Plate Tectonics

- Plate tectonics is the unifying theory of geology and revolutionized geology
  - cornerstone of Earth-system approach; explains connections between seemingly unrelated geologic phenomena
  - permits Earth’s history to be viewed as series of interrelated events.
  - explains how plate interactions determine locations of continents, mountain ranges, and ocean basins, and thus affect atmospheric and oceanic circulation patterns that control climate
  - explains influence of plate movement on distribution, evolution, and extinction of plants and animals.

Why Study Plate Tectonics?

- Geographic distribution of geologic hazards such as earthquakes and volcanic eruptions controlled by plate tectonics
- Many global and regional political and economic problems stem from uneven distribution of geologic resources such as oil and metal ores.
- Formation of geologic resources is controlled by plate movement.

Harry K. Brown Park, Kilauea
http://hvo.wr.usgs.gov

Early theories

- During the 1800's geologists believed the Earth had cooled from a molten mass
- Folded rocks and mountains were the result of crumpling of the rigid crust as it cooled and contracted
- Did not explain extensional features such as rift valleys

Early theories

- With the discovery of radioactivity and recognition that this generated heat it was suggested that the Earth was expanding
- This could account for some features but did not explain the mountain belts
- In the 1960’s we finally came around to the idea of plate tectonics but the basis for the theory came much earlier

Origins of a theory

Edward Suess (1885), an Austrian geologist, proposed India, Africa, Australia, and South America were once connected by land bridges (referred to this southern hemisphere landmass as Gondwana).

Chernicoff and Whitney (2002)

