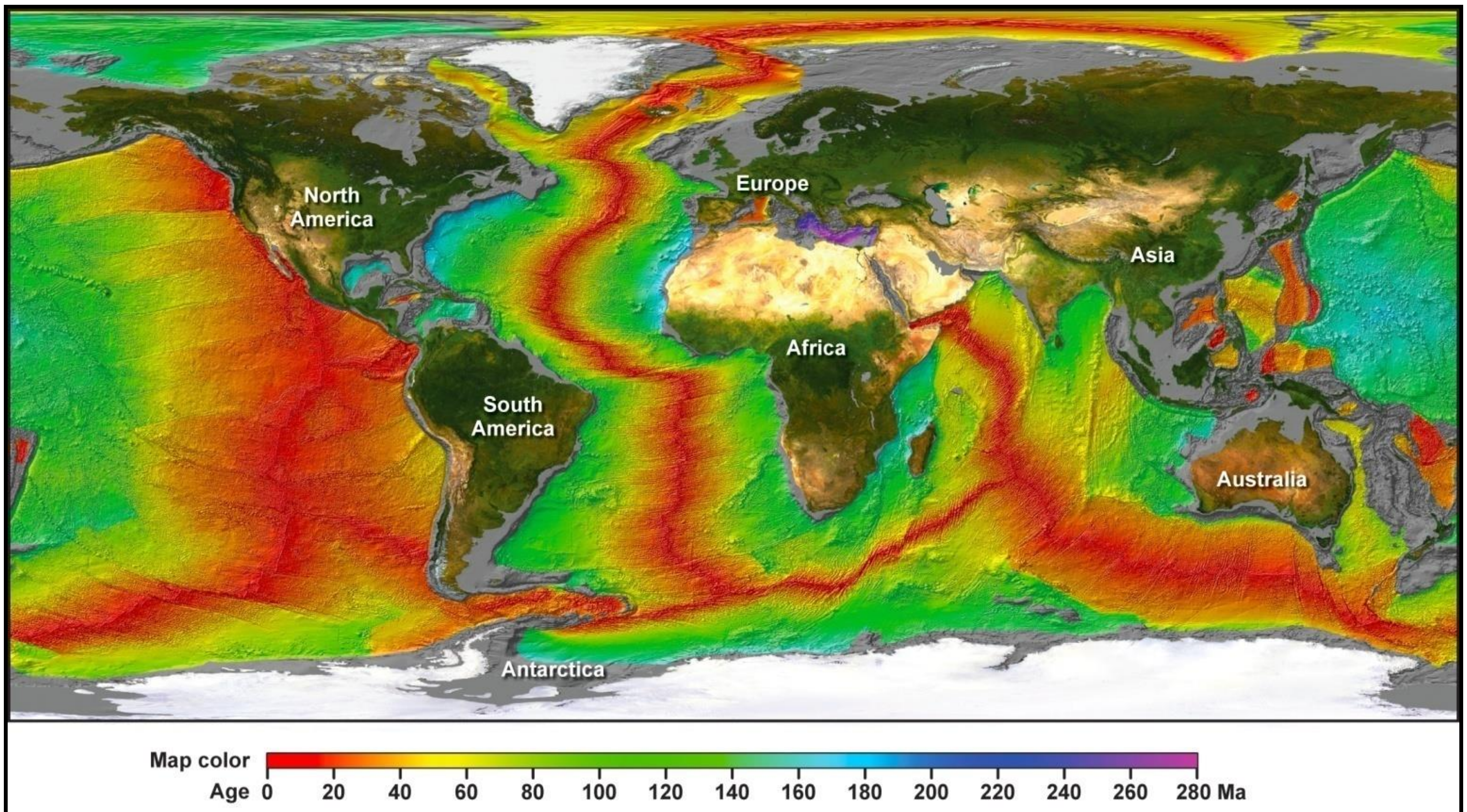
Mid-Ocean Ridges

- "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.



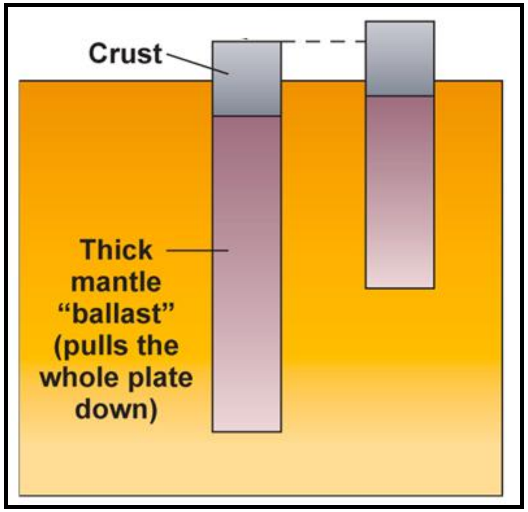
Ocean Crustal Age

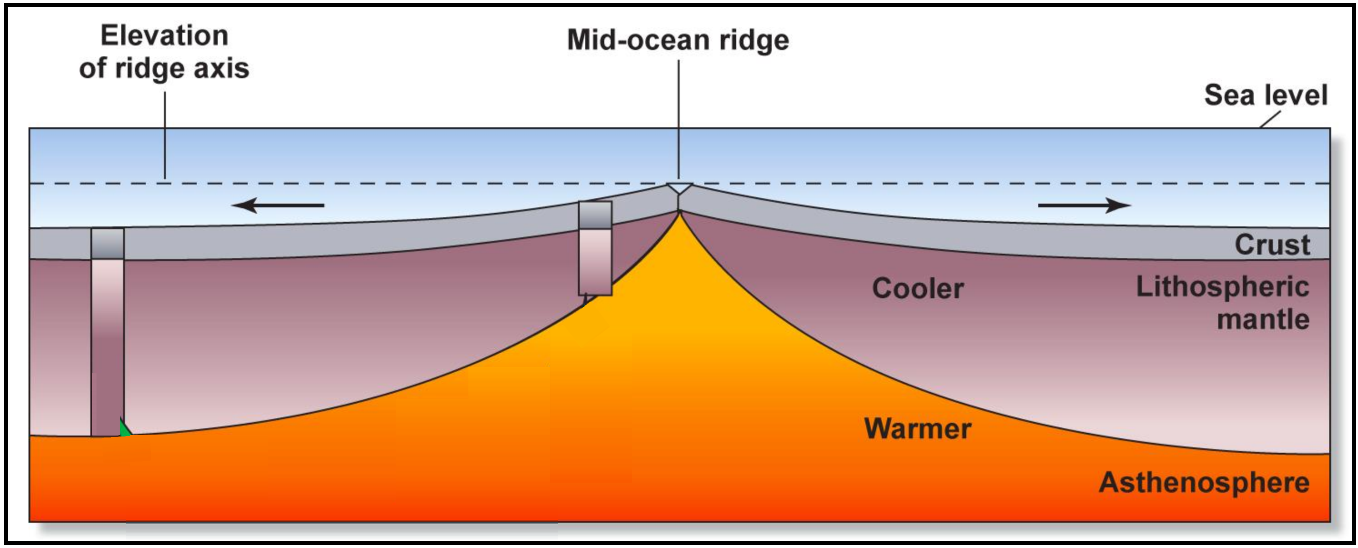
- Oceanic crust spreads away from the ridge axis.
  - New crust is closer to the ridge; older crust farther away.
  - Oldest oceanic crust is found at the far edge of the basin.



Oceanic Lithosphere

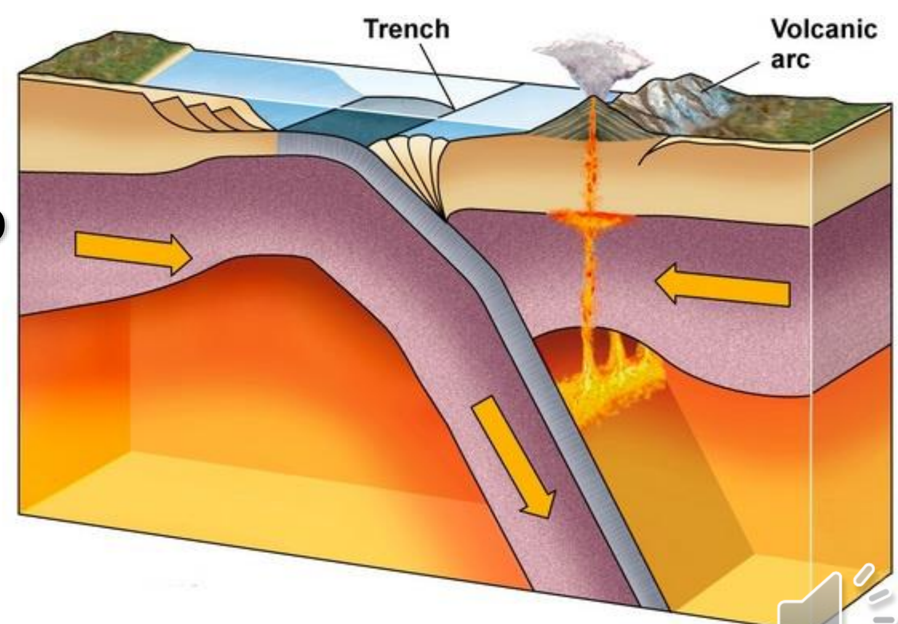
- The hot asthenosphere is at the base of the MOR.
- Aging ocean crust moves away from this heat source:
  - Cooling, increasing in density and sinking.
  - Older, thicker lithosphere sinks deeper into mantle allowing for ocean deepening.





