

### Topic 3: Results of Differentiation: Layering in the Earth

#### I. Compositional Layering of the Earth

##### A. **Atmosphere:** Gaseous envelope surrounding the Earth.

-Air we breathe, weather we experience is in layer only 13 km thick (radius of Earth = 6371 km).

-Total mass = 0.0001% of total mass of Earth. Trivial!

##### B. **Hydrosphere:** all water and ice on surface, in air, and under ground

-on smooth earth, would have a water layer only 2.25 km thick. Plenty deep for swimming, but still very very thin layer out of 6371 km

-Total mass = 0.02% of total Earth. Tiny!

Atmosphere + Hydrosphere = total gas and volatile inventory of Earth = trivial proportion of the Earth's mass. Recall that the Sun and the outer planets are almost entirely made of gasses/frozen volatile elements. Recall that the inner rocky planets had most of their gases blown away by the early Sun's solar wind. To us, atmosphere and oceans are vast, inexhaustible resources, but on the scale of the planet, early solar wind left us with almost nothing. It almost stripped the Earth to a bare, dry rock.

In fact, since it is possible that a good deal of the water and air on Earth came from comets that hit the Earth especially early in its history, the early solar wind may have been even more nasty than we think.

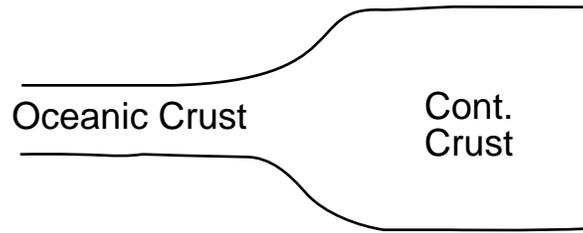
##### C. **Crust:** Total Mass = 0.4% of Earth

1. **Continents:** about 35 km thick, made of light colored and light weight rock called granite. Extra rich in Si, Al, Na, and K. Visualize thick, light, and fluffy styrofoam. Most important for today: density = 2.7 g/cc.

2. **Oceans:** about 7 km thick, made of dark grey, dense rock called basalt (cf, Hawaii). Extra rich in Fe and Mg. Visualize thin slap of dark heavy rock. Most important for today: density = 3.0 g/cc.

Density difference between continental rocks and oceanic rocks seems small, but this will make a HUGE difference that profoundly affects the behavior of the Earth.

**Draw both crusts to emphasize equivalent lateral positioning.**



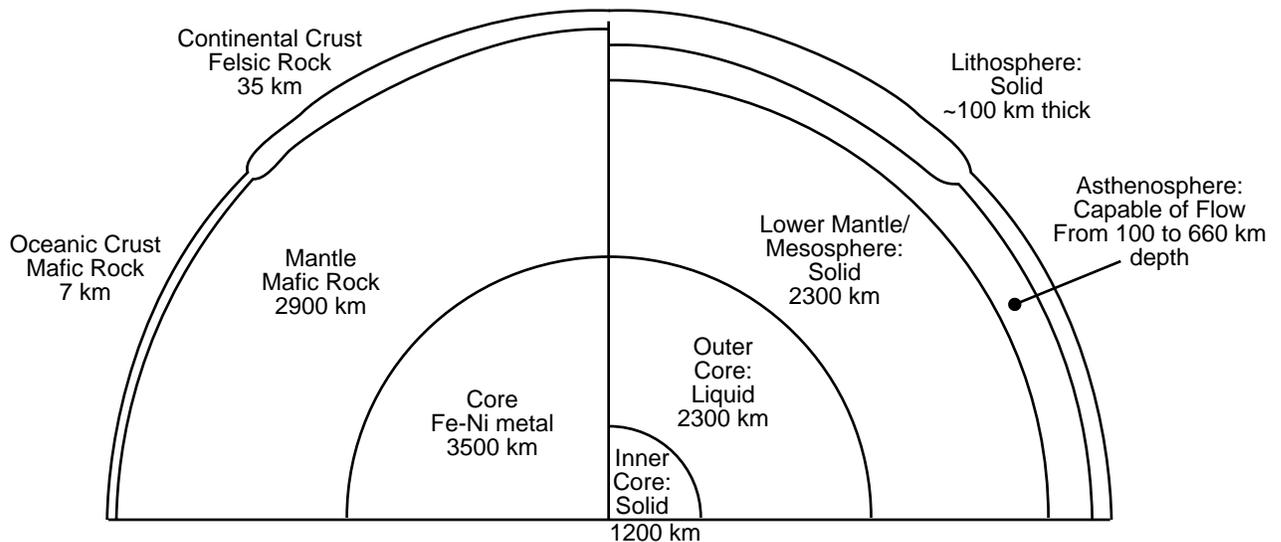
**OVERHEAD/handout of U.S.G.S. estimated crustal thicknesses around world.**

D. **Mantle:** About 2880 km thick. Rock is similar to basalt (oceanic crust), but denser (3.3 to 5.5 g/cc from top to bottom of mantle) Mass = 66% of Earth = by far largest part.

E. **Core:** 3480 km thick. Fe-Ni metallic center. Not rocky! Extremely dense: 10 to 13 g/cc top to bottom. Mass = 33% of the Earth. Second biggest part.

**Compositional Layers of the Earth**

**Mechanical Layers of the Earth**



**Lithosphere = Crust plus uppermost Mantle**

**Asthenosphere = Rest of Upper Mantle**

Drawing is to scale except for the crust and continental lithosphere layers; the crust would be too thin to show up and the difference in thickness between continental and oceanic lithosphere would be too small to show up.

**OVERHEAD(S) FROM TEXT, Hand out above**

## II. Layers based on **Physical Behavior (Rigid vs Plastic Layers)**

First, what causes changes in the ability of rocks to flow?

A. As you descend into the earth, the temperature and pressure increase.

-Pressure increases due to increasing weight of rocks over your head. You can imagine the difference between being buried under 1' of sand at the beach and 6' of dirt.

-Temperature increases because interior is heated by heat left over from the formation/melting of the planet plus decay of radioactive elements (mainly K, Th, U) plus the crystallization of Fe-Ni metal in the core (more later).

Radioactive decay emits He nuclei, electrons, and gamma rays. These hit nearby atoms and increase their vibrational motion. Each decay makes a little heat, but over the whole earth, they add up!