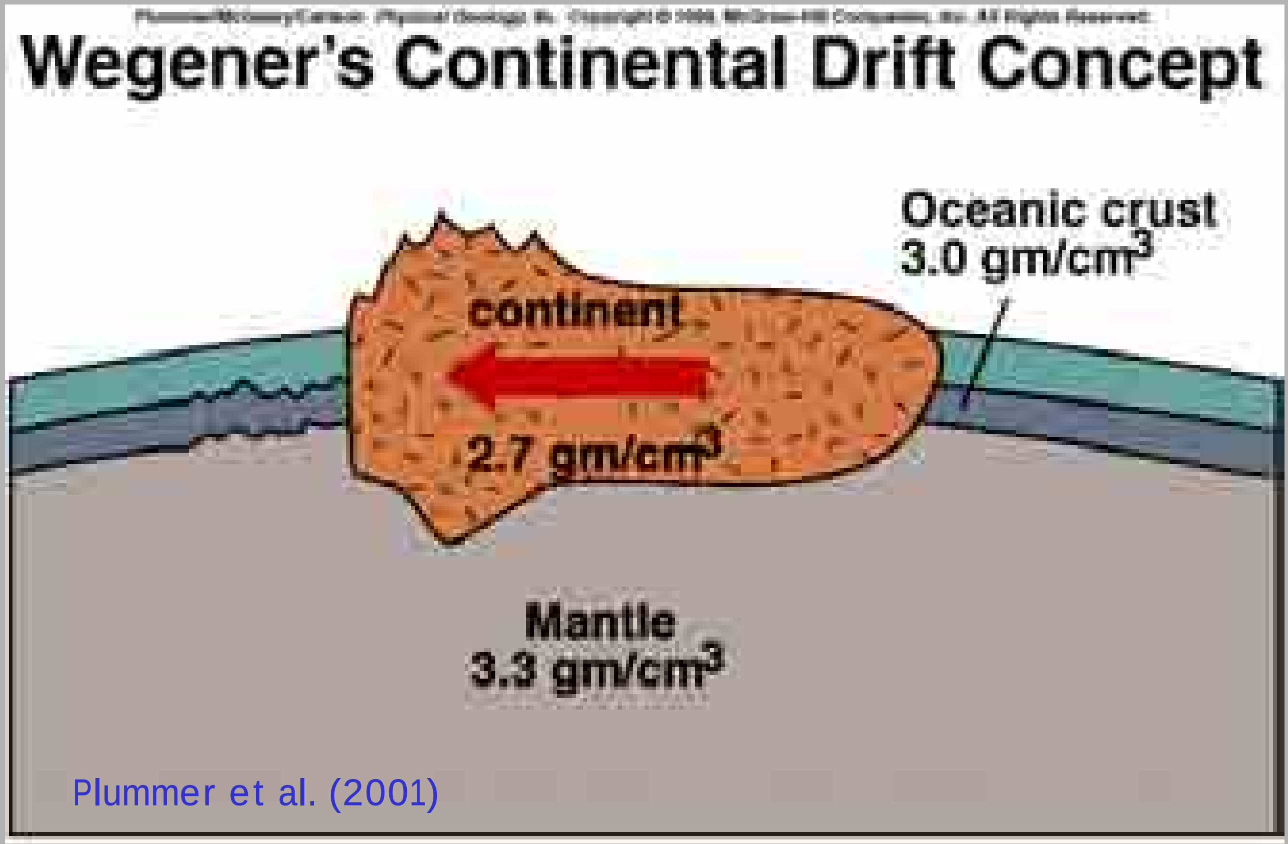
Origins of a theory

Chernicoff and Whitney (2002)

Alfred Wegener (1915), German meteorologist, proposed that all landmasses were once part of a single supercontinent (Pangaea); produced maps showing breakup of supercontinent and movement of fragments to position of present-day continents.

Wicander and Monroe (2002)

Origins of a theory



Plummer et al. (2001)

Alexander du Toit (1937), South African geologist, developed Wegener's ideas and introduced large body of geologic evidence to support continental drift (and referred to north landmass of Pangaea as Laurasia).

Continental drift

Chernicoff and Whitney (2002)

What is the Evidence for Continental Drift?

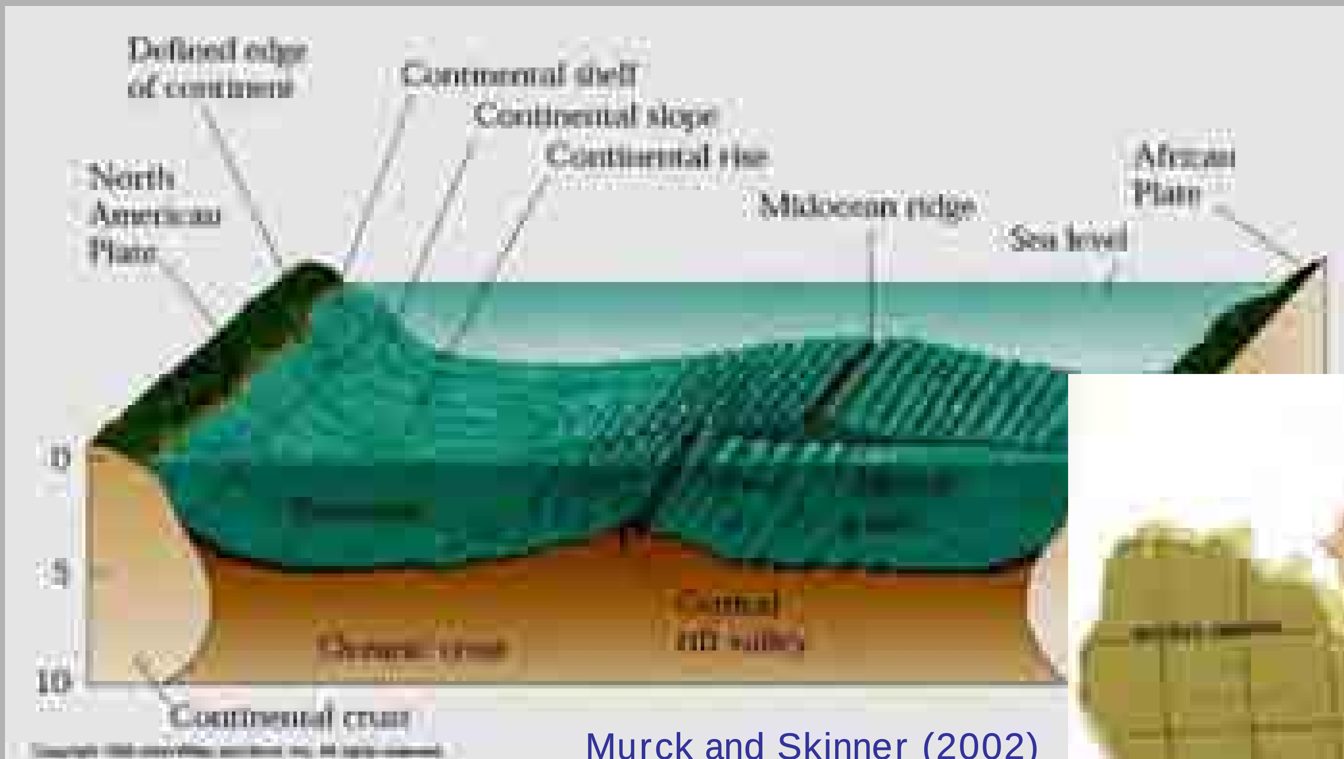
- Evidence for continental drift suggests that widely separated continents were once joined together.
  - Continental Fit
  - Similarity of Rock Sequences and Mountain Ranges
  - Distribution of Glacial Features
  - Distribution of Fossil Land Animals and Plants

