…a theory should be as simple as possible, *but no simpler*.
Albert Einstein

An Introduction to Plate Tectonics

Lithosphere & Astenosphere

Lection 1

Course: Particularities and Features of Cold Region Geology

by
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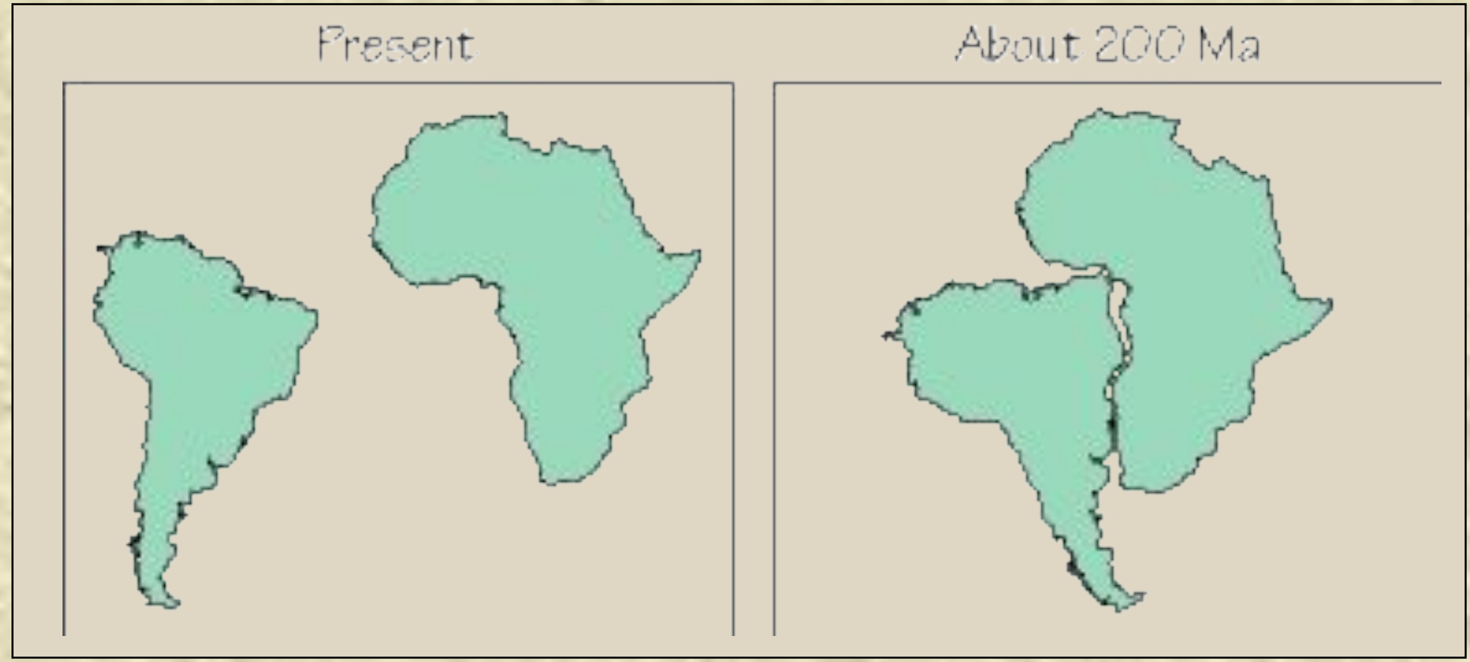
Continental Drift, Sea-Floor Spreading, and Plate Tectonics

Since the construction of the first good maps of the continents, people have puzzled over the close match between the coastlines of South America and Africa.



Continental Drift, Sea-Floor Spreading, and Plate Tectonics

Alfred Wegener
1880-1930

Alfred Wegener, a German meteorologist, proposed the **continental drift hypothesis** (between 1919-1929) to explain:

- the observed shape of the coastlines;
- the observation of fossils and rocks on opposite sides of the ocean etc.

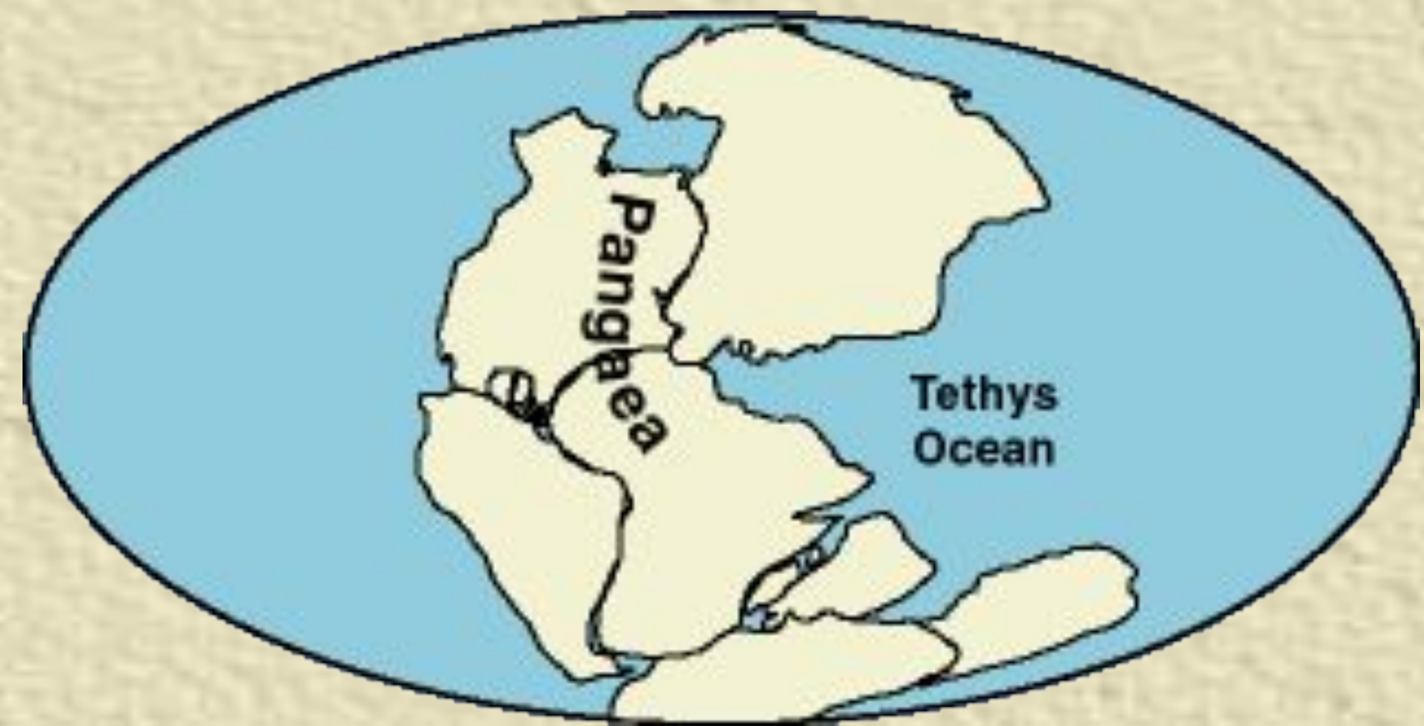
Continental Drift, Sea-Floor Spreading, and Plate Tectonics

Seed fern fossil, called ***Glossopteris***, is one of the many fossils that were found on both sides of the Atlantic Ocean.

How the seeds could have migrated across the oceans unless the continents were connected by mysterious land bridges.

Continental Drift, Sea-Floor Spreading, and Plate Tectonics

Wegener proposed that at one time, all the present-day continents actually were combined into a **"super-continent"** which he called **Pangaea** (or Pangea).



Continental Drift, Sea-Floor Spreading, and Plate Tectonics

PROBLEMS:

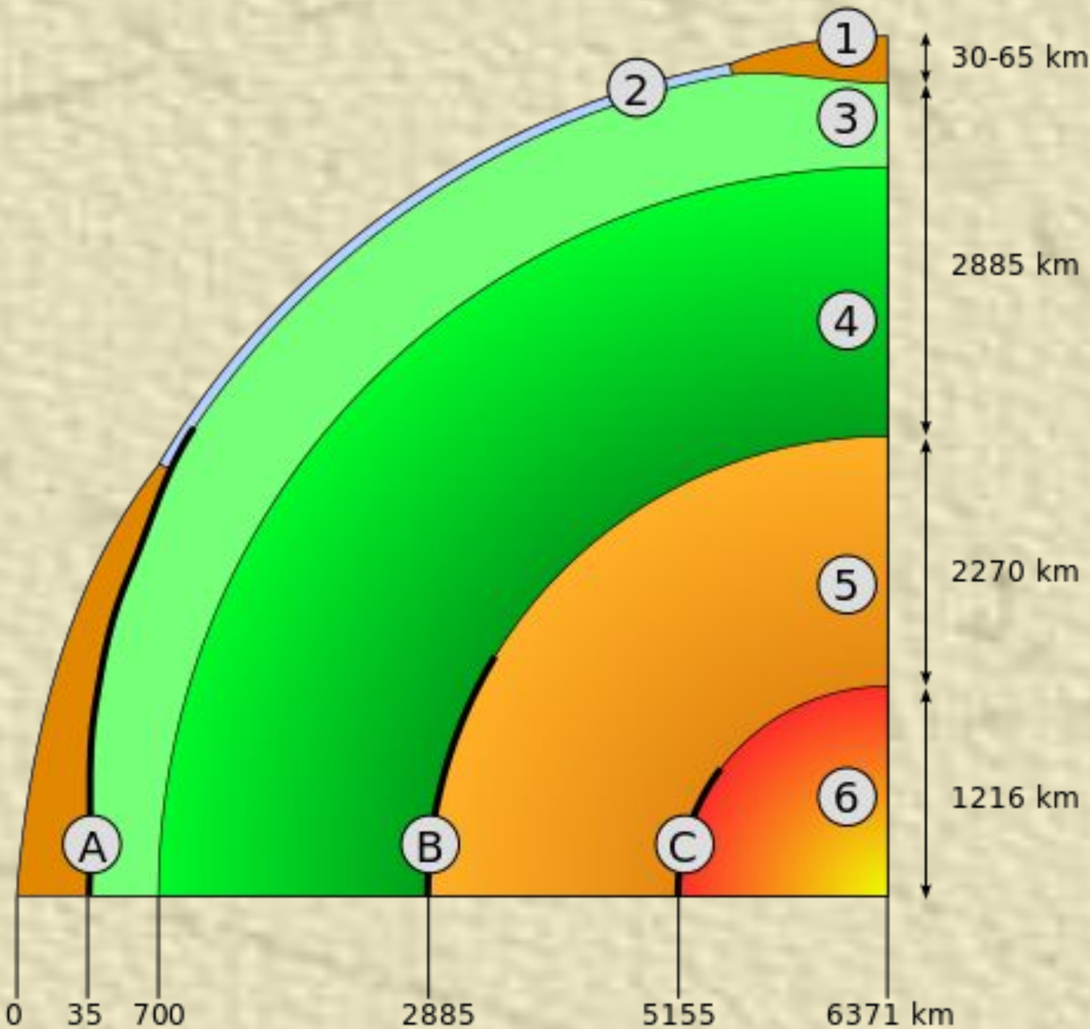
Alfred Wegener was unable to provide a reliable mechanism that explains the continental drift.

He supposed that the **centrifugal force of the Earth's rotation** or the **astronomical precession** caused the drift.

Simple calculations show that this is impossible.

The scientific community has rejected the hypothesis of Alfred Wegener.

Structure of the Earth



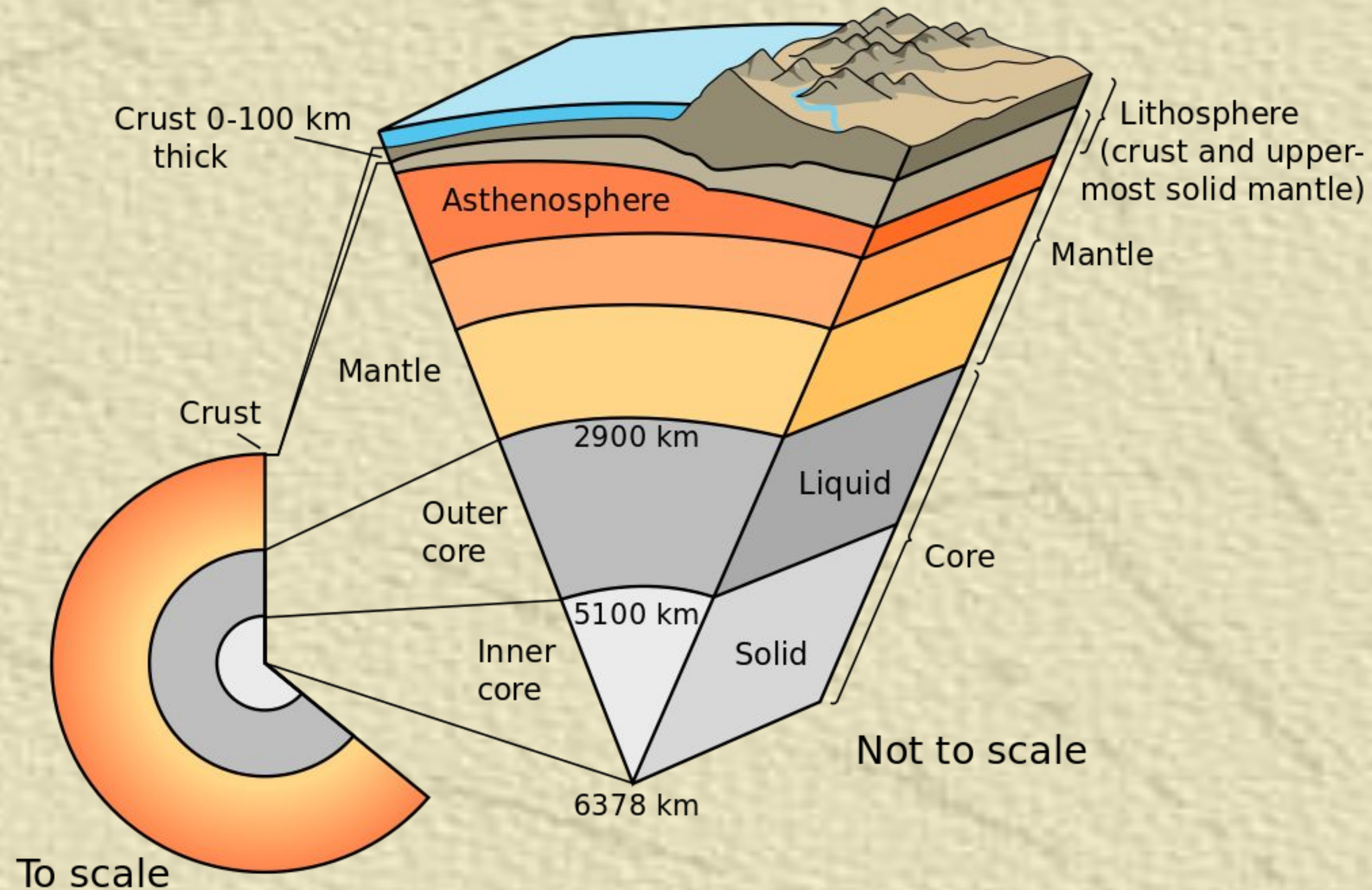
1. continental crust
2. oceanic crust
3. upper mantle
4. lower mantle
5. outer core (liquid)
6. inner core (solid)

A: **Mohorovičić** discontinuity – the boundary between **crust** and **mantle**.

B: **Gutenberg** discontinuity – the **core-mantle** boundary.

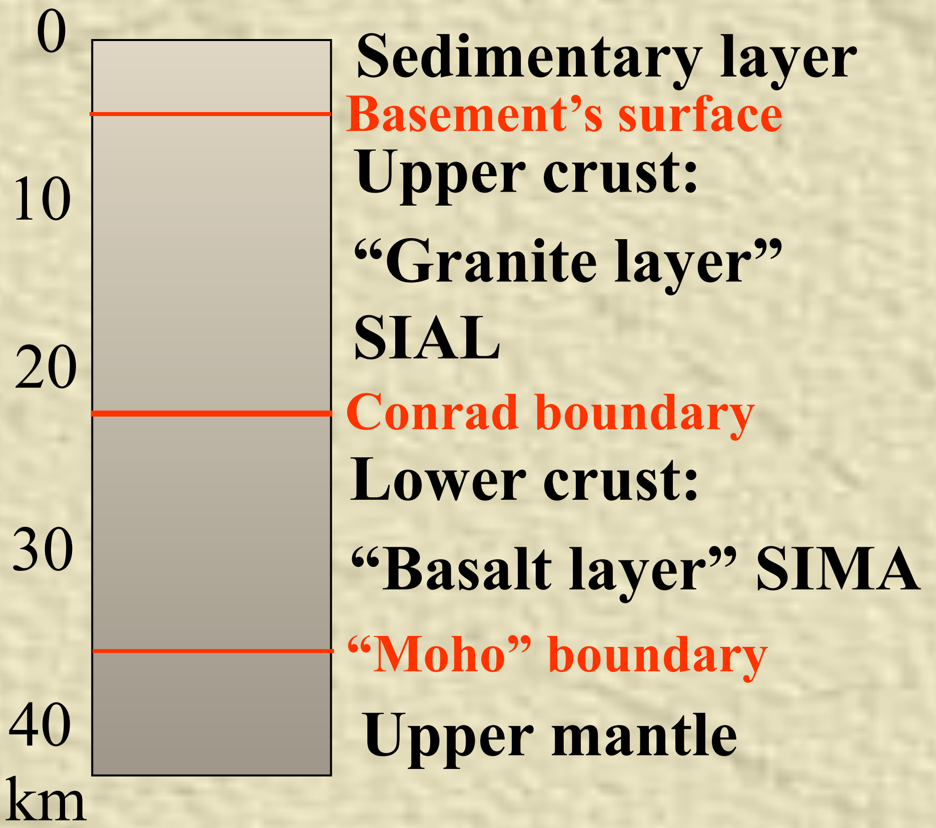
C: **Lehmann–Bullen** discontinuity – the inner-outer core bound

Structure of the Earth

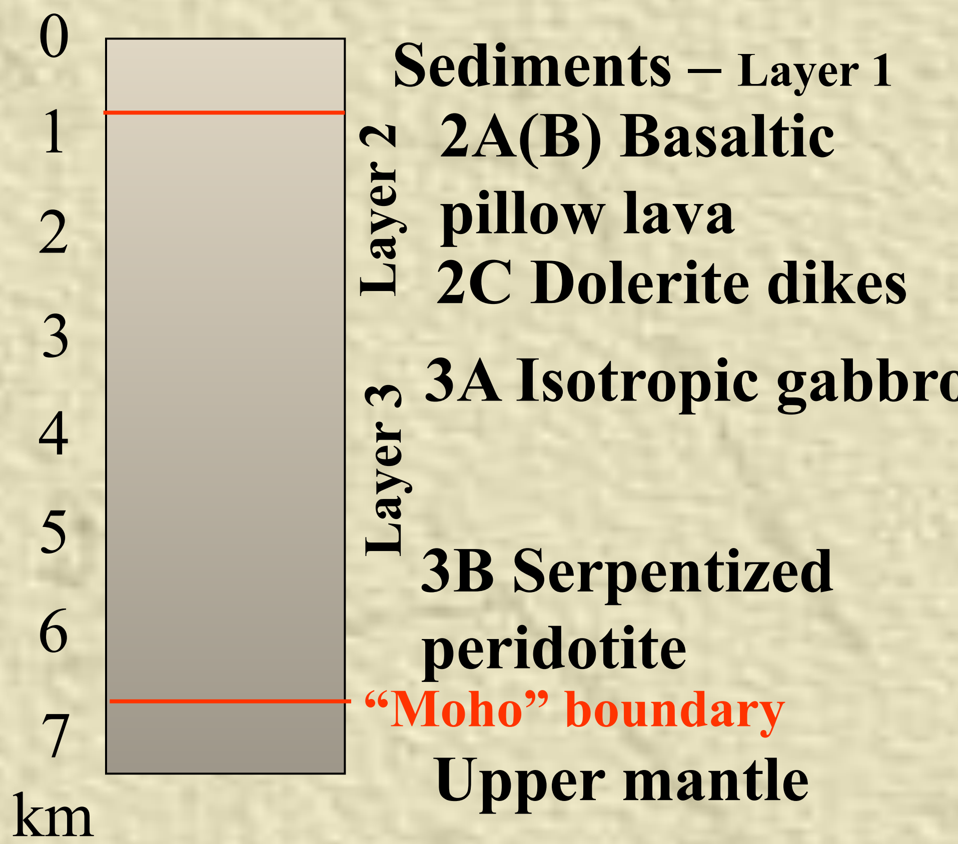


Two types of the Earth Crust

Continental crust



Oceanic crust



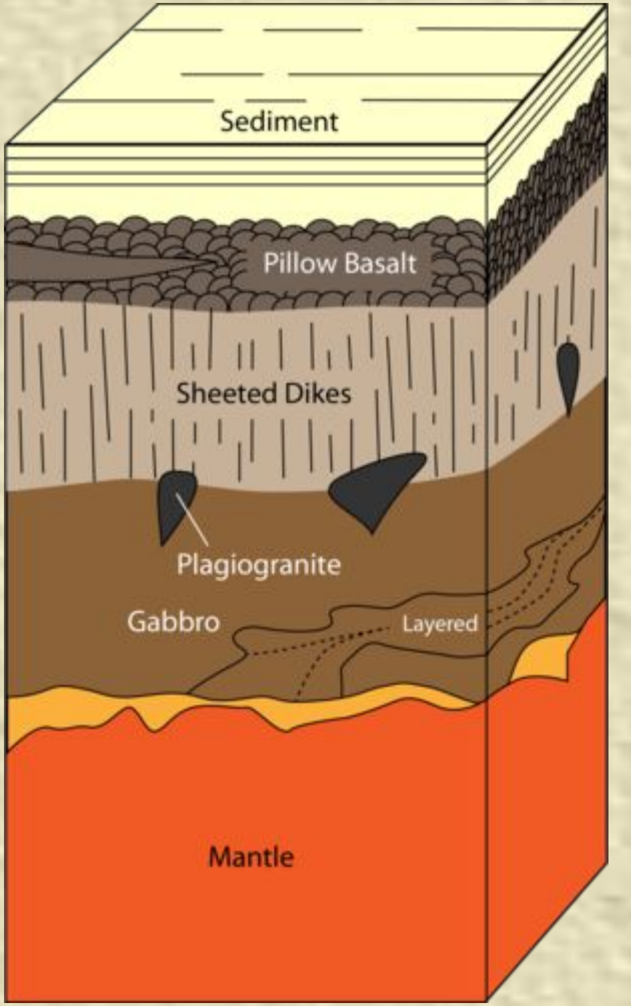
The lower density of continental crust allows it to float on the mantle.