If you tour an Iron Mine in the U.P. of Michigan, or a coal mine in Pocahontas Virginia/WV, you will find the air in the mine to be quite cold. Near surface mines reflect the average year-long weather temperature. Tours are often in the summer, when the air outside is hot and you are in shorts. The mines would feel warm in the winter.

If you go to South Africa and tour a deep diamond mine, you would find that after a while things get warmer and warmer, until at the bottom the temperatures will be like a hot summer day outside. Thus it is easily observed that the earth gets warmer with depth.

Also, don't forget volcanoes: they erupt at temperatures up to 1300 degrees C.

Temperature and pressure compete against each other:

Increased heat with depth causes rocks to soften and eventually flow. Like heating asphalt or butter.

Increased pressure tends to keep rocks hard and solid. Why? As you heat a rock, the atoms vibrate faster, pushing each other further apart. This causes the rock to expand. When a rock melts, the liquid takes up more space than the original rock.

Increasing pressure on this rock acts against the expansion and thus tries to keep a rock from melting or even softening. The pressure prevents expansion due to increased atomic vibrations.

**So, how do temperature and pressure play out in the Earth's interior?**

With increased depth, rocks heat up and begin to soften a bit. Below about 15 km depth, rocks begin to deform plastically, like modeling clay used to make clay pots and other ceramics.

Below about 100 km depth, rocks are heated to the point where they can actually flow relatively easily. This gives rise to the first major physical layer on the Earth:

**B. Lithosphere:** 'rock sphere' Temperatures are cool enough over upper 100 km to allow crust and the upper part of the upper mantle to behave as a solid layer. Below 15 km you can slowly deform it like modeling clay, but it will not flow.

Crust/mantle transition is strictly compositional; physically, they behave as one solid layer. This layer forms the plates that scoot around on Earth's surface.

**C. Asthenosphere:** 'weak sphere'. Between 100 km and 660 km depth, temperature increases to where the rocks soften and can flow plastically. Asthenosphere is not liquid, like water, but is analogous to ice. Ice is a solid, and you can smash it. However, if you apply slow pressure, ice flows like a liquid. Weight of glacier makes it flow down hill, and you can slowly push teeth into ice cube.

**Draw 60-m-thick glacier:**



Asthenosphere can flow very slowly. Compositionally = mantle; physically = solid that slowly flows like cold tar.

**D. Mesosphere/Lower Mantle:** With increased depth, pressure is so high that rocks are forced back into their solid behavior. There may be extremely slow flow within Lower Mantle (slightly soft) or no flow at all (totally solid).

**E. Core:** Change in composition from rocky to metallic is so extreme that it profoundly affects the physical properties.

**Outer Core** is liquid Fe-Ni. Same viscosity as your blood. Movement of liquid outer core responsible for the earth's magnetic field that you read when a compass needle points north.

**Inner Core:** Core is slowly crystallizing. Solid Fe-Ni crystals sink and accumulate at the center of the earth to form Inner Core.

When minerals crystallize, they release heat (= latent heat of crystallization). Every crystal that forms as the core crystallizes releases some heat into the core. Thus turns out to be quite a lot of heat; you can think of the core as being a

big heater in the center of the Earth.

Example: To form ice, start with a bucket of water at 10 degrees C. If you remove heat (say, in a freezer), the water cools down until it reaches 0 C. At this point, ice crystallizes and releases heat to the water. This heat has to be removed by the freezer and prevents the temperature of the water from going down until all of the water has turned to ice. The faster you remove the heat, the faster you make ice, but you will not change the water/ice temperature until no more ice is forming. Once you have a solid block, you can cool the ice down to as cold as you like.

III. At this point it is essential to introduce the most important theory in Geology: **Plate Tectonics: the lithosphere is broken into a number of rigid plates that move across Earth's surface.**

Earth's surface is MUCH more active than Mars and Venus, and Mercury and the Moon have been totally inactive to billions of years. A big question is why is the Earth so exceptionally active? This is a tough question, and we will begin by laying out some basics:

A. All processes on Earth are driven by two main energy sources:

1. Solar energy drives all sorts of surface processes, including the weather, erosion, glaciers, ocean currents, and the chemical reactions that sustain life. More later.
2. Internal energy: heat produced from initial formation of the planet 4.5 Byr ago (impacts + core formation) plus crystallization of core plus radioactive decay of several elements (mainly U, Th, K). This heat is what drives plate tectonics, earthquakes, volcanoes, mountain building, most everything big happening to the solid earth.

This heat is not enough to warm oceans, affect climate, or sustain life at the surface. It is produced so slowly to have noticeable impact. Main exception: hydrothermal vents along volcanic systems in the deep oceans sustain life independently of the surface. These weird communities have inspired folks looking for life on other planets (Mars, Europa = moon with possible liquid water below a surface layer of ice) in the solar system to seek out similar environments.

B. The lithosphere is not a solid shell like an egg, but rather is broken up into a number of fragments called plates. These plates are able to move across the surface of the asthenosphere because it is hot enough that it flows. Like steel sliding across a greased surface.

**OVERHEAD global plate map from text**

These plates move around on the asthenosphere at rates up to 10 cm/year. This is about the

same speed at which your fingernails grow. This may seem slow, but roughly 150 million years ago New England was joined with Africa. 150 Myr of drifting apart has made a rather wide Atlantic ocean!

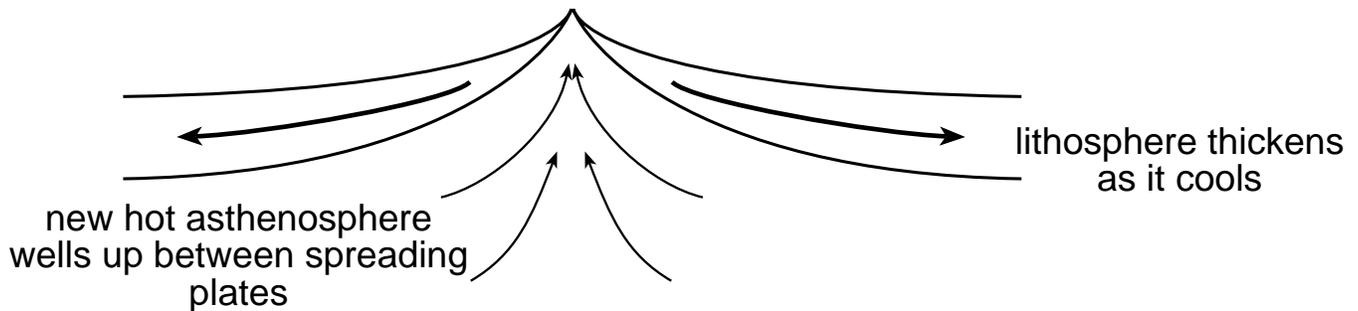
C. Since the plates all move in somewhat different directions, some move away from each other, some towards each other, and others just slide by. This leads to 3 types of boundaries:

1. **Divergent Plate Margins:** plates move apart. Asthenosphere rises to fill gap created as the plates move apart and volcanic eruptions result.