Continental Fit

Wicander and Monroe (2002)

- Best fit among continents results when they are matched along their continental slopes where erosion has not significantly reconfigured their shape.
- Here the continents are shown joined along their continental slopes to form the super-continent Pangaea, originally proposed by Wegener.

Continental fit

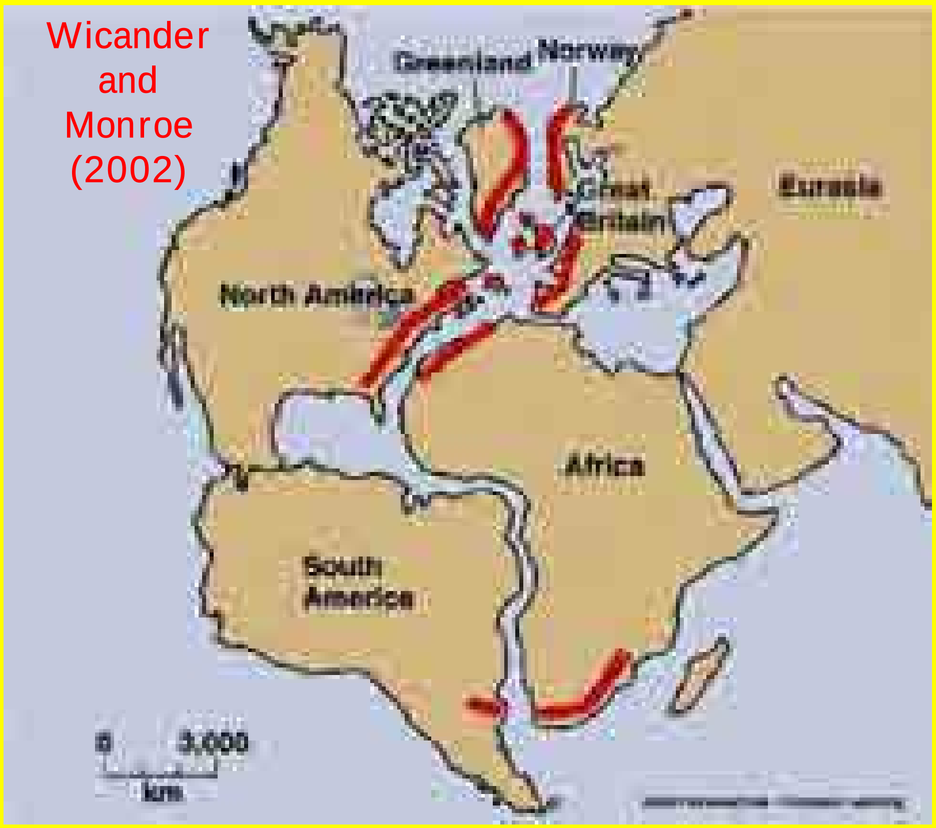


Murck and Skinner (2002)

Murck and Skinner (2002)

Similarity of Mountain Ranges and Rock Sequences

Wicander and Monroe (2002)



Mountain ranges along the margins of the continents surrounding the Atlantic Ocean match. Same age and style of deformation indicating they are fragments of once continuous ranges which were severed by breakup of Pangaea.

Pennsylvanian to Jurassic age rocks of Gondwana continents are nearly identical for all five continents, indicating they were once joined together.