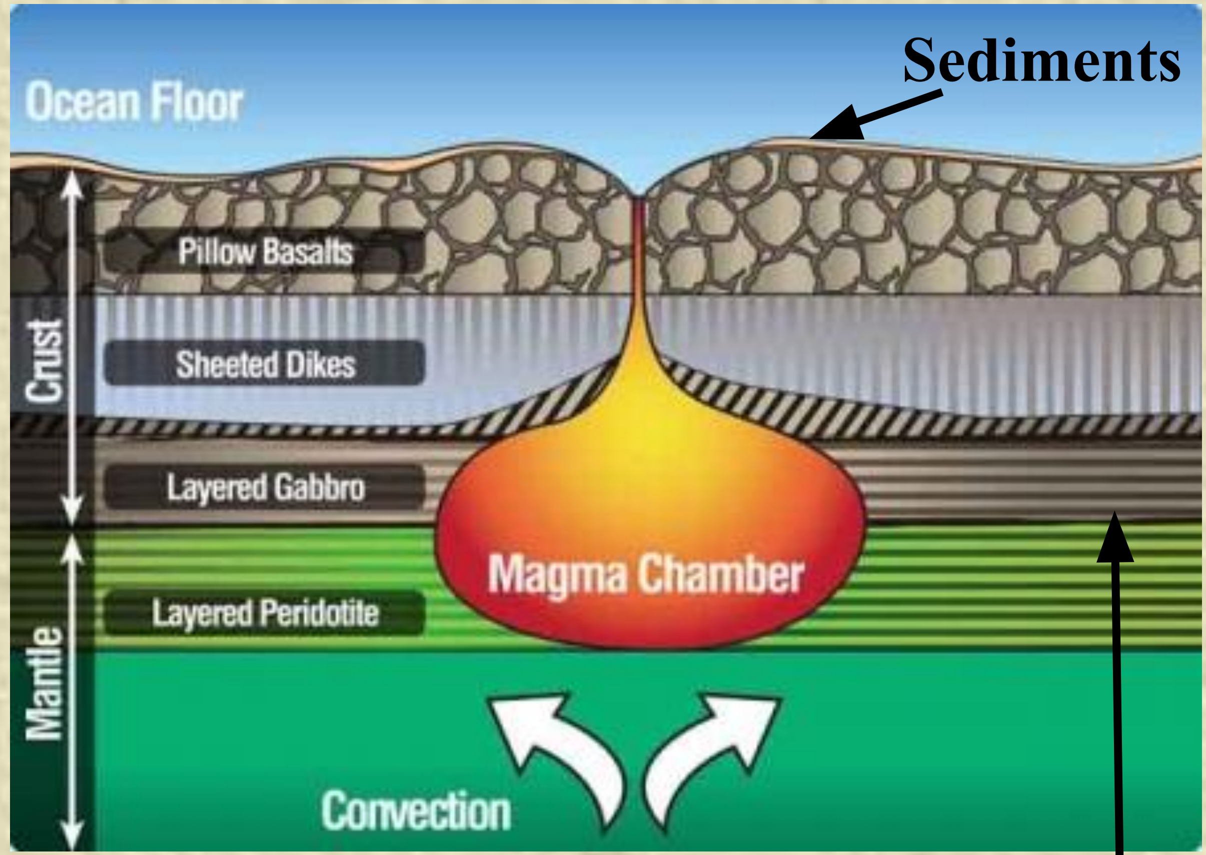
Layer 2: tholeiite (low-K olivine basalts)

Oceanic crust is mainly made of basalt whereas continental crust is mainly made of granite

Two types of the Earth Crust

Oceanic crust





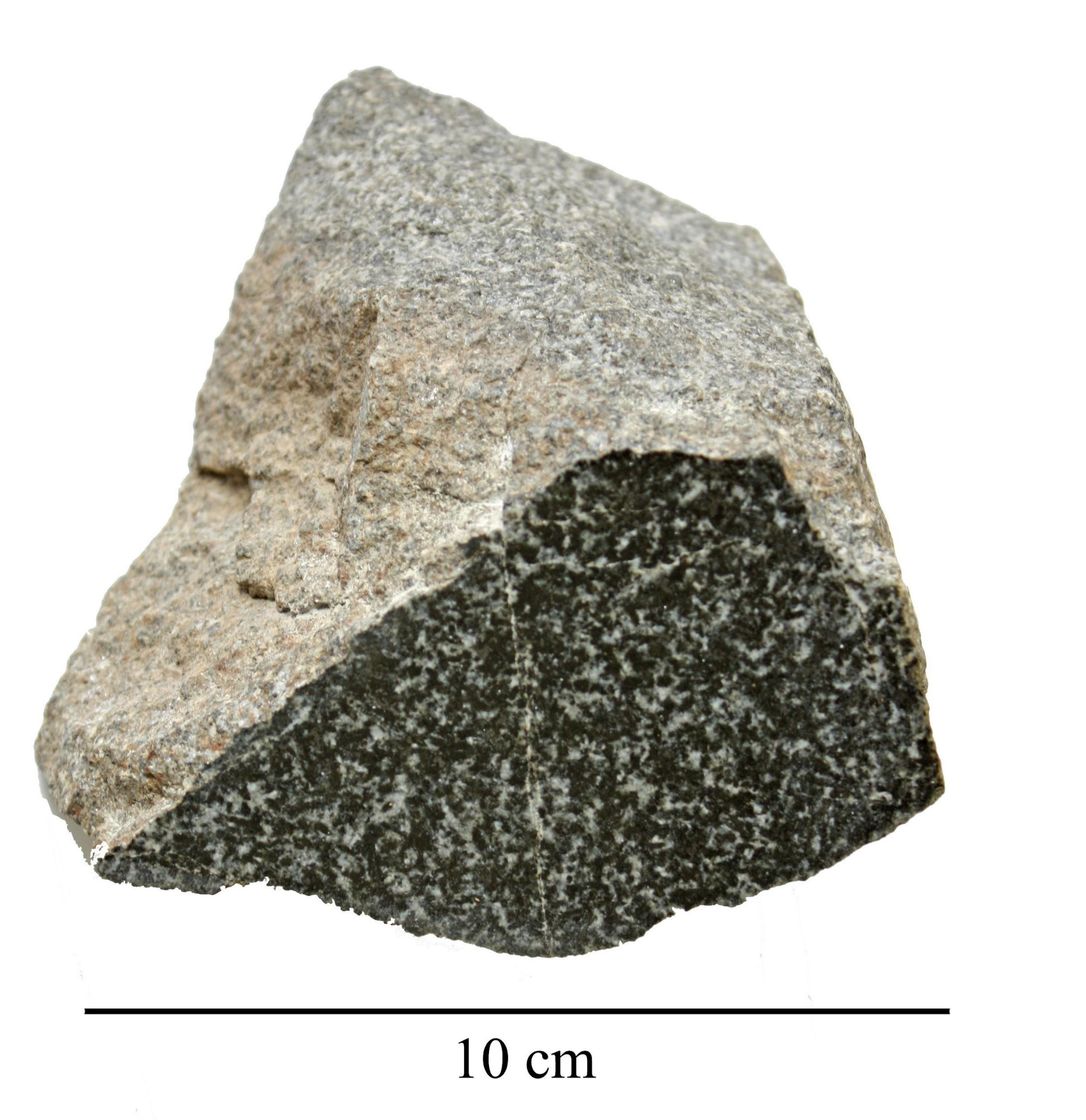
Sediments

Serpentinized peridotites

Oceanic crust

Recently formed **pillow lava (basalt)**, off Hawaii

Oceanic crust



A **dolerite** is the medium-grained equivalent of a **basalt** - a basic rock dominated by plagioclase and pyroxene.

Diabase is often used as a synonym of **dolerite** by american geologists, however, in Europe the term is usually only applied to altered dolerites.

Oceanic crust

Gabbro from ocean crust. The gabbro is deformed because of intense faulting at the eruption site.

Gabbro refers to a large group of dark, often coarse-grained, mafic intrusive igneous rocks **chemically equivalent to plutonic basalt.**

It forms when molten magma is trapped beneath the Earth's surface and slowly cools into a holocrystalline mass.

Oceanic crust

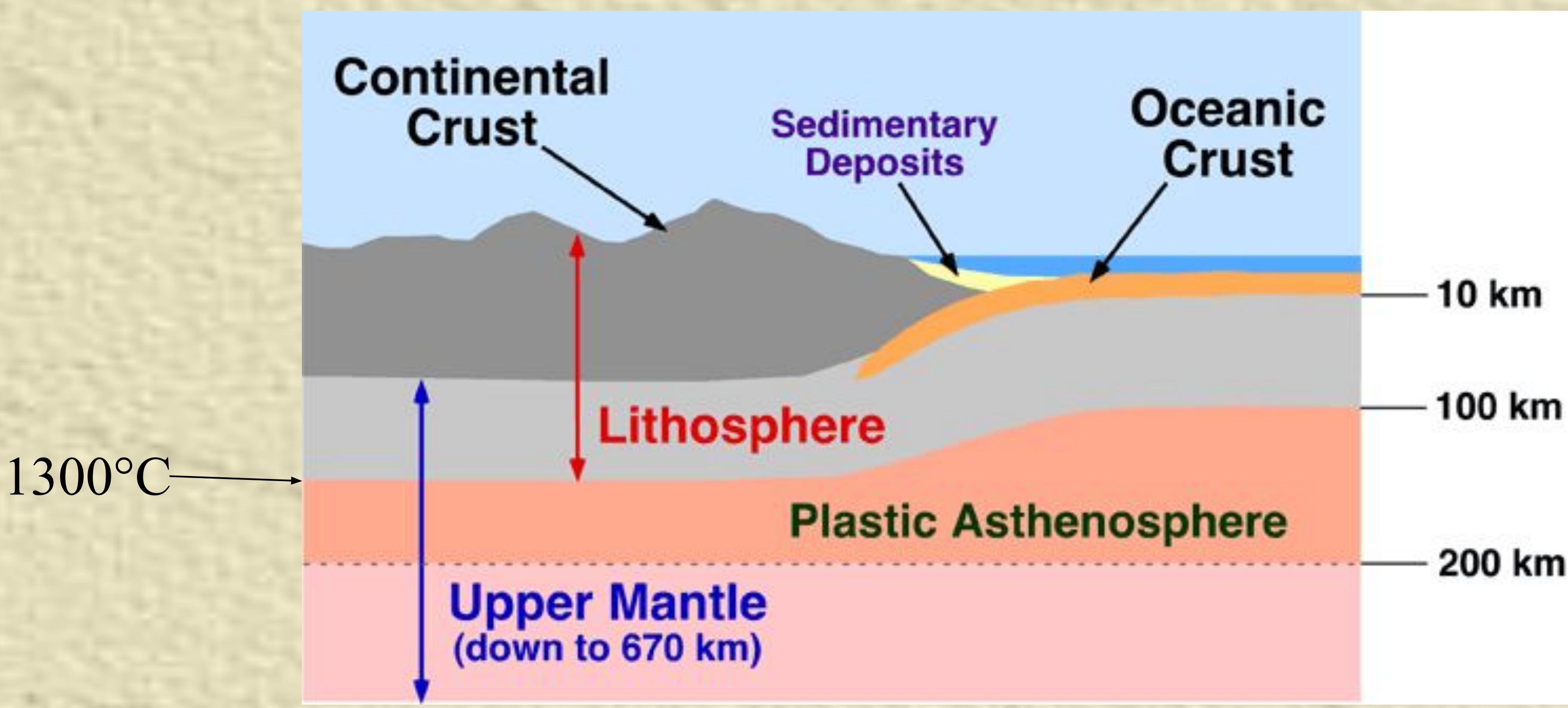
Serpentinized peridotite

Peridotite is classified as an ultramafic rock.
It has less than 45% silica in its structure.
It is mostly made of the minerals **olivine** and **pyroxene**.

Lithosphere & Astenosphere

Earth's **lithosphere** = the **crust** + the **uppermost mantle** → constitute the hard and rigid outer layer of the Earth.

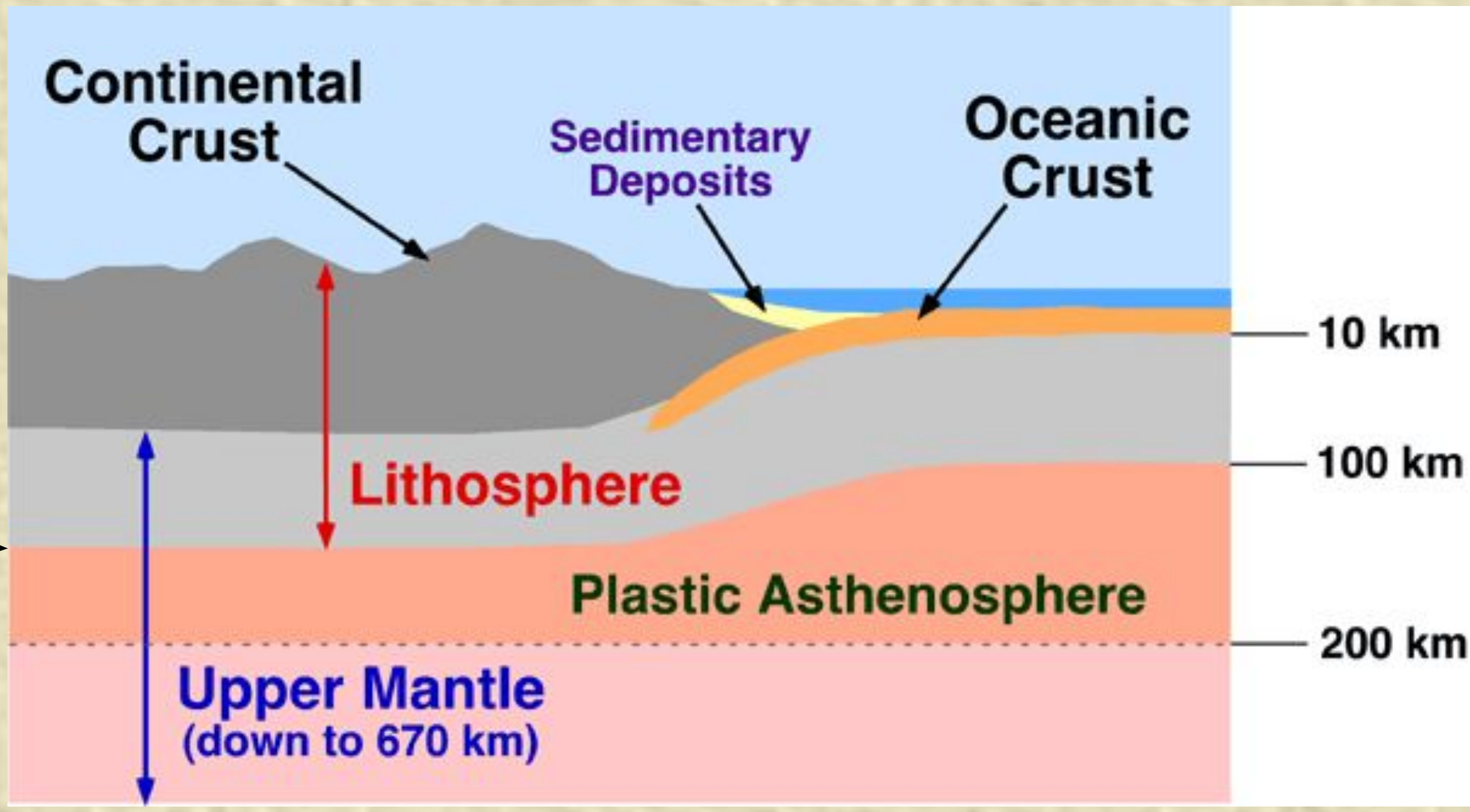
The **lithosphere** is subdivided into tectonic plates.



Lithosphere & Astenosphere

Astenosphere is the highly viscous, mechanically weak and ductilely-deforming region of the upper mantle.

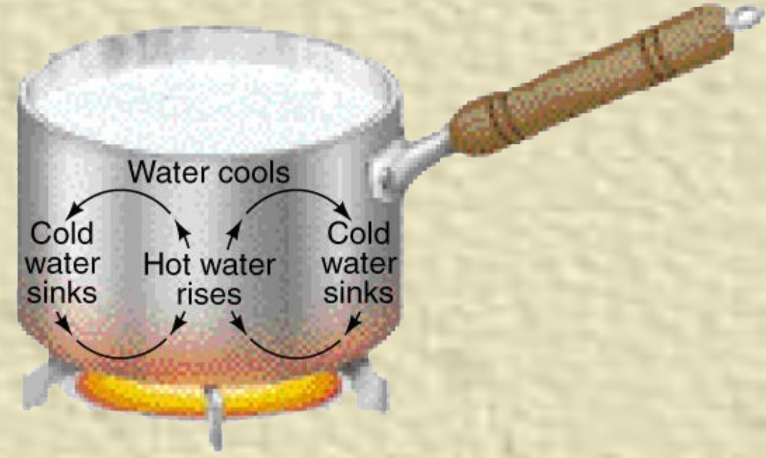
1300°C



At about 1300°C typical mantle material begins to melt, and softens dramatically. We call that part of the mantle **asthenosphere.** **It is a weak zone, that "decouples" the plate from the overlying mantle.**

Convection of Mantle

The **asthenosphere** is ductile and can be pushed and deformed like *silly putty* («умный пластилин») in response to the warmth of the Earth.



These rocks actually flow, moving in response to the stresses placed upon them by the churning motions («возвратно-поступательное движение») of the deep interior of the Earth.

The flowing **asthenosphere** carries the **lithosphere** of the Earth, including the continents, on its back.

Convection of Mantle

Cross section through the Earth showing the **convection cells** of the mantle.

Ridge push happens at **spreading** centers where plates are moving apart.

Slab pull happens at **subduction zones** where one plate is pulled down into the mantle.

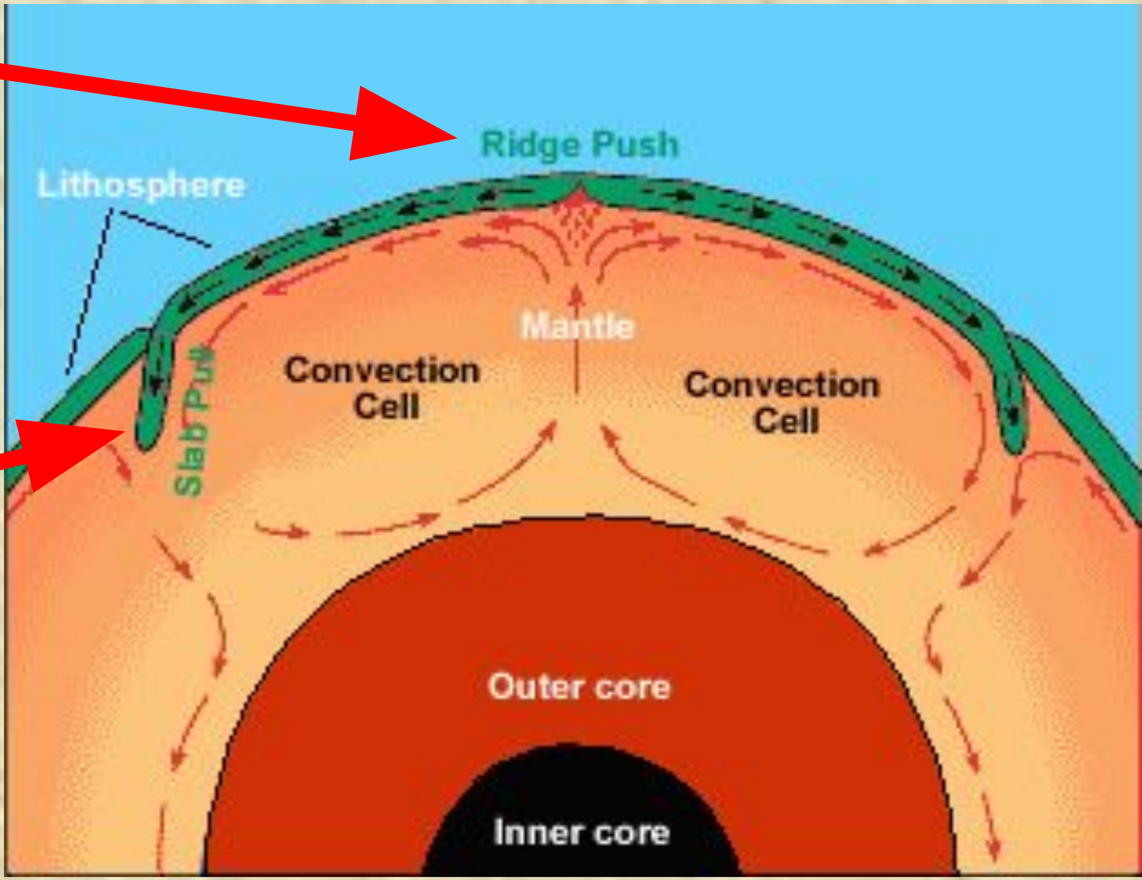


Plate Motion

- Movements deep within the Earth →
- carry heat from the hot interior to the cooler surface →
- the plates to move very slowly on the surface, about 2 inches per year.

Subduction zones → plates crash into each other; **spreading ridges** → plates pull away from each other; **large faults** → plates slide past each other.

