ESS2222H

Tectonics and Planetary Dynamics
Lecture 2

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Plate Tectonics Theory

Plate Tectonics

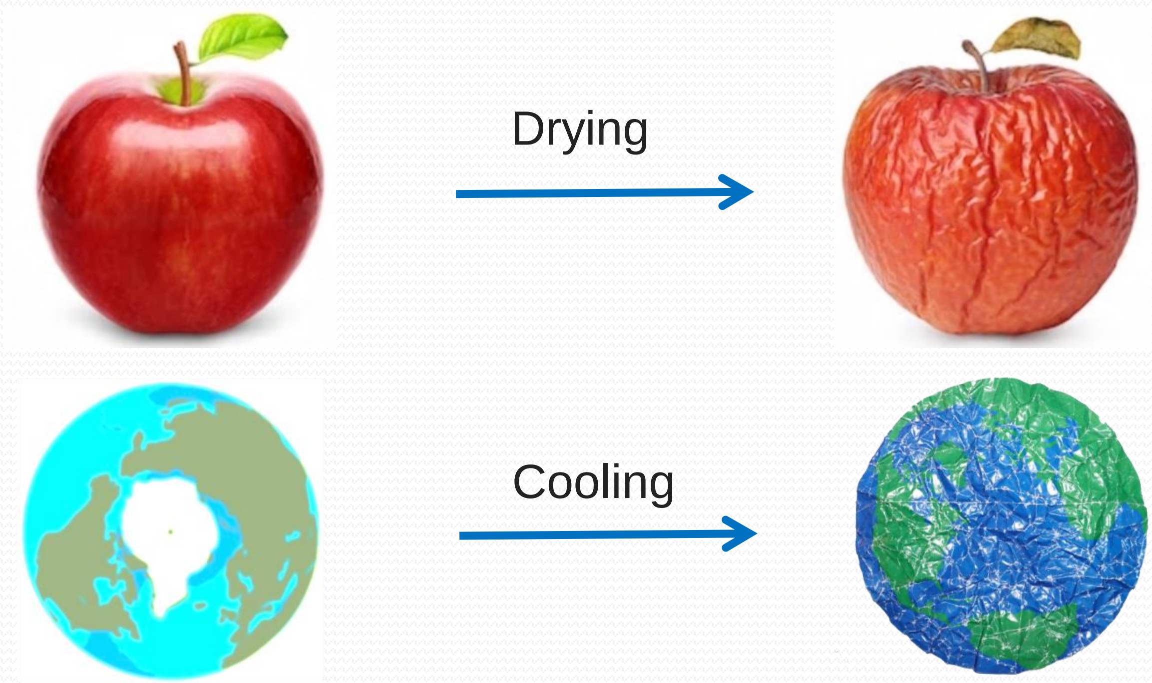
Plate tectonics explains the features and movement of Earth's surface in the present and the past. It is a **unifying** model that attempts to explain:

- ❑ Continental drift, and mid-ocean ridges activities
- ❑ Formation of mountain ranges and oceanic basins
- ❑ The origin of patterns of deformation in the crust
- ❑ Earthquake and volcano distributions
- ❑ A mechanism for the Earth to cool
- ❑ Reconstructing the Earth’s past continents and oceans
- ❑ The influence of plate interactions on atmosphere and climate
- ❑ Magnetic field of Earth

Early Theories

Contraction Theory

In early **nineteenth** century geologists believed the Earth had **cooled** from a molten mass. Mountains, valleys and folded rocks were the consequence of **crumpling** of the rigid crust as it cooled and contracted.



19th-century geology

Early Theories
Contraction Theory

Austrian geologist Edward Suess (1831-1914):

1) As the planet contracted, its surface wrinkled to accommodate the diminished surface area.

2) Suess assumed that Earth's initial crust was continuous, but broke apart as the interior shrunk.

3) The collapsed portions formed the ocean basins.

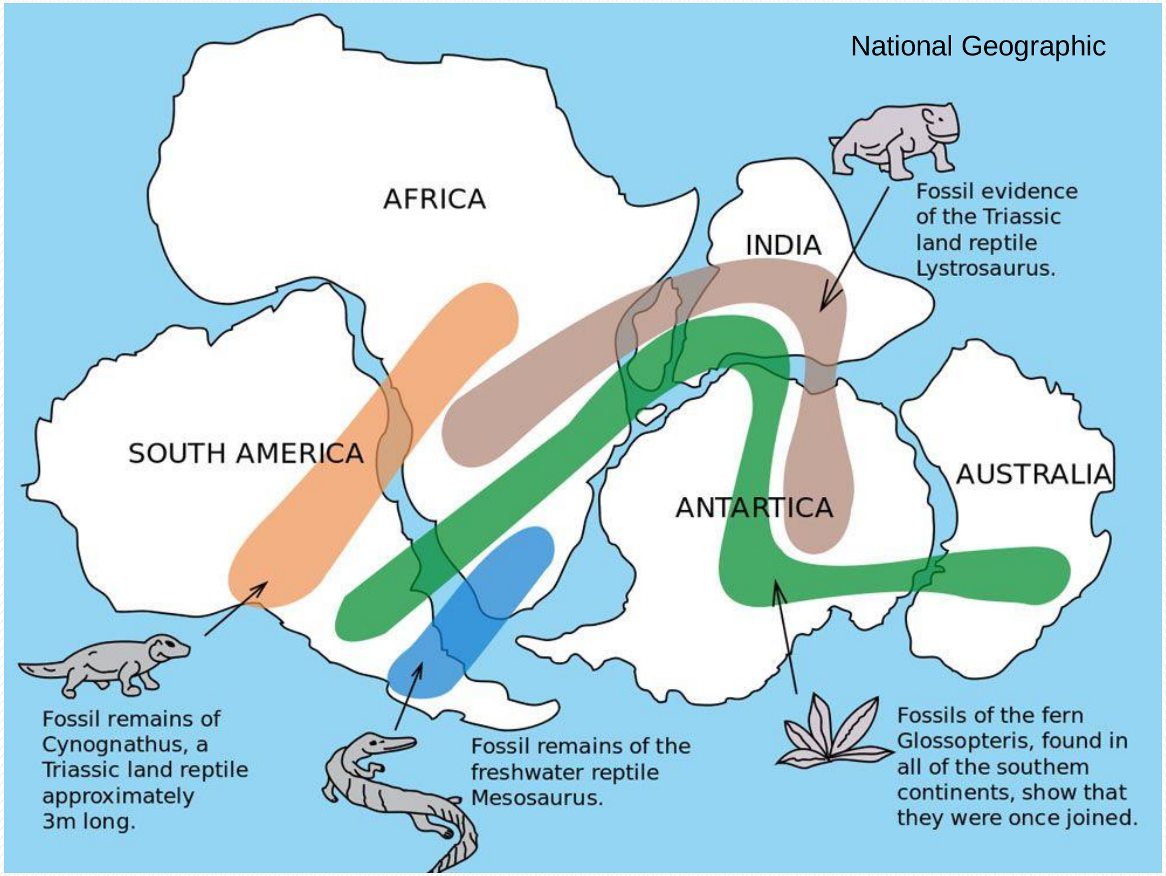
4) The remaining elevated portions formed the continents.

5) With continued cooling, the original continents became unstable and collapsed to form the next generation of ocean floor, and what had formerly been ocean now became dry land.

6) Over the course of geological history, there would be a continual interchange of land and sea, a periodic rearrangement of the land masses.

Contraction Theory
Jigsaw-Puzzle

Since the 19th century, geologists have known that some **fossil plants and animals** are extraordinarily similar across the globe, and some sequences of rock formations in distant continents are also strikingly alike. And the coastlines of different continents **fit together** like pieces of a **jigsaw puzzle**.



Contraction Theory
Theory of Gondwanaland

Suess explained these **similarities** (which were **problematic with Darwin's theory** of evolution) by attributing these similar species to an early geological age when the continents were contiguous in an ancient supercontinent called **Gondwanaland**.

Gondwanaland theory proposed by Suess account for these **similarities**: that a giant **supercontinent** had once covered much or all of Earth's surface before breaking apart to form continents and ocean basins.

Suess believed that huge **transverse forces** operated to push continental crust **sideways**, producing large-scale movements and immense folds.

And the only way to account for such **lateral forces** was to conclude that the earth was **slowly contracting**, leaving the crust too big for its foundation, leading to subsidence and lateral compression.

Contraction Theory
Two Step Solidification

James Dwight Dana (1813-1895):

1) Dana suggested that the continents had formed early in earth history, when minerals such as quartz and feldspar had (first) solidified.

2) Then the globe continued to cool and contract, until minerals such as olivine and pyroxene finally solidified: on the moon, to form the lunar craters; on Earth, to form the ocean basins (**unequal** contracting).

3) As contraction continued after Earth was solid, its surface began to deform.