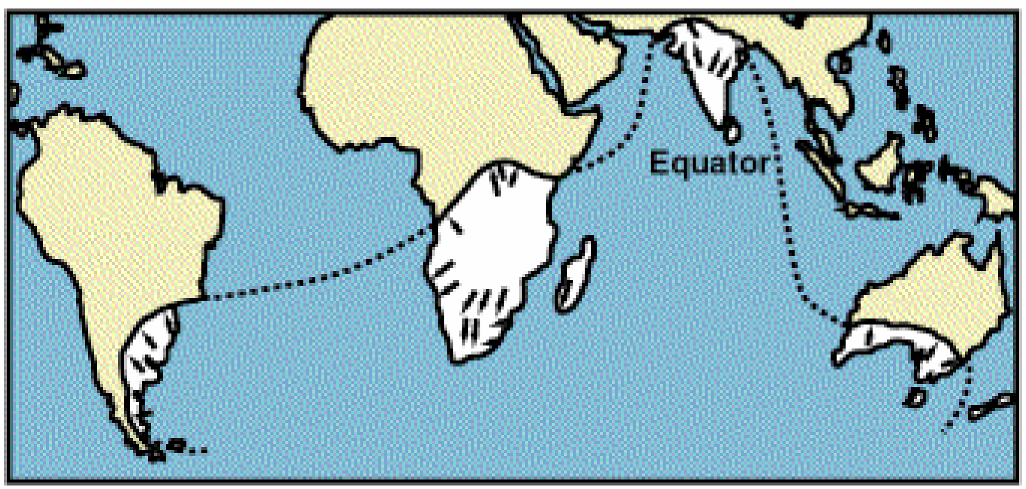
Glacial Features

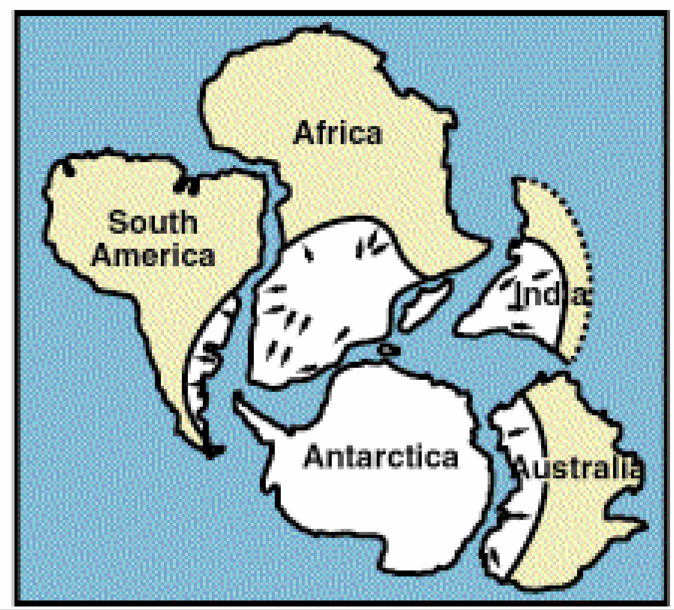
The distribution of glacial deposits (till) and striations (scratches) of similar age indicate that Gondwana continents were once joined together and situated in the vicinity of the South Pole, where a vast continental glacier covered large areas of all five continents.

Glacial Features

Arrows indicate direction of ice flow

Montgomery (2001)