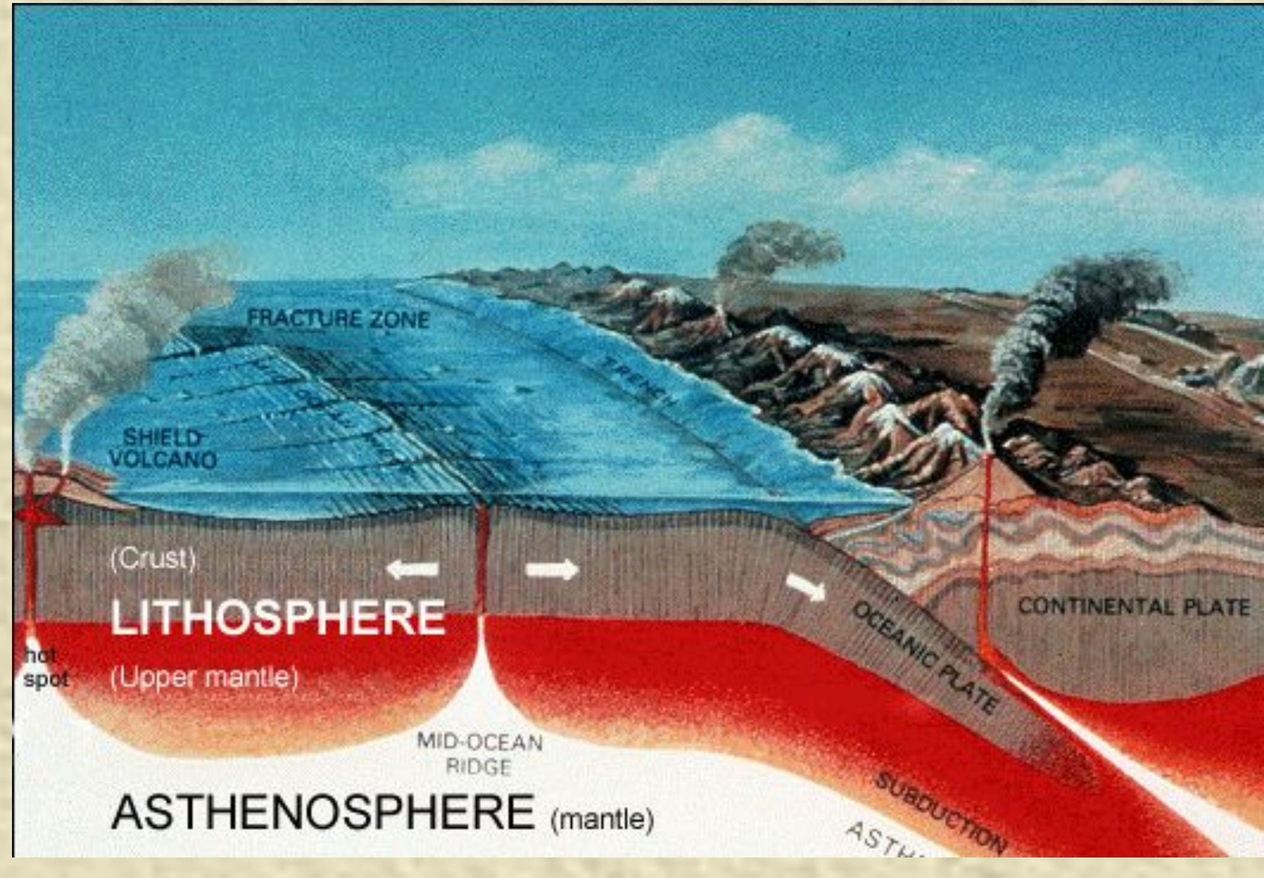
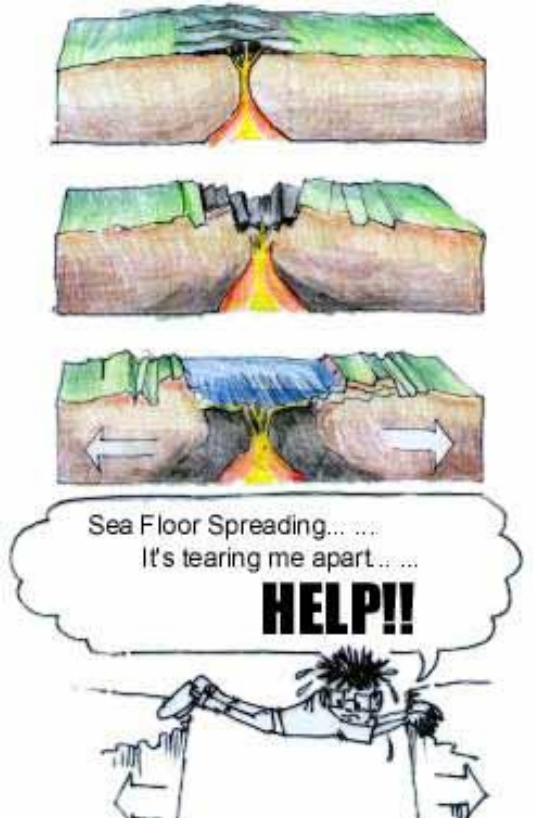
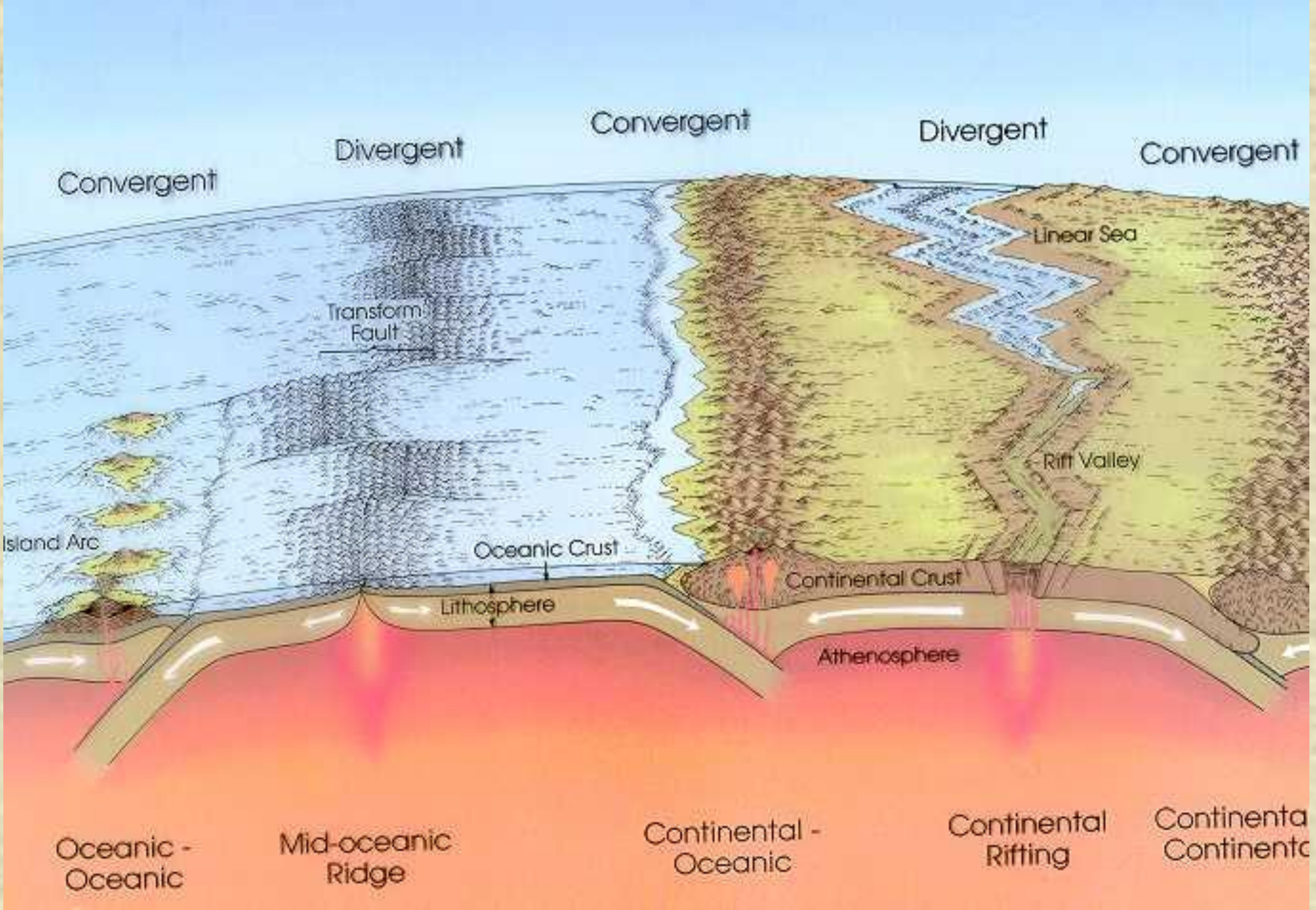


Plate Motion

There are many **evidence** that supports the theory of **plate tectonics**: **continental drift, earthquakes, volcanoes, magnetism,** and **heat flow** that cause seafloor elevation/spreading.

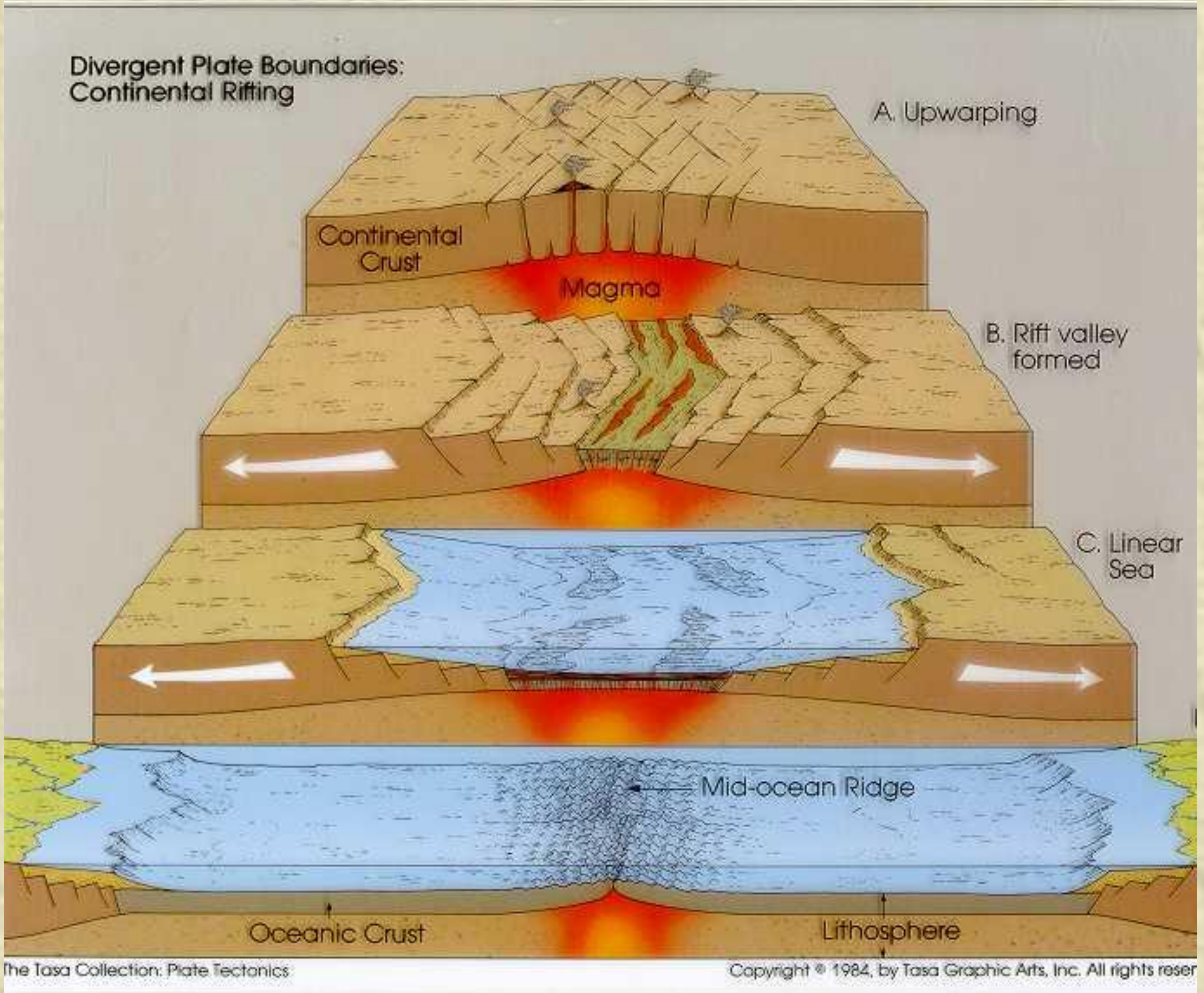


Divergent & Convergent boundaries

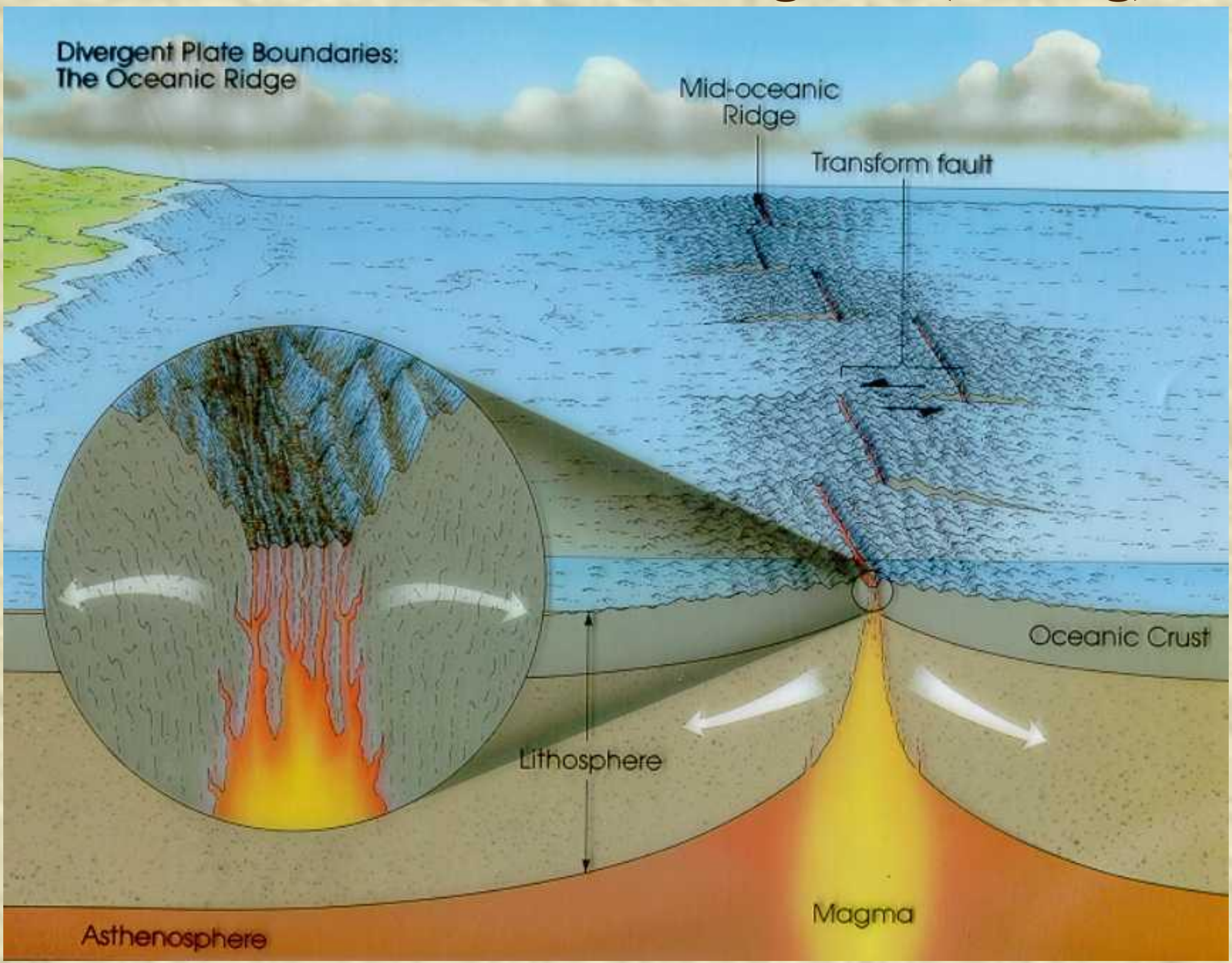


Divergent Plate boundaries.

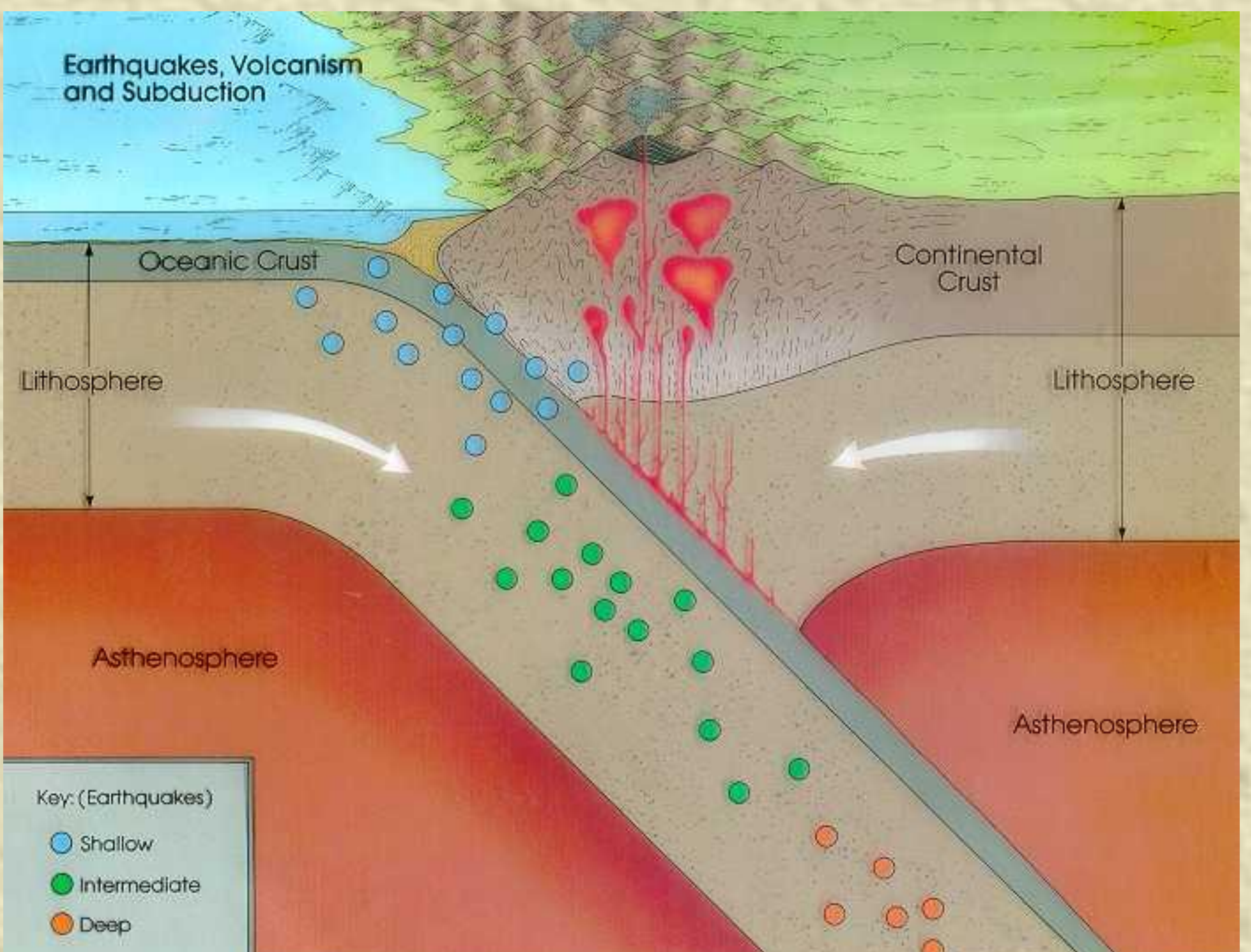
1. Continent – Continent Rifting (Diverging)



Divergent Plate boundaries.
2. Ocean – Ocean Divergence (Rifting).