4) The boundaries between continents and oceans took up most of the pressure and mountains began to form along continental margins.

Contraction Theory
Another Version

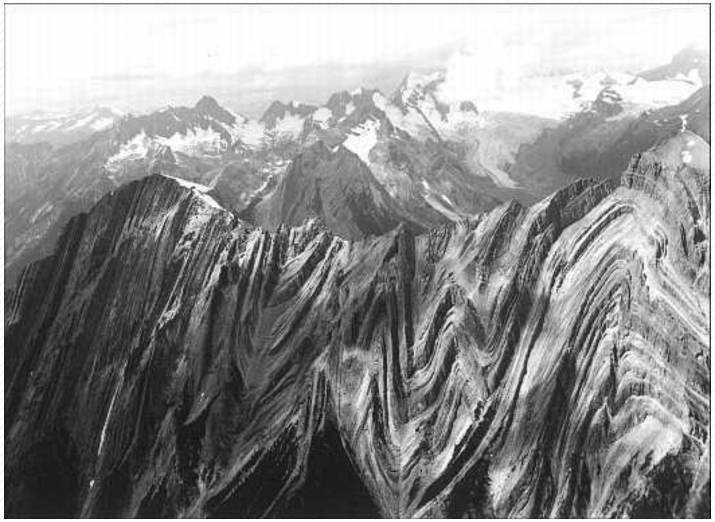
5) With continued contraction came continued deformation, but with the continents and oceans always in the same relative positions (permanent locations).

6) Climates and currents of the ocean also influences the evolution of the continents

Although Dana's theory was a version of contraction, it came to be known as **permanence theory**, because it viewed continents and oceans as globally permanent features.

Problems with the Contraction Theory

1) **Evidence from folded rocks -** Nineteenth-century geologists had worked in great detail to determine the structure of mountain belts, particularly the Swiss Alps and the North American Appalachians. When they mapped the folded sequences of rocks in these regions, they found the folds to be so extensive that if one could unfold them the rock layers would extend for hundreds of miles. Impossibly huge amounts of terrestrial contraction would have to be involved. Geologists began to doubt contraction theory as an explanation for the origins of mountains.



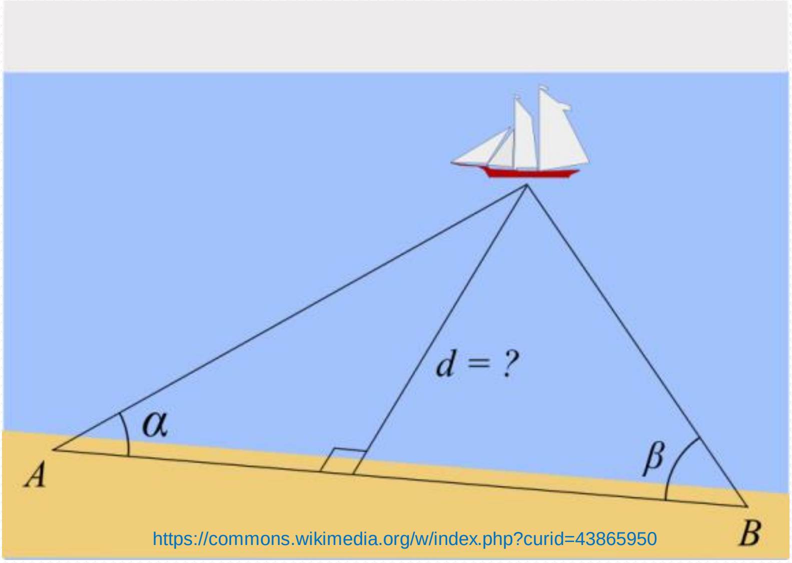
Problems with the Contraction Theory

2) **Evidence from geodesy -** A **discrepancy** in the measured distance between two stations, Kaliana and Kalianpur, 370 miles (600 kilometers) apart when measured:

a) On the basis of surveyor's triangulations and

b) On the basis of astronomical observation.

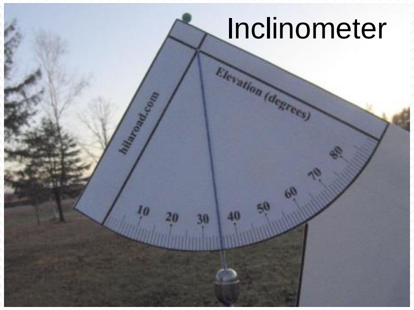
$$l = \frac{d}{\tan\alpha} + \frac{d}{tna\ \beta}$$



Problems with the Contraction Theory

The difference was thought to be due to the gravitational attraction of the Himalayas on the surveyors' plumb bobs. **John Pratt** (1809-1871) a Cambridge-trained mathematician and the archdeacon of Calcutta, was enlisted to examine the problem.

Pratt proposed that: The observed effects could be explained if the surface topography of the mountains were somehow compensated by a deficit of mass beneath them-an idea that came to be known as isostasy.



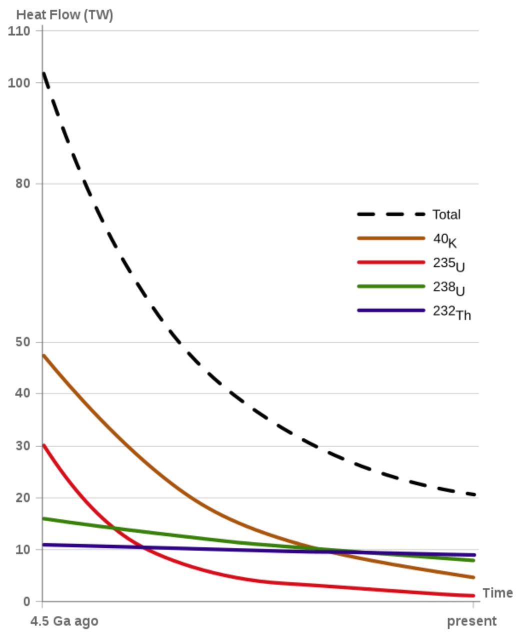
Problems with the Contraction Theory

3) **Extensional features** - Rift valleys (with steep sides and a flat floors) form where the Earth's crust spread or split apart. These features cannot be explained with contraction theory.

4) **Most fundamental problem -** Physicists discovered radiogenic heat, which contradicted the basic assumption of contraction theory that the earth was steadily cooling.

An estimate of the present-day major heat-producing isotopes[2]

Isotope	Heat release $\frac{W}{\text{kg isotope}}$	Half-life years	Mean mantle concentration $\frac{\text{kg isotope}}{\text{kg mantle}}$	Heat release $\frac{W}{\text{kg mantle}}$
^{232}Th	26.4×10^{-6}	14.0×10^{9}	124×10^{-9}	3.27×10^{-12}
^{238}U	94.6×10^{-6}	4.47×10^{9}	30.8×10^{-9}	2.91×10^{-12}
^{40}K	29.2×10^{-6}	1.25×10^{9}	36.9×10^{-9}	1.08×10^{-12}
^{235}U	569×10^{-6}	0.704×10^{9}	0.22×10^{-9}	0.125×10^{-12}



The Theory of Continental Drift

In 1912 German meteorologist Alfred Wegener (Nov. 1880–Nov. 1930) suggested an alternative explanation:

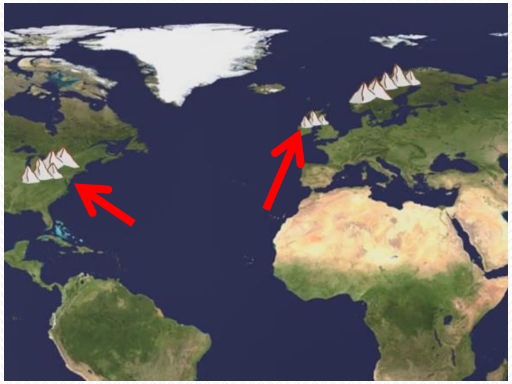
Continental drift

His hypothesis was controversial and not widely accepted until the 1950s, when numerous discoveries such as palaeomagnetism provided strong support for continental drift, and thereby a substantial basis for today's model of plate tectonics.

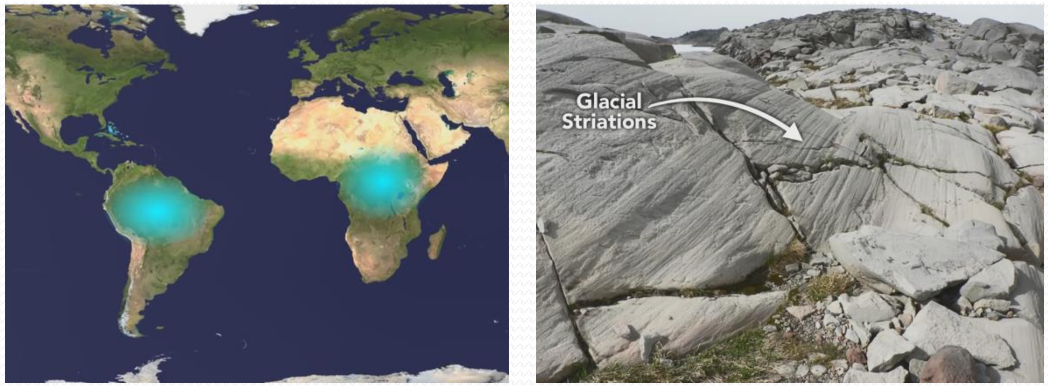
The paleontological patterns and jigsaw-puzzle fit could be explained if the continents had migrated across the earth's surface, sometimes joining together, sometimes breaking apart.