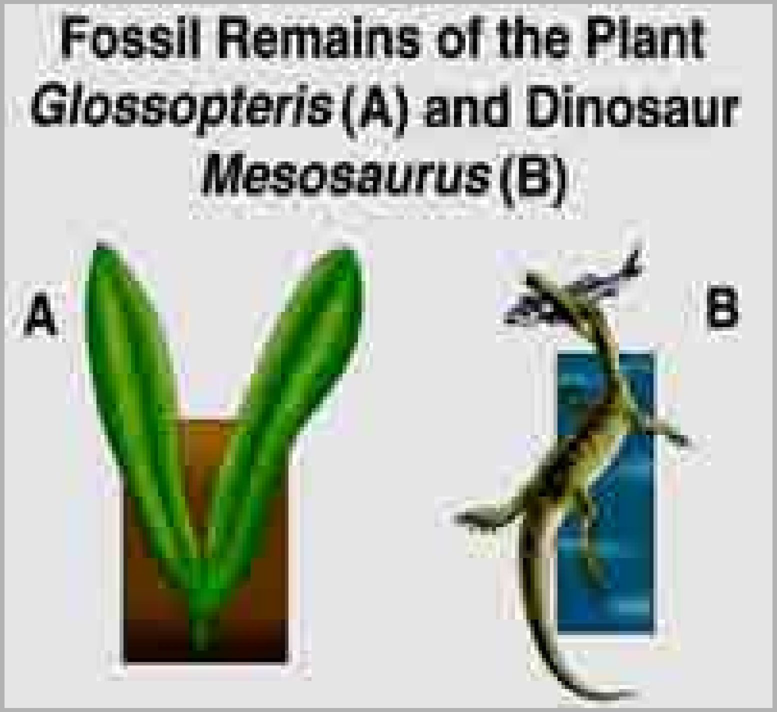


Distribution of Fossil Land Animals and Plants

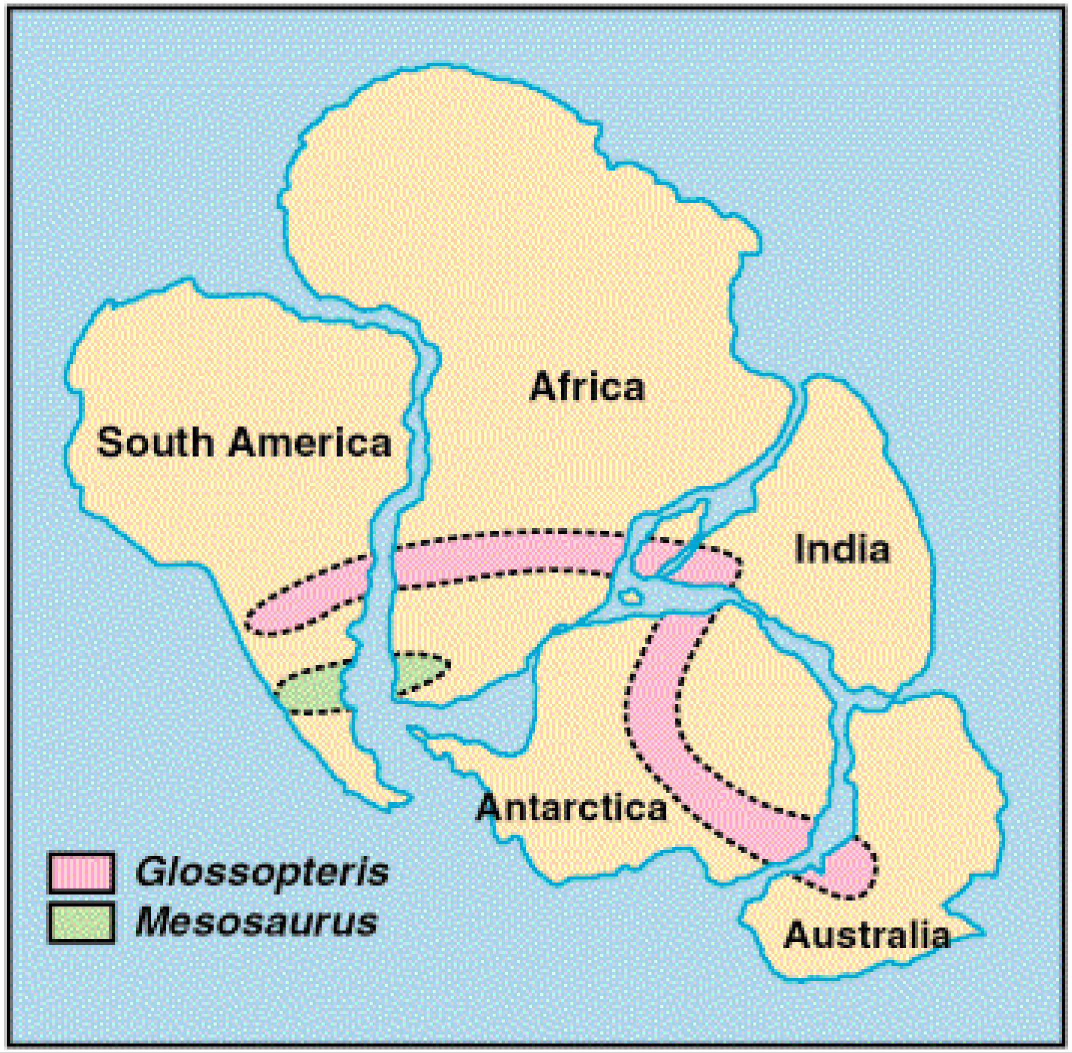
Fossils of land plants land-dwelling (and freshwater) reptiles are preserved in rocks of similar age on the Gondwana continents. Morphology and physiography makes it unlikely that they crossed a broad ocean to colonize widely separated continents.

