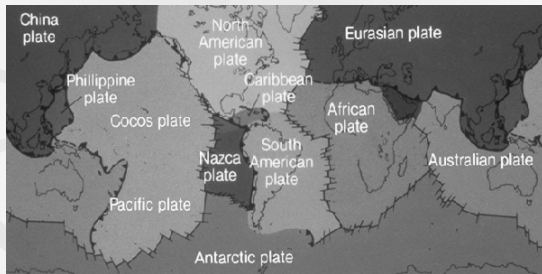


The Dancing Plates: The Plate Tectonic Revolution



How Can Rock Cycle Be Explained ?

Prior to the early 1900s, it was thought that Earth's exterior was essentially static.

The conditions necessary for the formation of the three rock classes were fairly well understood, but there was no unified explanation to explain *how* each rock class could be transformed into another.

The theory of plate tectonics provided a framework to explain the dynamics of the rock cycle, among several other things.



What is Plate Tectonics ?

Plate: A rigid slab that, together with other such slabs, comprise Earth's outer rocky shell (lithosphere)

Tectonics: A terms from Greek "*tekton*," meaning "builder."

Modern definition of plate tectonics: A theory that explains the global distribution of geological phenomena in terms of the formation, destruction, movement, and interaction of the earth's lithospheric plates.

Perhaps *the* most important scientific theory developed in geology, as it connects, or at least connected to, most of the major geological processes on Earth.

Birth of an Idea

Alfred Wegener (1880-1930)

The birth of plate tectonics is credited to German scientist Alfred Wegener.

From very simple observations of Earth's major features, Wegener concluded that over long periods of time, continents move.

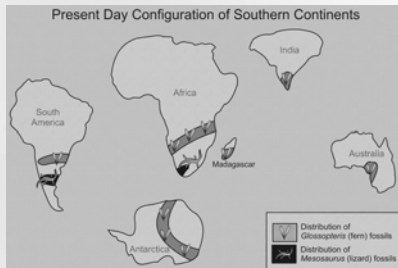


Continental Drift: Fossil Distribution

Wegener noticed that fossils of the fern *Glossopteris* were relatively common in the Southern Hemisphere continents.

Likewise, remains of the lizard *Mesosaurus* were known from South America and Africa.

How can this distribution be explained ?



Continental Drift: Jigsaw Puzzle Fit

Wegener considered the possibility that the present day distribution of these fossils resulting from the splitting up of a larger landmass.

With his observations on the distribution of Carboniferous fossils in the southern continents, the concept of a large ancient landmass became more tangible



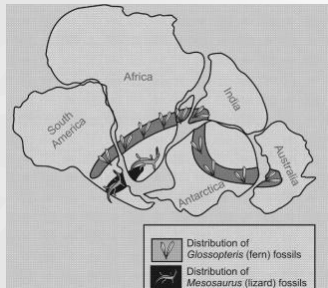
Wegener called this landmass **Pangaea** (meaning "all land")

Continental Drift: Fossil Evidence

Together with the jigsaw puzzle fit of the continents, the distribution of *Glossopteris* leaves made a good case for the notion that continents were joined in the past.

Likewise for the occurrence of the lizard *Mesosaurus* in South America and Africa.

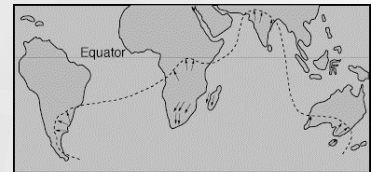
If the continents are assembled together, the distribution of fossil remains makes perfect sense !



Grooves left by Carboniferous-age have a rather haphazard orientation in the southern continents.

Ice in modern ice sheets is known to flow radially from the site of greatest ice accumulation (centre), so this doesn't agree with what the observed pattern.