**Ocean-Ocean Boundaries** marked by a mountain chain called a mid-ocean ridge or spreading center.

**OVERHEAD = Map.** Over whole Earth, mid-ocean ridges form a mountain chain that runs around the oceans like stitches on a baseball.

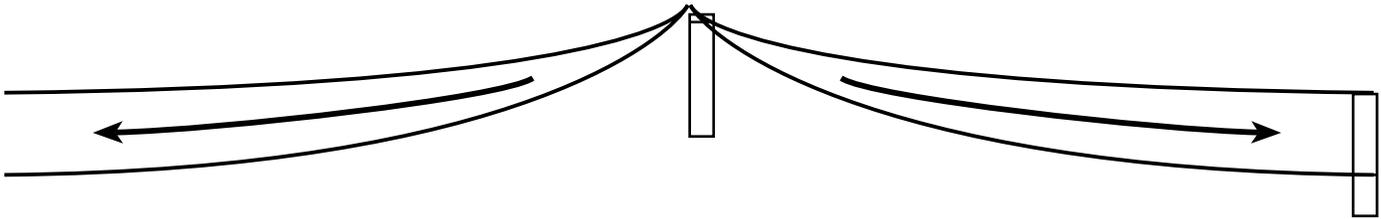
In cross-section (**draw!**), ridge comes up to about 2.5 km below sea-level, then eventually drops to 5 to 6 km depth.



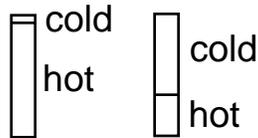
Lithosphere pulls apart at ridge axis. Asthenosphere upwells to fill in gap and volcanic eruptions put new crust on the sea floor ==> hydrothermal vents driven by the emplacement of this hot rock!

Why does lithosphere thicken? As ocean floor moves away from ridge axis, it cools. If you cool down asthenosphere, it no longer flows. It behaves as a solid rock and thus, presto! cooled asthenosphere is new lithosphere.

Why is there a ridge where the sea-floor is pulling apart? Why not a hole in the ground? Look at two columns 1 km square that go down roughly 150 km below surface:



Place columns side-by-side and look at relative thickness of hot asthenosphere and cold lithosphere:



For a given mass of rock, which is going to take up more space? Hint: you heat something up and it expands.

Thus, ridge exists because there is a lot of fresh hot rock emplaced along the ridge axis. As the lithosphere moves off-axis, it cools, thickens, and the swelling goes down.

**Continent-Continent: Rift:** to split apart. When continents split, they are stretched apart. Stretching causes thinning and faulting. Eventually, continents rift apart, and new oceanic crust is produced between them. **Draw/Overhead**



Starting Continent



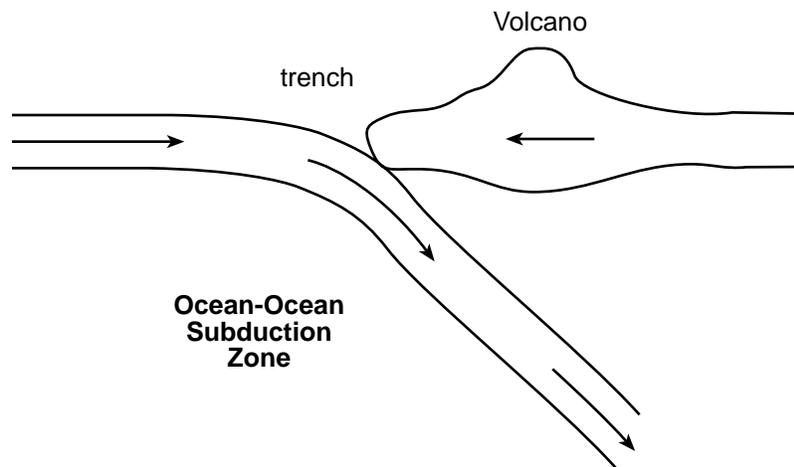
Stretches and thins (and the surface shows fractures)



Continent separates, new oceanic crust/spreading center forms

2. **Convergent Plate Margins:** plates come together. If plates are moving apart in one place, there either has to be a collision somewhere else or the earth has to expand. Satellite measurements indicate that earth is NOT expanding. Also, a slowly cooling earth should contract, if anything.

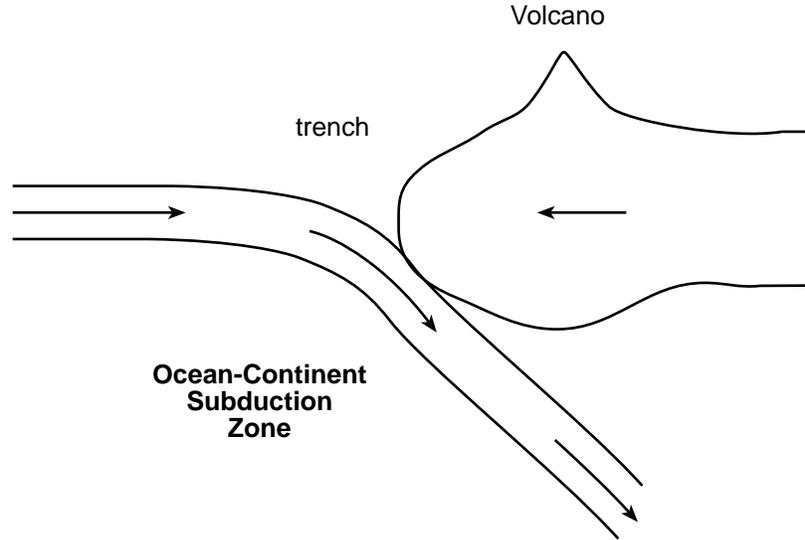
**Ocean-Ocean:** When two oceanic plates collide, one will eventually override the other, forcing the lower plate down into the asthenosphere.