Wicander and Monroe (2002)

Fossil distribution



Montgomery (2001)



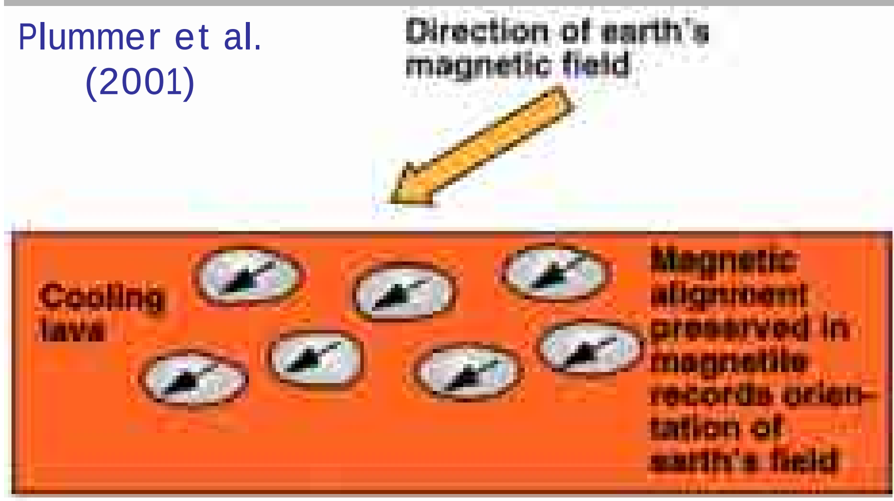
Beginnings of consensus

- Wegener and du Toit cited the bodies of evidence listed above to support their theory of continental drift, but as late as the 1950s most geologists did not accept the idea of moving continents.
- The lack of a viable mechanism was the main reason that the theory did not gain wide acceptance for 40 years
- By the 1960s, studies of the paleomagnetism of rocks had yielded strong evidence for continental drift.

Magnetic polarity

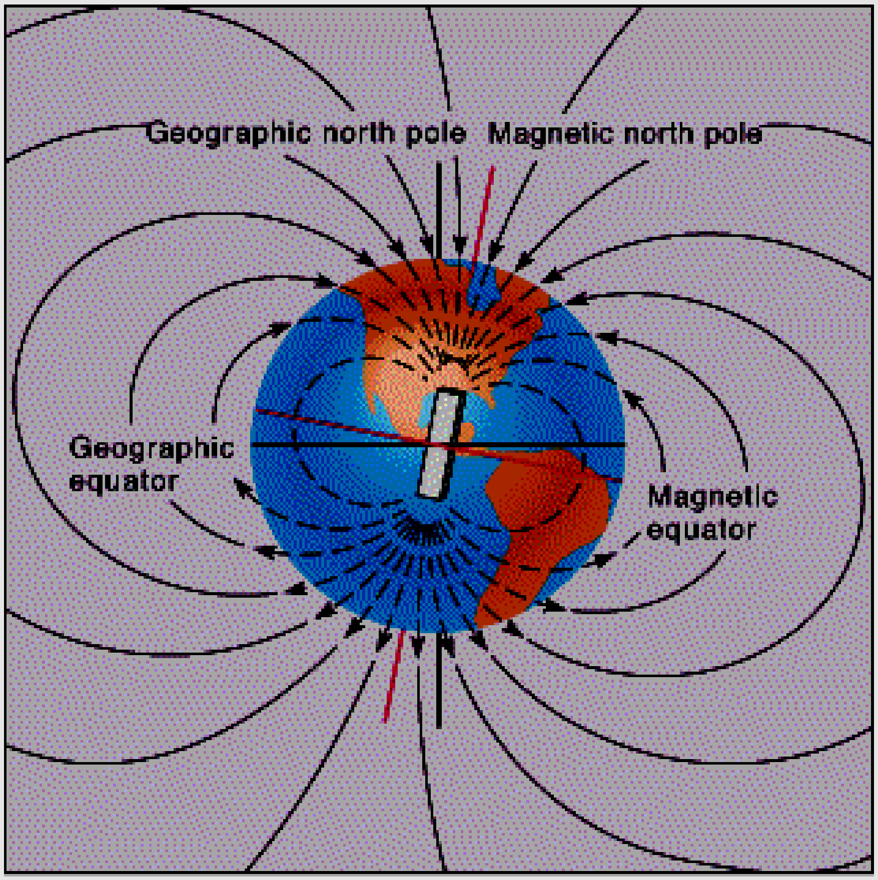
- The Earth has a magnetic field
- Once these minerals fall below their Curie point (580°C for magnetite) they become permanent magnets
- Once below the Curie point a rock will preserve the polarity at the time it formed