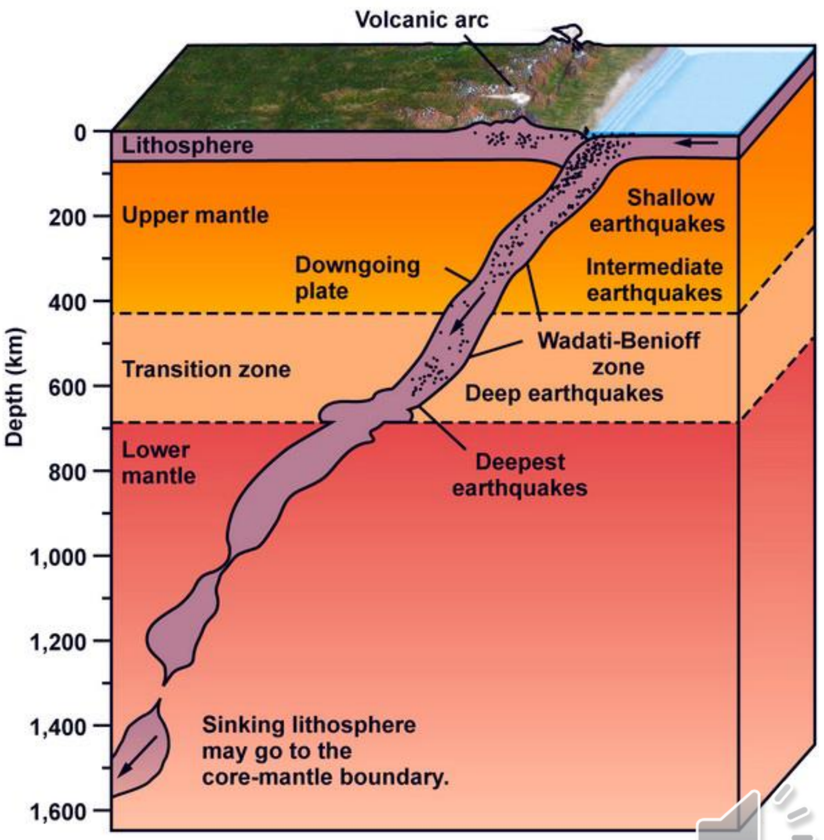
Convergent Boundaries

- Lithospheric plates move toward one another.
- One plate sinks back into the mantle (subduction).
- The subducting plate is always oceanic lithosphere.
- Continental crust cannot be subducted—too buoyant.
- Subduction recycles oceanic lithosphere.
  - Subduction is balanced by sea-floor spreading.
  - Earth maintains a constant circumference.
- Convergent boundaries also called *Subduction Zones*.
- The Cascadia Subduction zone and the 1700 mega-thrust event.



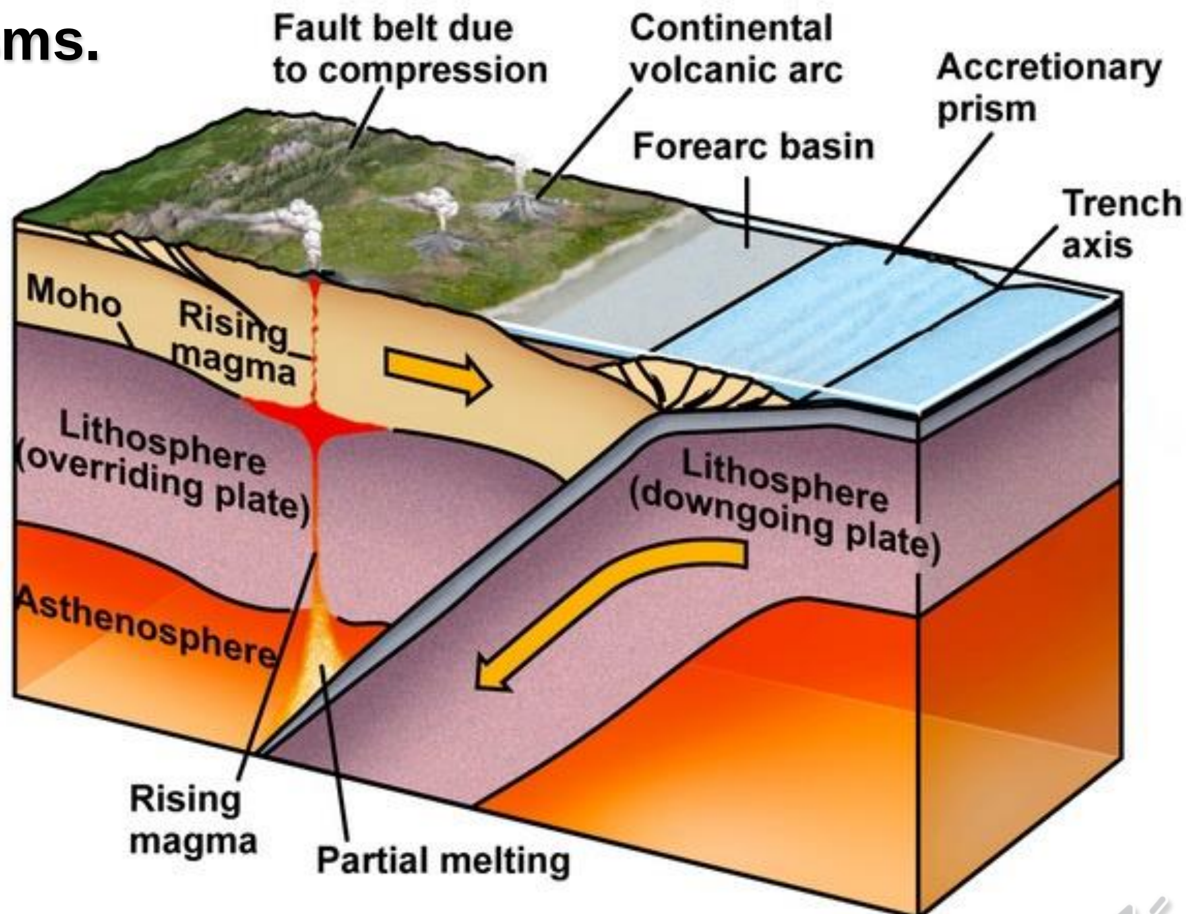
Convergent Boundaries

- The subducting plate descends at an angle of about 45°.
  - Plate descent is revealed by Wadati-Benioff earthquakes.
    - Earthquakes deepen away from trench.
- Quakes cease below 660 km.
- Plate descent may continue past the earthquake limit.
- The lower mantle may be a "plate graveyard."