Continental Drift: Evidence From Inferred Ice Flow Directions

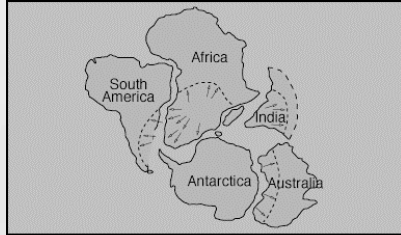


Grooves carved by glaciers (shown by arrows) provided evidence for continental drift. This diagram assumes the continents were in their present-day locations.

Also, glaciers cannot flow over water for any great distance.

Continental Drift: Evidence From Inferred Ice Flow Directions

If the southern continents are fit together, the expected radial flow pattern is obvious !



The distribution of glacial features can be best explained if the continents were part of Pangaea.

Further Evidence of Continental Drift

If the continents were joined before the Permian Period, one would expect that major geologic features that pre-dated this split-up could be traced between continents.

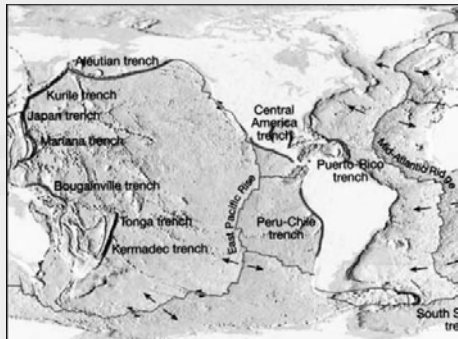
Lo and behold, it was found that the Caledonian mountains of Europe and the Appalachian mountains of North America (both pre-Permian in age) could be connected to form a continuous mountain belt.



Seafloor Topography

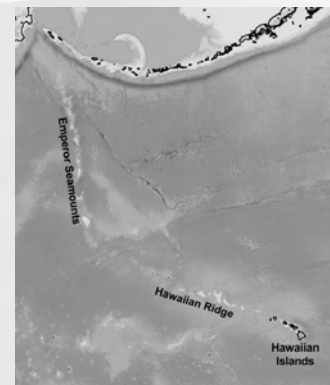
By the 1950s, sonar surveys had confirmed the existence of mountain belt-like features called *oceanic ridges* (or *mid-ocean ridges*) in the oceans.

Submarine trenches were found to occur along the margins of some landmasses.



Seafloor Topography

Furthermore, linear patterns of volcanic islands and submerged seamounts, all seemingly unrelated to trenches or mid-ocean ridges, were known.



Foundation of the Ocean Floor

Drilling and deep sea sampling also indicated that little-weathered basalt (apparently extruded recently) was exposed along the axes of mid-ocean ridges (later identified as pillow basalt). On the other hand, the basalt rock of the seafloor was obscured by sedimentary deposits progressively further away from the axes of mid-ocean ridges.

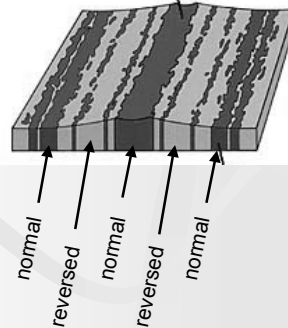


Pillow basalt, as observed recently on mid-ocean ridge

Pillows are formed when basaltic magma is extruded into water. The outer part of the lava "blob" is quenched, producing a pillow-like form.

Magnetic Stripes

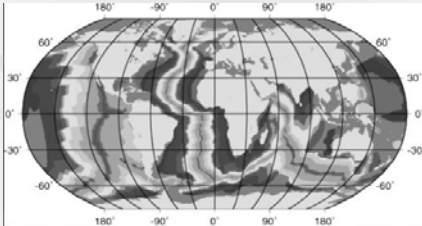
Midocean Ridge



Geophysical surveys indicated that the magnetic polarity of magnetite crystals within ocean floor rock (basalt) alternated from normal to reversed in a symmetrical pattern.

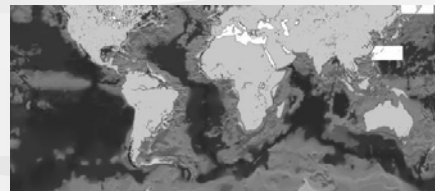
Age of Ocean Floor

Dating of ocean floor basalt also revealed a symmetrical pattern in relation to mid-ocean ridges, with the youngest ages along the crests of mid-ocean ridges and the oldest ages nearest the edges of continents (this was surprising).