Plummer et al. (2001)



Murck and Skinner (2002)

The Earth's Magnetic Field



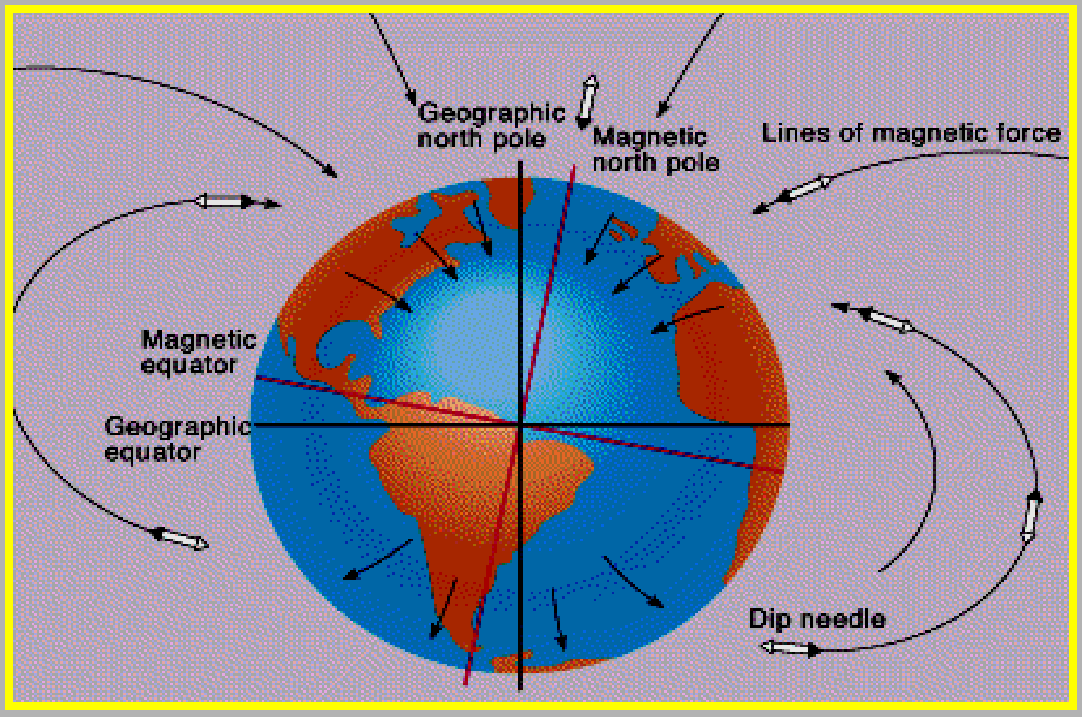
(a)

Wicander and Monroe (2002)

- Earth's magnetic field consists of invisible lines of force akin to those surrounding a bar magnet.
- Remnant magnetism in rocks records Earth's ancient magnetic fields and the location of Earth's ancient magnetic poles at the time the rocks formed and is referred to as paleomagnetism.