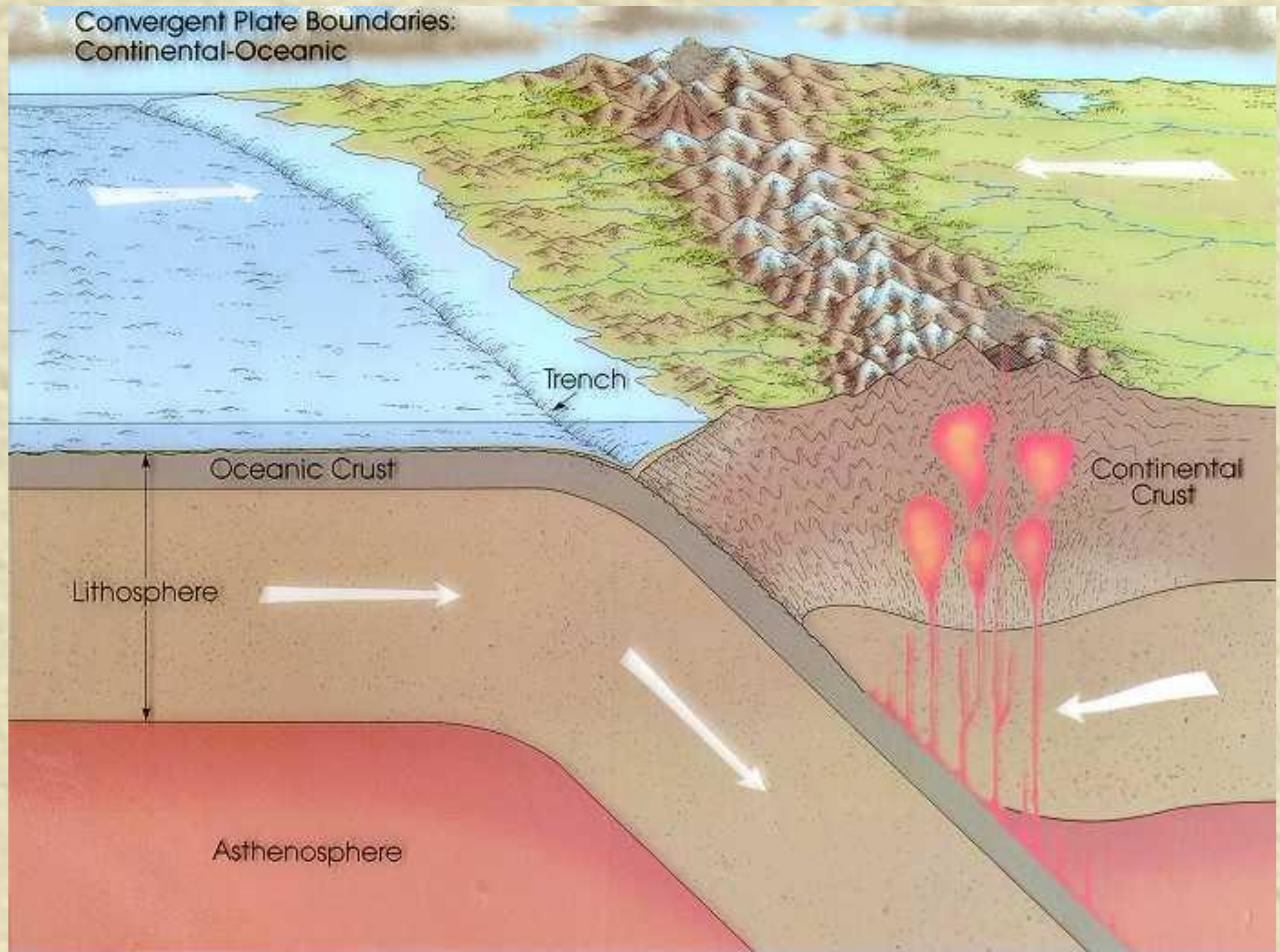


Convergent Plate boundaries.
1 stage. Conversion of oceanic crust to continental crust.

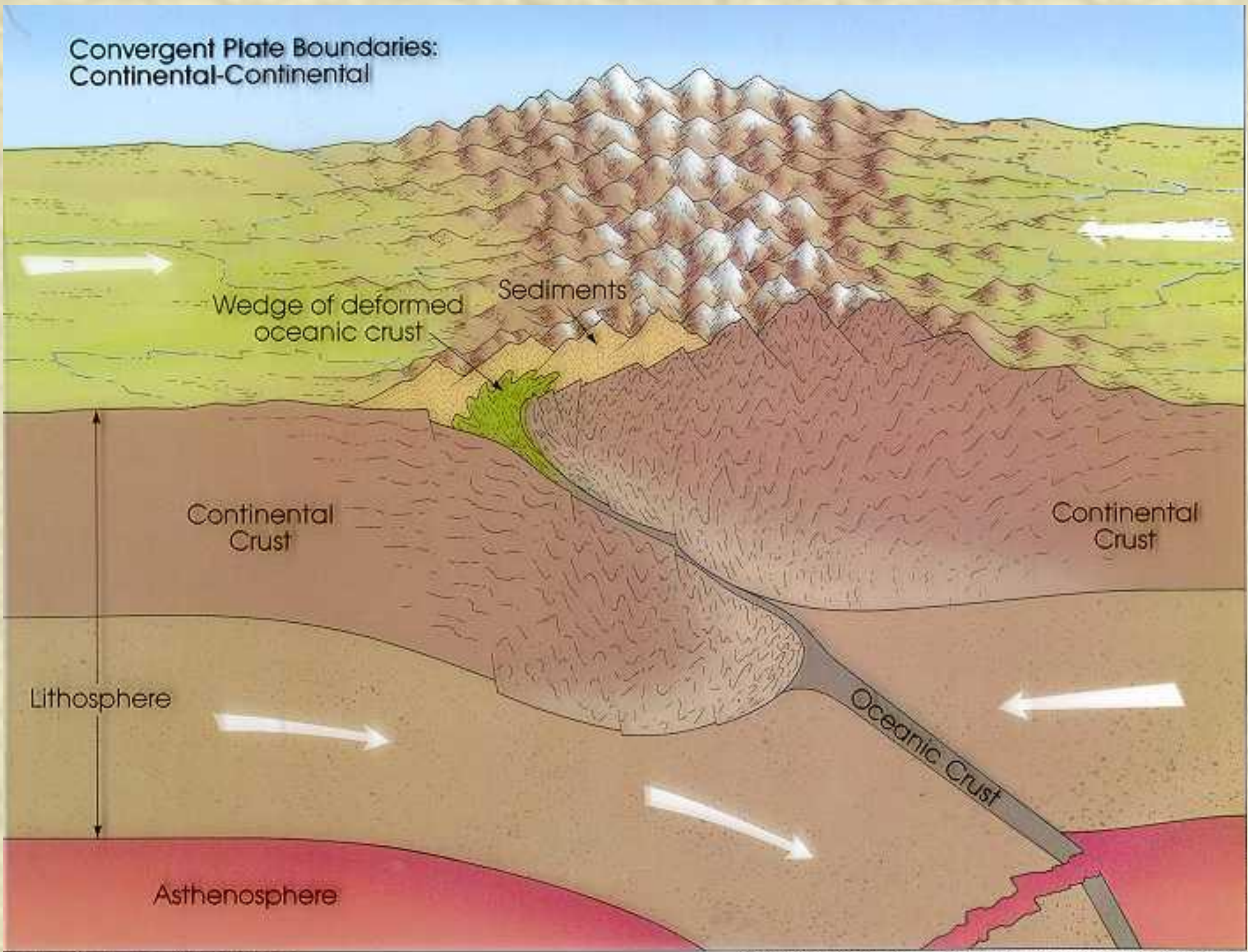


Convergent Plate boundaries.

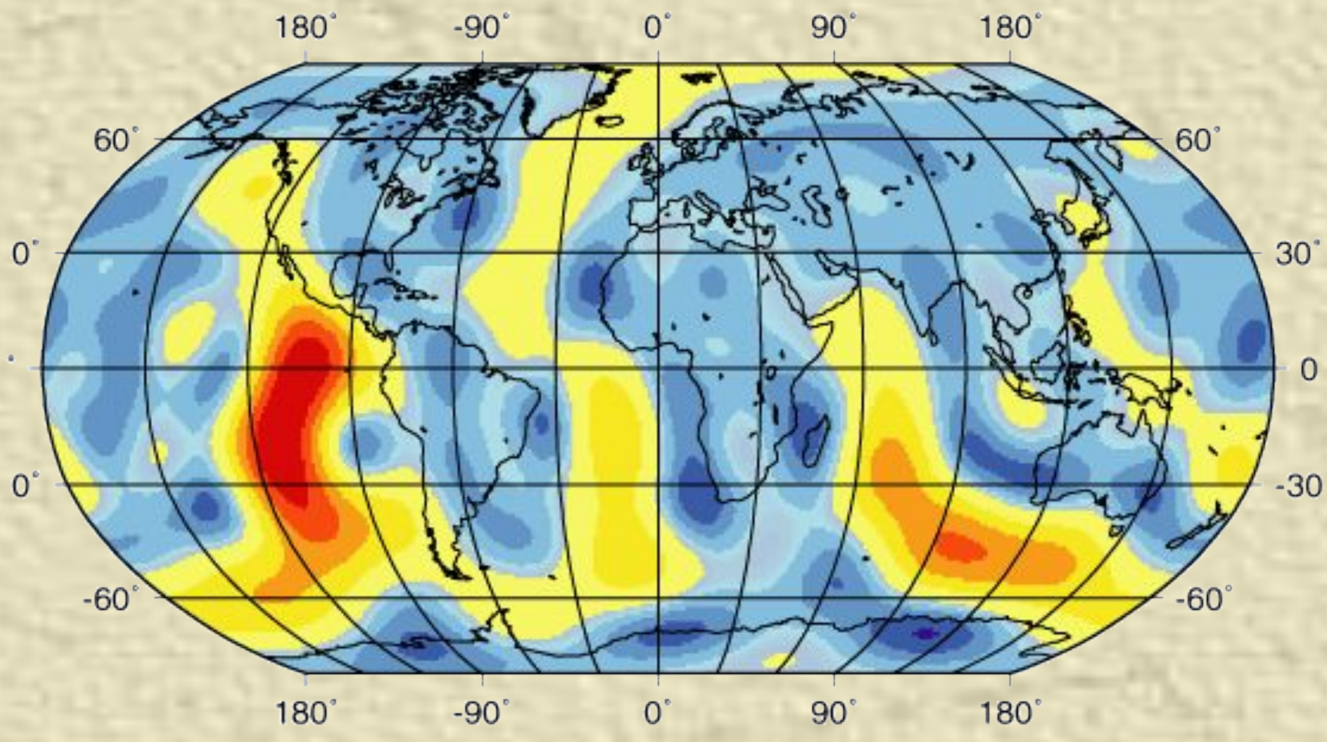
2 stage. Converging Plate Boundary - Continent to Ocean



Convergent Plate boundaries.
3 stage. Converging - Continent to Continent

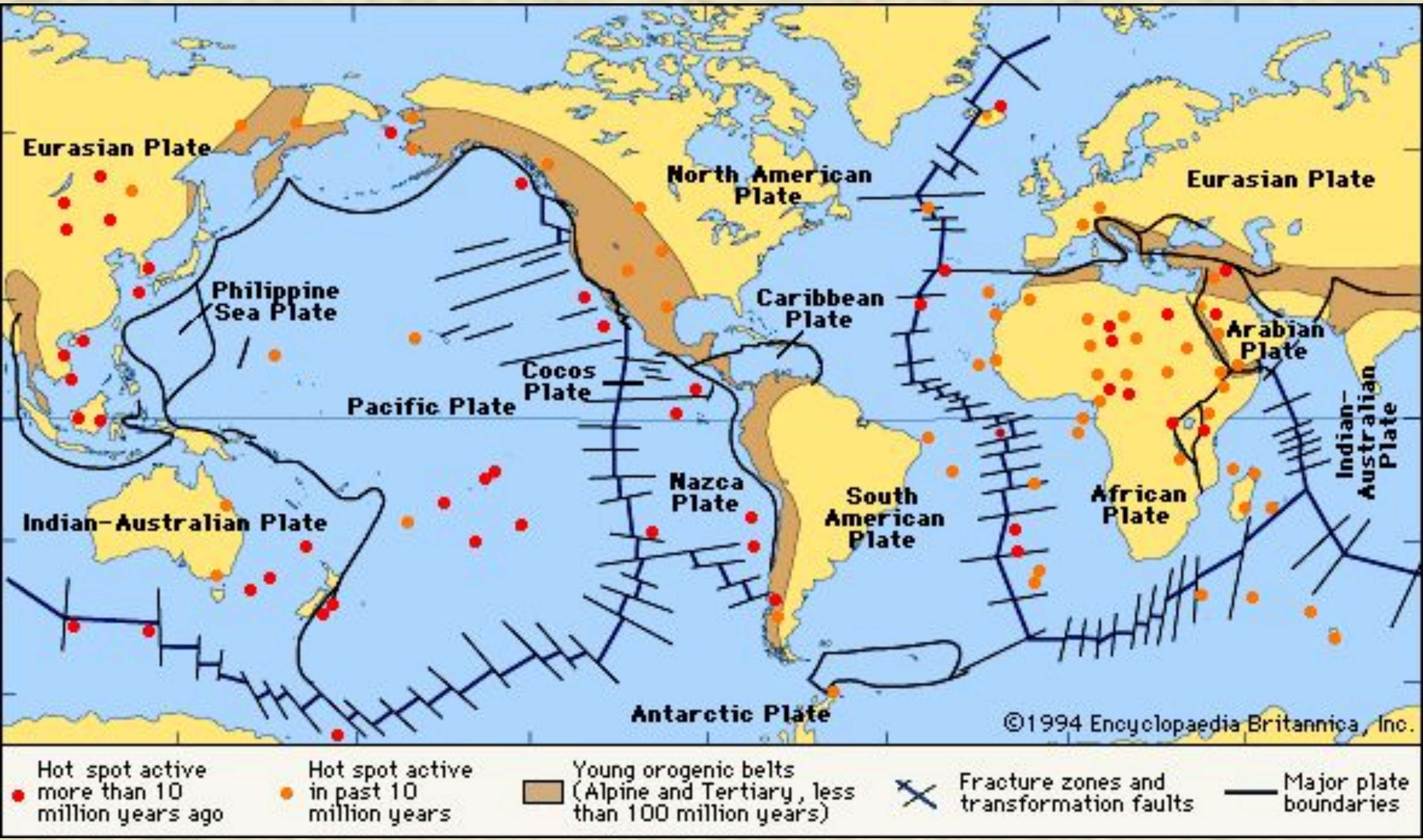


HEAT FLOW



The average **continental heat flow** is about **57** milliwatts per square meters (mW/m^2), the **oceanic heat flow** is about **100 mW/m^2**. The "warm" colors yellow-orange-red indicate higher than average heat flow, the blues are lower. **The heat flow is greatest along the system of mid-ocean ridges.**

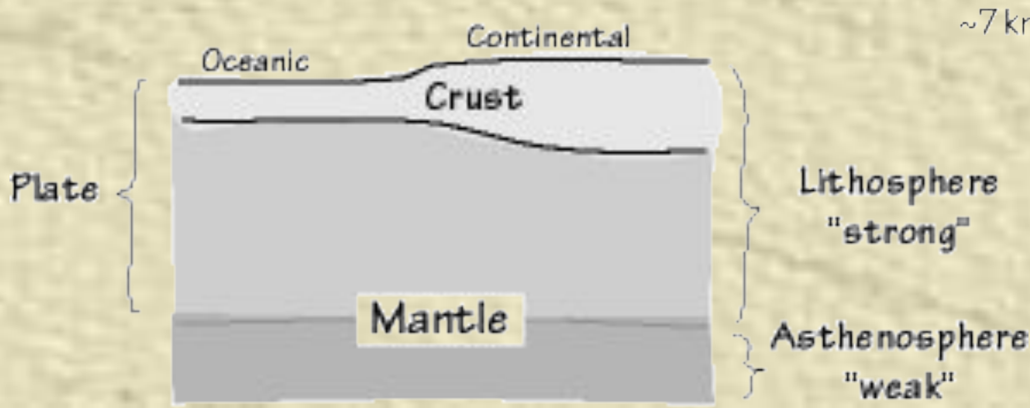
Plates of the Earth

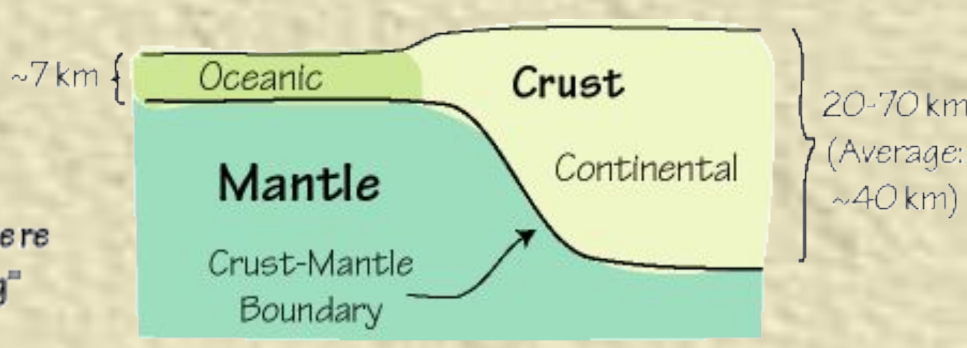


Plates of the Earth: What Is A Plate?

Plates are large pieces of the upper **few hundred kilometers** of Earth (usually on the order of **100-200 km** thick) that move more or less as a **single unit**.

It is easier to think of plates as rigid "rafts" **floating on the mantle**, but some plates also have some internal deformation. However, it is clear that the most active **deformation** of the plates occurs along their **boundaries**, where they interact with other plates.





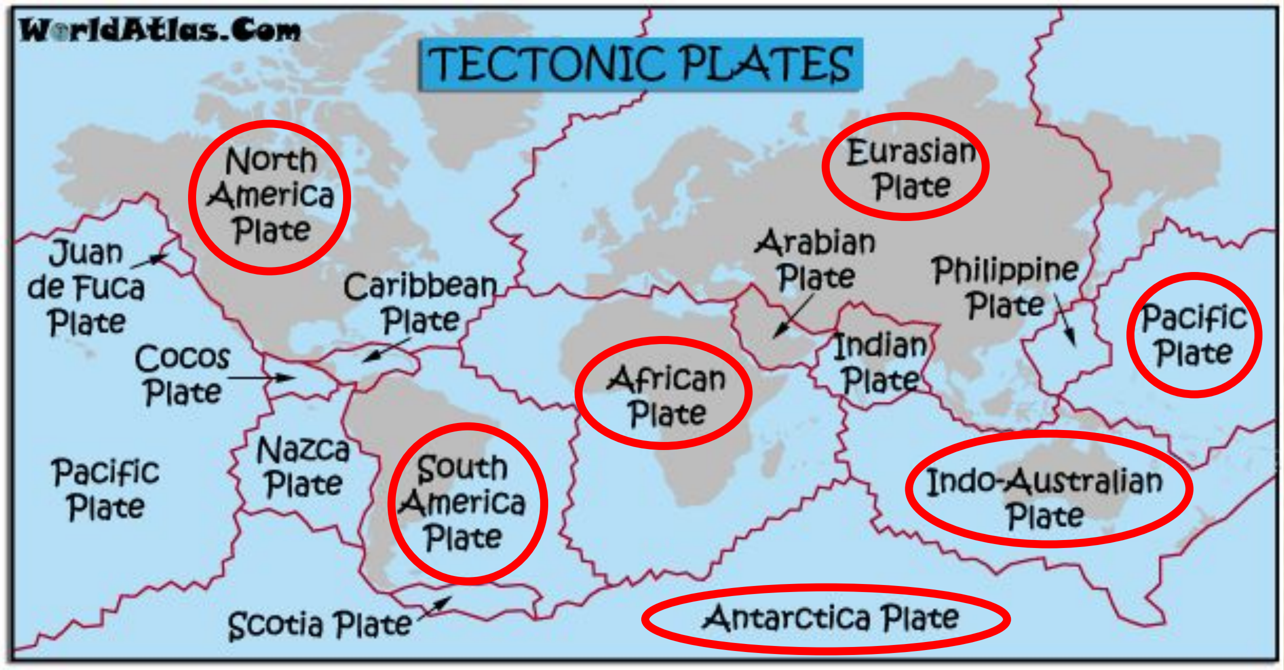
Plates of the Earth

Primary plates

These seven plates make up most of the seven continents and the Pacific Ocean.

1) African Plate; 2) Antarctic Plate; 3) Eurasian Plate;

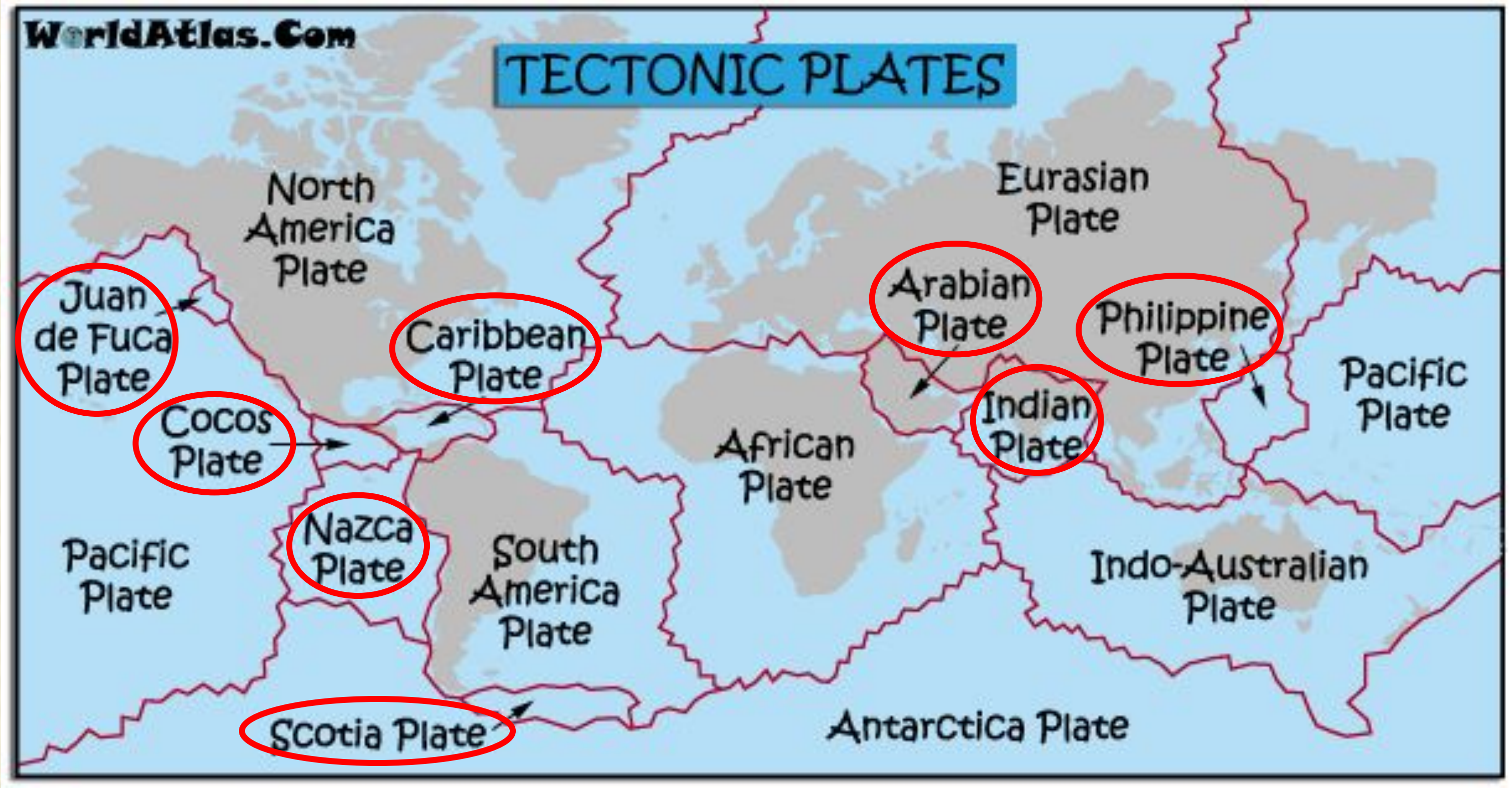
4) Indo-Australian Plate; 5) North American Plate; 6) Pacific Plate; 7) South American Plate