The youngest regions are shown in midlines of oceans and oldest near the edges of continents.

Thickness of Oceanic Sediment



thin  thick

It was thought that the ocean basins had existed for billions of years and that the sediment layer would be very thick.

But by 1947, surveys of the ocean floor indicated that that the thickness of oceanic sediment overlying the basalt foundation increases away from the axes of mid-ocean ridges.

What Does It Mean ?

In 1962, Princeton geologist Harry Hess presented an explanation for the mid-ocean ridge system.

Harry Hess proposed that new ocean floor is formed along the axis of a mid-ocean ridge.

He explained further that new crust moved laterally away from the ridge, eventually plunging downward into a submarine trench along a continental margin.

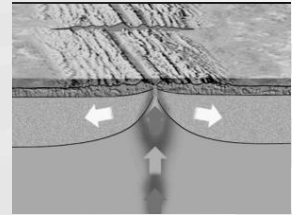


Sea-floor Spreading

Hess' hypothesis, to be later called "sea-floor spreading" formed the foundation for the concept of plate tectonics.

The sea-floor spreading hypothesis explained why seafloor basalt is youngest at the crests of mid-ocean ridges.

Magma, sourced from the mantle is injected into the central rift of a mid-ocean ridge, forming new sea-floor.

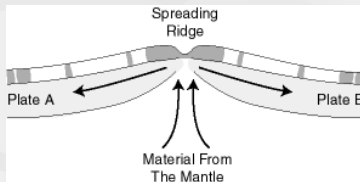


Explanation of Magnetic Stripes

As new ocean crust is formed along the axis of a mid-ocean ridge, magnetite crystals that crystallize from basaltic magma (extruded as lava) are aligned in the direction of the magnetic field.

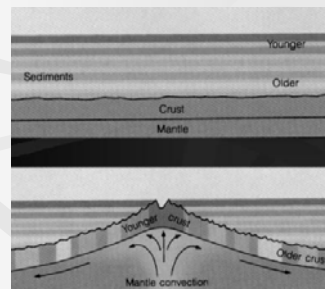
As the cools, the magnetite crystals are "frozen into place," thus preserving their orientation during the time of crystallization.

Due to the symmetrical pushing apart of new crust, a symmetrical pattern of polarity "stripes" is preserved.



Explanation of Sediment Thickness

Variations in the thickness of seafloor sediment was also explained.



Without seafloor spreading, the entire ocean would be expected to be covered with a thick blanket of oceanic sediment

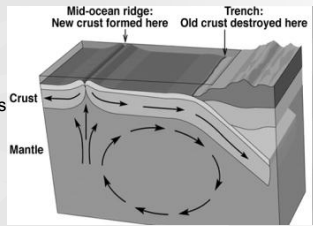
With seafloor spreading, the sediment pile would be expected to thicken away from the ridge axis (older crust is furthest away from the ridge).

Explanation of Trenches

If seafloor is made at mid-ocean ridges, it must be destroyed somewhere else (otherwise the Earth would be expanding).

To Hess, submarine trenches seemed to be the obvious places where ocean floor would be destroyed.

Here, he reasoned, the crust underlying the seafloor plunged downward (was *subducted*) under an adjacent plate to ultimately be assimilated in the mantle.

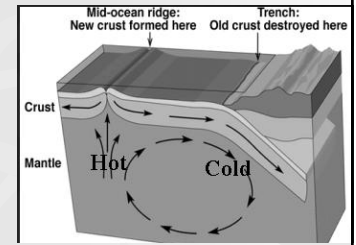


Notion of Mantle Convection

If crust is consumed by the mantle in some places and extruded from the mantle in others, there must be some form of cycling within the mantle itself.

Hess reasoned that this cycling of material was the result of mantle convection.