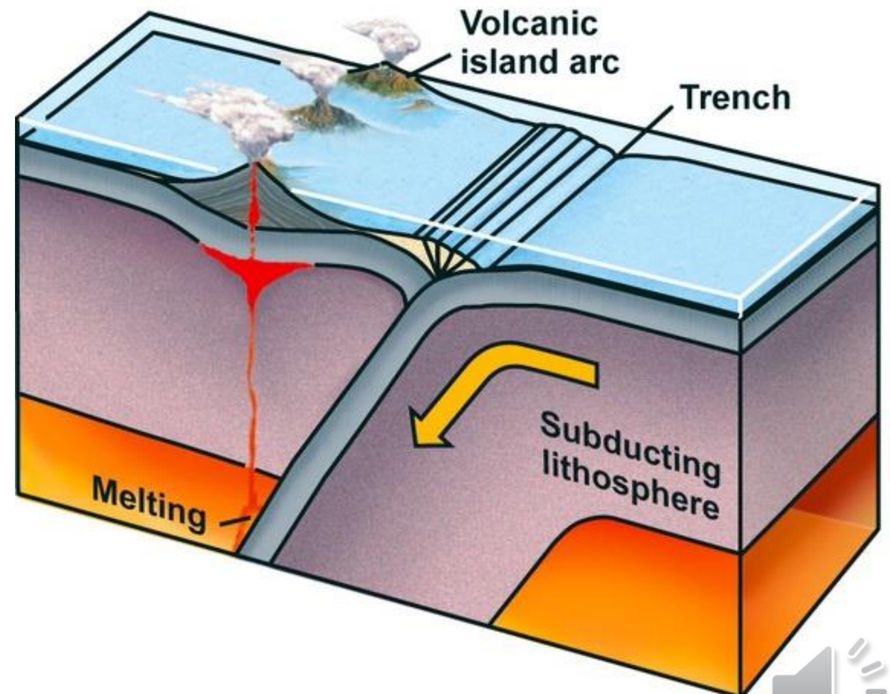
Subduction Features

- Subduction is associated with unique features:
  - Deep-ocean trenches.
  - Accretionary prisms.
  - Volcanic arcs.
  - Back-arc basins.



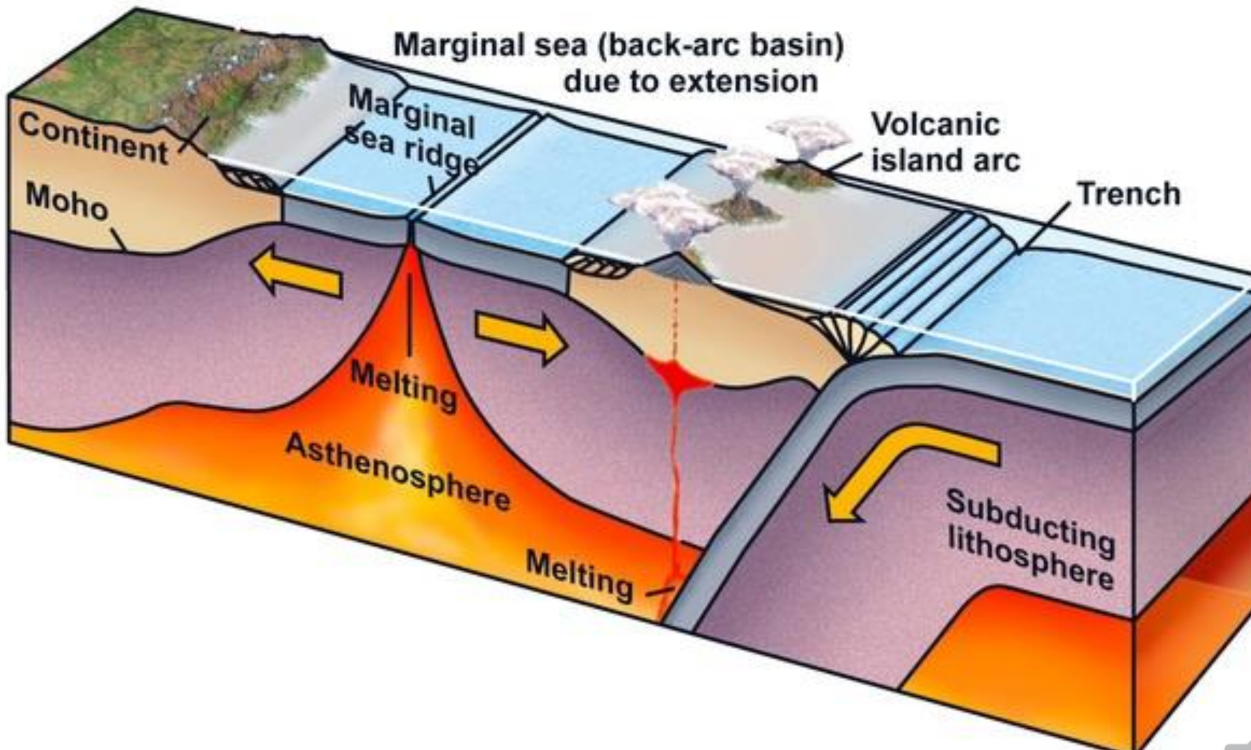
Convergent Boundaries

- **Volcanic Arc—a chain of volcanoes on overriding plate.**
  - **The descending plate partially melts at ~150 km depth.**
  - **Magmas rise and melt through overriding plate.**
- **Arc type depends upon the overriding plate.**
  - **Continental crust—continental arc.**
  - **Oceanic crust—island arc.**



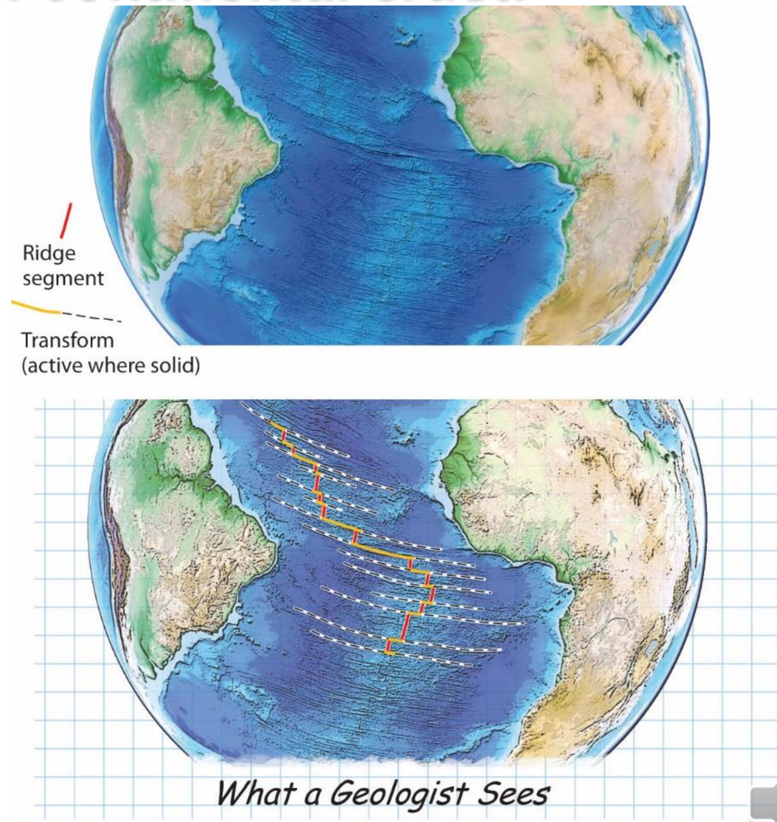
Convergent Boundaries

- Back-arc basins—a marginal sea behind an arc.
  - Forms between an island arc and a continent.
  - Offshore subduction traps a piece of oceanic crust, or
  - Stretching lithosphere creates a new spreading ridge.