Evidence

I. The apparent fit of the coastlines of the continents
II. Fossil correlation
III. Rock and mountain correlation, similarity of mountain ranges, rock sequences, the same types of rocks and the same age of rocks
IV. Paleoclimate data – a) Glacial striations found in the bedrock in the tropical rainforests,– b) Coal deposits (formed by tropical plants) found in cold regions.



Evidence

(a) 

(b) 

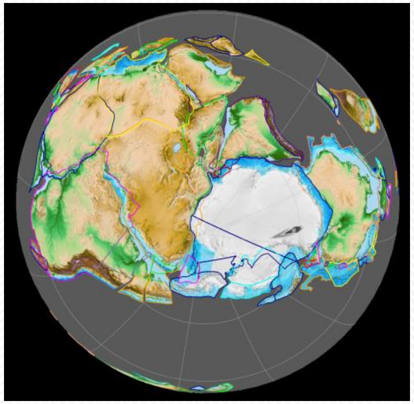
a) Glacial striations, b) Coal deposits

The Theory of Continental Drift

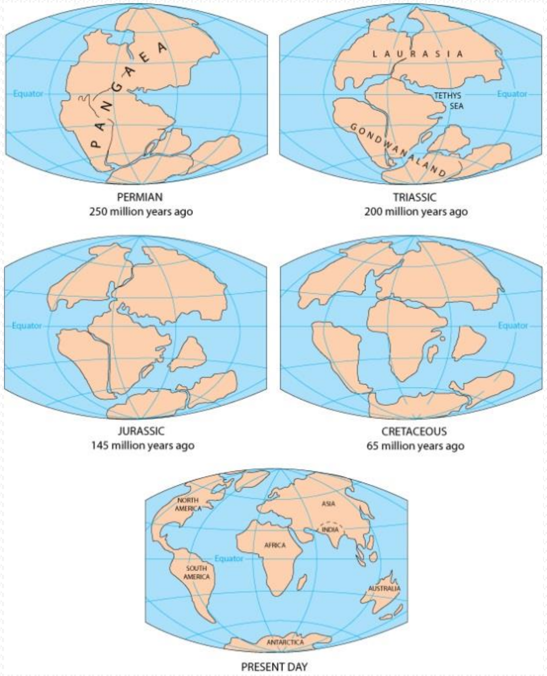
Wegener argued that for several hundred million years during the **late Paleozoic** and Mesozoic eras (200 million to 300 million years ago), the continents were united into a supercontinent that he labeled Pangea (all Earth).

Continental drift would also explain **paleoclimate** change, as continents drifted through **different climate zones** and ocean circulation was altered by the changing **distribution** of **land and sea,** while the interactions of **rifting** and **drifting** land masses provided a mechanism for the origins of **mountains**, **volcanoes**, and **earthquakes**.

Pangea, the most recent supercontinent, attained its condition of maximum packing at ~250 Ma. At this time, it consisted of a northern part, **Laurasia**, and a southern part, **Gondwana**. Gondwana contained the southern continents—South America, Africa, India, Madagascar, Australia, and Antarctica (Continents and supercontinents - John J. W. Rogers and M. Santosh).



Gondwana 420 Ma (Paleozoic Era 541–251.902 Ma)

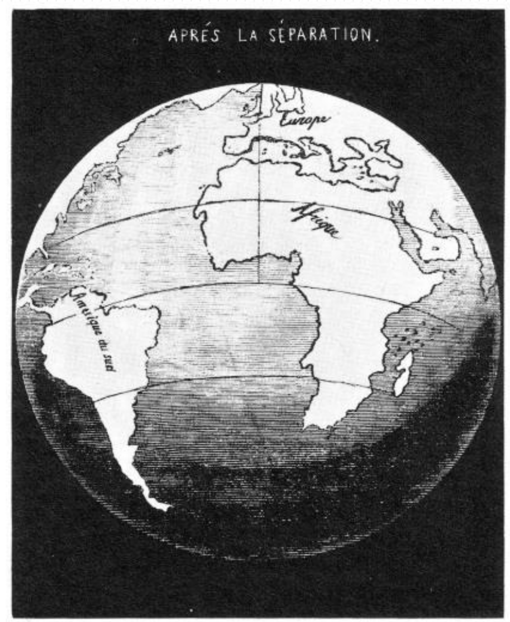


Pangaea: All the Earth

Theory of the Continental Drift

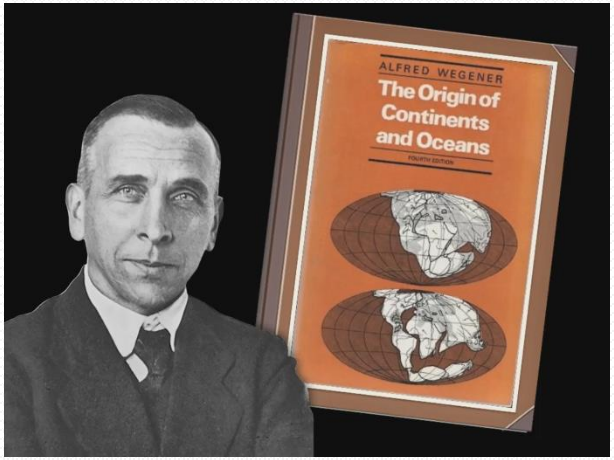
Antonio Snider-Pellegrini (1802–1885) was a French geographer and scientist who theorized about the possibility of continental drift, anticipating **Wegener's** theories concerning Pangaea by several decades.

He proposed that all of the continents were once connected together during the Pennsylvanian Period (323-299 Ma). He based this theory on the fact that he had found **plant fossils** in both **Europe** and the **North America** that were identical. He found matching fossils on all of the continents.



Expedition to the North Pole for More Evidence

Wegener could not explain what force was driving the motion of the continents and what the supercontinent ripped apart and what caused the accretion of the continents to form a supercontinent.



The body of Alfred Wegener, the founder of the theory of continental drift, remains buried under the Greenland snow.

Theory of the Continental Drift

Alexander Logie du Toit was supporter of **Alfred Wegener's theory** of continental drift documented in his book: **Our Wandering Continents**; An Hypotheses of Continental Drifting, in which he proposed the theory of **two super continents** separated by **one ocean**, colliding to form Pangea.

The **lack** of a applicable and feasible mechanism for the plates motion **delayed** the acceptance of this theory for 40 years.

Strong evidence from palaeomagnetism

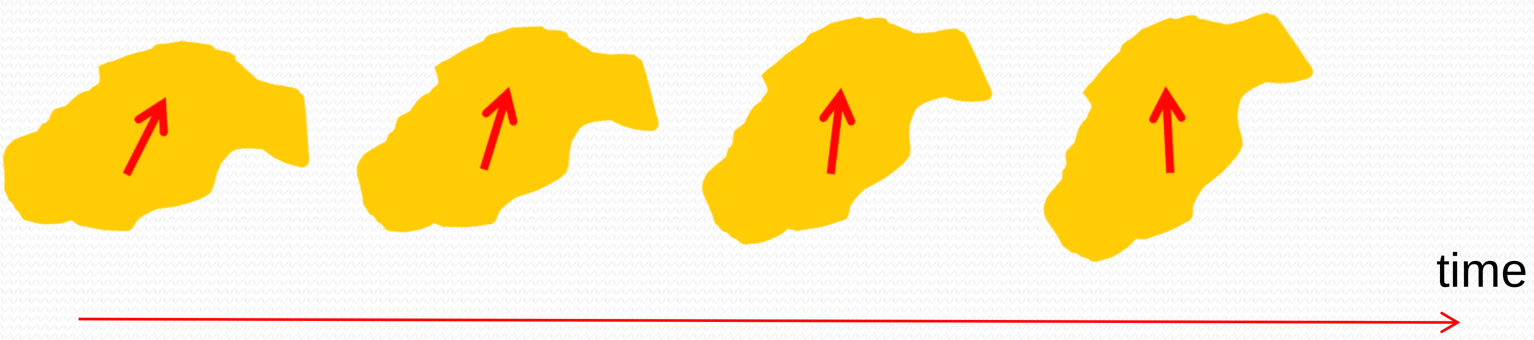
By the 1960s, paleomagnetic studies of rocks had provided strong evidence for continental drift.