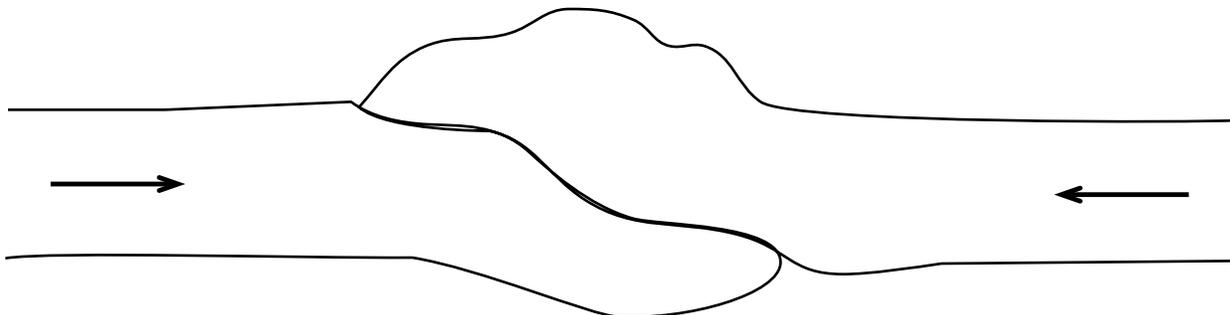
**Subduction zone:** area where one plate is forced into mantle. Volcanoes are very common on overriding plate at all subduction zones.

**Ocean Trench:** a deep trough is formed when the stiff lithosphere is forced to bend under the overriding plate. Deepest point on earth is Marianas Trench (-10 km), where Pacific Plate is forced under Philippine plate.

**Ocean-Continent:** Oceanic lithosphere is denser (and thinner) than continental lithosphere, so oceanic crust always subducts under continental crust. (Analogy: if you pushed a sheet of styrofoam against a sheet of plywood, the styrofoam would be the one to end up on top.) Once again get, subduction zone, trench, and volcanoes.



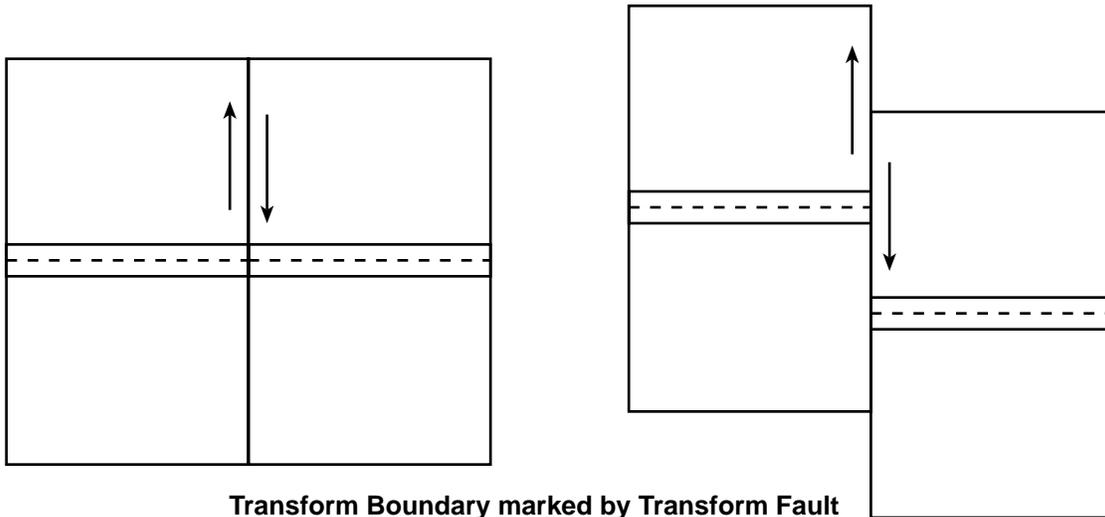
**Continent-Continent:** Continental crust is too light to be forced into the mantle. It's like trying to force a balloon under water. So, when two continents collide, they make huge mountain belts. (Analogy: Two Volkswagens collide. Front parts are compressed and wrecked, but back parts still undeformed. One may pile over the other to make a tall heap.)



**Continent-Continent Collision**

Himalayas and Alps were formed by recent collisions. The Appalachians were formed when Africa and North America bumped together ~300 Myr ago.

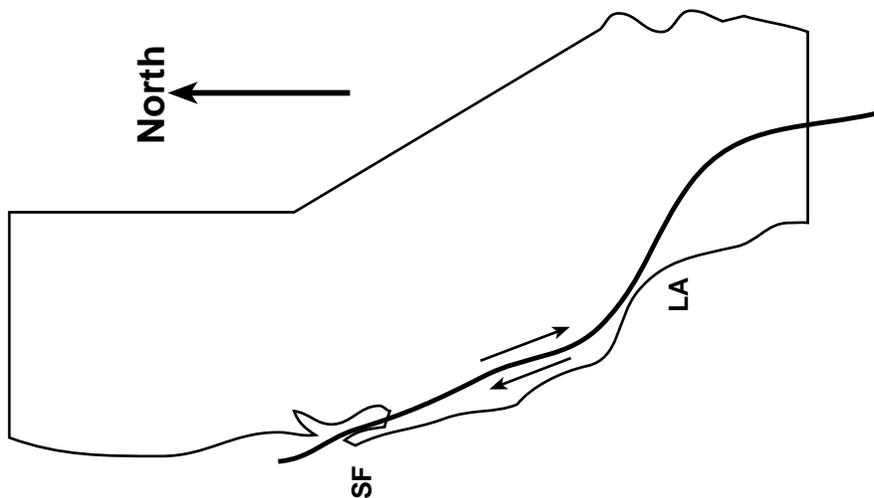
3. **Transform Plate Margins:** plates slide by one another (no lithosphere created or destroyed). **Draw.**



**Transform Boundary marked by Transform Fault**

**Transform Fault:** a fracture in rocks or crust/lithosphere where opposite sides slide by each other.

**Continent-Continent:** Best example is **San Andreas Fault (overhead)** in California. Los Angeles is moving north; eventually will join San Francisco in a big miasmic heap.