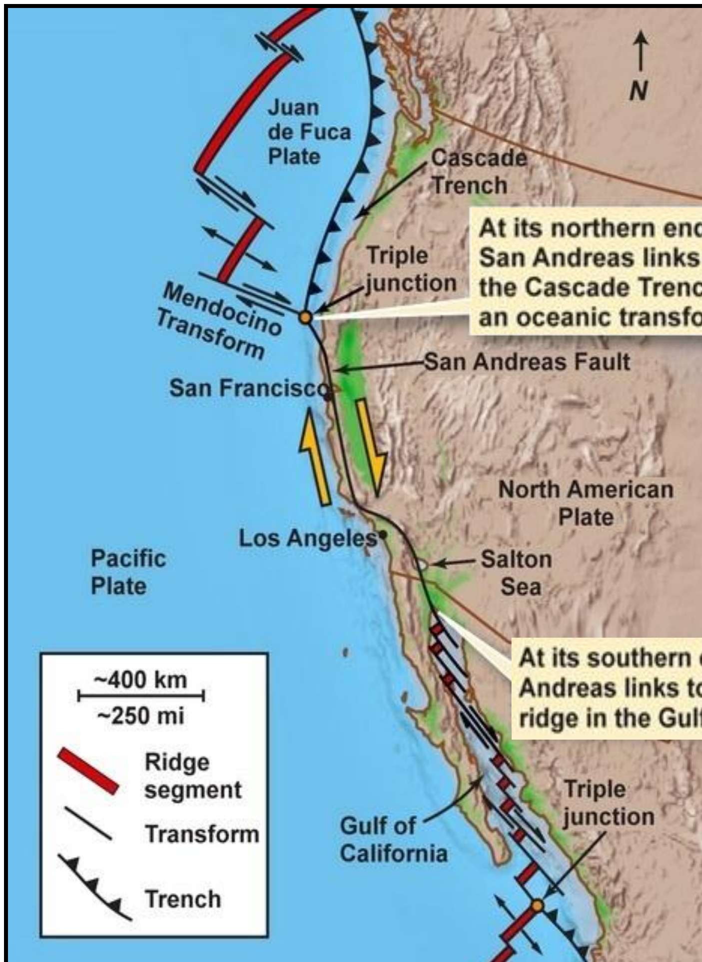
Transform Boundaries

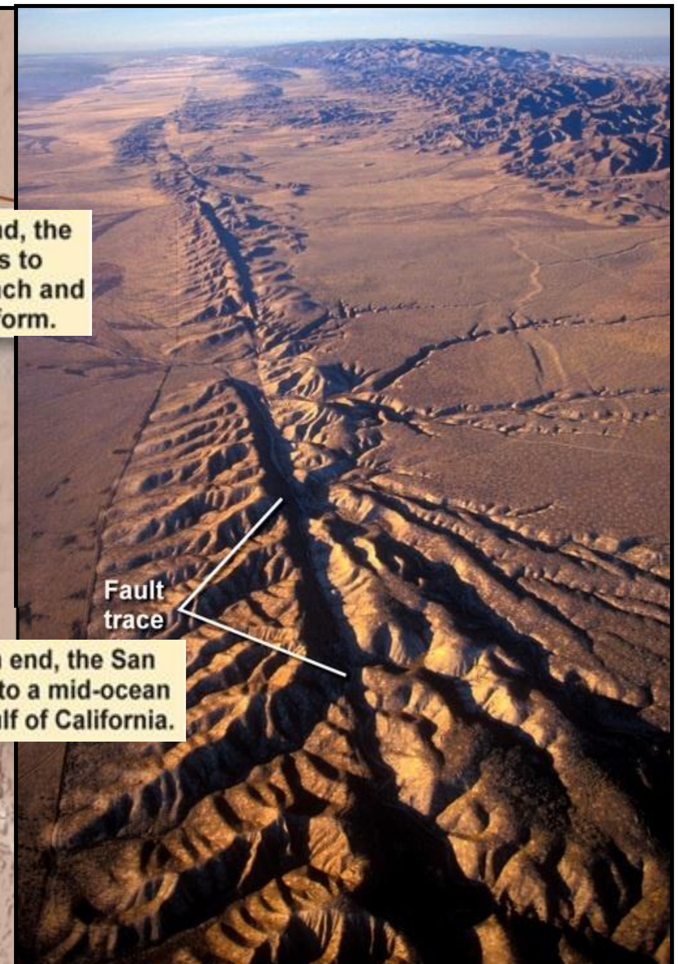
- Lithosphere fractures and slides laterally
  - No new plate forms; none consumed.
  - Many transforms offset spreading ridge segments.
  - Some transforms cut through continental crust.
- Characterized by:
  - Earthquakes
  - Absence of volcanism



Transform Boundaries

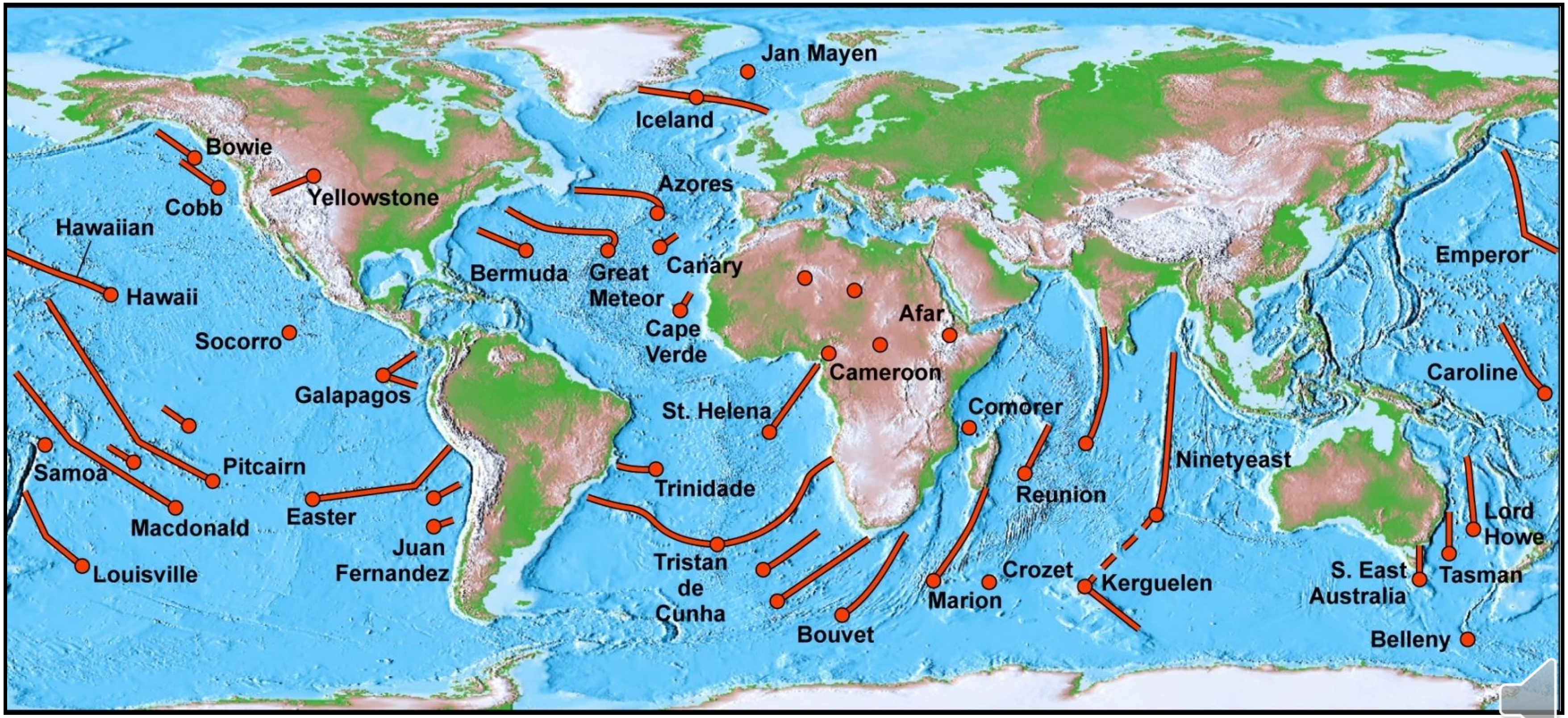
- Continental transforms—cut across continental crust.
  - Example: The San Andreas Fault, California