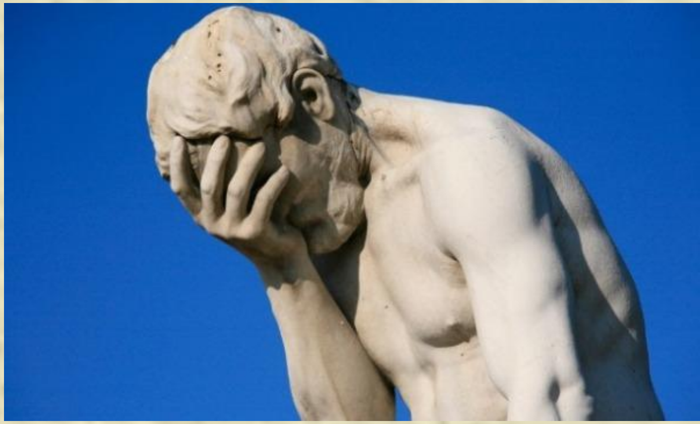
Plates of the Earth

Secondary plates

Arabian Plate; Caribbean Plate; Cocos Plate; Juan de Fuca Plate; Indian Plate; Nazca Plate; Philippine Sea Plate; Scotia Plate



Rate of Plate Movement



San Andreas Fault - 5.5 cm/yr

Mid-Atlantic Ridge

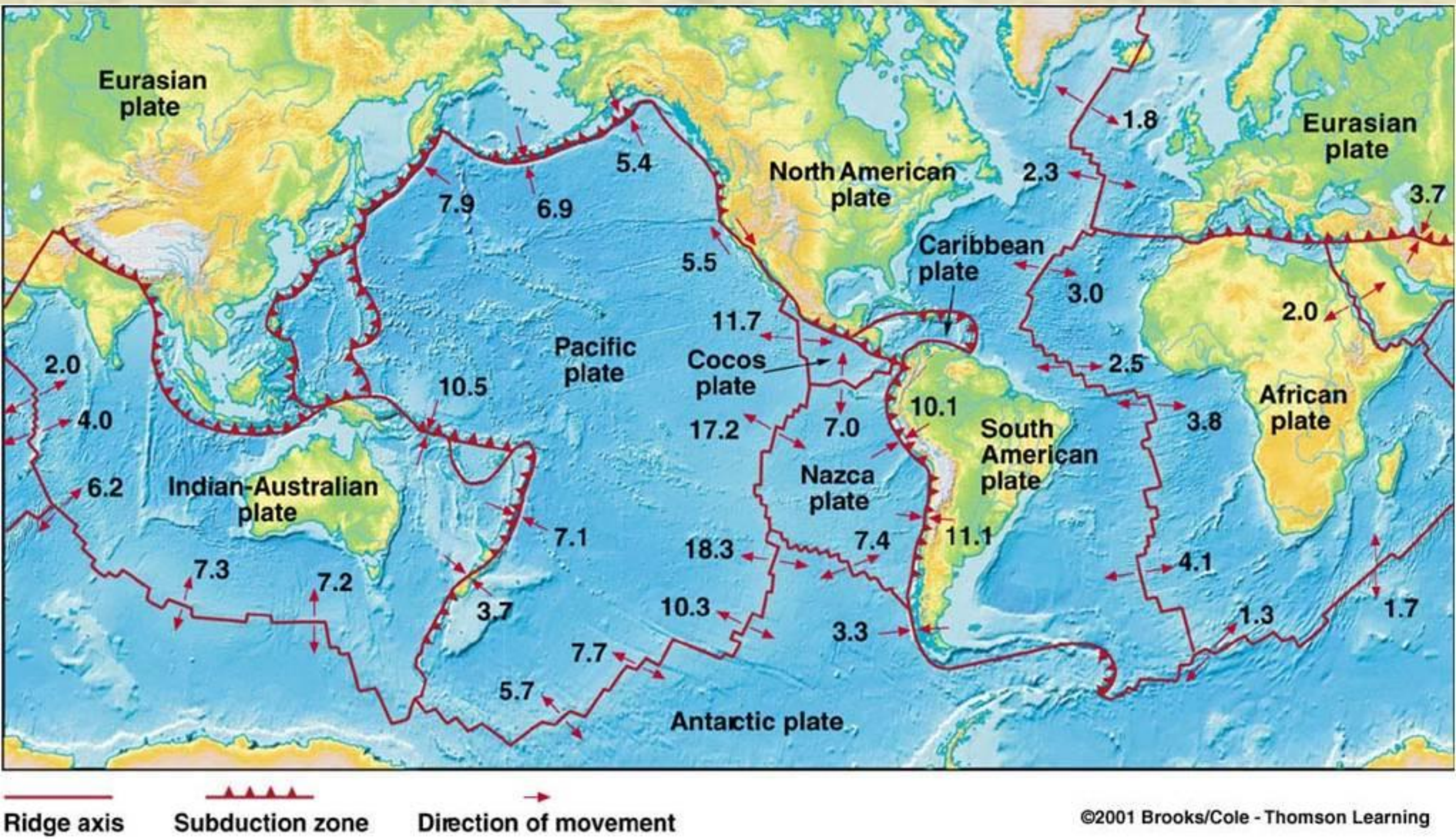
Iceland - 1.8 cm/yr;

South Atlantic (Ascension Island) - 3.9 cm/yr

East Pacific Rise - off South America

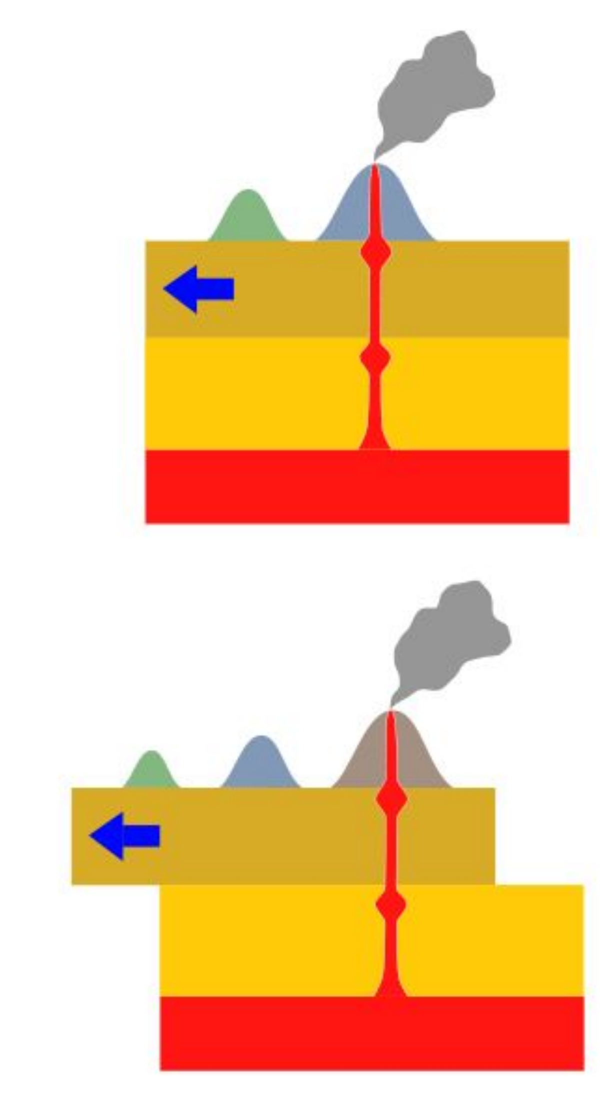
Most rapid movement - 17.1 cm/yr

Tectonic Rate Map



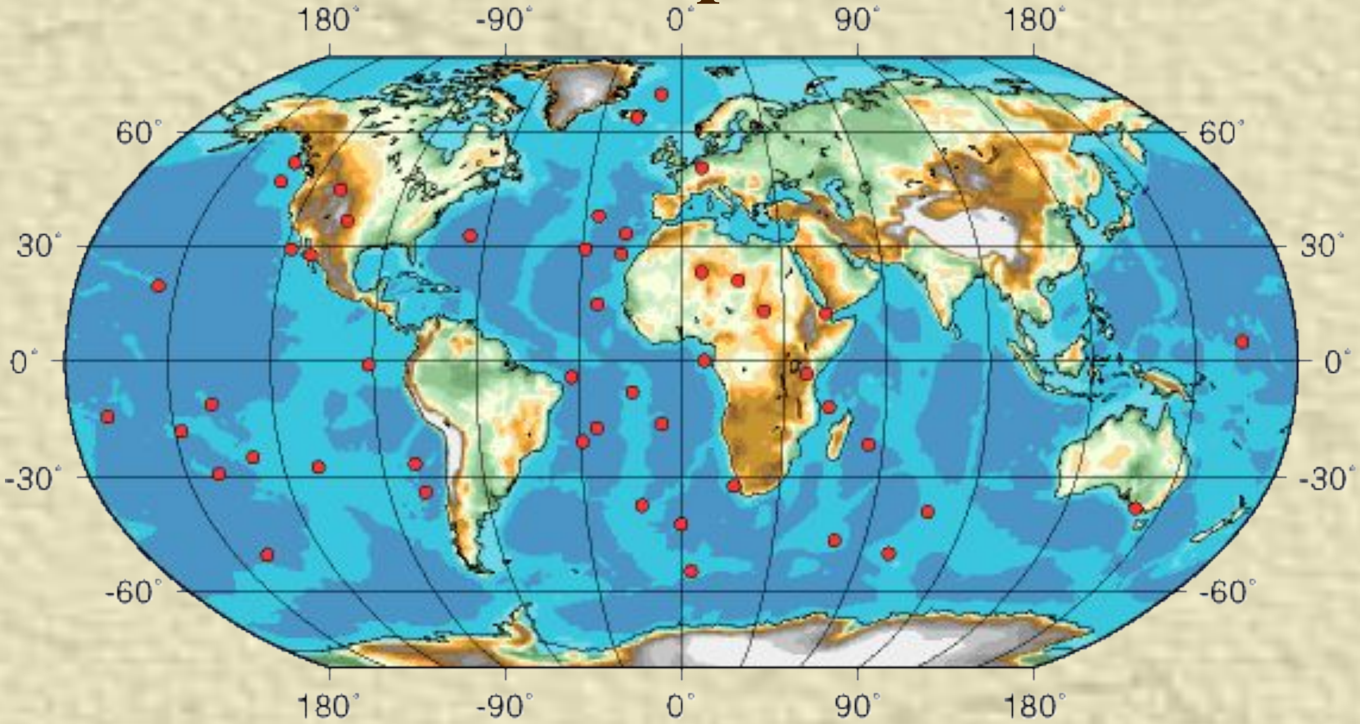
Hot Spots

A **volcano hotspot** is a region on the Earth's surface that has experienced volcanism for a long time. A good example of this is the **Hawaiian Islands**. Each of the islands in the long chain were created by the same volcano hot spot.



The **volcano built up an island** that extended above the surface of the ocean, and then **plate tectonics carried the island away**, creating an extinct volcano. But there's always a **new volcano** being created by the **same hot spot**.

Hot Spots



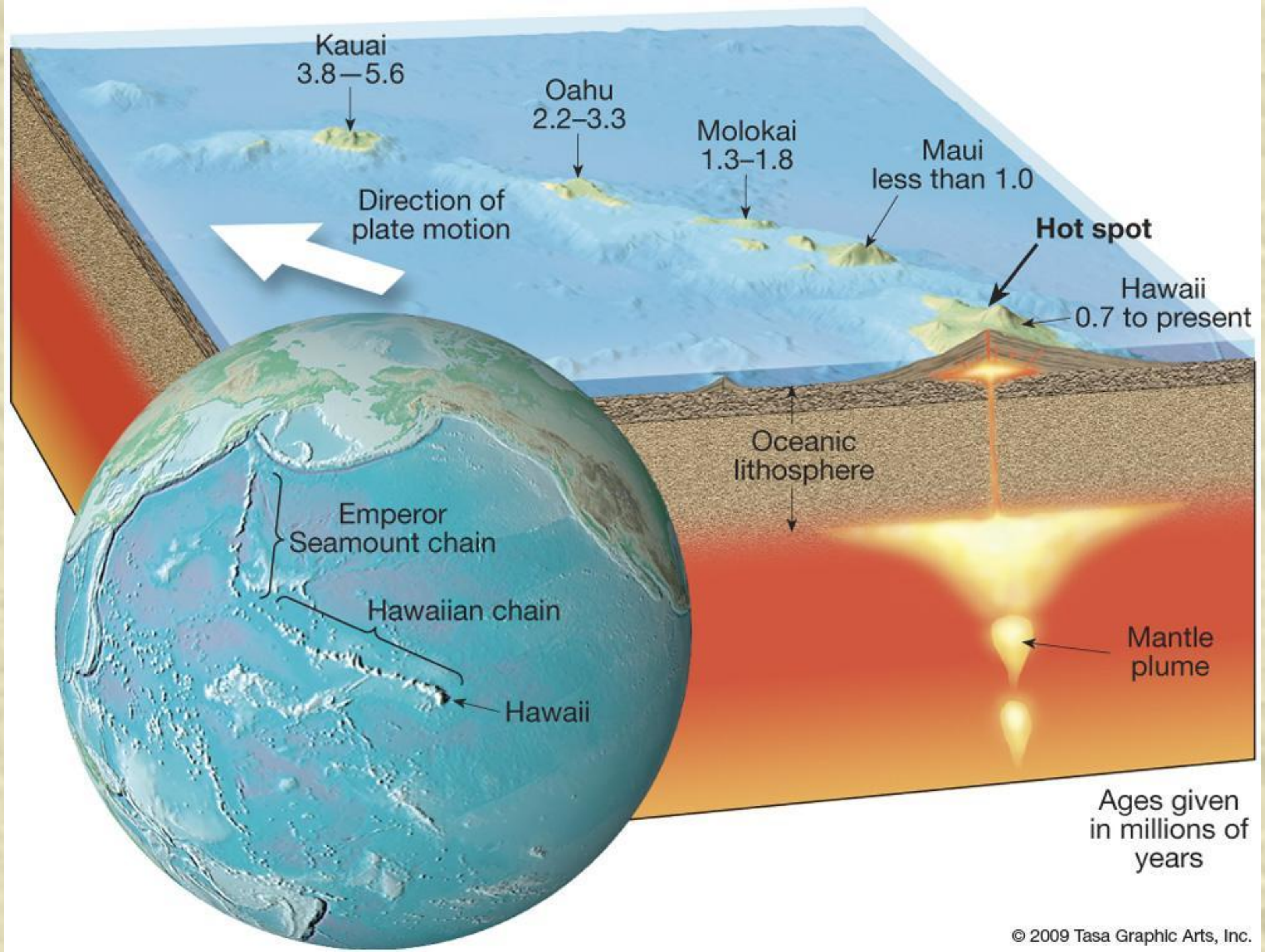
Much remains unknown about the **nature of hot spots**.

Where they originate: upper mantle/lower mantle/ core-mantle boundary?

Are they stationary or slowing drifting (but moving slower than the plates)?

The large number of hot spots in the Atlantic ocean are suspected to have played a role in the breakup of **Pangaea**.

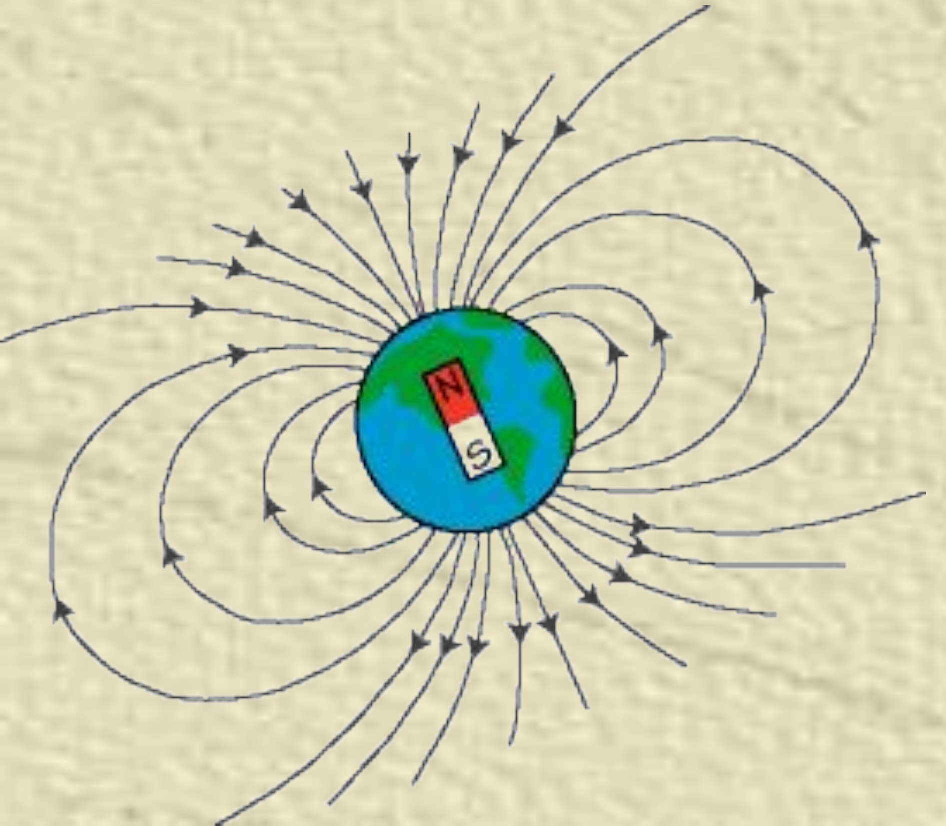
Hot Spots



Kauai
3.8 – 5.6
Oahu
2.2–3.3
Molokai
1.3–1.8
Maui
less than 1.0
Direction of
plate motion
Hot spot
Hawaii
0.7 to present
Oceanic
lithosphere
Emperor
Seamount chain
Hawaiian chain
Hawaii
Mantle
plume
Ages given
in millions of
years
© 2009 Tasa Graphic Arts, Inc.

Magnetic Anomalies

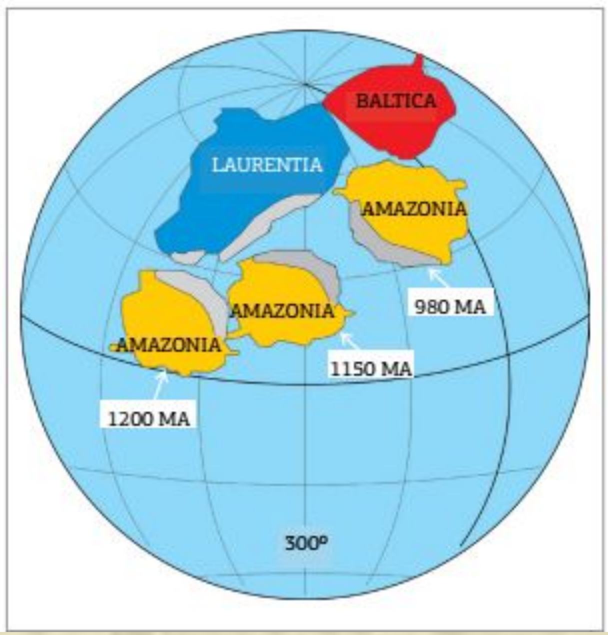
The **"geomagnetic" field** is generated by motions of the **iron** in the **outer core**. One property of a moving conductor *«электродинамический»* (such as the flowing iron in the outer core) is that it produces a **magnetic field**.



That same magnetic field allows us to use a compass to navigate around Earth's surface.

Magnetic Anomalies

The **Earth's magnetic filed** provides some valuable information on the **location of rocks** when they form.

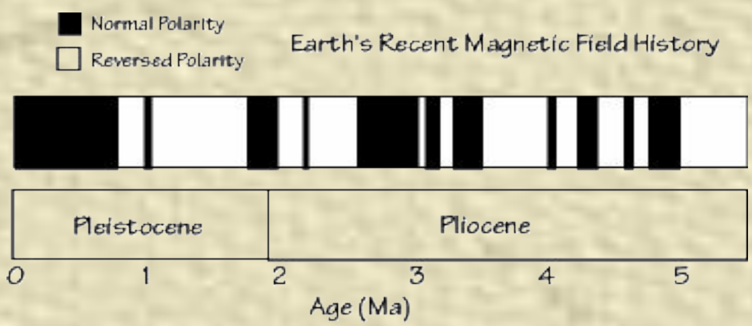


As the **lava cools** the **iron** they contain is preferentially **oriented** by the **magnetic field** of Earth, like mini-compasses.

As the rock continues to cool, its temperature decreases below the "**blocking temperature**" and the magnetically induced alignment of iron is frozen into the rock.

The net result is that the **rock** storing **information** on the **orientation** of Earth's magnetic field at the **time** the **rock cooled**.