**Seafloor: (OVERHEAD)** intimately associated with divergent boundaries. Zones of divergence are often offset by transform faults when moving along ridge axis.

**Note:** I may occasionally use 'crust' when I should say 'lithosphere'! The crust is a relatively thin layer that is part of the thicker lithospheric plate. The crust does not move independently

of lithosphere. But, crust is easier to say and to write so it becomes a short-hand.

D. Map of the world's plate boundaries (**overhead**) shows that mountain belts, earthquakes, and volcanoes tend to occur near plate margins. Places where moving plates bump and grind is where most of the action is going to be!

E. Plate Motions over the past 200 Myr: The opening of the Atlantic Ocean: **OVERHEADS-Handouts-Fig's in Text**

This history is well known because we can use evidence preserved in the sea floor to work things out. The further back you go before 200 Myr, the more difficult it is to work things out. Very sketchy before about 500 Myr.

F. Planetary View: subduction zone trenches, strings of volcanoes along subduction zones, and long mountain belts are obvious planetary features that are visible from space and that scream "PLATE TECTONICS". Since we do not see such obvious features on other planets, the Earth appears to be extraordinarily active. Why is this? What is it that drives these plate motions on the Earth?

These are tough questions, and we won't get to a possible answer in this set of lectures. But, to even address these questions we need to first outline some important principles:

#### IV. Heat Transfer Out of Earth

A. **Conduction:** Heat transfer in solids (atomic vibrations). Put metal spoon on electric stove burner. Heated atoms in burner are rapidly vibrating. These vibrations are transmitted to spoon (= heats up). Vibrating atoms in hot part of spoon hit atoms in cooler part of spoon, causing this part to heat up. The heat (atomic vibrations) is thus transmitted (conducted) all the way to end of spoon.

Lithosphere: too rigid to allow convection. Thus, convection is the main way of heat transfer from interior.

-Surface = about 20°C (heat radiated from surface into atmosphere)

-Base of lithosphere = about 1200°C.

-Roughly linear increase in temperature with depth (roughly 20°C/km depth near surface). **Draw.** This rate of temperature change defined as the **geothermal gradient.**

Rock is a poor conductor of heat (= excellent insulator); thus heat loss by conduction is extremely slow. Thus, the lithosphere is an excellent blanket that keeps the interior of the planet nice and hot.

B. **Convection:** heat transfer by movement of hotter material to cooler area.

Example: Pot of water on stove (**draw**) or hot Miso soup

Water heated at base of pot ==> expands ==> less dense ==> rises upwards. When it hits top, pushed aside by rising material behind it, cools at surface (steam release) ==> contracts ==> more dense ==> sinks along sides.

**Convection Cell:** a loop created by heated material rising and cooled material sinking to be heated again.

This is a very efficient way to get rid of heat because it moves the hottest stuff (water near burner) to coolest area (top of pan next to the open air). Conduction is very inefficient because the hottest stuff is always insulated from the coolest stuff by the intervening solid.

For example: a bowl of soup rich in broth cools much more quickly than a thick stew or oatmeal (which cannot convect)

Conduction: atomic vibration in solids

Convection: physical movement of masses of hot material to cold areas

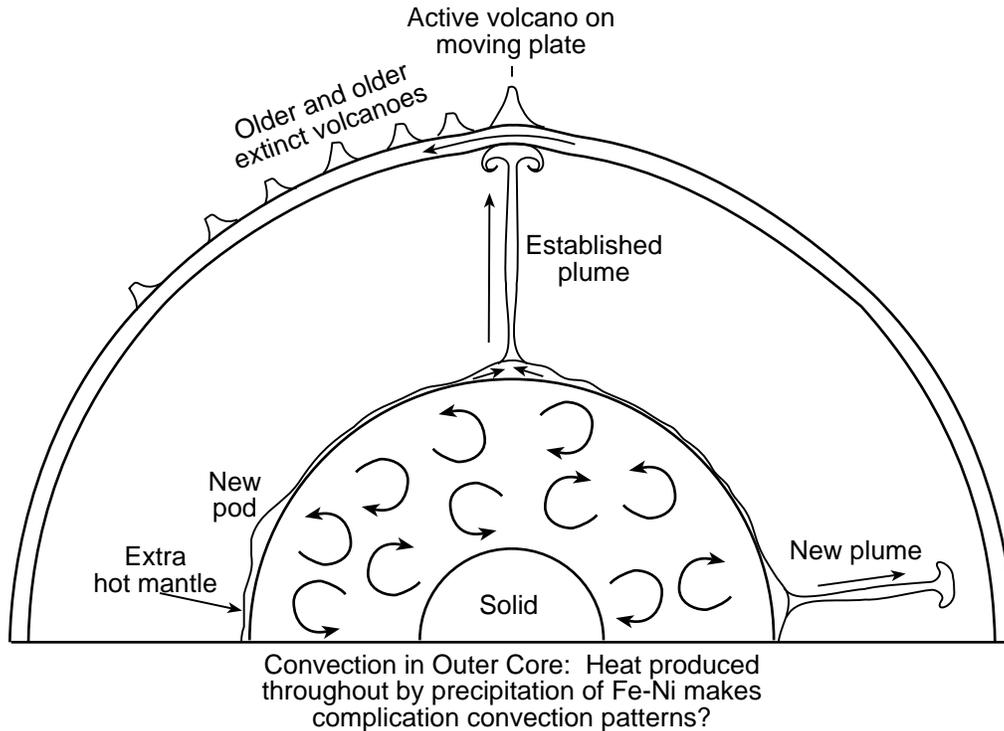
C. **Convection within the Earth:** More complicated than soup (**overhead Fig. 2.26**)

1. Mantle Plumes:

- a. Liquid outer core rapidly convects, transferring a lot of heat to the base of the mantle.
- b. Lower mantle is far too viscous (thick) to convect fast enough to remove this heat. Thus, base of mantle gets extra hot. Eventually this rock softens to where it can slowly flow to form large pods of heated, less dense soft rock at the base of the mantle.

Analogy: when you try to heat up cold stew or oatmeal on a stove, it is very easy to burn it. Stew is too thick to convect, so heat just builds up in stew at base of pot until it burns. Rest of stew may still be cold. It is tough to burn watery soup because convection rapidly transfers heat from base of pot to upper surface and thus forms convection cells.