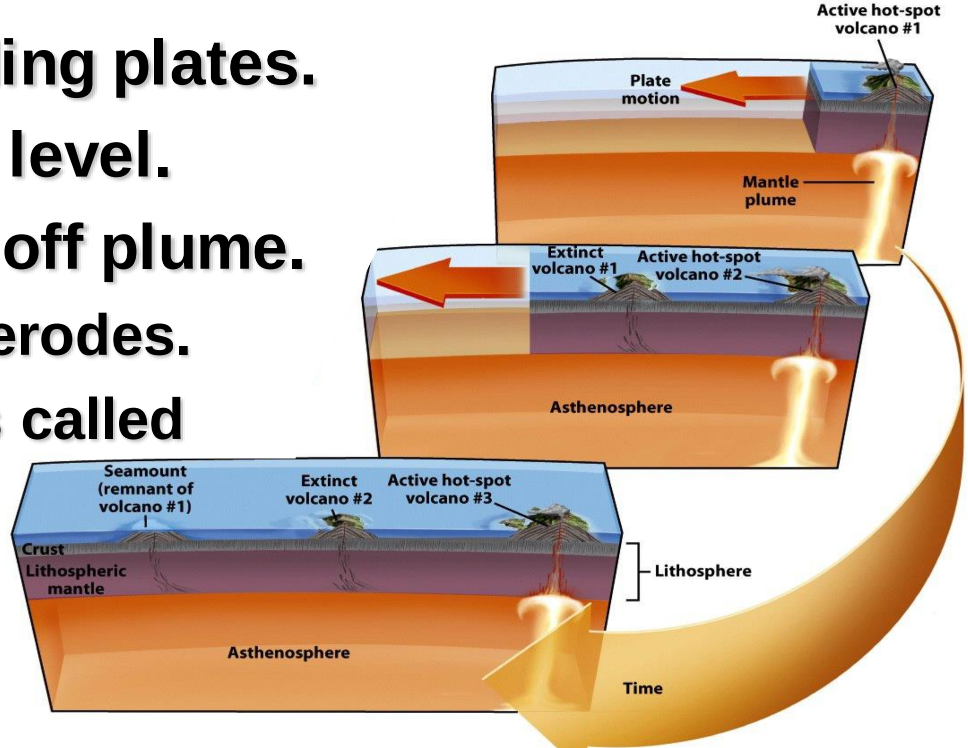
Hot Spots

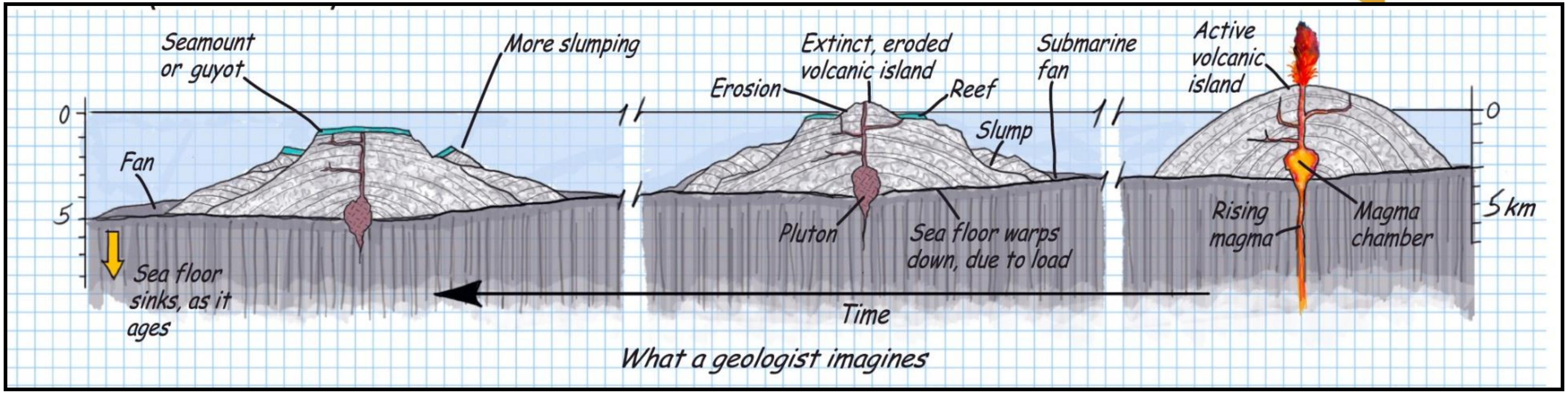
- Plumes of deep mantle material independent of plates.
  - Not linked to plate boundaries
  - Originates as a deep mantle plume (?? OJ)
  - Plume partially melts lithosphere; magma rises to surface.



Hot Spots

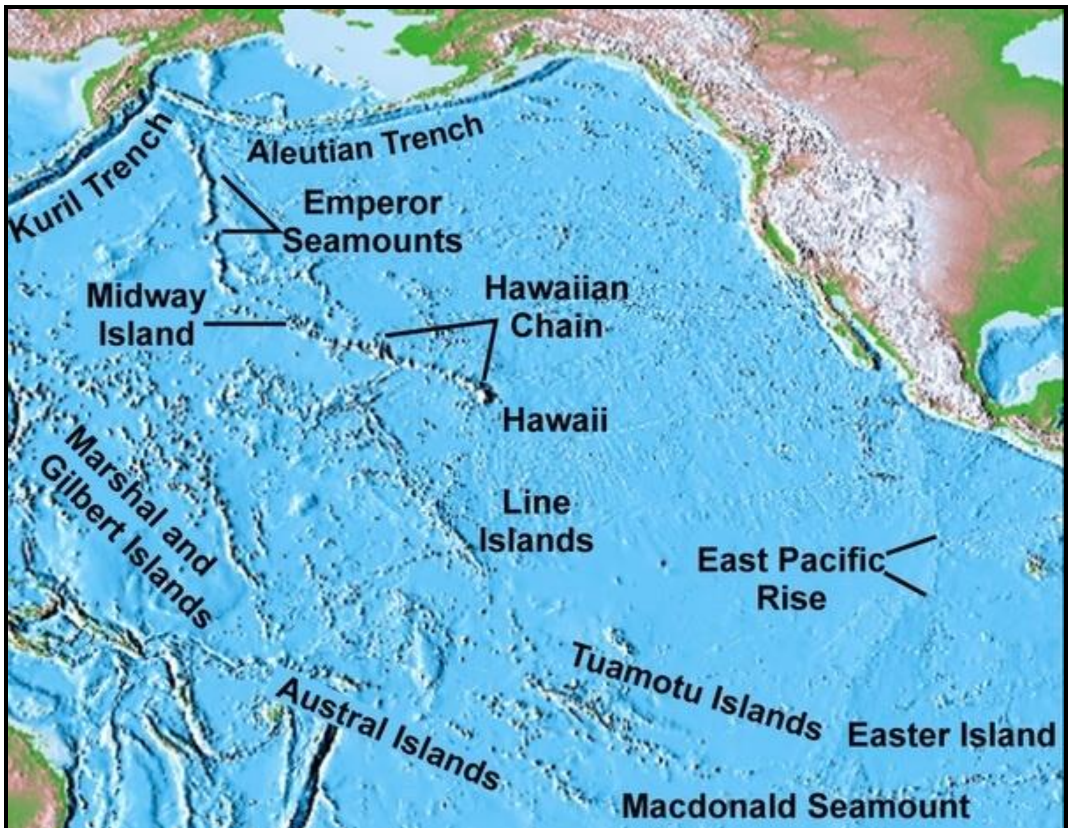
- Hot spots perforate overriding plates.
- Volcanoes build above sea level.
- Plate motion pulls volcano off plume.
  - Volcano goes extinct and erodes.
  - Chain of extinct volcanoes called a *hot-spot track*.
- Hot spots reinforce sea-floor spreading.