Magnetic Anomalies

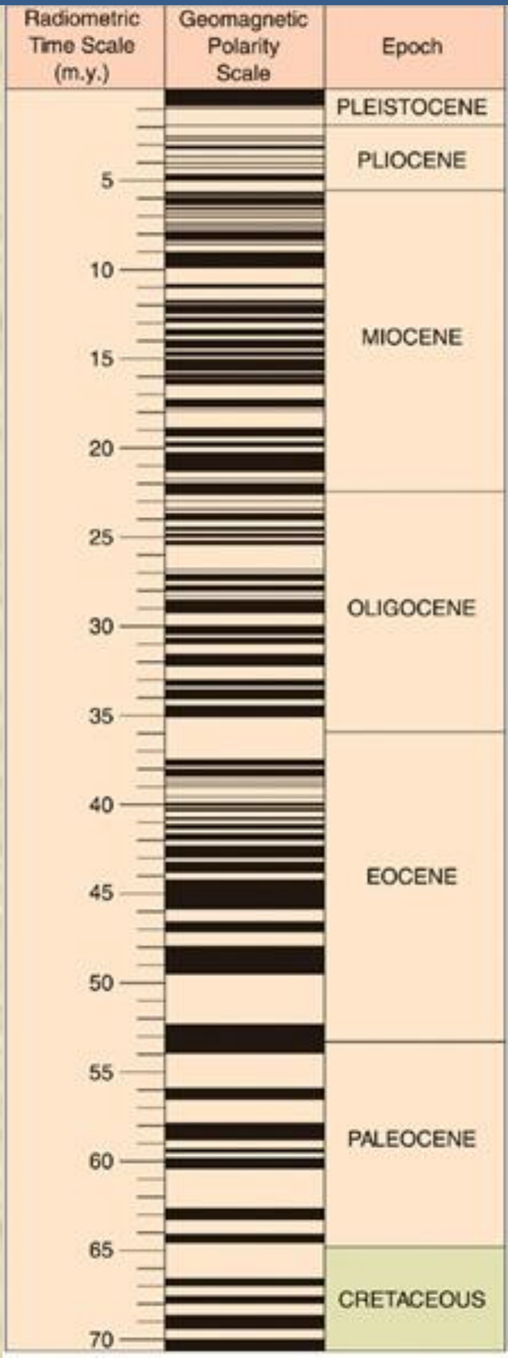


Magnetic reversal time scale over the past 70 million years.

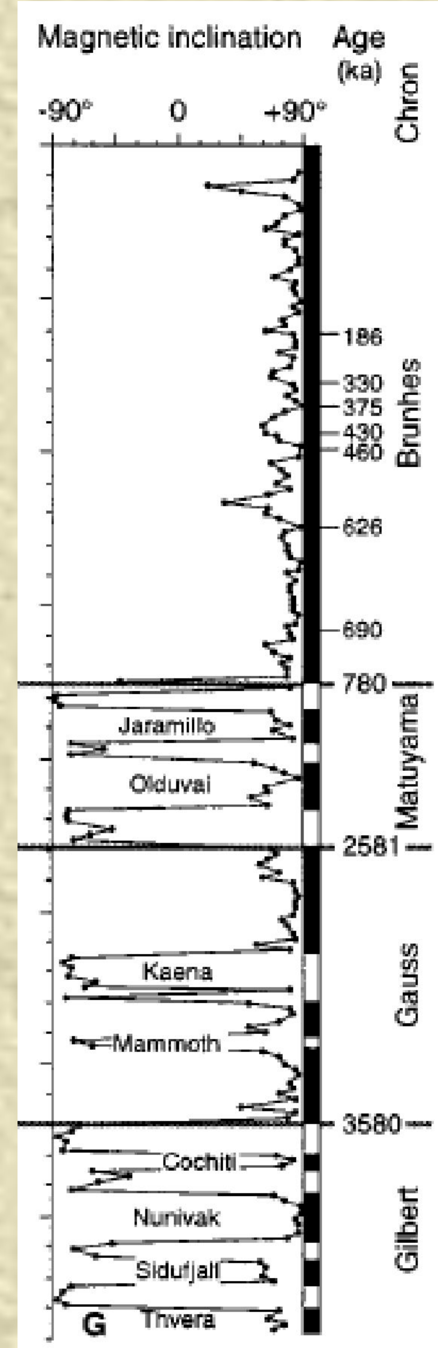
Black intervals had **normal** polarity (like that today),

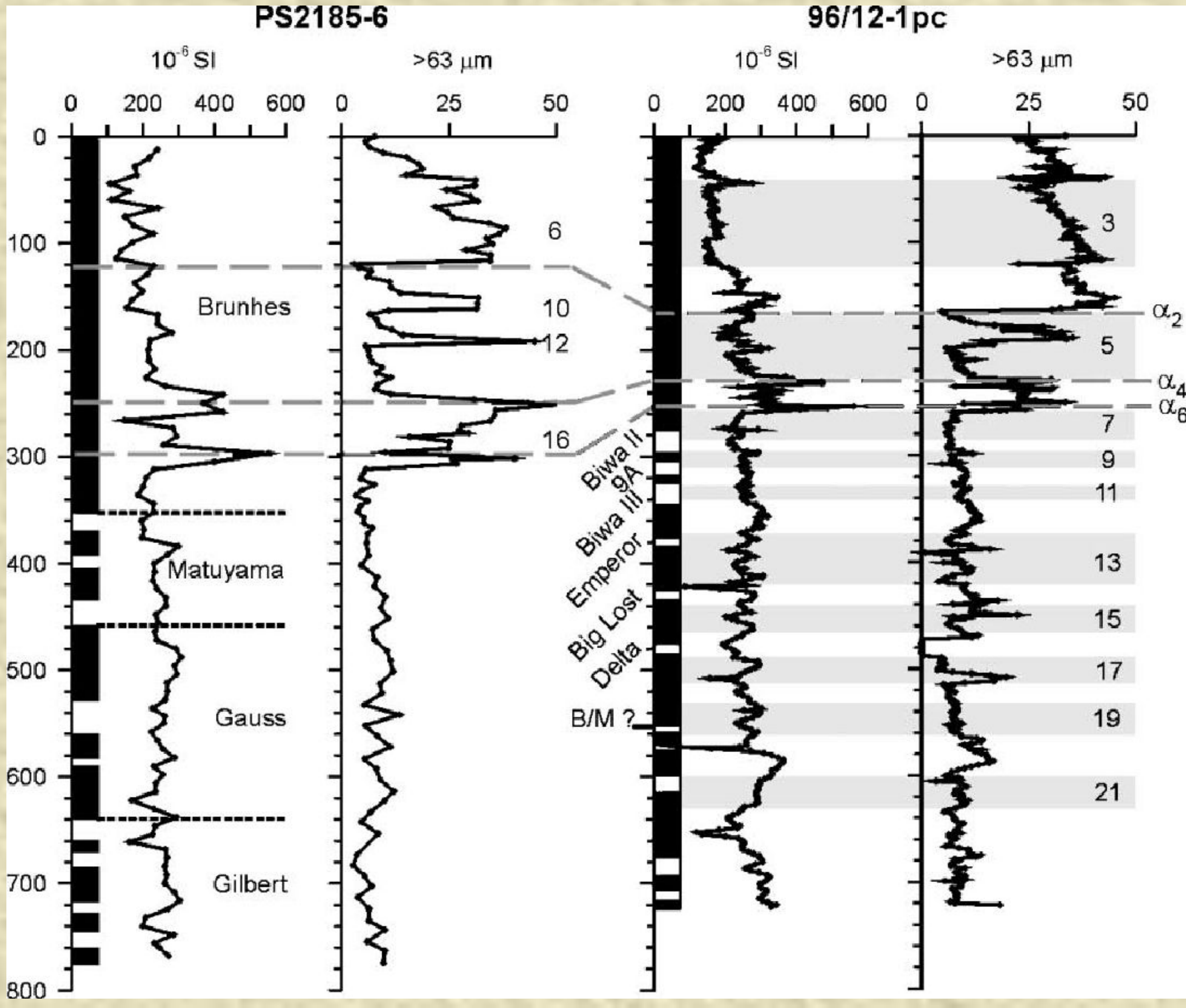
and

white intervals had **reversed** polarity.

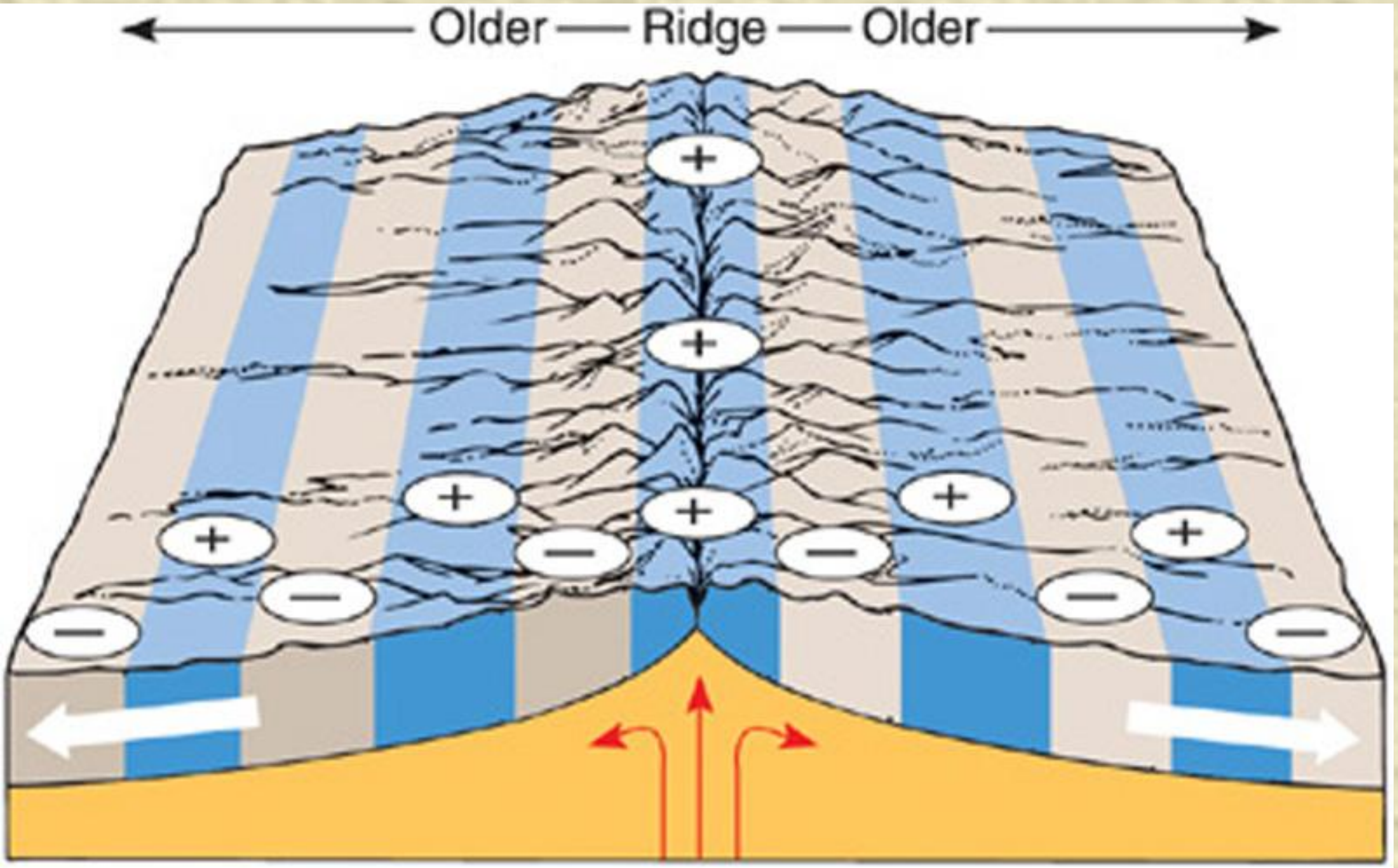


Magnetic Anomalies



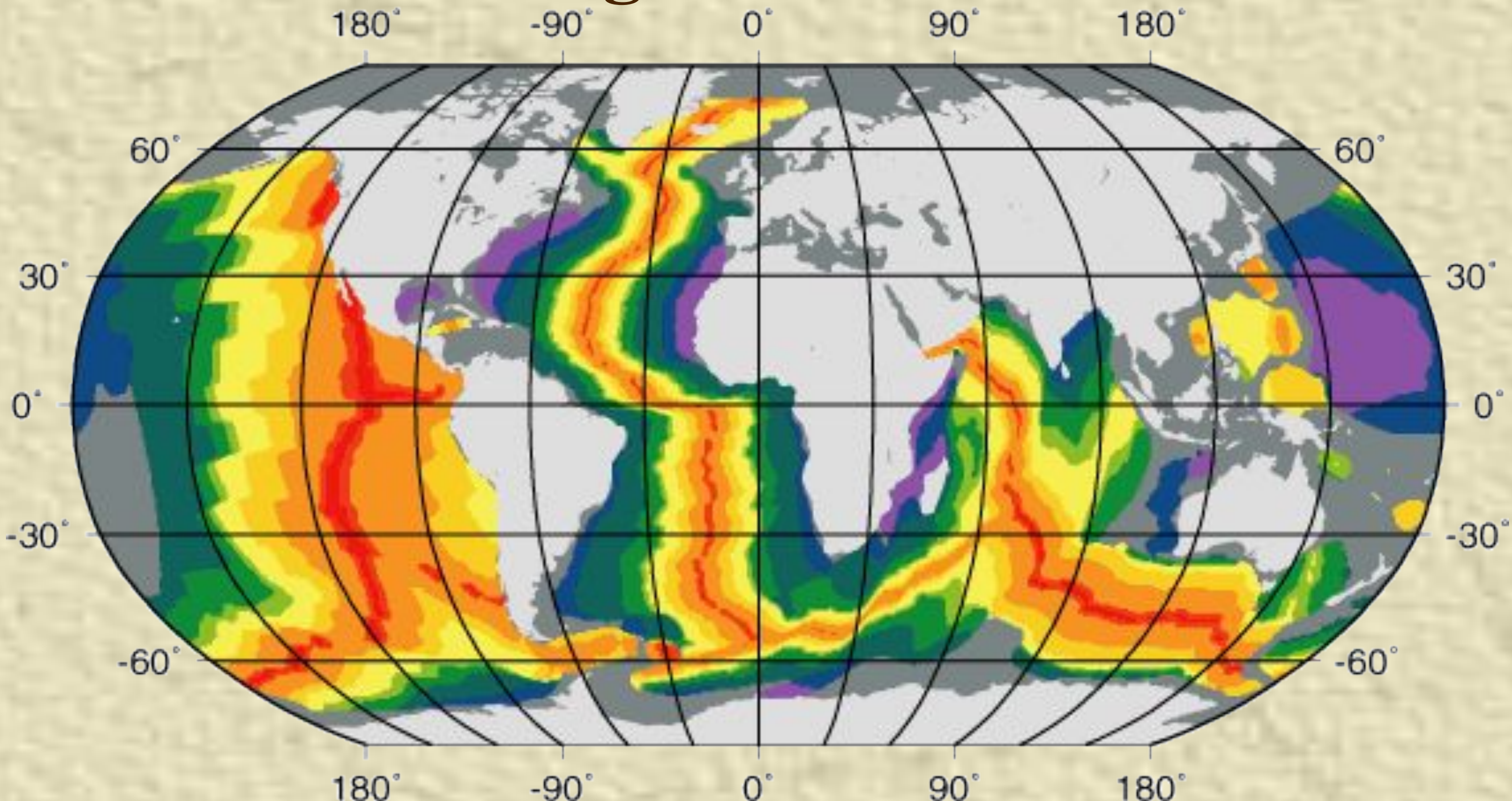


Magnetic Anomalies



Normal (+) and reversed (-) magnetization of the seafloor about the mid-ocean ridge.
Note the symmetry on either side of the ridge.

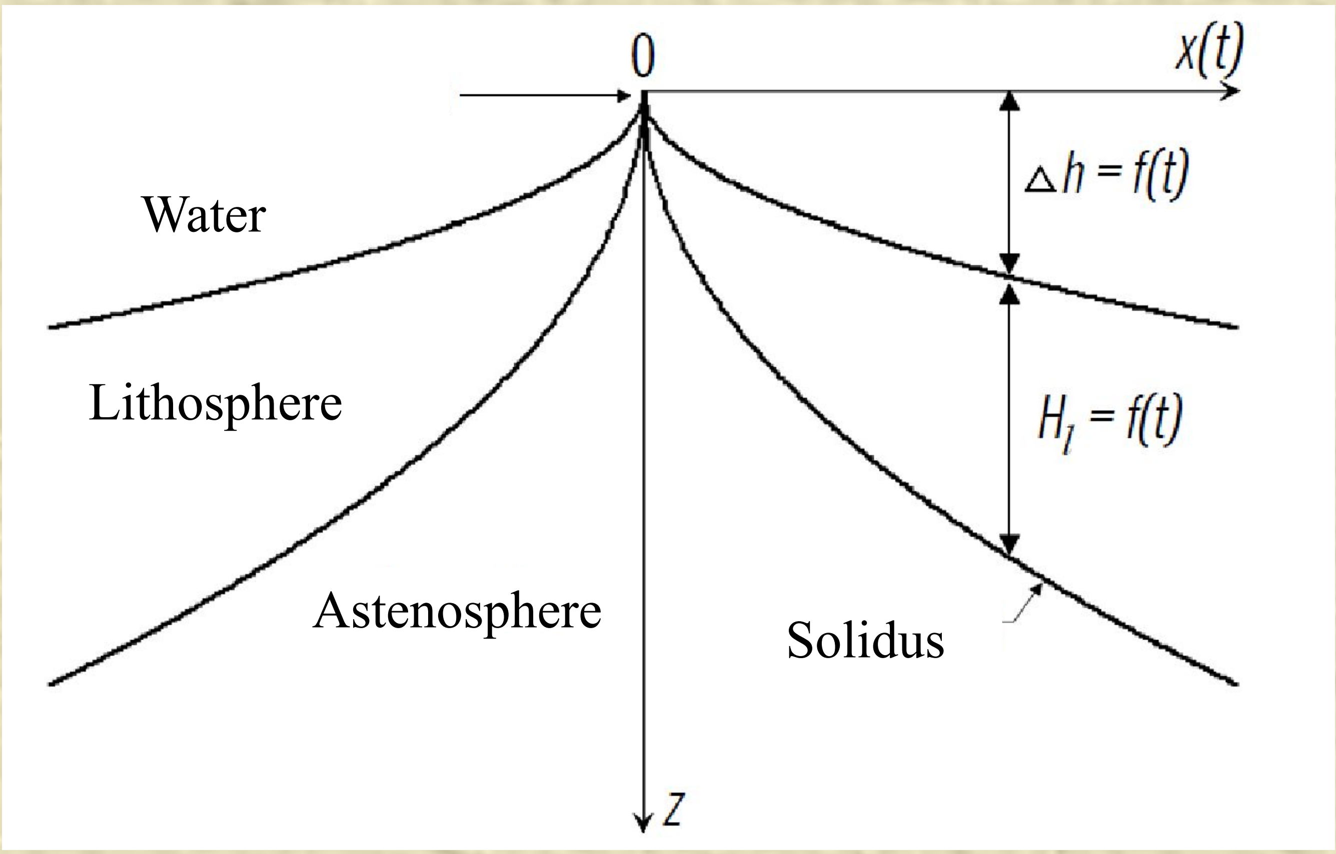
Magnetic Anomalies



The youngest regions are shown in red (age < 2 Ma) and red-orange (age 2 Ma < 5 Ma), the older regions in orange, gold, yellow, green, blue, and violet.

It is clear from the Figure that the **ocean ridges are the youngest part of the oceans**.

Spreading is slower in the mid-Atlantic than along the east-Pacific.