Palaeomagnetism

Ppalaeomagnetism, is the study of the magnetic records in rocks, sediments, and archaeological materials. The **direction** and **intensity** of the magnetic field of Earth are recorded in minerals when fall below their Curie point (580°C for magnetite). Lavas or sediments become permanent magnets (preserving signature of the ambient magnetic field at the time of deposition) which provide valuable information about **Earth's magnetic field**, **motion** and **locations** of **tectonic plates**.

The recorded magnetic polarity points towards the **paleopoles** and deviations from the present magnetic pole location is a **superposition** of the change in the location of the Earth's magnetic pole and the plate motion.

The geologists in the mid of twentieth century used this concepts to calculate the **apparent polar wander curves**.

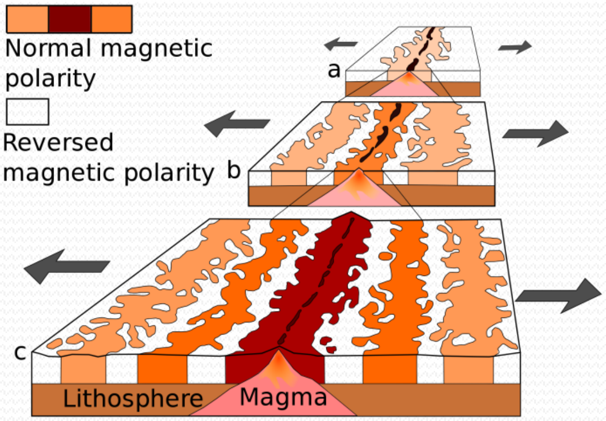


Geomagnetic Reversal

A geomagnetic reversal is a change in a Earth's magnetic field where the **north** and **south** magnetic poles are **interchanged**. During the last **83 million years** there have been **183 geomagnetic reversals**.

Seafloor magnetic anomalies

The studies in 60's revealed alternating bands of magnetic polarity on the ocean floor which were symmetrical about ocean ridges.



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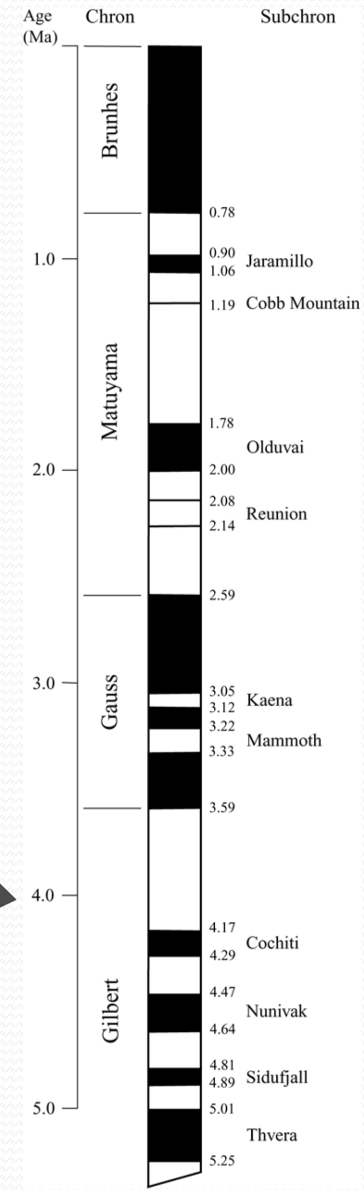

Geomagnetic polarity during the last 5 million years (Pliocene and Quaternary, late Cenozoic Era). Dark areas denote periods where the polarity matches today's normal polarity; light areas denote periods where that polarity is reversed.

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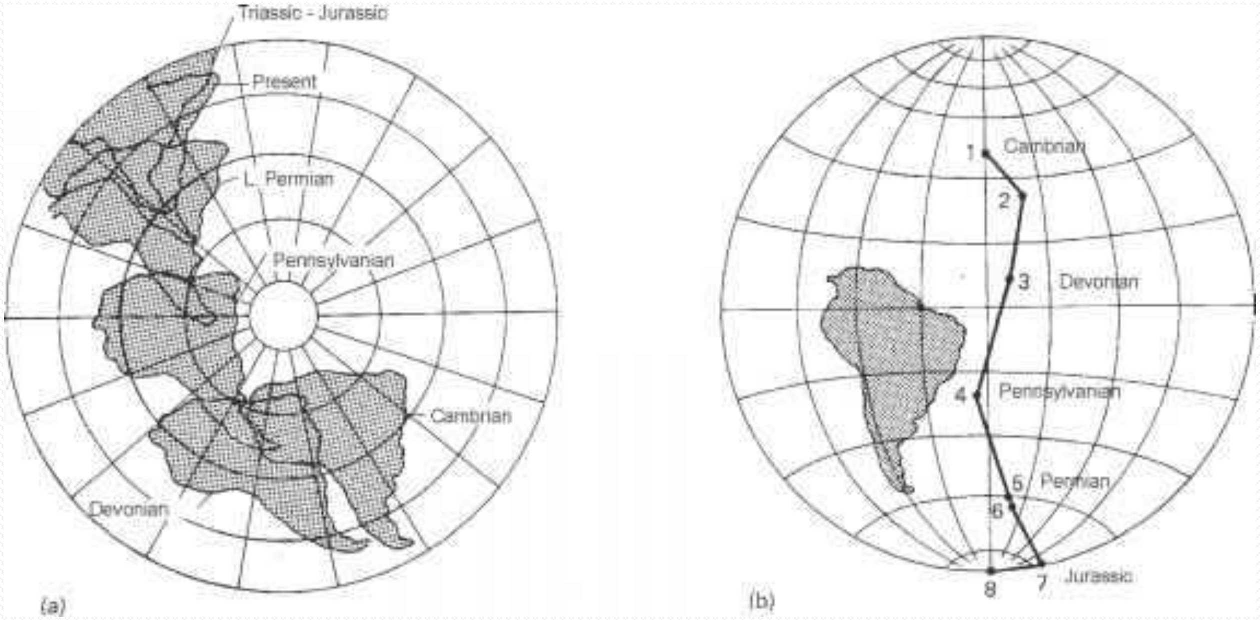
Apparent polar wander

Apparent polar wander (APW) is the perceived movement of the Earth's **paleomagnetic poles** relative to a continent (the continent being studied as fixed in position).



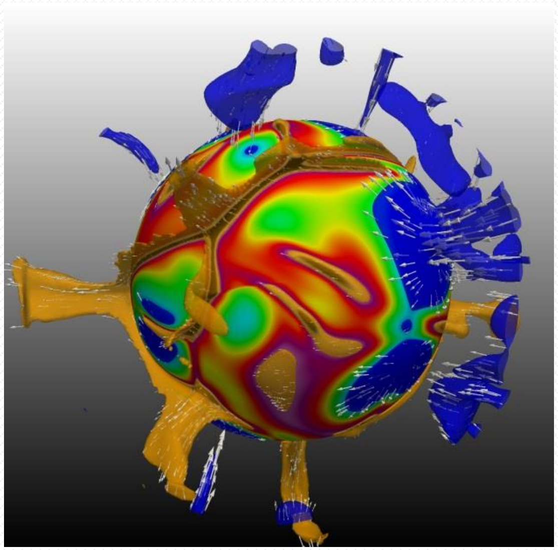
Two different representation of paleomagnetic data
a) assuming fixed magnetic poles
b) assuming a fixed continent and plotting a polar wander path (APW)
(Paleomagnetic data from the Gondwanic continents; K.M. Creer, 1965)

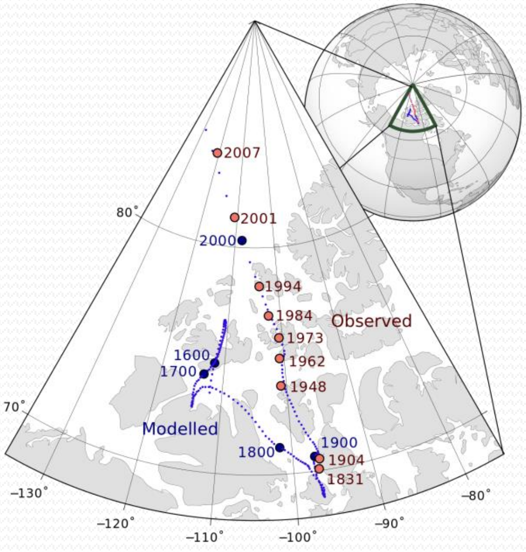
Polar wander

Polar wander is the motion of a pole with respect to a reference frame.
Ex. – The motion of Earth's magnetic north pole relative to the Earth's rotation axis.