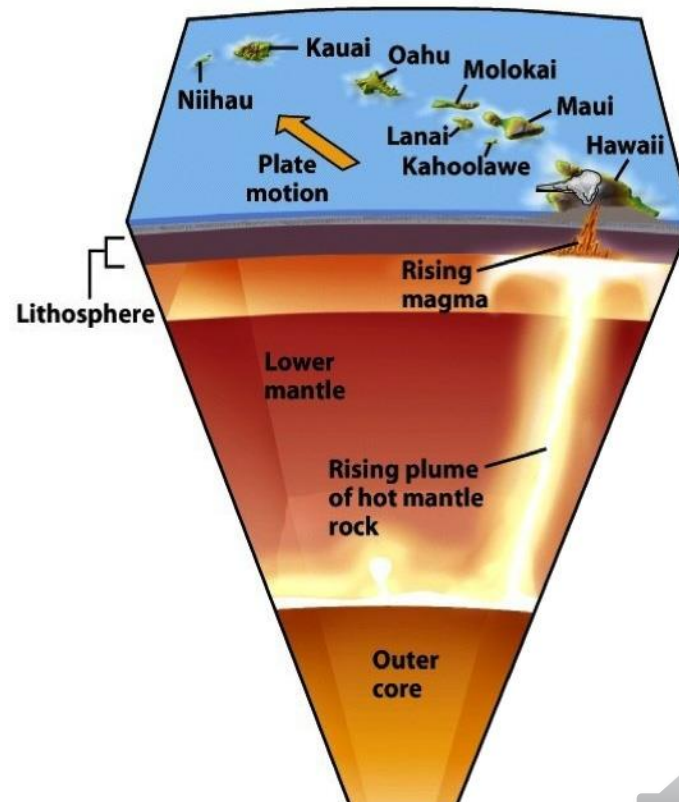




Hot Spots

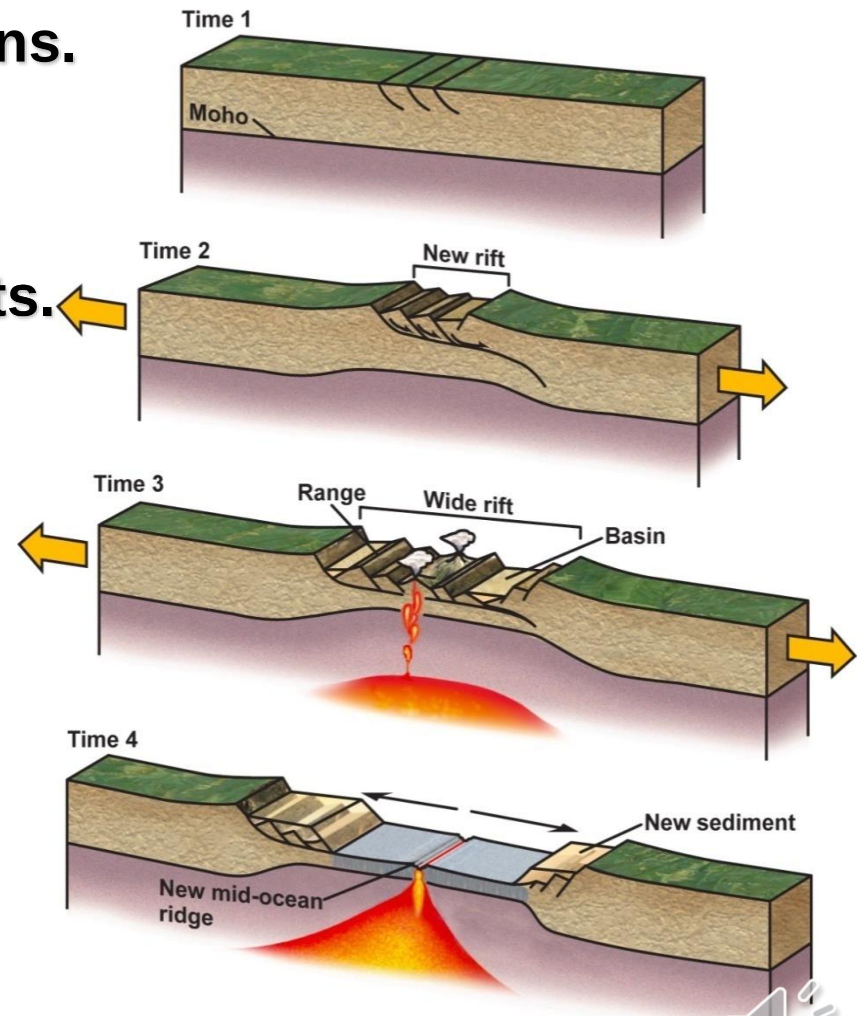
- Hot-spot seamounts age away from originating hot spot.
- Age trend defines rate of plate motion.
- Line of seamounts indicates direction of plate motion.





Continental Rifting

- Continental lithosphere can break apart.
  - Lithosphere stretches and thins.
  - Brittle upper crust faults.
  - Ductile lower crust flows.
  - Asthenosphere rises and melts.
  - Magma erupts.
- Continuation can create a new mid-ocean ridge.
- This process led to the breakup of Pangaea.



Continental Rifting

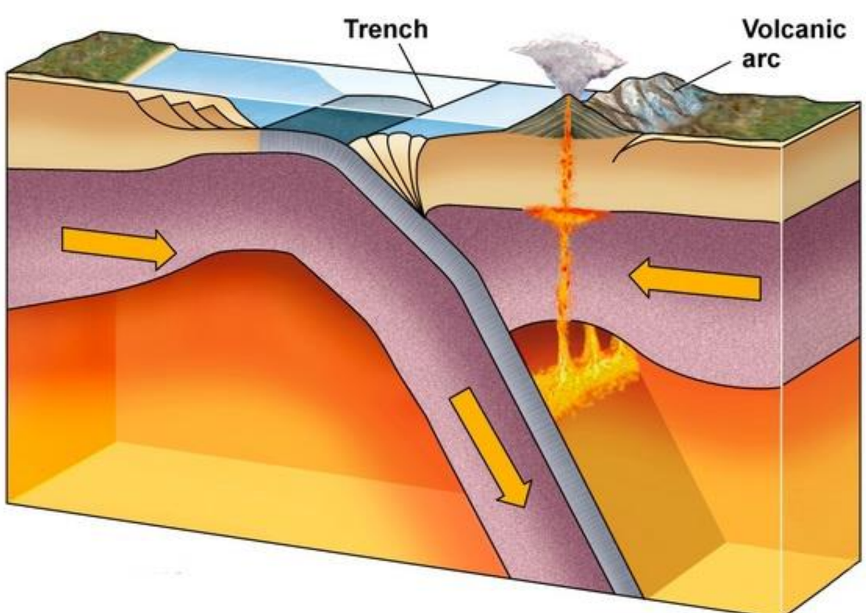
- Western U.S. Basin and Range Province is a rift.
  - Narrow north-south mountains separated by basins.
  - Rifting tilted blocks of crust to form mountains.
  - Sediment eroded from blocks, filling adjacent basins.

Continental Rifting

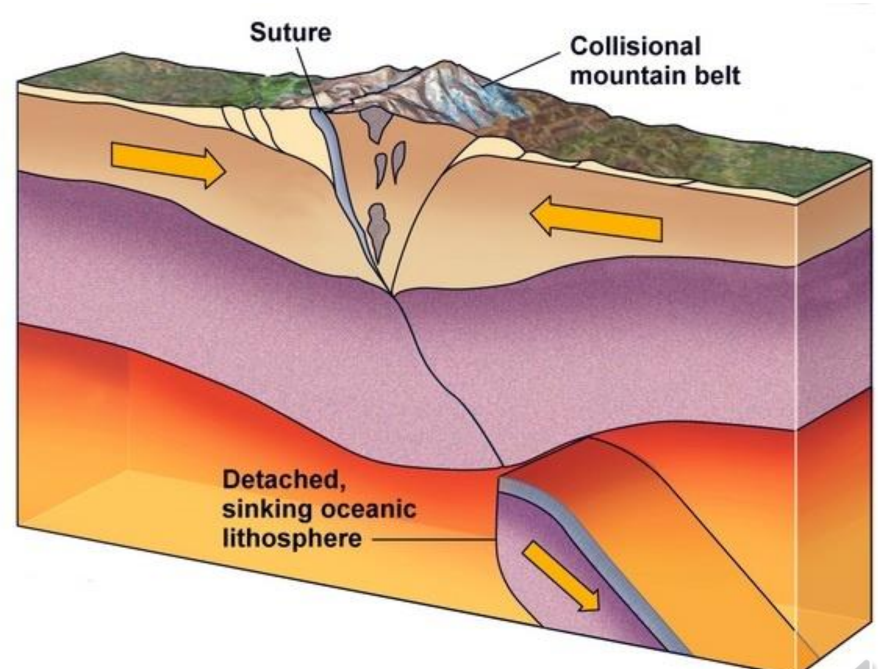
- East African Rift:
  - The Arabian plate is rifting from the African plate.
  - Rifting has progressed to sea-floor spreading in:
    - The Red Sea.
    - The Gulf of Aden.
  - Stretching continues along the East African Rift.
    - Elongate trough bordered by faulted high cliffs
    - Volcanoes – Mt. Kilimanjaro
  - The rift and two spreading ridges comprise a triple junction.

Plate Collision

- Subduction consumes ocean basins.
- Ocean closure ends in continental collision.
  - Subduction ceases, subducting plate detaches, sinks.
  - Continental crust is too buoyant to subduct.
  - Collision deforms crust, mountains are uplifted.



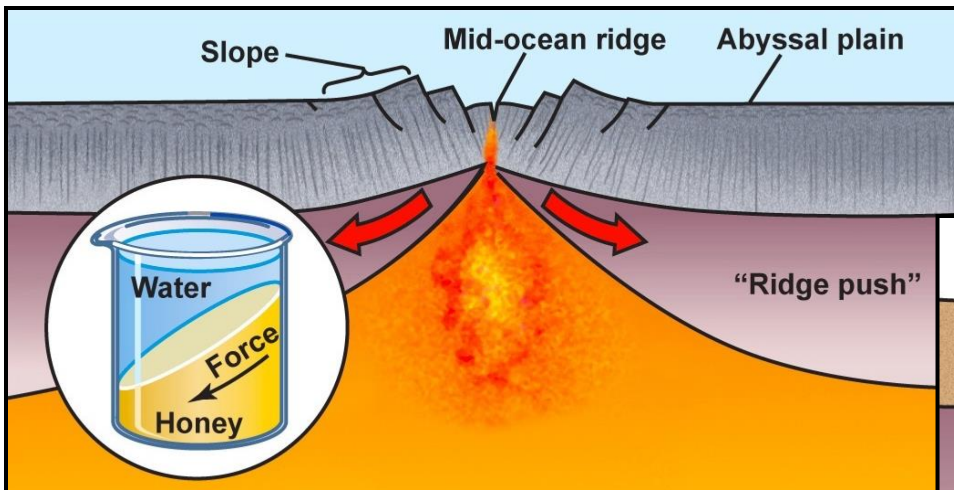
Time 1: Before



Time 2: After

Driving Mechanisms

- Two forces drive plate motions:
  - Ridge-push—elevated MOR pushes lithosphere away.
  - Slab-pull—denser subducting plate is pulled downward.
  - Convection in the asthenosphere speeds or slows motion.