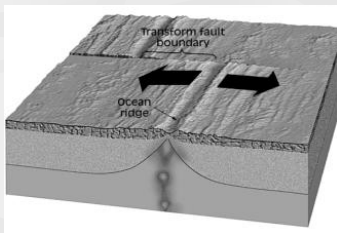
Upward-flowing currents would deliver hot magma to mid-ocean ridges, whereas downward-flowing currents would drag cold crust into the mantle at trenches.



Transform Faults

Another important scientist who contributed to the understanding of plate tectonics was J. Tuzo Wilson (University of Toronto), who first interpreted the role of transform faults.

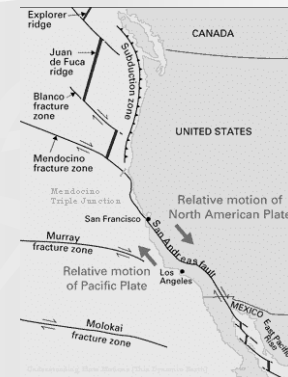
Compensating for Earth's curvature are *transform faults*, along which plates move alongside on another.



Transform Faults

Transform faults offset spreading ridges on the ocean floor

Rarely, transform faults can be seen on land (e.g. the San Andreas fault).



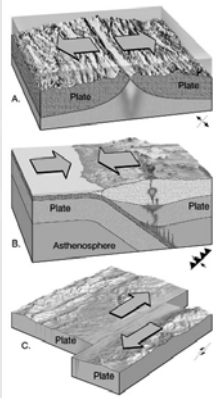
Three Types of Plate Boundaries

So...we can now refer to three basic types of plate boundaries:

A) Divergent: where two plates are moving away from each other

B) Convergent: where two plates are approaching one another

C) Transform: where two plates are moving alongside one another.



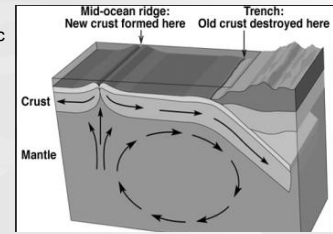
How Do Continents Fit Into the Picture ?

Dating of the oldest seafloor basalt (at trenches) has indicated that the oldest oceanic crust is only about 200 million years old (early Jurassic - very young in geological terms).

In contrast, the oldest continental crust is about 4 billion years old (4,000 million years old).

Oceanic lithosphere is constantly recycled, continental lithosphere is not.

Why ???



Oceanic and Continental Crust Are Different !

Oceanic Crust (Basaltic composition)

Average Density: 3.0 g/cm³ Average Thickness: 7 km

Continental Crust (Granitic composition)

Average Density: 2.7 g/cm³ Average Thickness: 35-40 km

Lithospheric Mantle

Average Density: 3.3 g/cm³ Average Thickness: 60 km

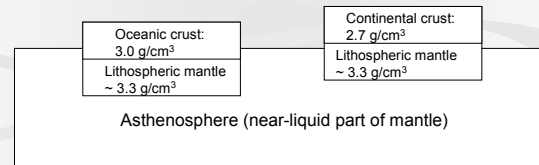
Lithosphere = crust + lithospheric mantle

The bottom line:

Continental lithosphere is lighter and thicker than Oceanic lithosphere !

Effect of Density

A slab of continental lithosphere (continental crust + lithospheric mantle) stands higher than a slab of oceanic lithosphere (containing oceanic crust) of the same dimensions.



This means:

Oceanic lithosphere floats low on asthenosphere (forms basins)

Continental lithosphere floats high on asthenosphere (forms continents)

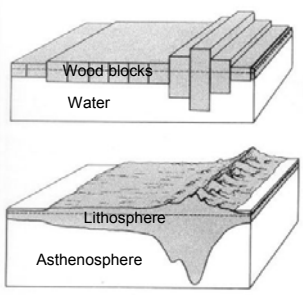
Effect of Lithospheric Thickness:

In a material of the same density, a thick block stands higher than a thin block.

Example: top surface of thick block of wood stands higher above water level than that of thin block of wood.

However, the *proportion* of material standing above and below water mark is the same for all blocks.