- c. From these pods, heated rock flows upwards in narrow circular conduits towards the earth's surface. When it hits lithosphere, it is stopped. New rising material forces older stuff to flow to the side, forming a huge mushroom head at the top of the column. Column of rising hot soft rock + Mushroom head =  
**Mantle Plume**



d. Plume heads cause lithosphere to dome up. Often 2000 km across.

**Overhead: Afar Plume in east Africa**

Does stuff on edge of plume head cool and become a part of the asthenosphere, or does it sink through the asthenosphere back to lower mantle?

e. Location of plumes is marked by volcanoes. E.g., in oceans: Hawaii, Tristen de Cuna, Iceland. On land: Yellowstone National Park, Ethiopia.

There are many others. Plumes are associated with those volcanoes that do not occur along mid-ocean ridges or subduction zones.

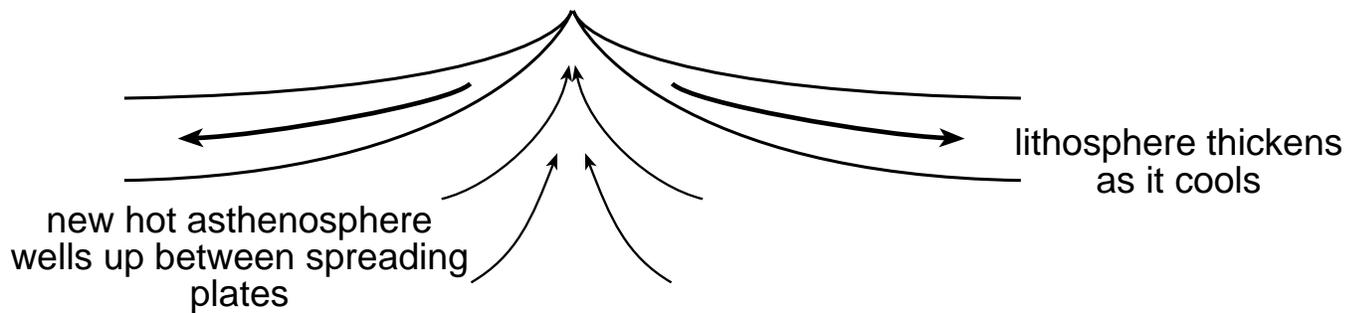
f. A cool property of plumes: since they originate so deep, they are not affected by movement of plates on Earth's surface. Most are fairly stationary.

So, as plate moves over a plume, it creates a whole string of volcanoes. Volcano over plume is active, the rest on inactive (**Overhead: Hawaiian Island chain**). In addition, as lithosphere moves off plume, it sinks as it moves away from the swell of the plume and as previously heated lithosphere cools and contracts (and thus becomes denser). Thus, see an age-progression in the Hawaiian Island volcanoes, and see that only the youngest are still above water.

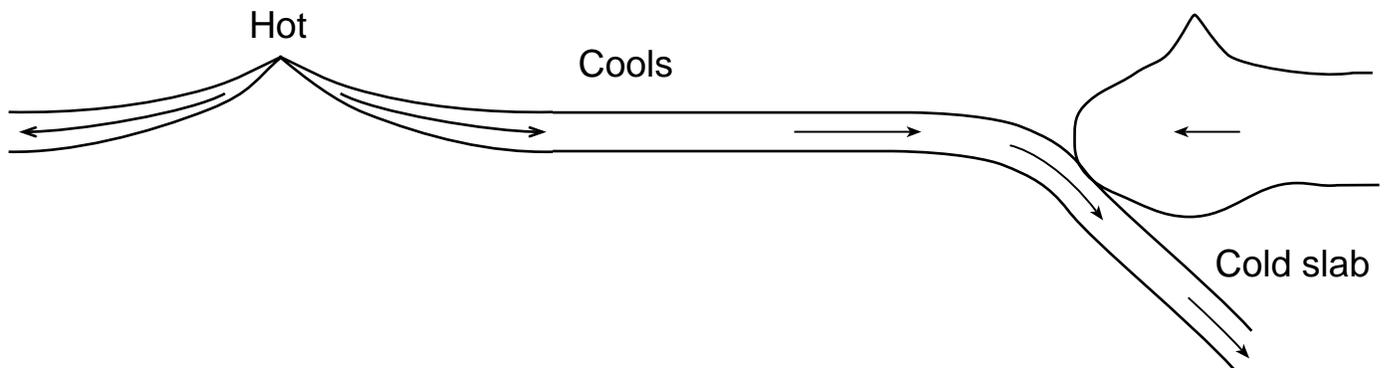
Other examples, Tristan de Cuna, other Pacific seafloor volcanic chains, Reunion and Deccan hotspots, Yellowstone (Columbia River in eastern Oregon through present-day Wyoming (Yellowstone).

2. Mantle convection is not yet precisely understood.
  - a. Based on calculations, many believe the asthenosphere is convecting. This would help transmit heat to the base of the lithosphere.
  - b. Best understood: Mid-ocean ridges

As the lithosphere pulls apart, the asthenosphere upwells to fill the gap (= convection). This upwelling also triggers volcanic eruptions, which again is the physical movement of heated material to the cool surface.



3. Return of cooled material:
  - a. Convection cells within asthenosphere?
  - b. **Subduction of oceanic crust.** Igneous rocks at mid-ocean ridges gradually cool as oceans spread. Eventually, ocean crust is subducted under oceanic crust and these cool slab of material is pushed deep into the mantle. Sinks to base of asthenosphere? Base of mantle? How long does it last as a solid?