True Polar wander

True polar wander represents the motion of the **geographical** poles relative to Earth's surface (after accounting for the motion of the tectonic plates) which is caused by the **rearrangement** of the mantle and the crust in order to align the maximum inertia with the current rotation axis.





Magnetic North Pole Position

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Earth’s Axial Tilt (Obliquity) – Axial Precession

Axial tilt - Giant Impact Hypothesis

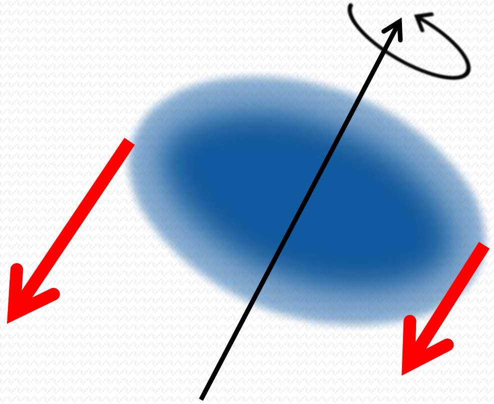
Based on a current prevailing theory an impact about 4.5 billion years ago is assumed to be the cause for the Earth’s **axial tilt** and creation of Earth’s moon. Earth's present axial tilt, or mean obliquity is about 23.4°.

Axial Precession

Precession is a change in the orientation of the rotational axis of a rotating body. The gravitational pull of Sun, Moon and to a lesser extent the other planets in conjunction with equatorial bulge (necessary) causes the Earth’s precession with a rotation in a cycle of approximately 26,000 years.

Earth's obliquity oscillates between 22.1^{o} and 24.5^{o} on a 41,000-year cycle.

One side of the Earth gets tugged a little bit more and this causes the Earth's axis to spin. This didn’t happen if Earth were a full shpere.



Axial precession

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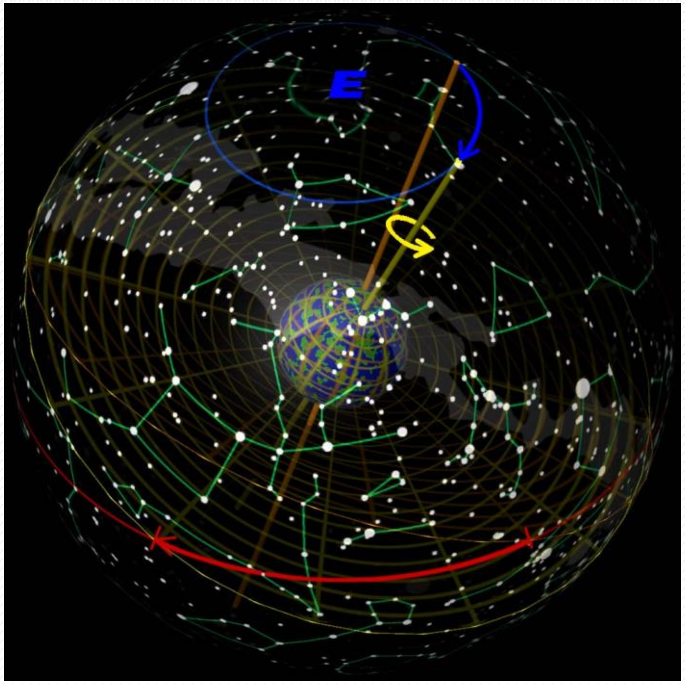

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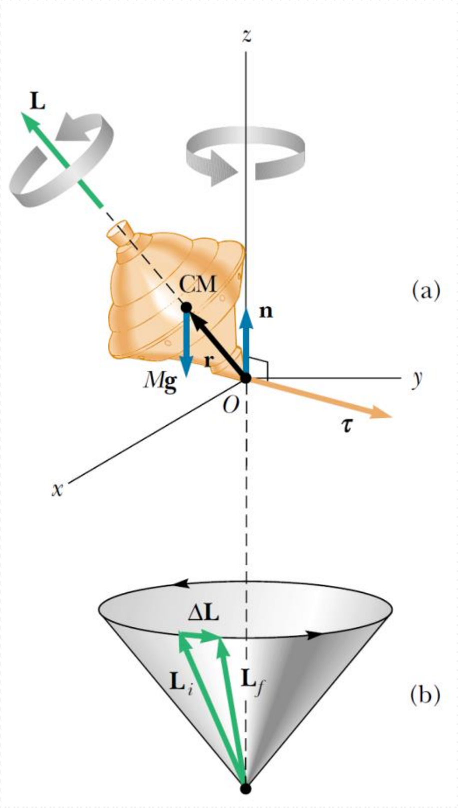

Halliday-Resnick-Walker

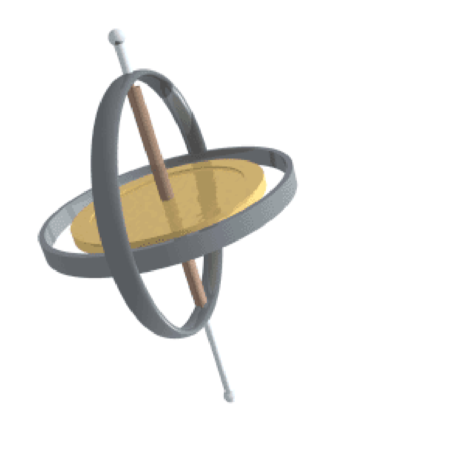

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Plate Tectonics

Plate tectonics based on concepts proposed by Alfred Wegener is a **unifying** model that attempts to explain the origin of patterns of deformation in the crust, earthquake distribution, continental drift, and mid-ocean ridges, as well as providing a mechanism for the Earth to cool.

Two major premises of plate tectonics are:

1) The outermost layer of the Earth, known as the lithosphere, behaves as a strong, rigid substance resting on a weaker region in the mantle known as the asthenosphere.

2) The lithosphere is broken into numerous segments or plates that are in motion with respect to one another and are continually changing in shape and size.

Plate Tectonics

Other:

1) The continents once were part of a supercontinent called Pangaea.

2) Plates move one to few centimeters per year.

3) Three types of boundaries are: a) Convergent, where plates collide, b) Transform, where plates slide past one other, c) Divergent, where plates move apart.

4) Volcanoes and mountains form at convergent boundaries.

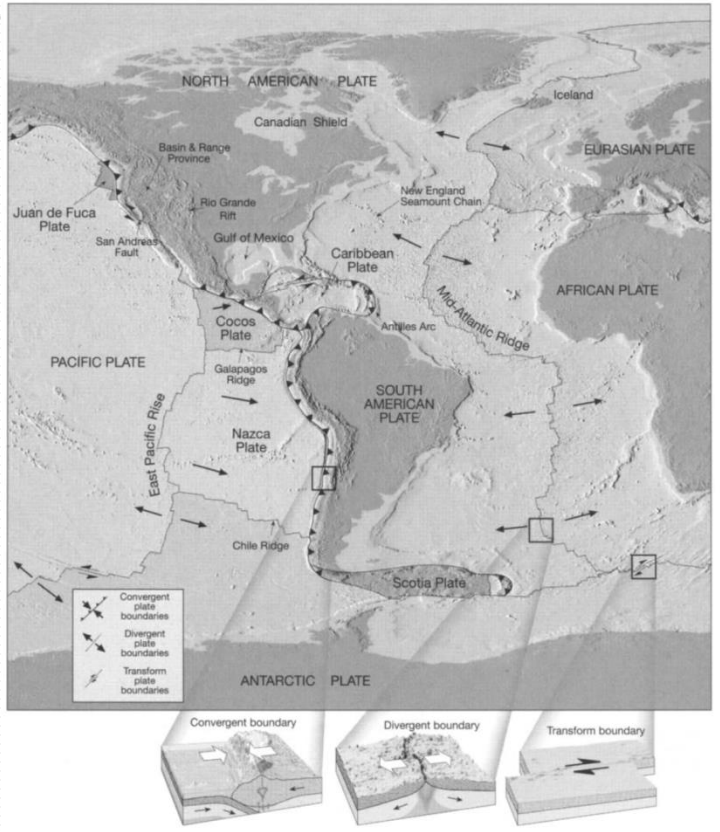
5) Earthquakes and tsunamis occur at convergent and transform boundaries.

6) Fissures, cracks and rifts in the surface occur at divergent boundaries.

7) Seafloor spreading occurs at divergent boundaries on the ocean floor.