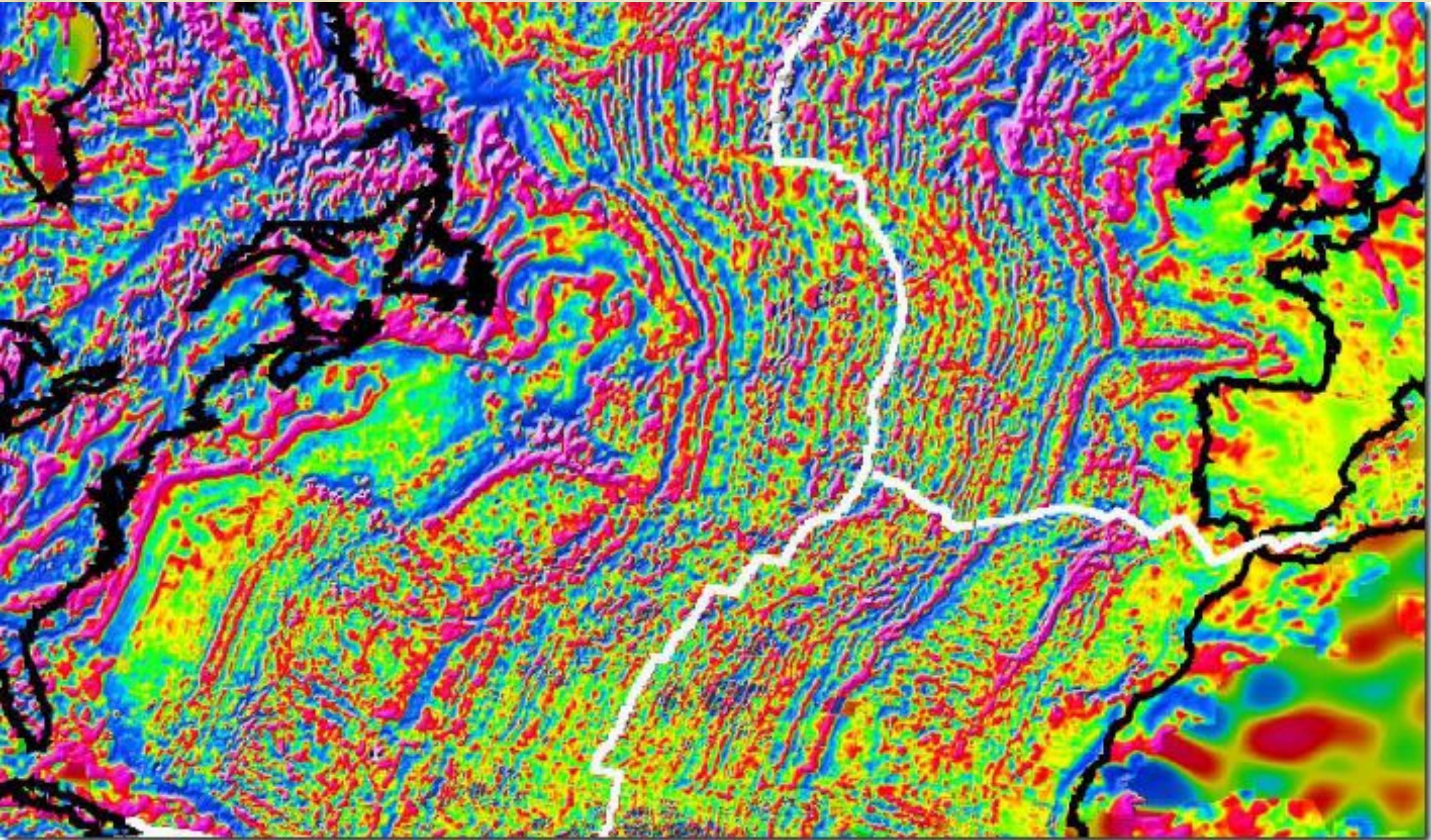


$$H_l = 6{,}5 + 8{,}5\sqrt{t}$$

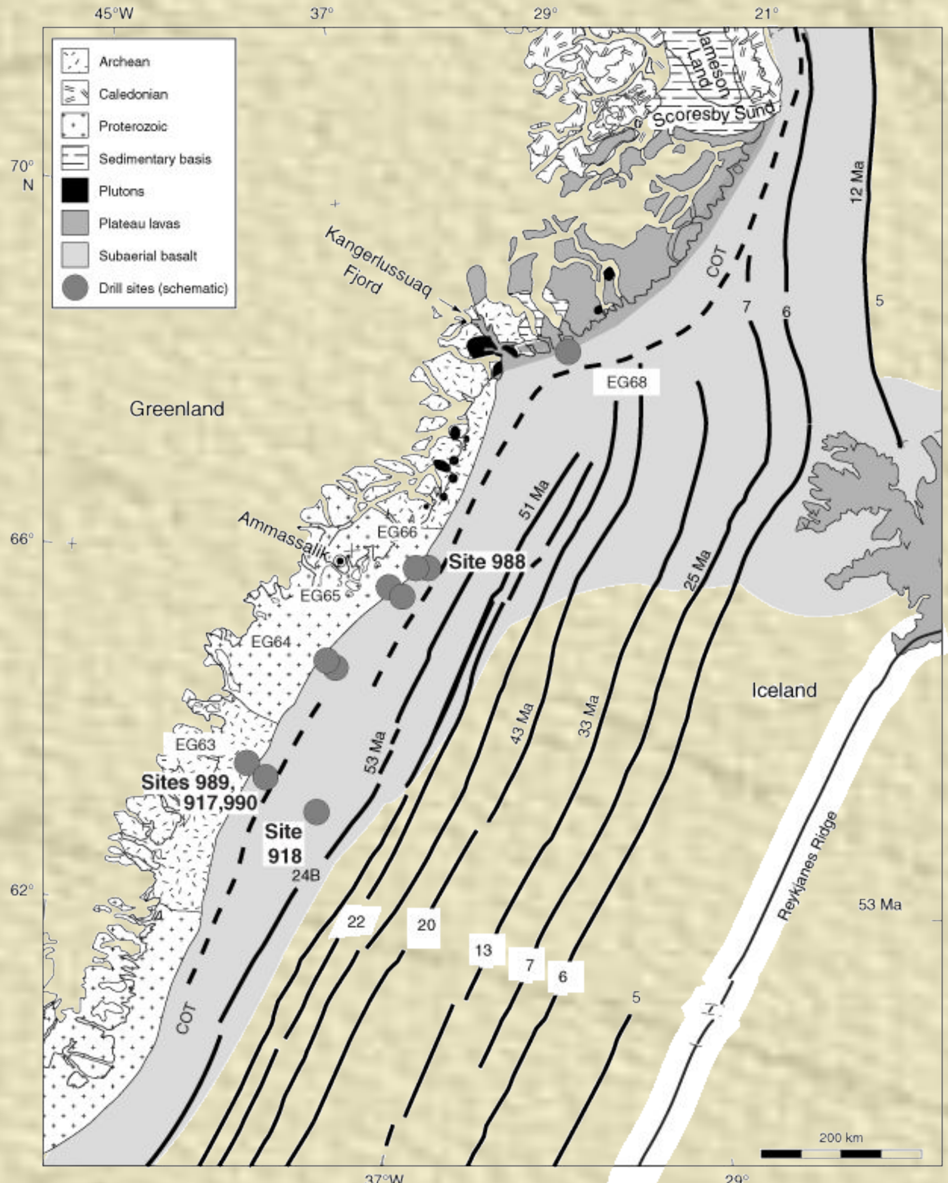
$$\Delta h \approx 0{,}35\sqrt{t}$$

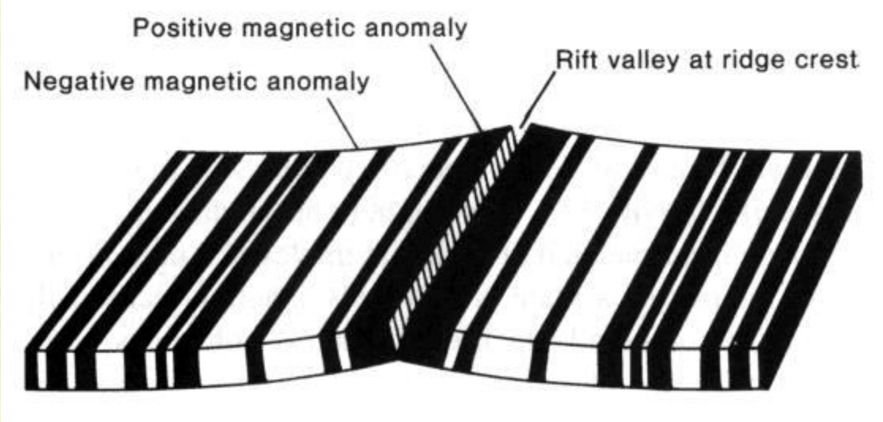
Increasing the thickness of lithosphere with time.

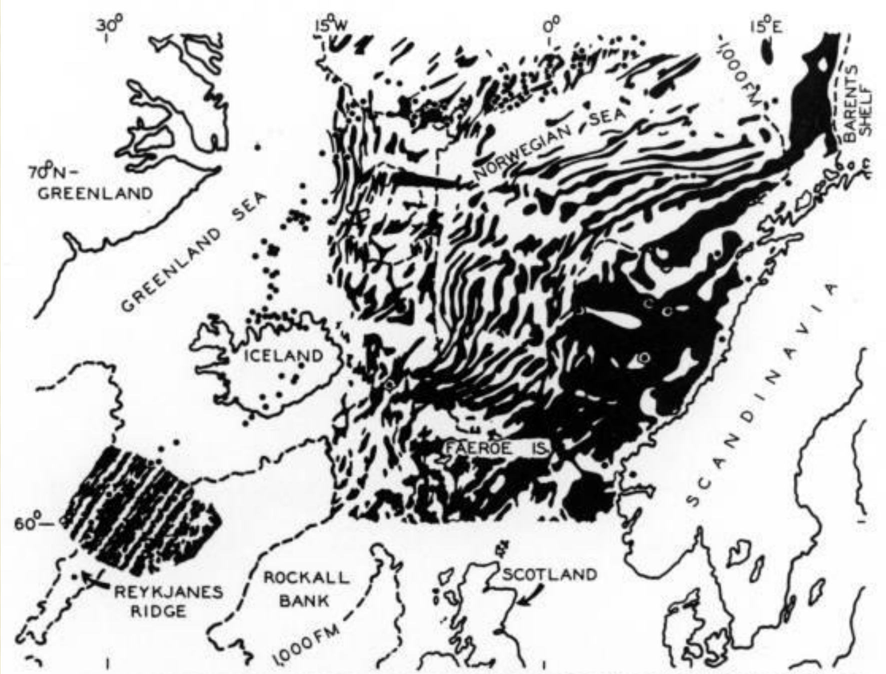
Magnetic Anomalies



Magnetic Anomalies

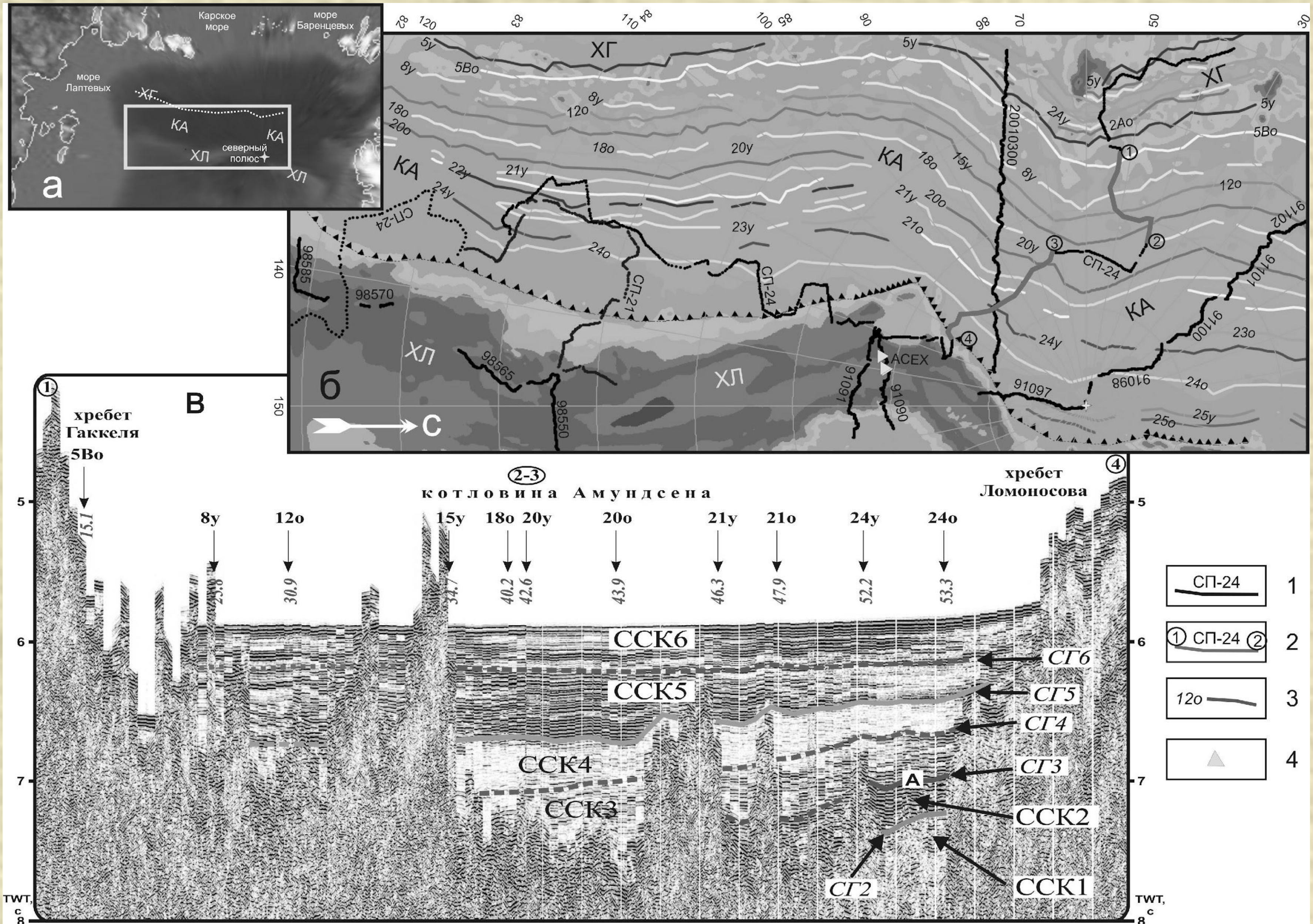






•EARTHQUAKE EPICENTERS. NOTE THAT LINEAR ANOMALIES CROSS MIDOCEAN RIDGE AT OBLIQUE ANGLE NORTH OF ICELAND

Magnetic Anomalies



Cycles of Plate Tectonics

Wilson Cycle:

1) Rifting of continents by mantle diapirism

(2) Continental drift, seafloor spreading & formation of ocean basins

(3) Progressive closure of ocean basins by subduction of ocean lithosphere

(4) Continental collision and final closure of ocean basin

Cycles of Plate Tectonics

Numerous cycles of breakup and collision have preceded Wegener's Pangea

Late Precambrian - continents together in one land-mass

Break apart during Cambrian and Ordovician, come back together

Devonian through Permian - reassemble Pangea .

Form Appalachian Mtns.

Cycles of breakup and collision have influence on biological evolution

Breakup/rifting - continents separate

Milder climate, separation of forms - genetic drift. Diversity of species

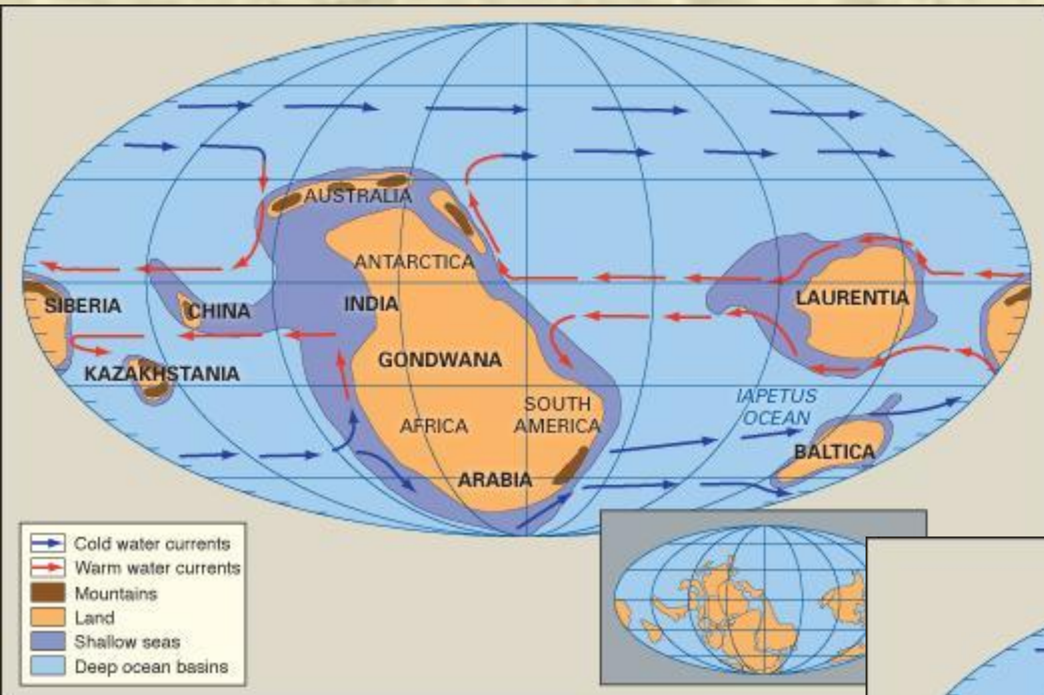
Collisions - continents reassembled

More extreme climate - land masses together

Species brought together - competition

Continents reassembled - times of extinction

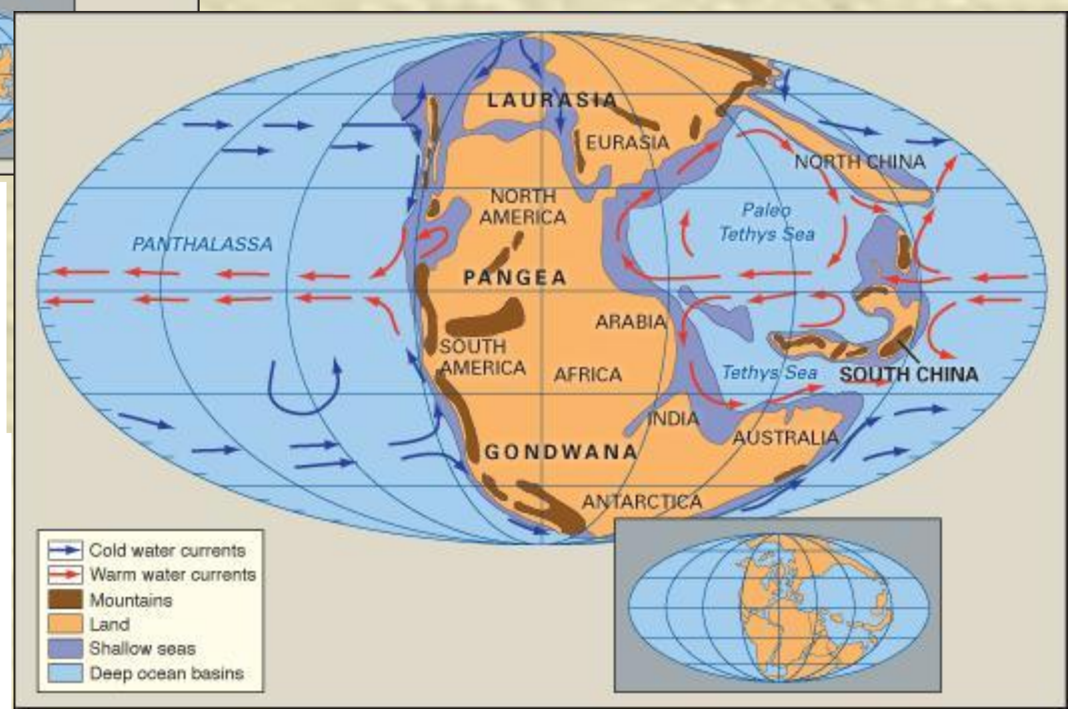
Cycles of Plate Tectonics



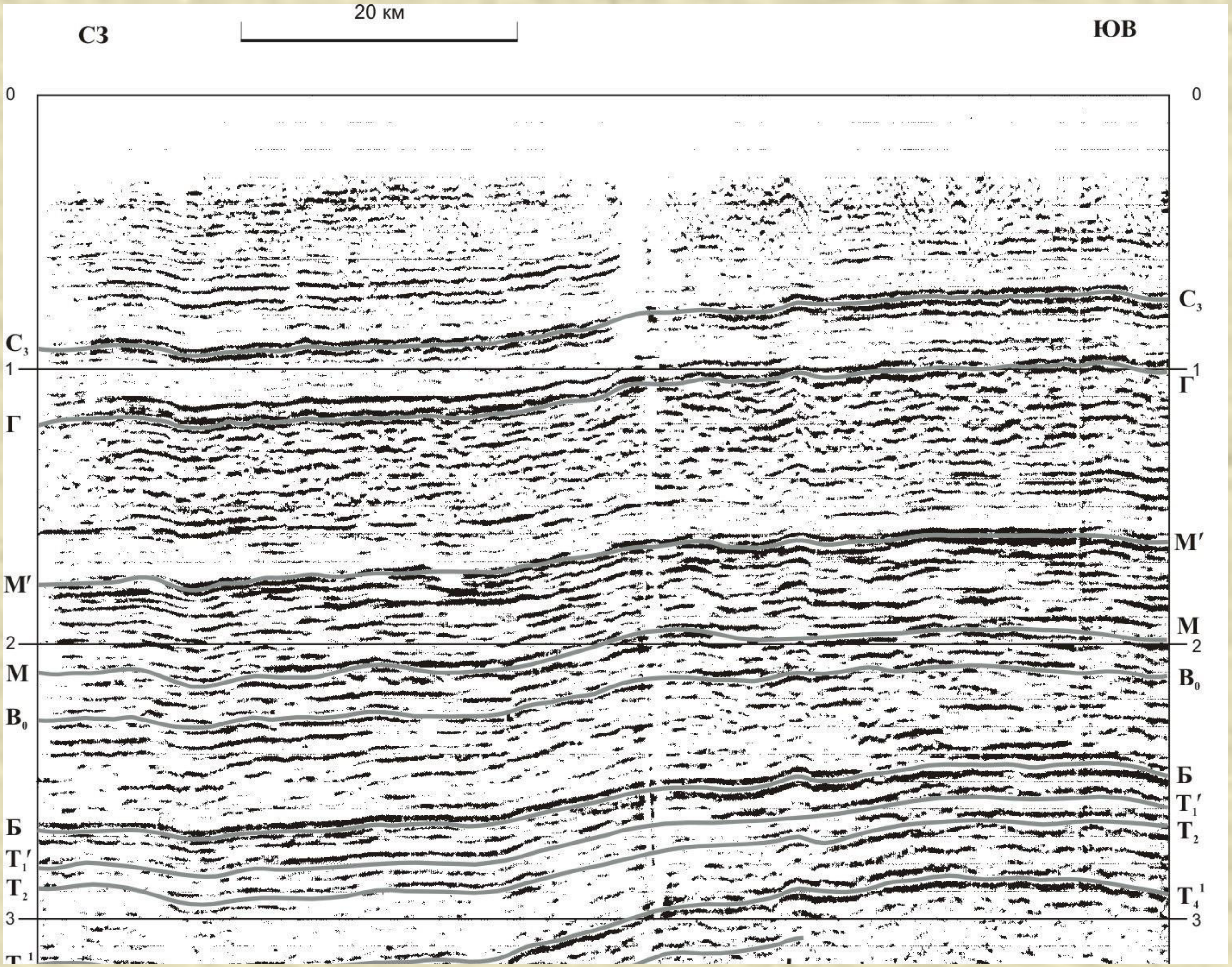
GONDWANA, ancient supercontinent that incorporated present-day South America, Africa, Arabia, Madagascar, India, Australia, and Antarctica.

PANGEA, a "supercontinent" that incorporated almost all of Earth's landmasses and covered nearly one-third of Earth's surface.

LAURASIA, ancient continental mass in the Northern Hemisphere that included North America, Europe, and Asia (except peninsular India).