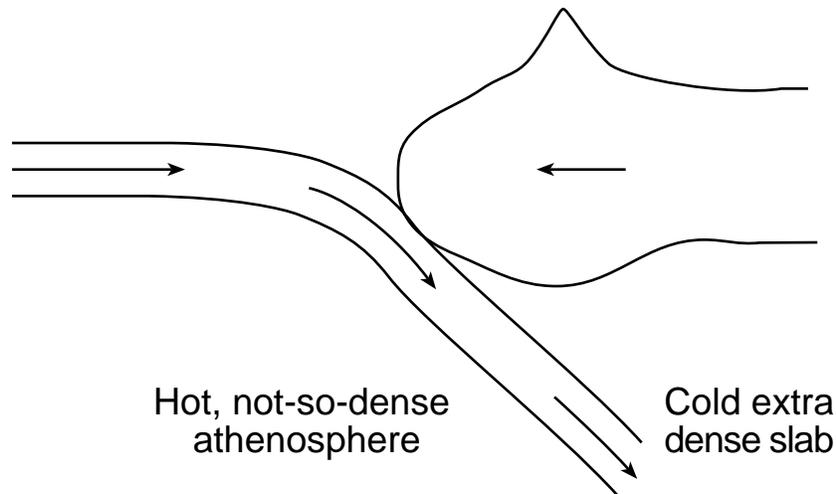
**D. Driving Forces of Plate Tectonics:** driven by convection (**overhead**)

1. **Asthenospheric convection?** NO! Most likely ten-times slower than observed plate velocities.

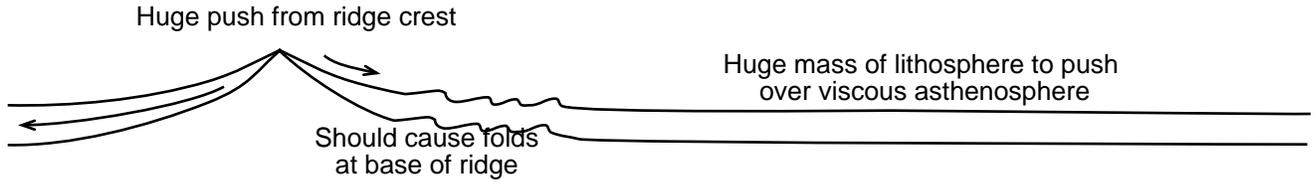
2. **Slab Pull:** a subducting slab becomes increasingly compressed by overlying rock. Although slab and surrounding mantle experience the same pressure, the slab stays cool for a long time (rock is a poor conductor so takes a long time to heat up by conduction). The cool temperatures allow high pressures to force new, more compact minerals to form in the slab: thus, whole deep slab becomes significantly denser below about 670 km depth. In the hot asthenosphere, the atomic vibrations are so high that these extra dense minerals cannot form.

Now you have a very dense slab in the midst of less dense mantle: the slab wants to sink like a rock through water! Sinking slab pulls the rest of the oceanic lithosphere with it.

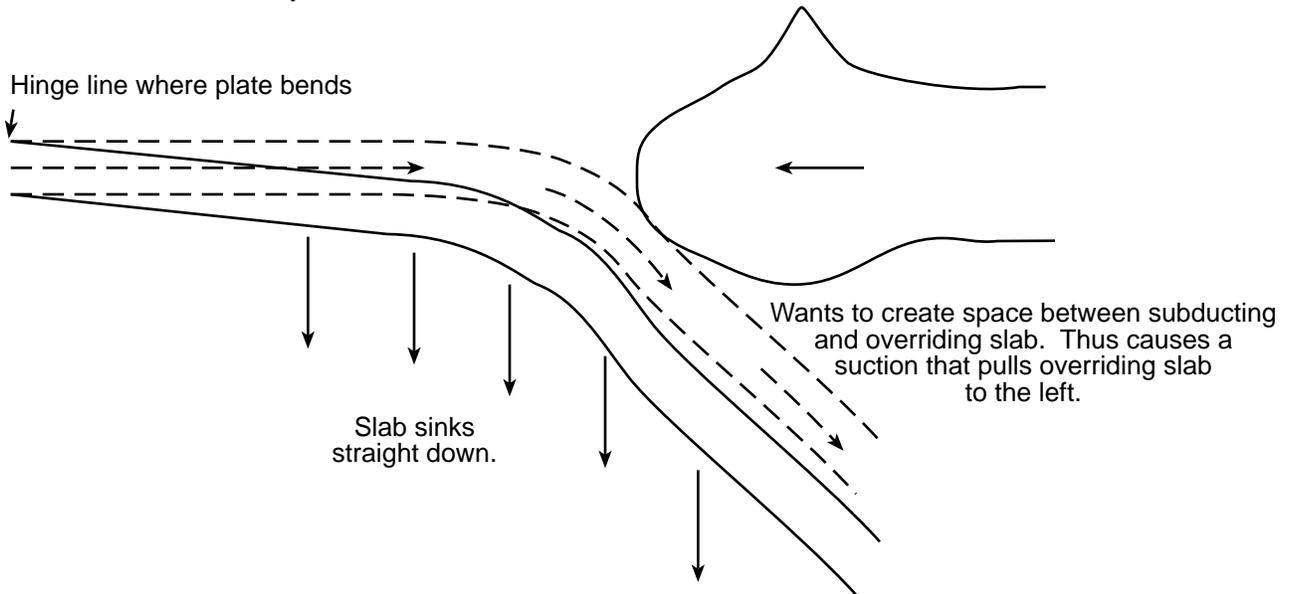
Probably most important force.



3. **Ridge Push:** lithosphere slides off bulge under mid-ocean ridge. A push from above would cause some distinctive folding and fracturing, especially where the distance from the ridge axis to the subducting slab is great. A LOT of pushing is required. But, no compression features are seen, so Ridge Push is probably not important except in a few areas.

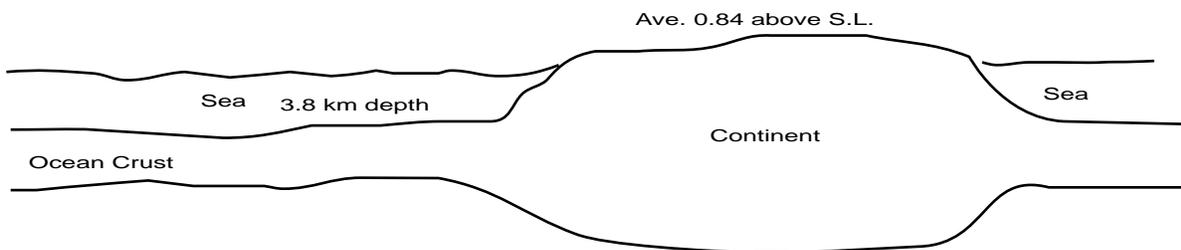


4. **Slab suction:** Some subducting slabs don't just get pulled down subduction zone, but also sink vertically. This creates vacuum right along trench and pulls overriding plate along. Analogy: sweeping a paddle towards yourself in water can bring a floating boat towards you.