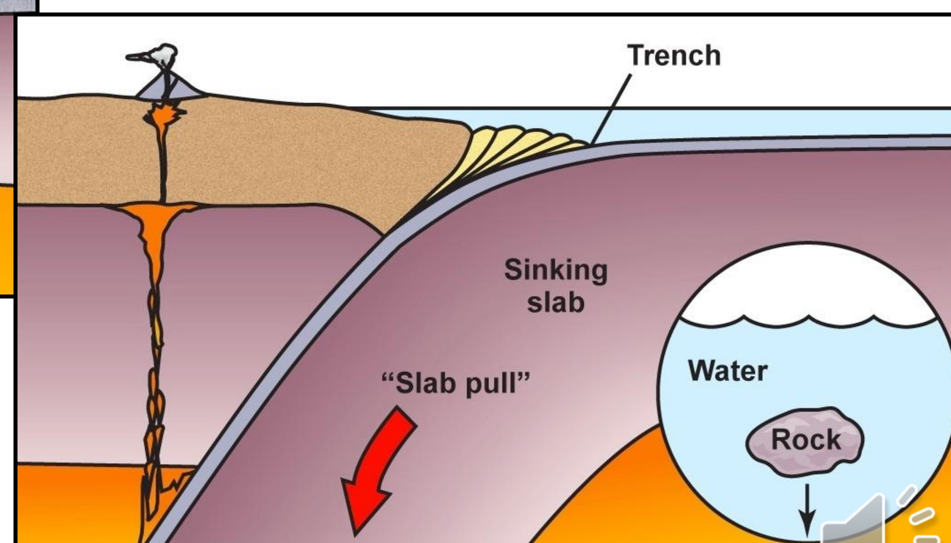
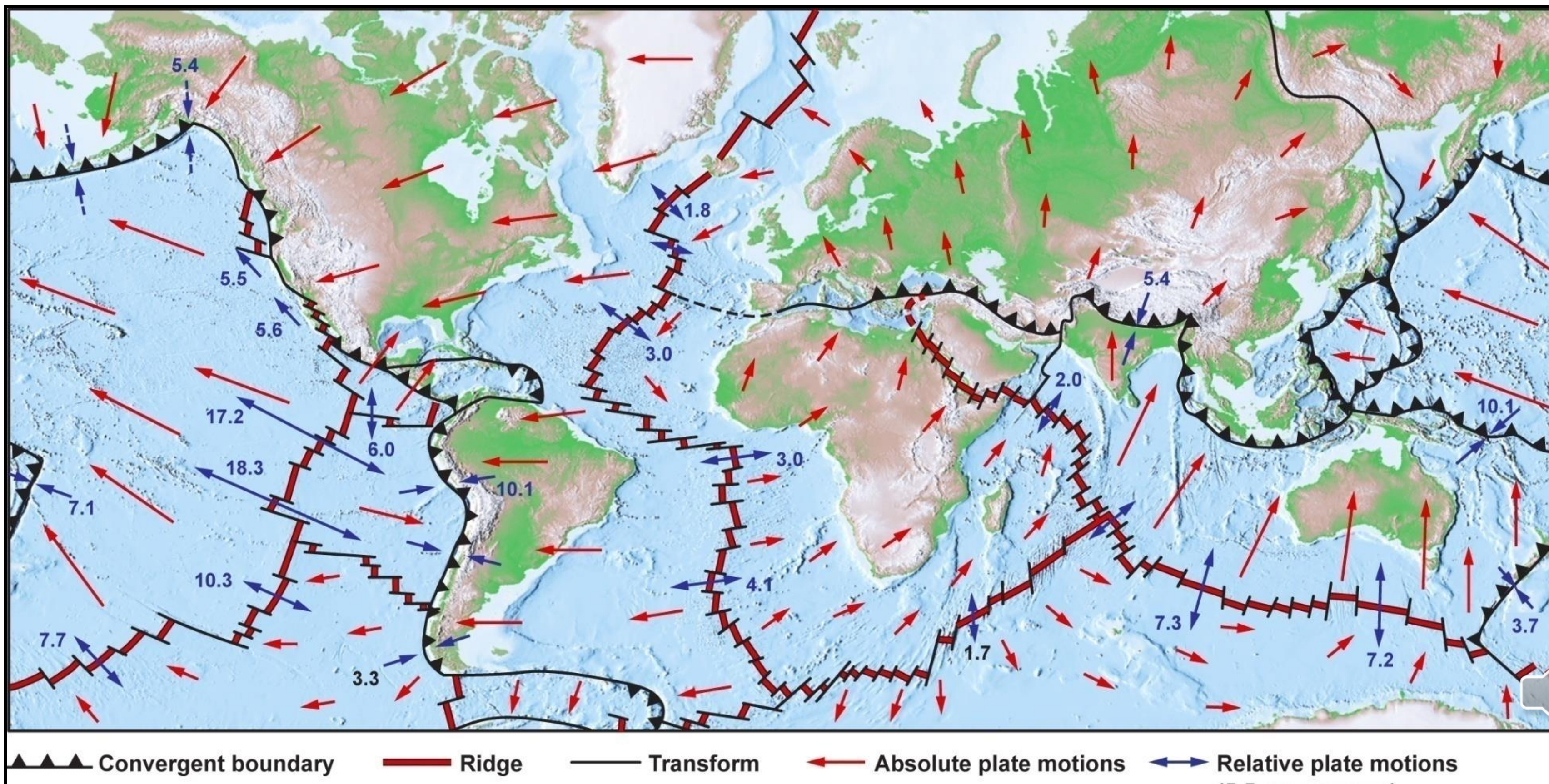


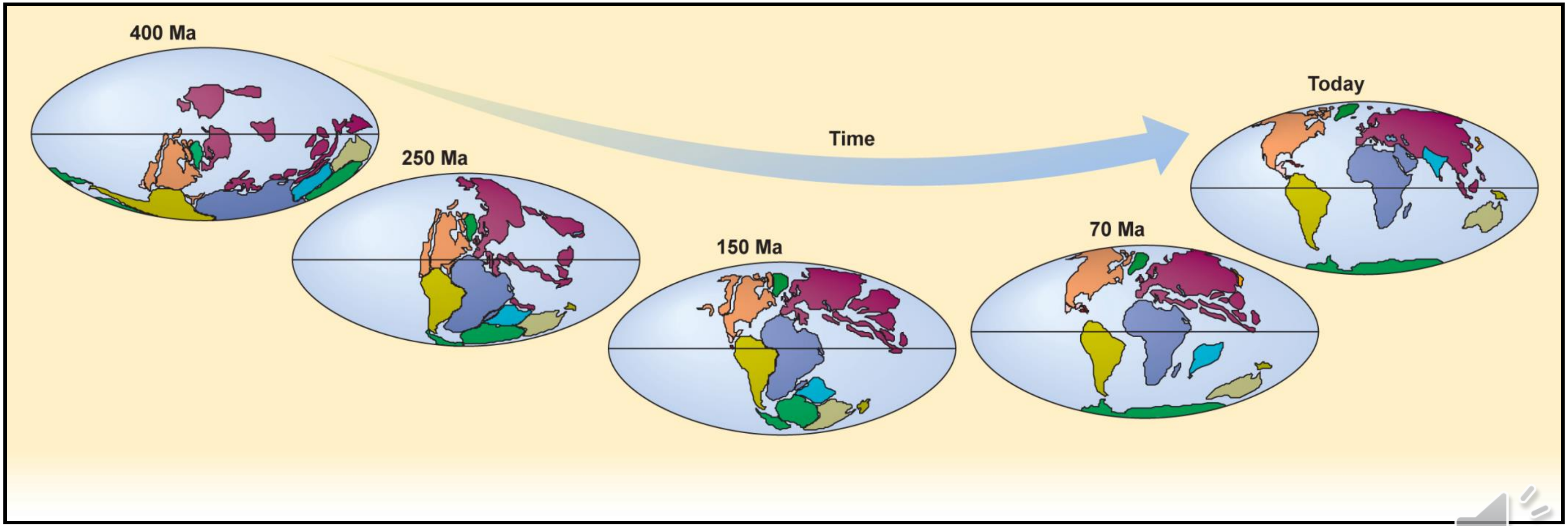
Plate Velocities

- **Absolute plate velocities may be mapped by:**
  - **Plotting plate motion relative to a fixed spot in the mantle.**
  - **Measuring volcano ages/distance along a hot spot track.**
  - **GPS (relative) positions on plates**