Seafloor Spreading

The parental theory of plate tectonics, **seafloor spreading**, states that new lithosphere is **formed** at **ocean ridges** and moves away from ridge axes. To accommodate the newly-created lithosphere, **oceanic plates return** to the **mantle** at **subduction zones** such that the surface area of the Earth remains

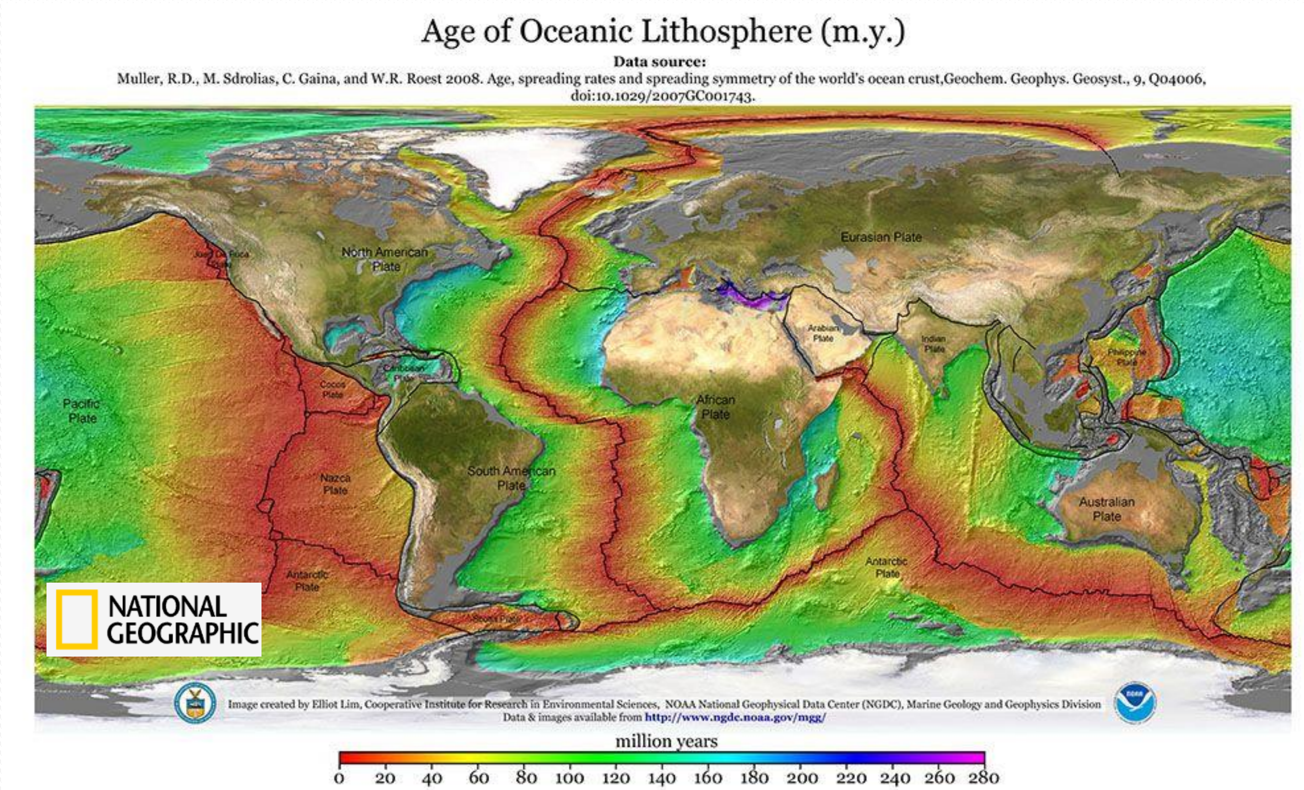


Map of the major lithospheric plates on Earth. Arrows are directions of plate motion. Filled barbs, **convergent** plate boundaries (subduction zones and collisional orogens); single lines, **divergent** plate boundaries (ocean ridges) and transform faults. Cross-sections show details of typical plate boundaries. Artwork by Dennis Tasa, courtesy of Tasa Graphic Arts, Inc.

Age of Oceanic Lithosphere

Age of the oceanic crust

Results from radiometric dating: Oceanic crust is youngest at mid-ocean ridges, and increases in age with distance from mid-ocean ridges.



The oldest oceanic crust is ~180 million years old - the oldest continental crust is ~ 4 billion years old.

First Evidence for Continents' Motion

Mantle convection
The explanation for the **rejection** of continental drift was the lack of a causal mechanism. Rigorous international debate over the possible mechanisms of continental migration, ultimately settled on the same explanation generally accepted today for plate tectonics: **Convection currents in the earth's mantle**.

Implications from Isostasy
If continents **floated** in a **denser substrate**, then this substrate had to be either **fluid** or **plastic**, and continents could at least in principle move through it.

There was good evidence that this was indeed the case (glacial rebound):
In Scandinavia, geologists had documented a progressive uplift of Finland and Scandinavia since the end of the Pleistocene epoch (10,000 years ago), which they called the Fennoscandian rebound. The accepted explanation for this phenomenon was that during the Pleistocene epoch, the region had been depressed under the weight of a thick sheet of glacial ice; as the ice gradually melted, the land surface gradually rebounded. This provided empirical evidence that continents could move through the substrate in which they were embedded, at least in the vertical direction and at least during the Pleistocene.

Horizontal Motion

Driving Force

What force would cause horizontal movement? Would the substrate respond to **horizontal movement** as it did to vertical movement?

In the United States, the question was addressed by Harvard geology professor **Reginald A. Daly** (1871-1957), North America's strongest **defender of continental drift**. Daly argued that the key to tectonic problems was to be found in the earth's **layered structure.**

Advances in seismology suggested that the earth contained **three major layers: crust**, substrate (or **mantle**), and **core**. The substrate, he suggested, might be **glassy**, and therefore could flow in response to long-term stress just as old plates of glass gradually thicken at their lower edges and glassy lavas flow downhill.

The Wilson Cycle

Geological evidences supports two (possibly more) complete opening and closings of ocean basins.

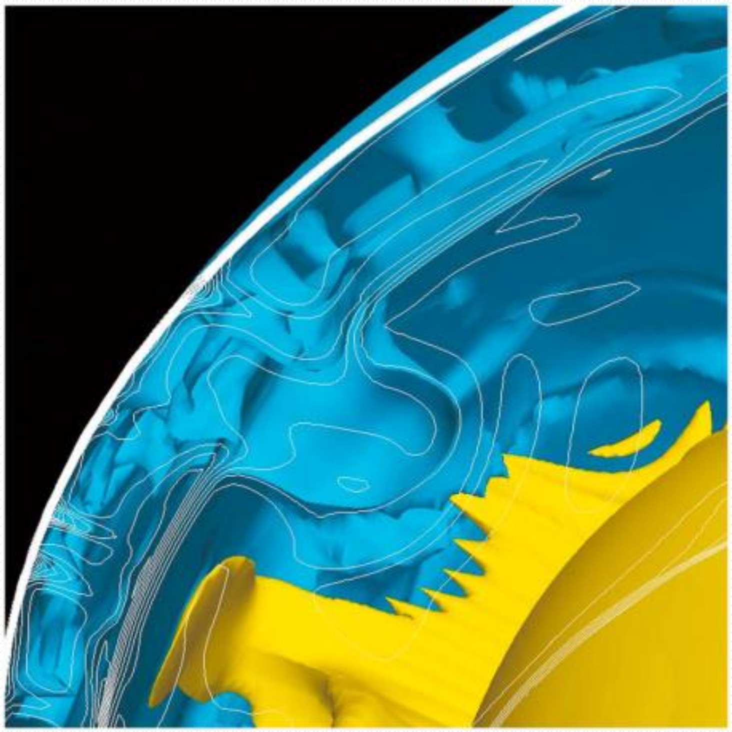
Wilson cycle is a model where a continental rift breaks up a continent leading to the formation of an ocean basin between two lithospheric plates. The separation of the two plates is then followed by convergence that leads to the closure of the ocean basin, and eventually to the collision of the two continental blocks.

Continental rift is easy to understand, but what does bring the plates together?