V. **Isostasy!** (Chapt. 5: 124-127)

A. If we were to strip away the oceans, we would be struck by the topographic contrast between the continents and the ocean basins.



1. Average elevation of continents = 0.84 km, of oceans = 3.8 km below sea level. This is difference of 4.6 km! Tallest mountain is 8.85 km.

2. Note that the boundaries between oceans and continents are pretty sharp, topographically, and that the oceans are so full that they overlap onto the continents. The beach is thus of no special significance to the boundary between continental and oceanic crust.

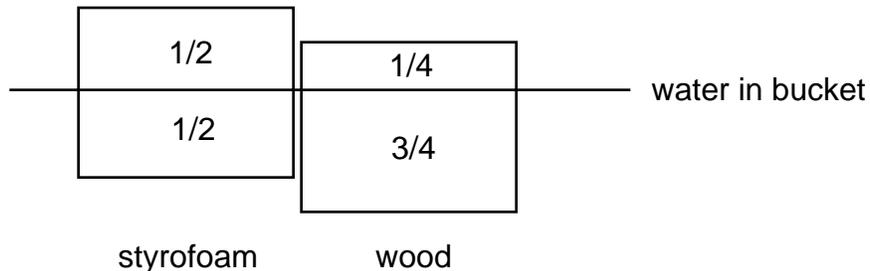
Two-fold topographic division is a very fundamental aspect of the earth.

B. What maintains this huge topographic contrast? Isostasy!

Isostasy (def. 1): a solid floating in a liquid will displace a mass of fluid equal to the mass of the solid.

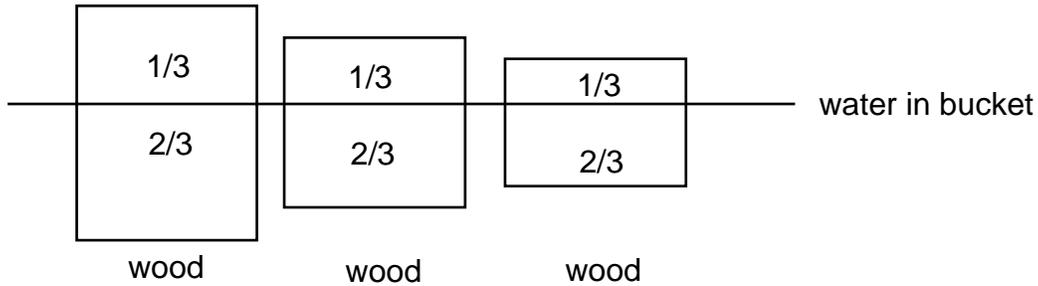
Best illustrated by two experiments that separate density and thickness:

1. Take two blocks of same thickness, but different density, e.g. styrofoam and wood, and place in bucket of water. The less dense material floats higher in the water. Since styrofoam is less dense than water, 20 g of styrofoam occupies a larger volume than 20 g of water and it rises higher.



How does gravity see this? SUM UP MASS OF WATER ABOVE A CERTAIN REFERENCE LINE! SHOW MASSES EQUAL, and that wood sinks to displace more water to get equivalent mass.

2. Now take same three blocks of same density but different thickness. Each sinks such that the same proportion rises above the water line, in this case 1/3. But the one that is taller has a deeper 'root' to allow the block to have its upper surface higher than its shorter neighbors.



### 3. Oceanic versus Continental Crust

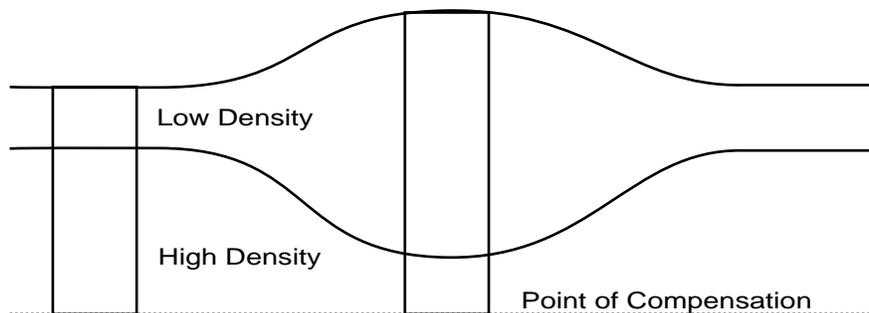
Although the upper mantle is part of the solid lithospheric plates that drift around on Earth's surface, it turns out that upper mantle rocks are able to deform and flow over very long time periods. Thus, we can regard the crust as floating in a liquid.

Since the continental crust is both thicker and lighter than the oceanic crust, it makes sense that it would ride higher on the upper mantle than the oceanic crust. Continents = thick pieces of styrofoam; oceanic crust = thin blocks of oak.

Although it seems to us that the oceanic crust has 'sunk', in fact, the deep continental roots under our feet have lifted us higher away from the mantle.

C. Geologically better view of isostasy: huge weight of continental crust is transmitted downwards until at some point in the upper mantle, there is enough flow to the side that there is no more downwards push, just the normal average pressure from the weight of rocks overhead.

Fluids do not transmit a downwards push, just equal pressure from all sides (isostatic pressure). This point in the upper mantle is called the **point of compensation**, and is a useful reference line.



In order for things to be floating in 'isostatic equilibrium' (where they ought to be), the total weight above the point of compensation has to be the same. Add together medium

density oceanic crust plus high density mantle. Must equal a thicker column of low density continental crust plus high density mantle.

D. Isostasy also explains why mountains can be so high. A tall mountain range must have a thick low-density crustal root as compared to adjacent continental crust.

**Isostatic equilibrium:** if you put a block of wood in honey, it will take some time for it to sink to where it is in equilibrium (displaces equivalent mass of honey). Similarly, mountain chains may be subsiding if collision is causing them to grow faster than their roots will support, or erosion may be removing mass, causing the mountains to rise up due to their too thick roots. (1 km removed gets about 5/6 km of **isostatic rebound**).

Also works for glaciers. Huge glaciers on Greenland, Antarctica, and 20,000 years ago on Canada and NW Europe caused continental crust to sink. Today, eastern Canada and NE U.S. and NW Europe are rising out of the sea.