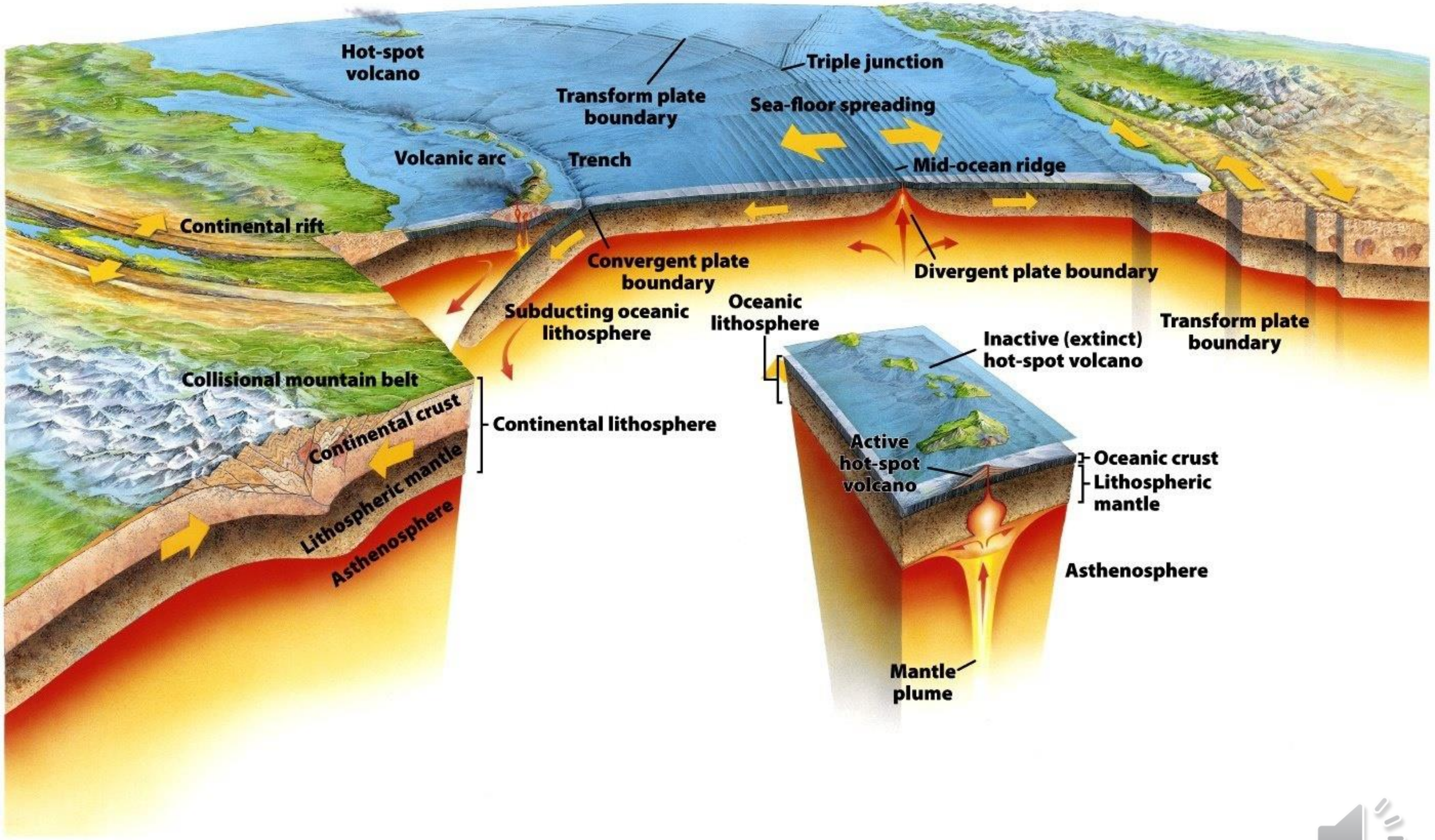


The Dynamic Planet

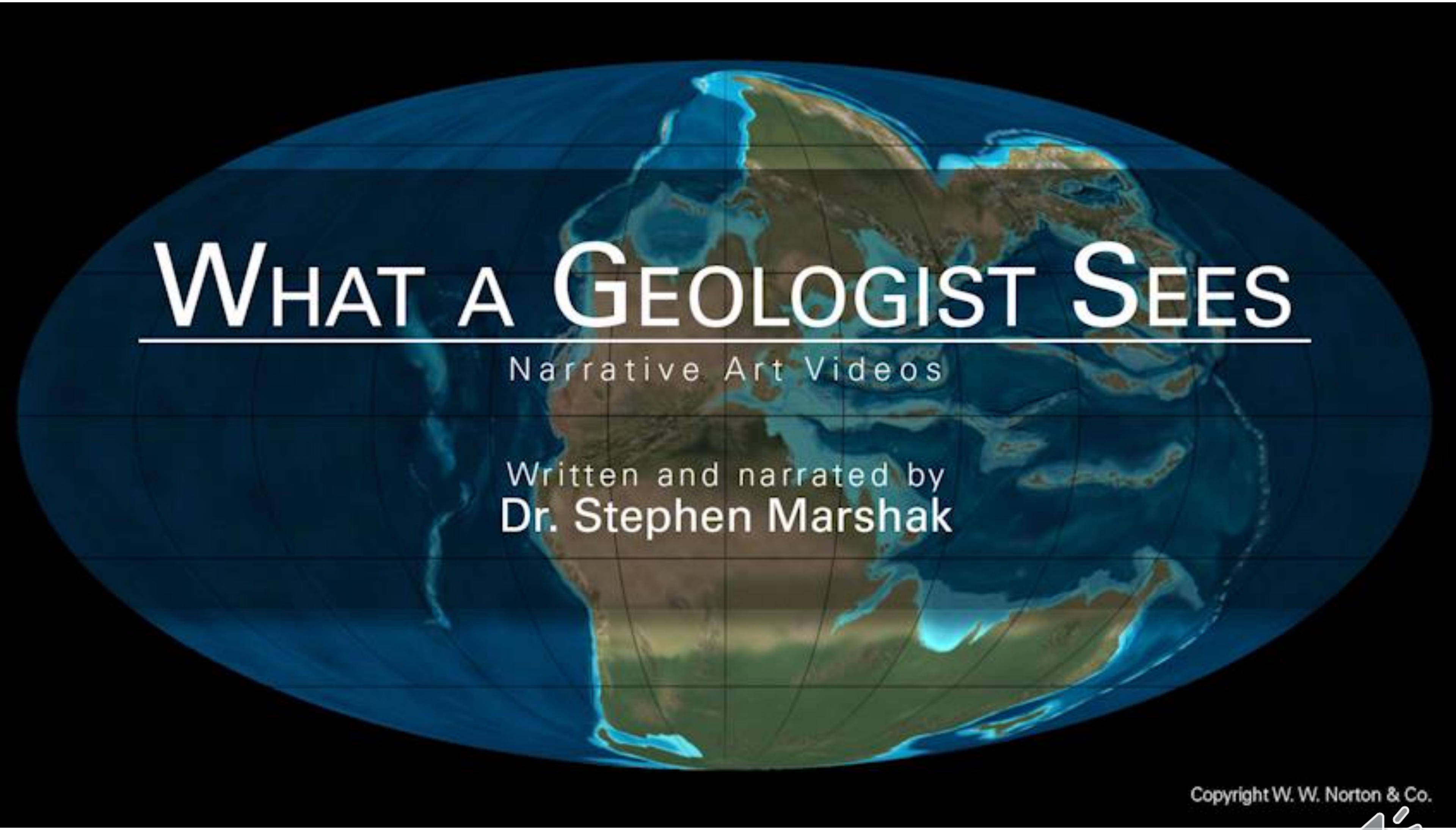
- Earth's surface changes continuously.
  - These changes appear slow to us.
  - Geologically, change is rapid; the last 700 million years.
- Earth looked very different in the past.
- Earth's geography will look very different in the future.



The Dynamic Planet



Video Summary



Video Summary

PLATE
TECTONICS

Video Summary

A reconstruction of past geography and projection to future changes.

This is a 12-minute ***Youtube video*** by Christopher Scotese of UTexas-Arlington