Likewise, thick continental lithosphere stands higher on the asthenosphere than thin oceanic lithosphere



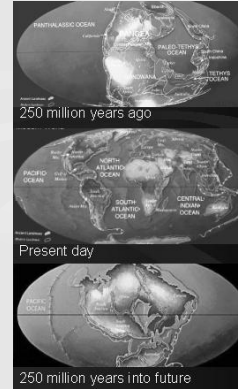
Continents are Floating Rafts

Oceanic lithosphere is continuously created and destroyed (so is quite young)

However, slabs of continental lithosphere float like rafts.

Continental lithosphere *can never be completely assimilated back into the mantle* (it is too buoyant).

Consequently, continents contain old rocks (up to about 4 billion years old).



Several lithospheric plates are now recognized on Earth's surface

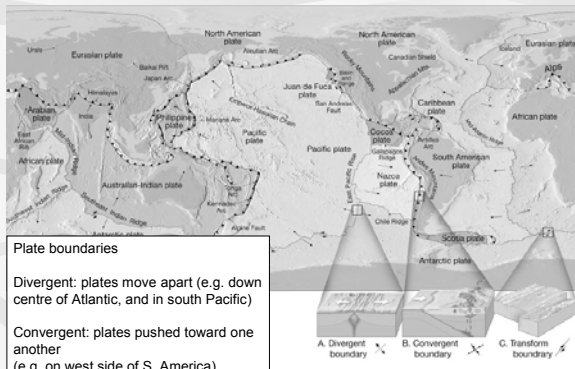


Plate boundaries

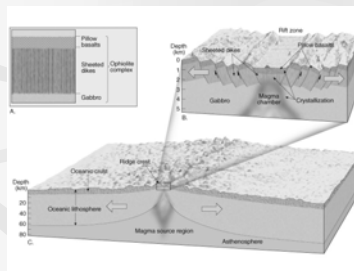
Divergent: plates move apart (e.g. down centre of Atlantic, and in south Pacific)

Convergent: plates pushed toward one another (e.g. on west side of S. America)

Transform: plates slide alongside one another (e.g. San Andreas fault)

Divergent Plate Boundaries:

Divergent plate boundaries are where seafloor spreading occurs, producing new oceanic crust. "Runny" mafic magma sourced from the mantle intruded into fractures as plates are move apart. New oceanic crust is made, so this type of boundary is said to be "constructive" or to represent a "spreading centre."



Upper crust of oceanic plate is made of basalt (aphanitic mafic rock)

Lower part of crust is made of gabbro (phaneritic mafic rock)

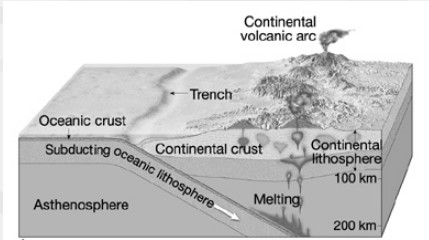
So same composition of magma (from molten mantle), but different textures.

Ocean basins ultimately originate when continental landmasses split apart

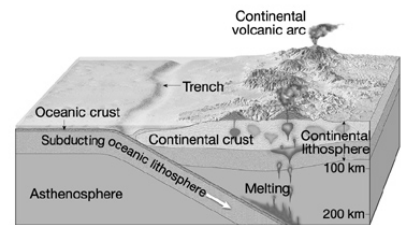
Convergent Plate Boundaries

Zones where lithospheric plates move toward one another and where oceanic lithosphere is consumed back into the mantle. Because oceanic lithosphere is destroyed, convergent plate boundaries are commonly called "destructive" plate boundaries or "subduction zones."

A slab of oceanic lithosphere can be subducted under continental lithosphere or another slab of oceanic lithosphere.



Convergent Plate Boundaries

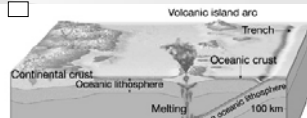


At the surface, igneous rocks include pyroclastic deposits and andesite or rhyolite.