UNDEFORMED MARINE SEDIMENTS



Horizontal layering

Conformably of layering

Permanent thickness of sediment layers

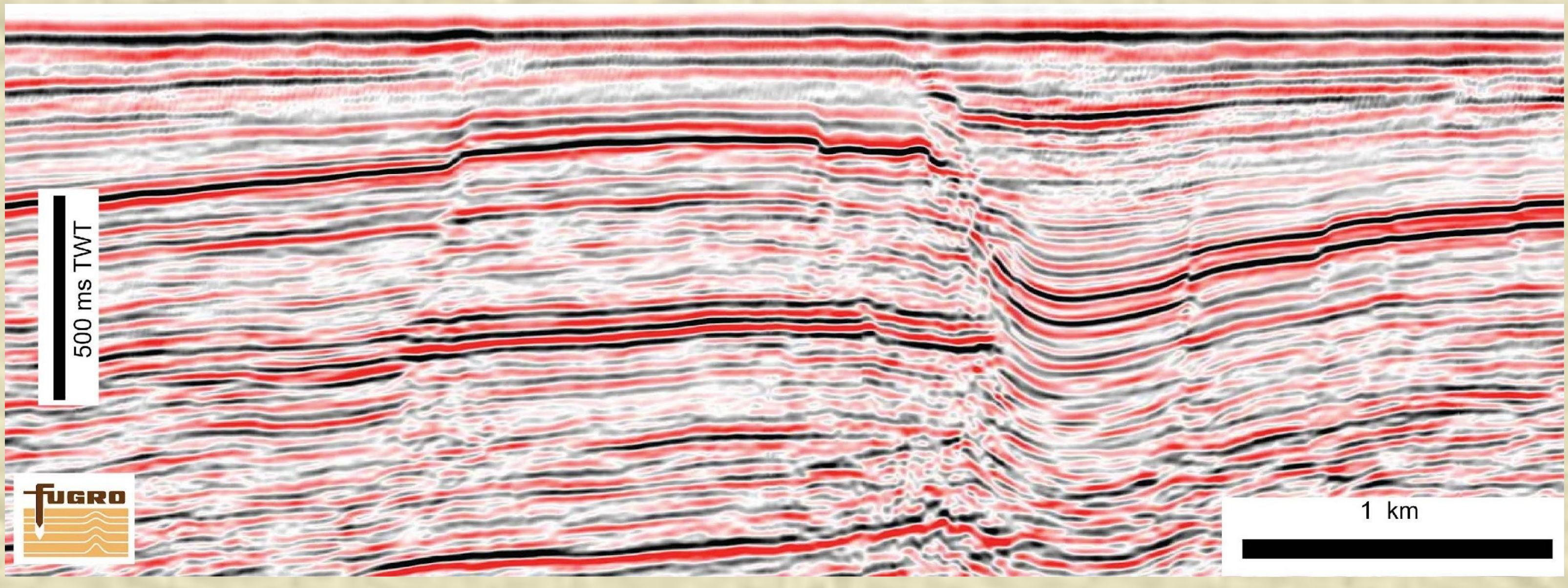
DEFORMATION

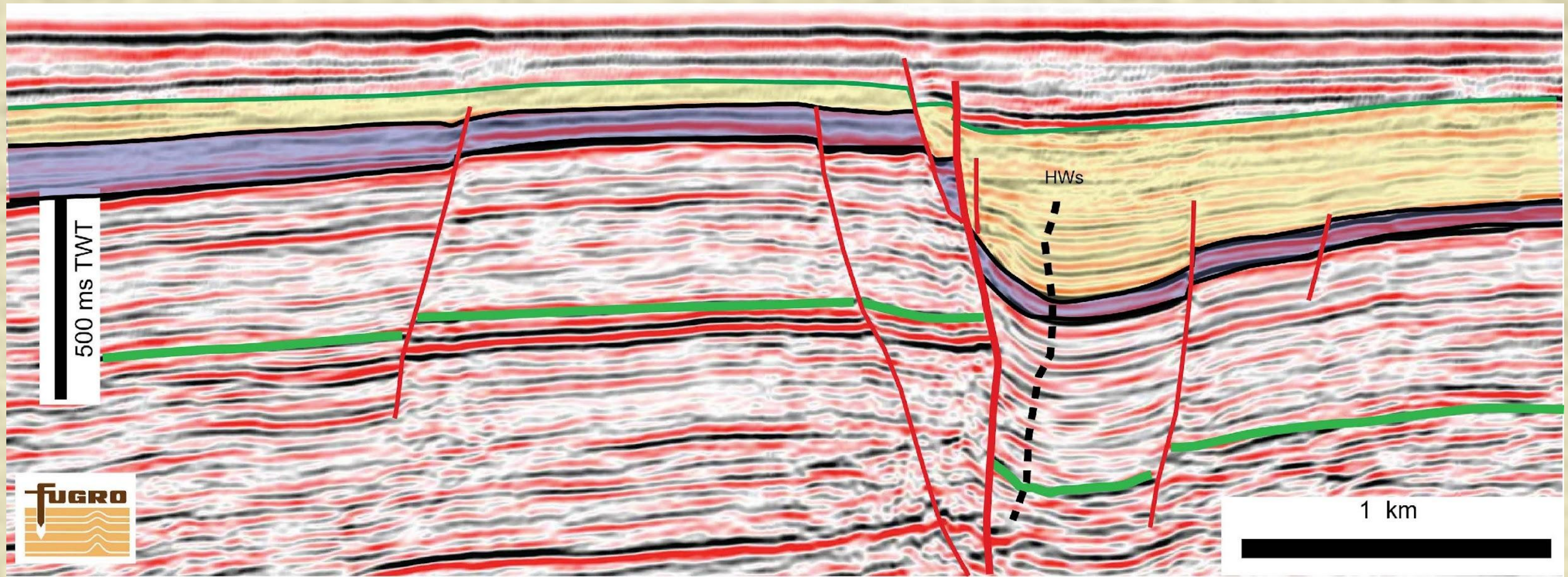
Chapter 7 Opener
Understanding Earth, Sixth Edition

Deformation-

Modification of Rocks by Folding and Fracturing

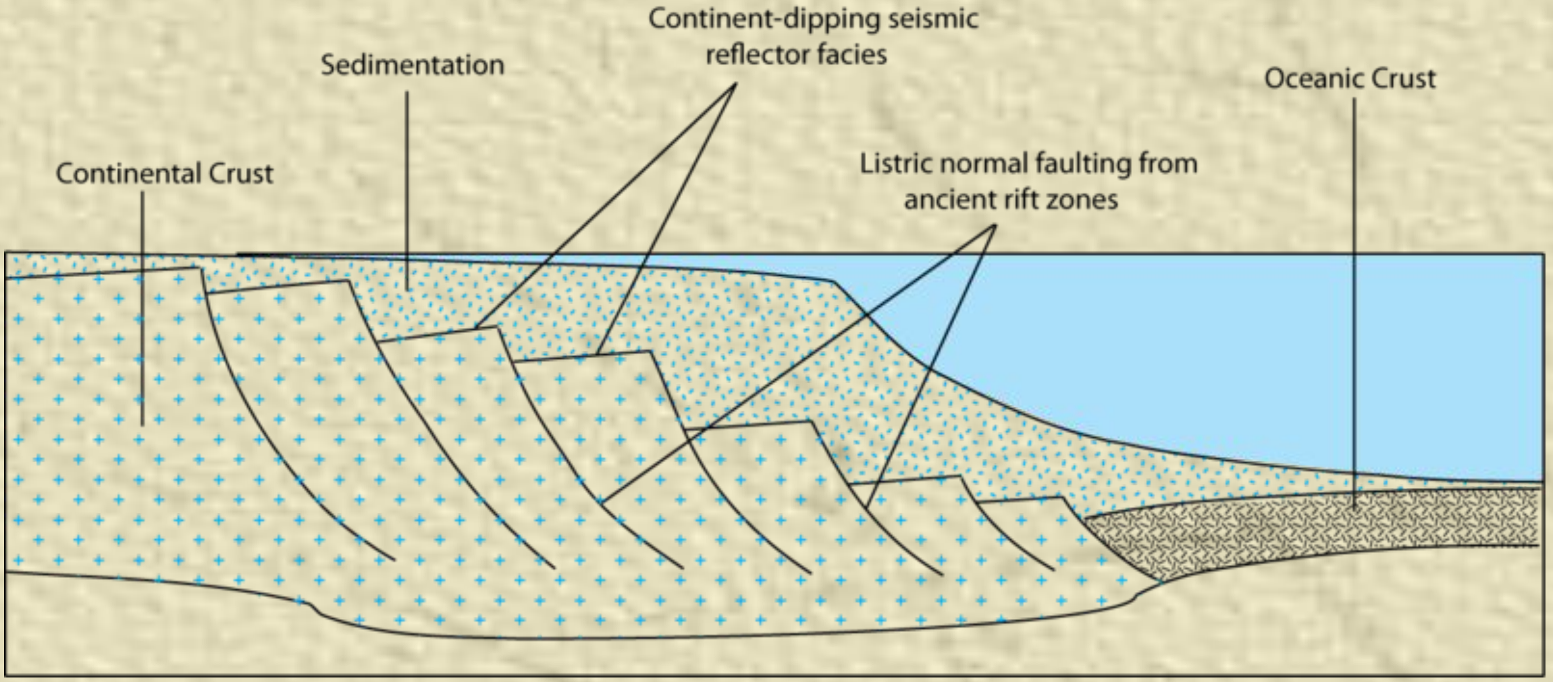
FAULTS





CONTINENTAL SLOPE

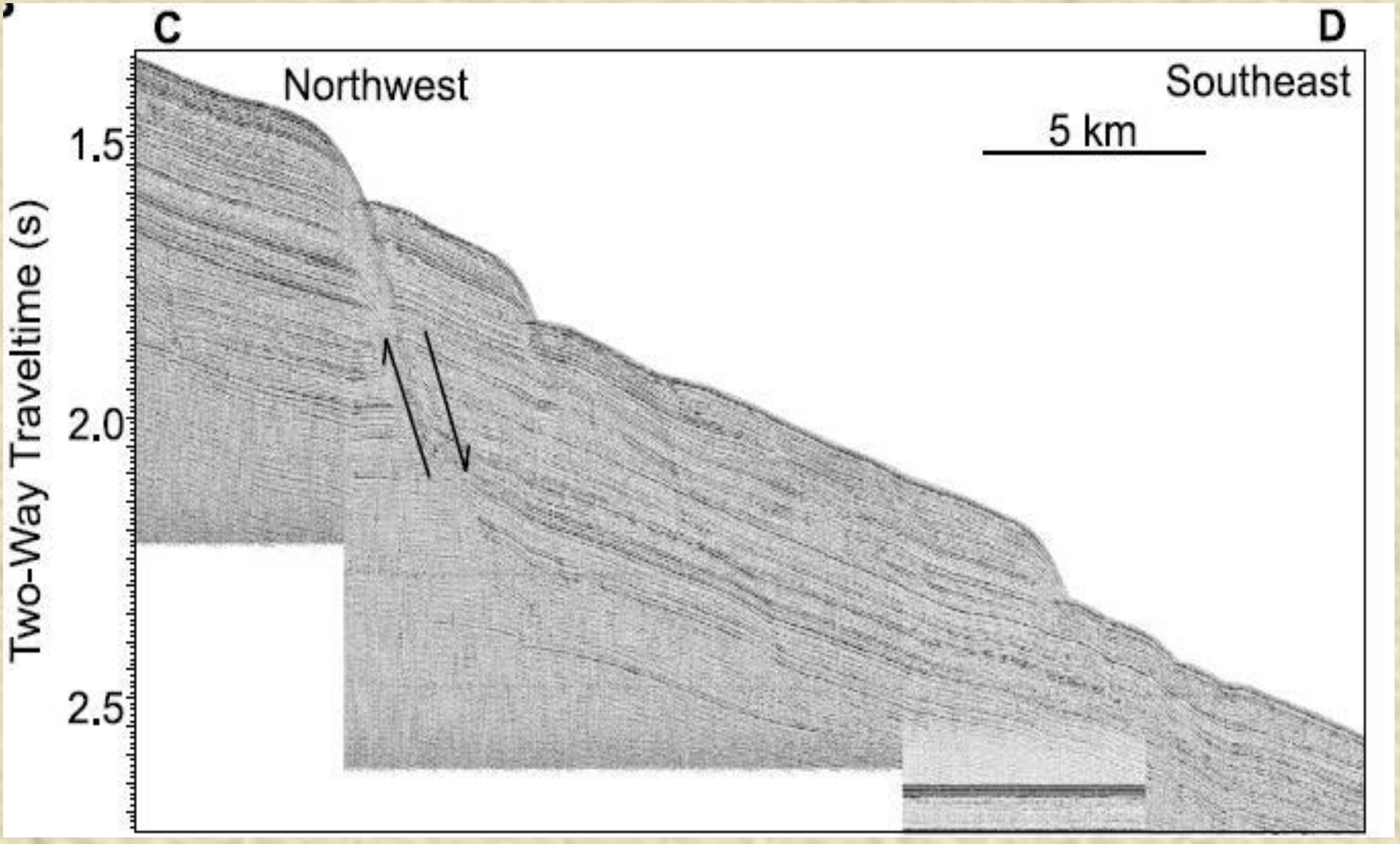
Rifted Passive Margin



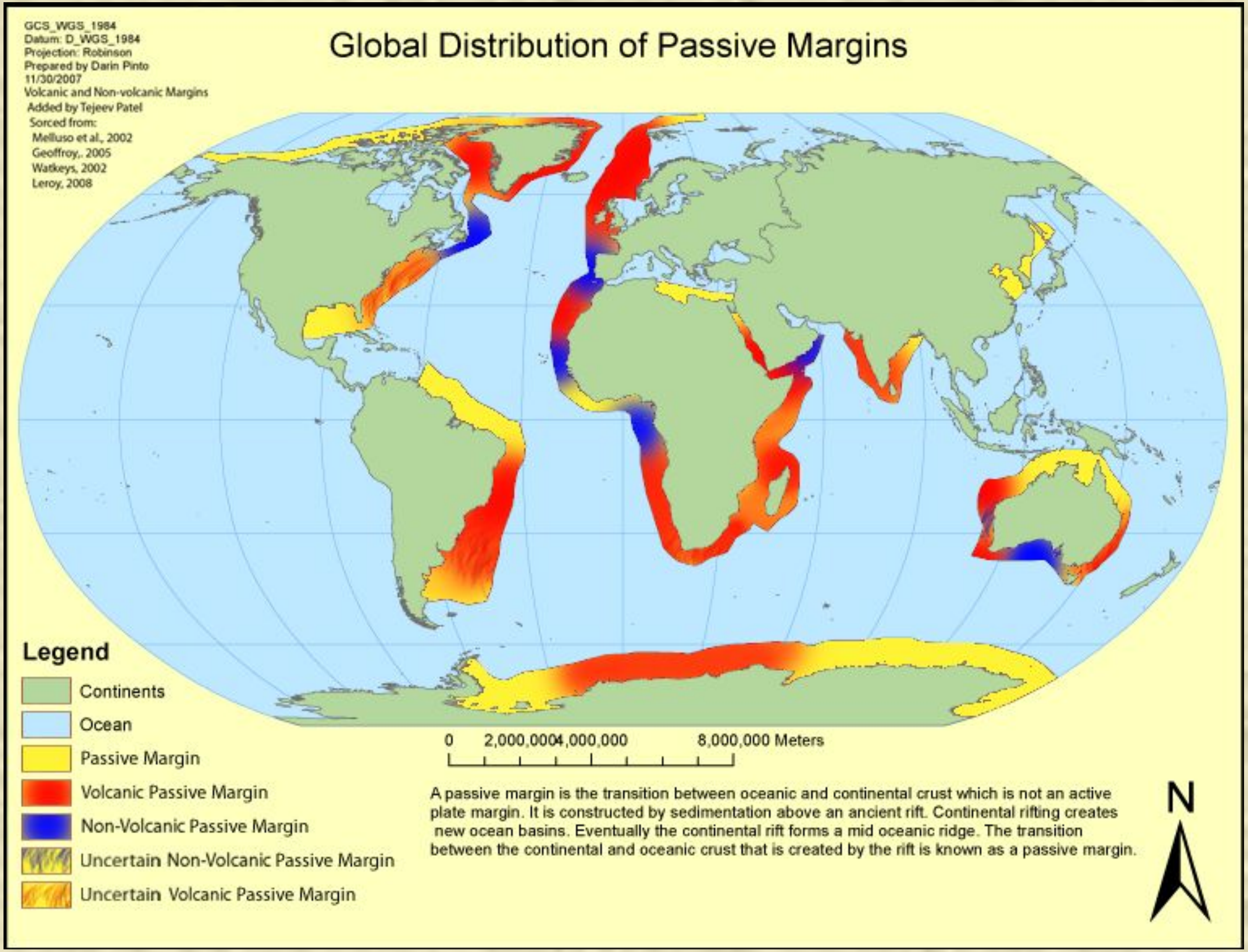
A passive margin is the transition between oceanic and continental crust which is not an active plate margin.

While a weld («шов») between oceanic and continental crusts are called a **passive margin**, it is **not an inactive** margin. Active subsidence, sedimentation, growth faulting, pore fluid formation and migration are all very active processes on **passive margins**.

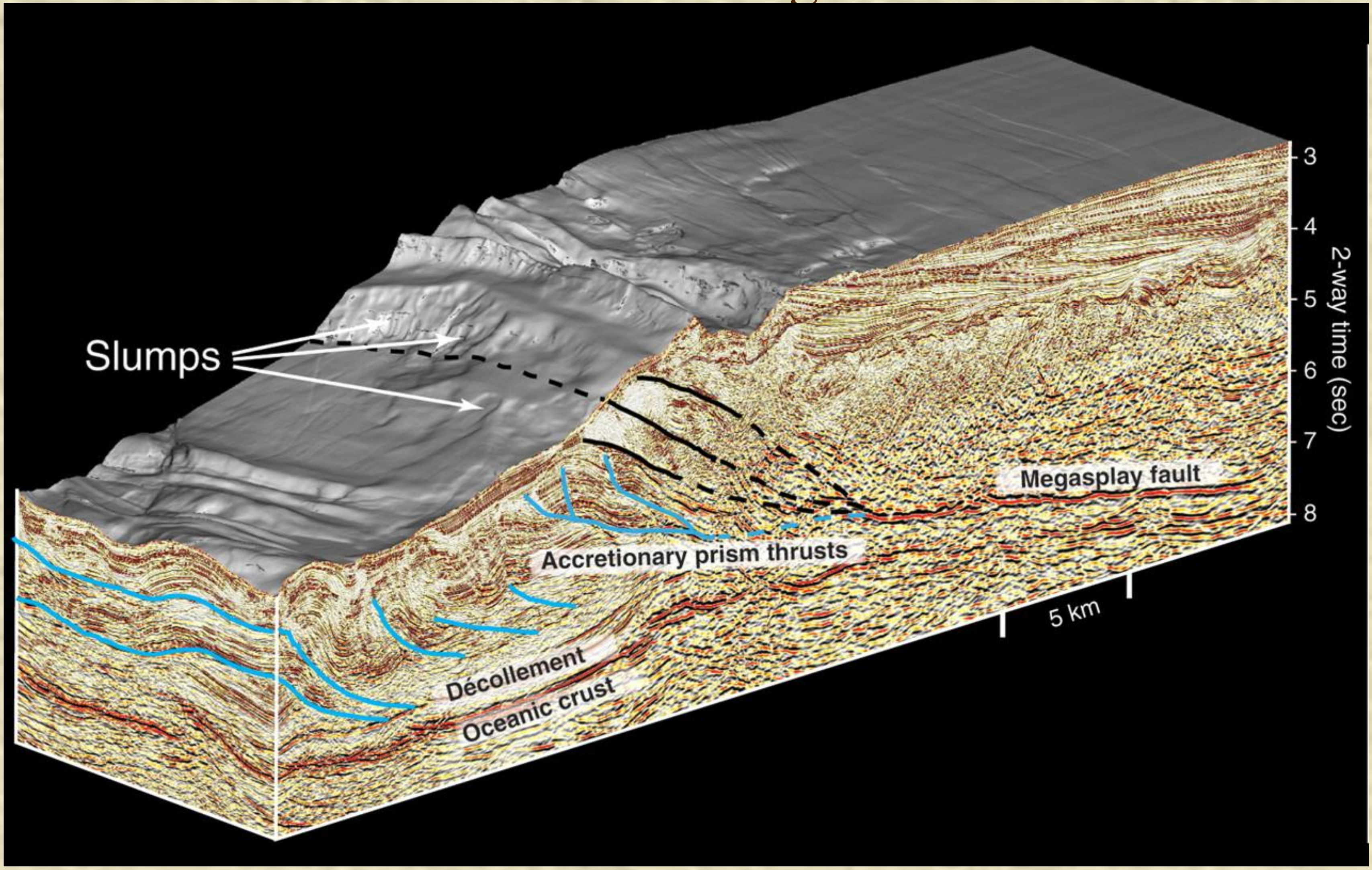
CONTINENTAL SLOPE
Passive margin



CONTINENTAL SLOPE
Passive margin



CONTINENTAL SLOPE
Active margin



Active continental margins, i.e., when an oceanic plate subducts beneath a continent, represent about two third of the modern convergent margins.

The END

Myths on Plate Tectonics

Myth 1: Plates Are Rigid

Unlike dinner plates, lithospheric plates are not truly rigid, just stiff with a brittle crust on top. **Rocks can and do deform**, not only within the lower crust and upper mantle (that is, most of the lithosphere), but far from the active edges of plates. And of the world's plate boundaries, marked by crisp lines on the map, about 15 percent are actually soft and diffuse. The best example is the Tibetan Plateau.

Myths on Plate Tectonics

Myth 2: Spreading Ridges Push

The thought (and footage) of red-hot lava rising at the deep mid-ocean ridges plants the notion that rising magma is thrusting the plates apart. But **spreading ridges are passive features**. The **main driving force** of plate tectonics is **gravity**, specifically the downward fall of subducting slabs at the other end of the plate. There is a much lesser driving force called "ridge push," because the seafloor slopes downhill away from ridges — but at the ridge itself this too is a passive pull. It's the release of pressure where the ridge pulls apart that allows mantle rock to melt and rise by buoyancy, not the opposite.

Myths on Plate Tectonics

Myth 3: Ridges Are Fixed

You always see pictures of Africa and South America splitting apart with the Mid-Atlantic Ridge sitting exactly between. Even though new oceanic crust usually moves away from ridges in both directions, the **ridge itself moves sideways too**. Consider Africa, almost surrounded by spreading ridges created as the Americas, Antarctica and India split away from it during the breakup of ancient Pangea. If you move those neighbors back toward Africa, the ridges move too. This is universal. As spreading ridges move, they crawl across the whole upper mantle releasing magmas from below. The geochemical record of those different magmas gets smeared in the process, homogenizing mid-ocean ridge basalts (MORB) and hiding much of the variation in the mantle beneath.