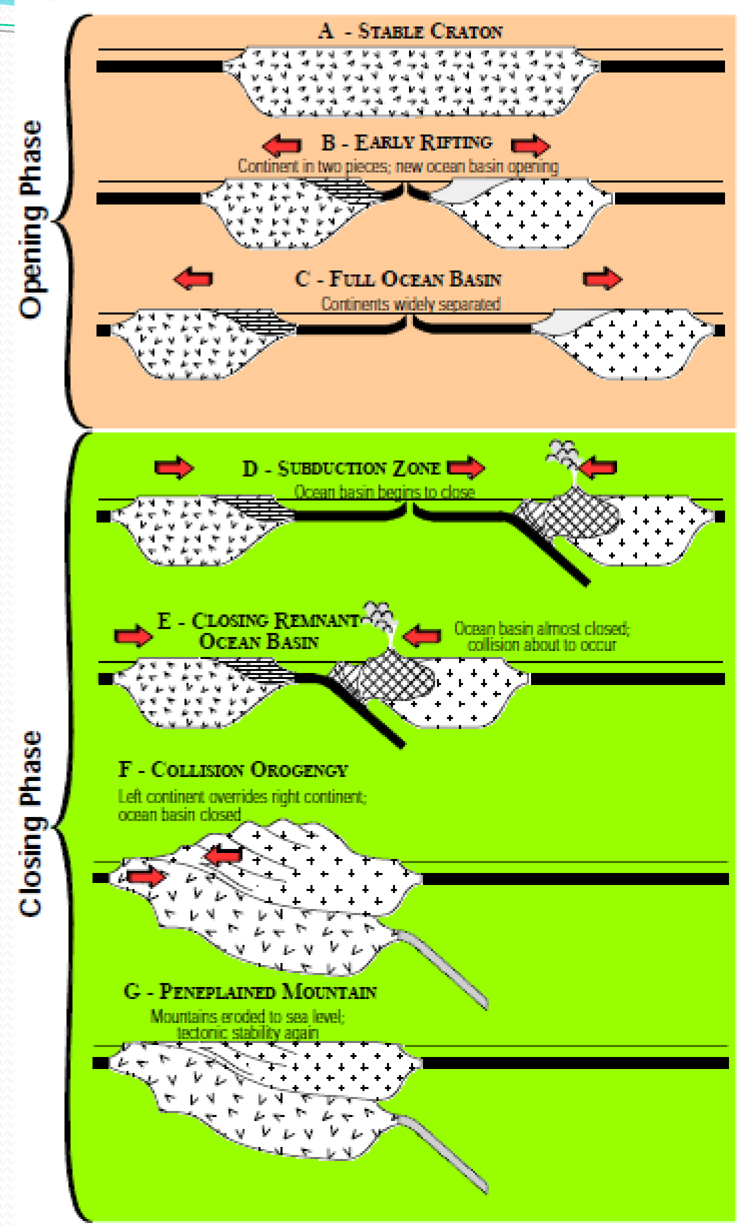
The Wilson Cycle

Mantle avalanches theory

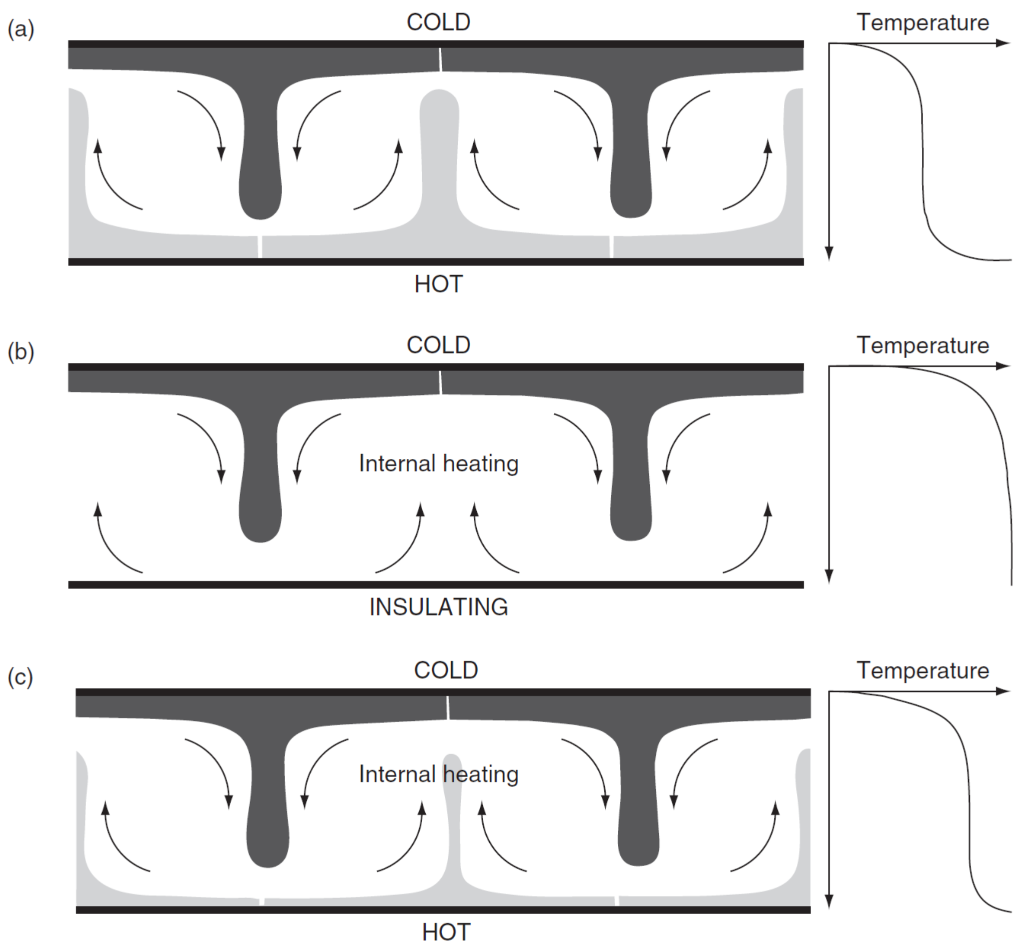
Mantle avalanches caused by the endothermic phase transition at 660 km depth. Superplasticity at this depth enhances this effect



Shahnas & Peltier, 2015



Mantle Convection as Driving Mechnisim



Heated bottom, no internal heating

No bottom heating, internal heating

Heated bottom, internal heating

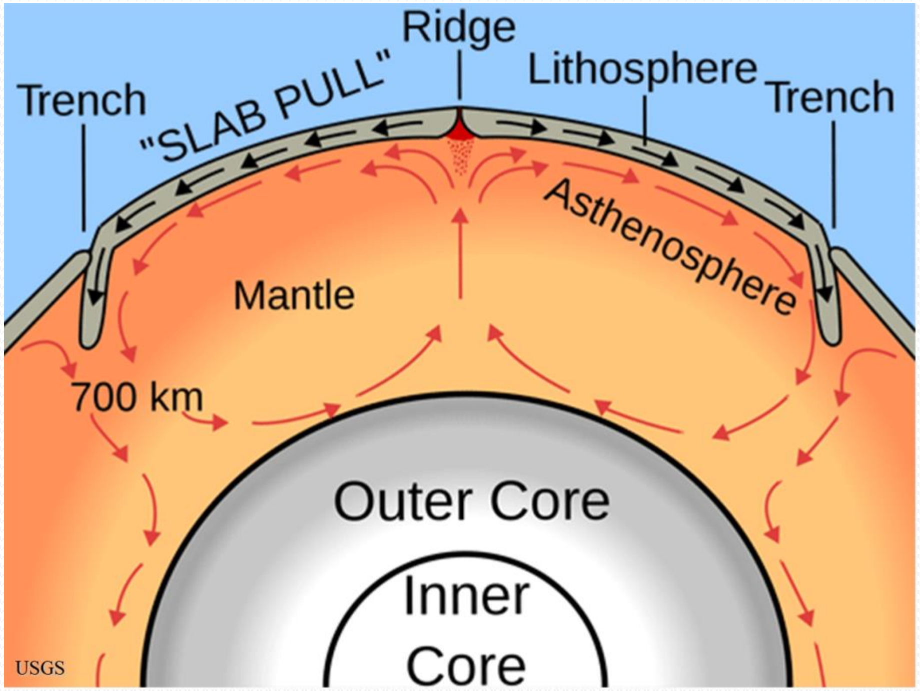
a) Convection is driven equally by more dense downwelling and less dense upwelling.
b) Cold, dense downwelling drives convection; upwelling is Passive.
c) Dense downwelling but weaker.

Convection in mantle is similar to C.