At depth, the magma cools slowly to produce diorite or granite.

Magma at a convergent boundary is produced by the partial melting of the downgoing (subducted) slab of waterlogged oceanic lithosphere. The magma produced tends to be intermediate to felsic (rich in light-coloured minerals such as quartz) and very thick and sticky – this is why volcanoes at convergent boundaries (e.g. Mt. St. Helens) are explosive.

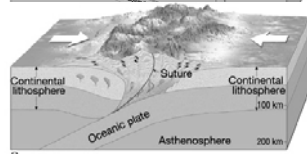
Types of Convergent Plate Boundaries



Oceanic-oceanic convergence
-subduction of oceanic lithosphere under another plate of oceanic lithosphere
-molten material from subducting slab rises to form an island arc (e.g. Japan)



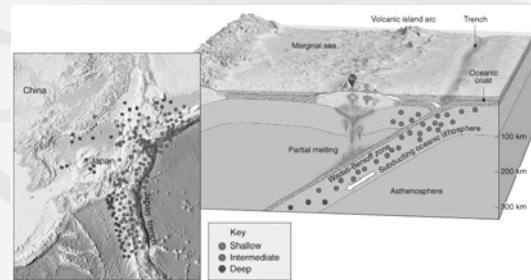
Oceanic-continental convergence
-subduction of oceanic lithosphere under a plate of continental lithosphere
-molten material from subducting slab rises to form a continental arc (e.g. Cascades with Mt. St. Helens)



Continent-continent collision
-where two pieces of continental lithosphere meet (intervening ocean becomes completely closed)
-continental lithosphere can't be subducted, so basically shortens
-Earth's highest mountain belts produced in this way (e.g. Himalayas)

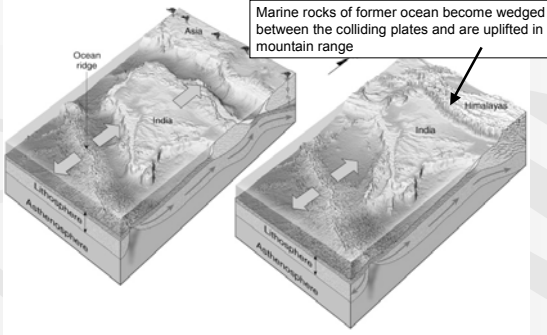
Evidence of Subduction

Areas with most severe earthquakes (indicating severe compression and subsequent release of energy)
-focal points of earthquakes are deeper inboard of the trench
-the oblique array of earthquake occurrences that indicate the position of the descending slab is called a "Wadati-Benioff" zone (but you don't have to remember this name).



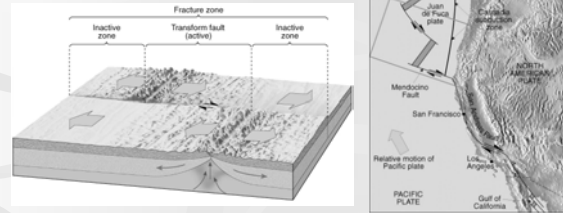
Subduction Leading to Collision

Rocks of oceanic origin found high and dry in the largest mountain ranges



Transform Plate Boundaries

Zones where lithospheric plates move alongside one another
No oceanic lithosphere is created or destroyed (sometimes called "strike-slip" boundaries)



Most common in oceanic lithosphere of ocean basins (offset segments of divergent plate boundaries)
Sometimes occur in continental lithosphere (e.g. San Andreas fault)

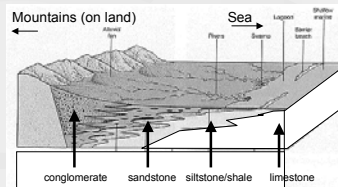
No magma is generated in this type of boundary

Other geologic consequences of plate tectonics

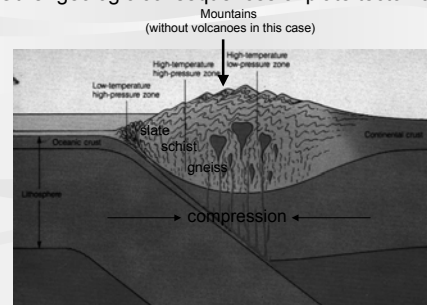
Clastic sediments are derived from wearing-down of mountains that ultimately owe their existence to the convergence of plates (remember how mountains are formed when stuff between plates gets crumpled).