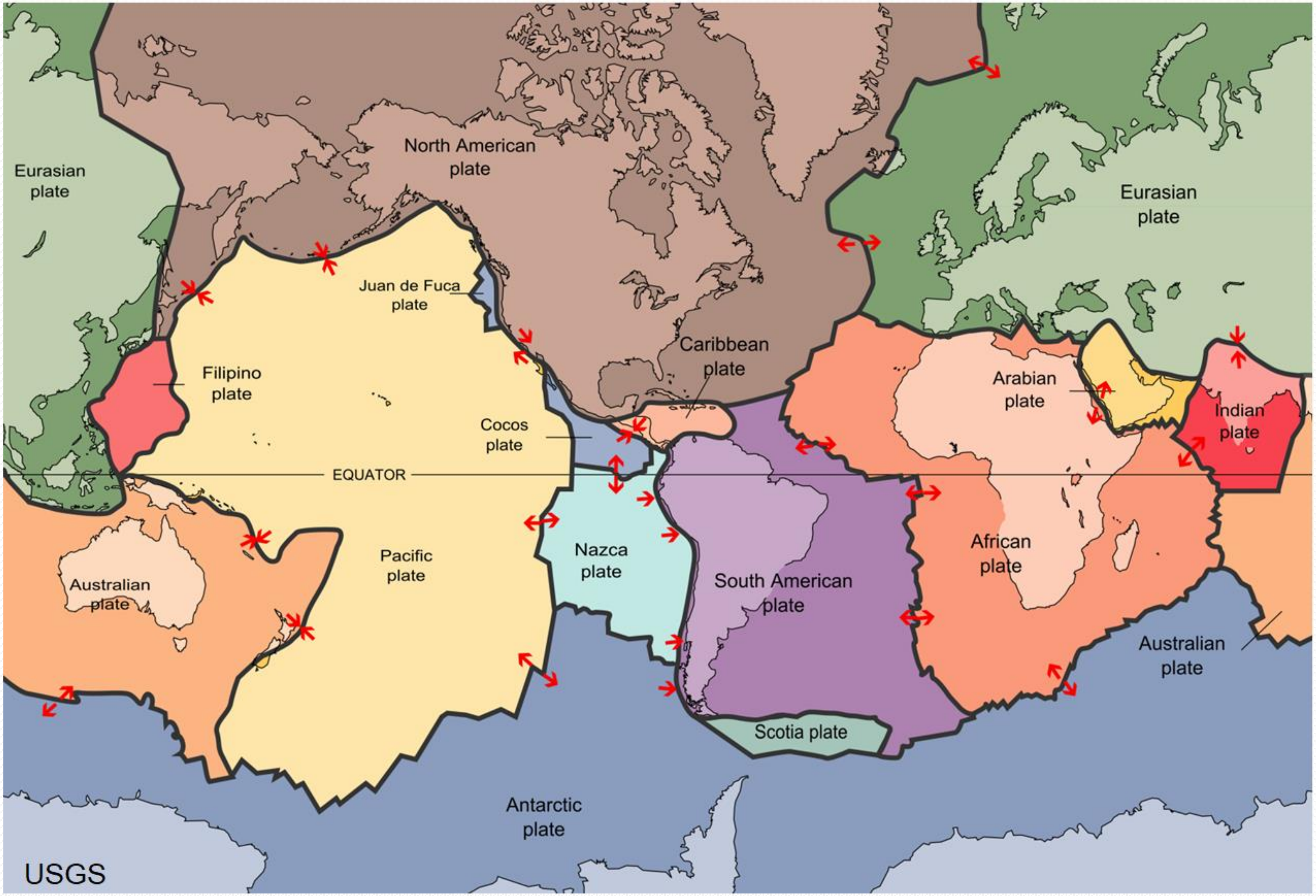
Ridge Push and Slab Pull

Ridge push
The magma intruding along divergent margins pushes plates apart at mid-oceanic regions.

Slab pull
The old oceanic plates eventually are pulled into the mantle by ongoing subduction at the convergent boundaries.

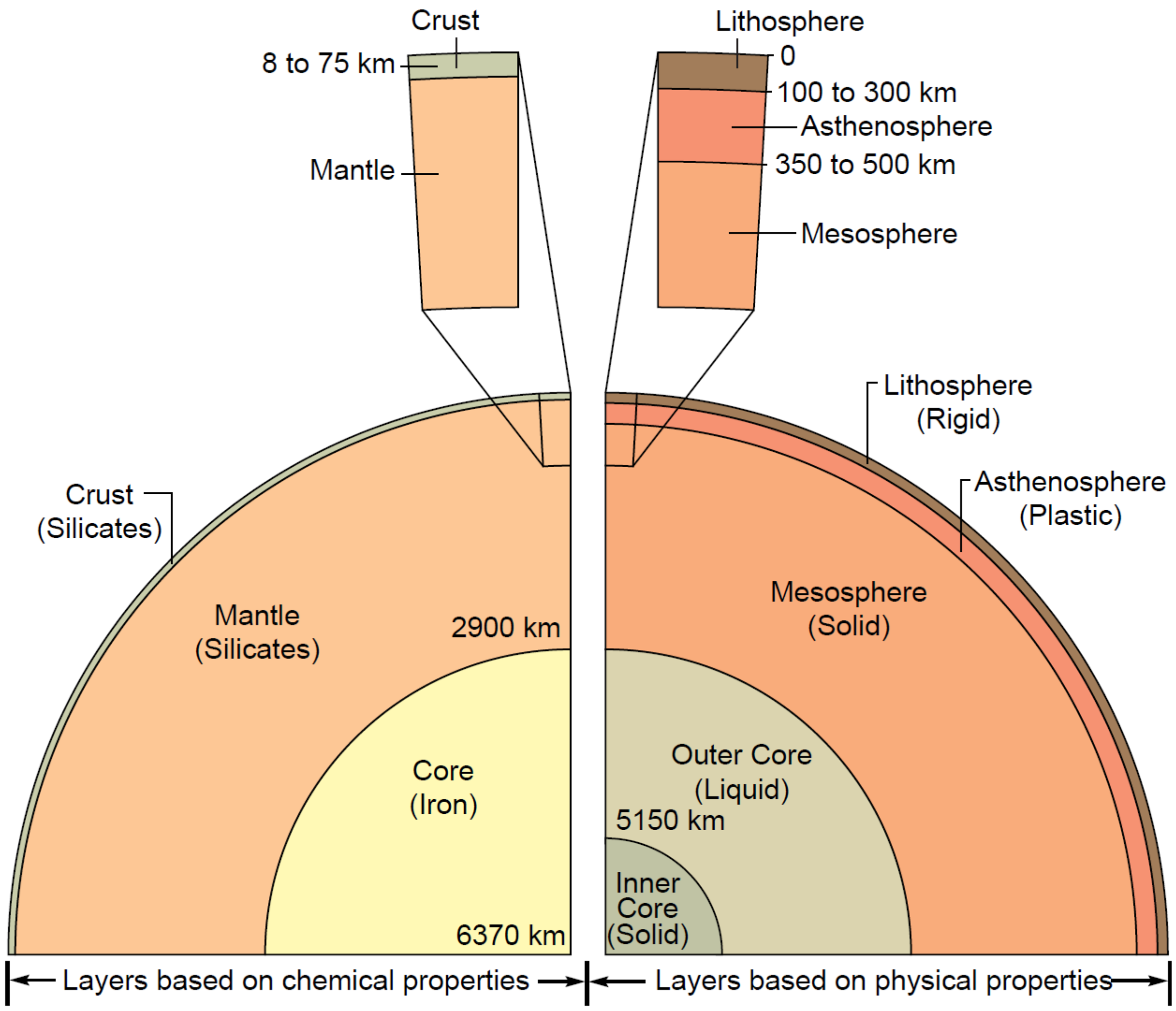


Moving Plates



Earth Structure

Compositional (chemical) and mechanical (physical) layers of Earth



Earth Structure

Compositional Layers

The Earth has different compositional and mechanical layers. Compositional layers are determined by their components, while mechanical layers are determined by their physical properties.

Information about the compositional layers

Layer	Definition	Depth
Crust	The outermost solid layer of a rocky planet or natural satellite. Chemically distinct from the underlying mantle.	0-100km silicates
Mantle	A layer of the Earth (or any planet large enough to support internal stratification) between the crust and the outer core. It is chemically distinct from the crust and the outer core. The mantle is not liquid. It is, however, ductile, or plastic, which means that on very long time scales and under pressure it can flow. The mantle is mainly composed of aluminum and silicates.	100-2900km iron and magnesium silicates
Core	The innermost layers of the Earth. The Earth has an outer core (liquid) and an inner core (solid). They are not chemically distinct from each other, but they are chemically distinct from the mantle. The core is mainly composed of nickel and iron.	2900-6370km metals

https://www.e-education.psu.edu/marcellus/node/870

Earth Structure

Mechanical Layers

The mechanical layers of the Earth a differentiated by their strength or rigidity. These layers are not the same as the compositional layers of the Earth, such as the crust, mantle, and core, though sometimes the boundaries fall in the same places.

Information about the mechanical layers

Layer	Definition	Depth
Lithosphere	The outermost and most rigid mechanical layer of the Earth. The lithosphere includes the crust and the top of the mantle. The average thickness is ~70km, but ranges widely: It can be very thin, only a few km thick under oceanic crust or mid-ocean ridges, or very thick, 150+ km under continental crust, particularly mountain belts.	0-100 km
Asthenosphere	The asthenosphere is underneath the lithosphere. It is about 100km thick, and is a region of the mantle that flows relatively easily. Reminder: it is not liquid.	100-350 km Soft plastic *note: The mantle is not liquid!
Mesosphere	The mesosphere is beneath the asthenosphere. It encompasses the lower mantle, where material still flows but at a much slower rate than the asthenosphere.	350-2900km stiff plastic
Outer Core	A layer of liquid iron and nickel (and other elements) beneath the mesosphere. This is the only layer of the Earth that is a true liquid, and the core-mantle boundary is the only boundary of Earth's layers that is both mechanical and compositional. Flow of the liquid outer core is responsible for Earth's magnetic field.	5100-6370 km solid

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