If a mountain chain is close to the sea a "clastic wedge" can form (more on this in next lecture):

- conglomerates generally occur on land, close to the mountains
- sands occur close to the shoreline
- mud (silt + clay) is generally deposited offshore
- beyond the reach of mud (i.e. where water is clear), limestone can be deposited on a "carbonate platform"



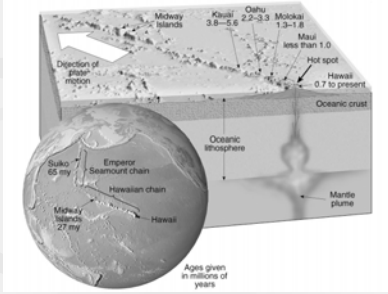
Other geologic consequences of plate tectonics



Compression created by converging plates, together with heating of rock as the crust is thickened and lowered downward produces regional metamorphism (metamorphic grade increases with depth)

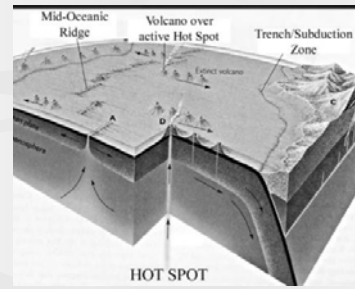
Hotspot Volcanoes

Tracks of *hotspot volcanoes* are produced by movement of plate over stationary magma plume from a point source of heat in the mantle. These are formed independently from volcanoes at divergent and convergent boundaries, and can actually occur in the stable interior of a plate.

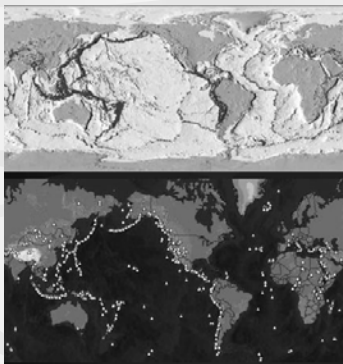


Hotspot Volcanoes

Heights of hotspot volcanoes decrease with increasing distance from point of active volcanism (due to sinking of lithospheric material as it cools and becomes more dense)



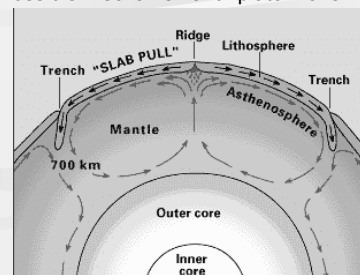
It's So Obvious Now !



Epicentres of Earthquakes follow plate boundary pattern

Volcanoes also follow plate boundaries (extra localities represent hot spot volcanoes)

Possible Mechanisms for plate movement



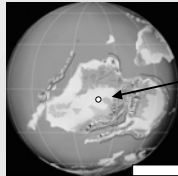
- Convection (plates move in response to convection in mantle) ?
- Ridge push (plates forced apart at divergent boundaries by injection of magma at spreading ridges ?
- Slab pull (oceanic plates dragged down at convergent boundaries due to increasing density as they cool) ?
- Or...combination of these ?

Implications for the History of Life

Climatic change

For example, remember that Ontario was once in the tropics.

Continental drift causes long-term changes in environmental conditions on the continents (e.g. temperature), as well as in the oceans (e.g. flow directions of oceanic currents).



London, Ontario

Earth, 430 million years ago

Implications for Evolution

Plate tectonics produces barriers for migration (= genetic isolation)

Oceans are barriers for land life

Land masses are barriers for marine life



Plate tectonics can also remove barriers

Connections between seas/oceans allow interchange of marine organisms

Connections between landmasses allow interchange of land organisms



End of lecture