The Earth's Magnetic Field

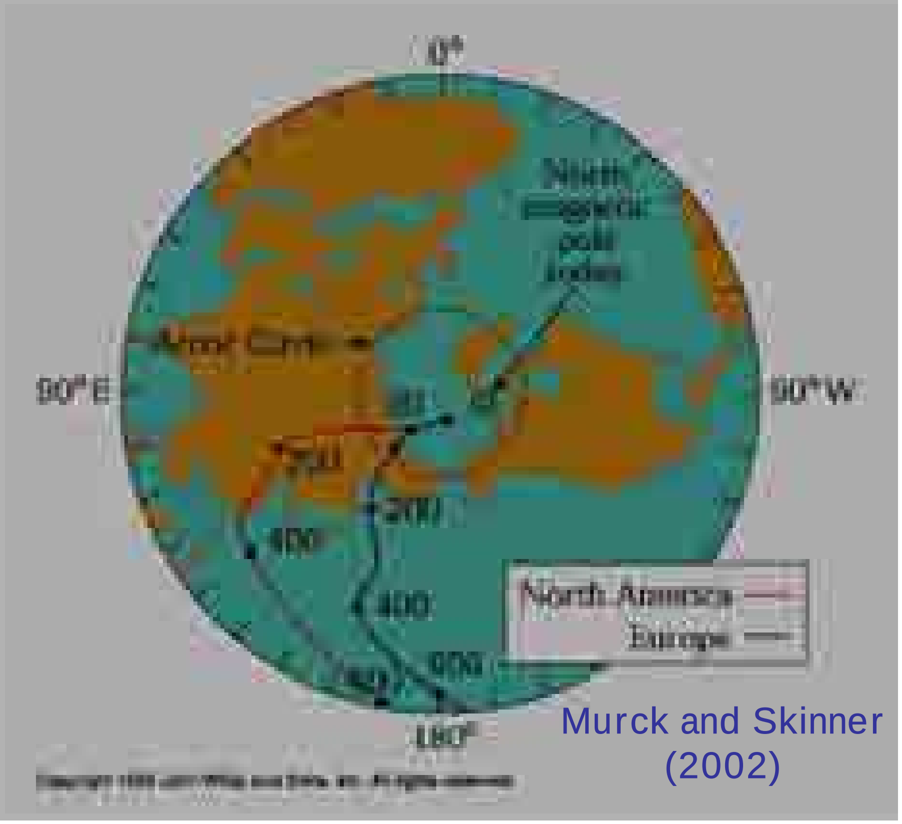
Inclination of the lines of force comprising Earth's magnetic field varies with distance from the equator. At the equator, they parallel Earth's surface, but their inclination increases with distance from the equator until at the magnetic poles they are perpendicular to Earth's surface.



Wicander and Monroe (2002)

Paleomagnetism

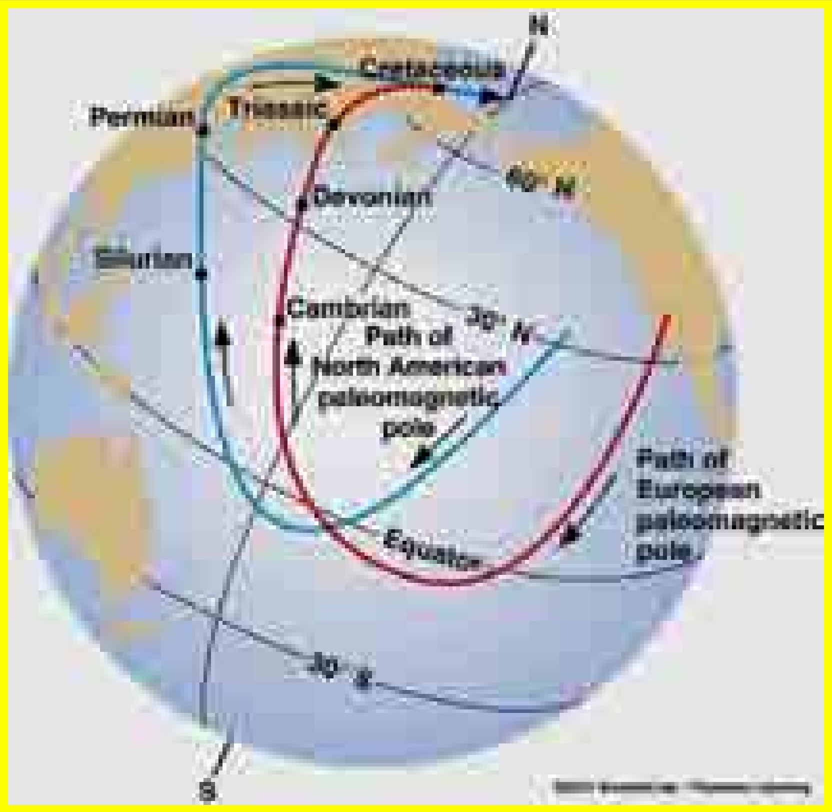
- In addition to preserving polarity magnetic minerals will point towards the paleopoles
- In the 50's scientists used this to generate apparent polar wander curves



Murck and Skinner (2002)

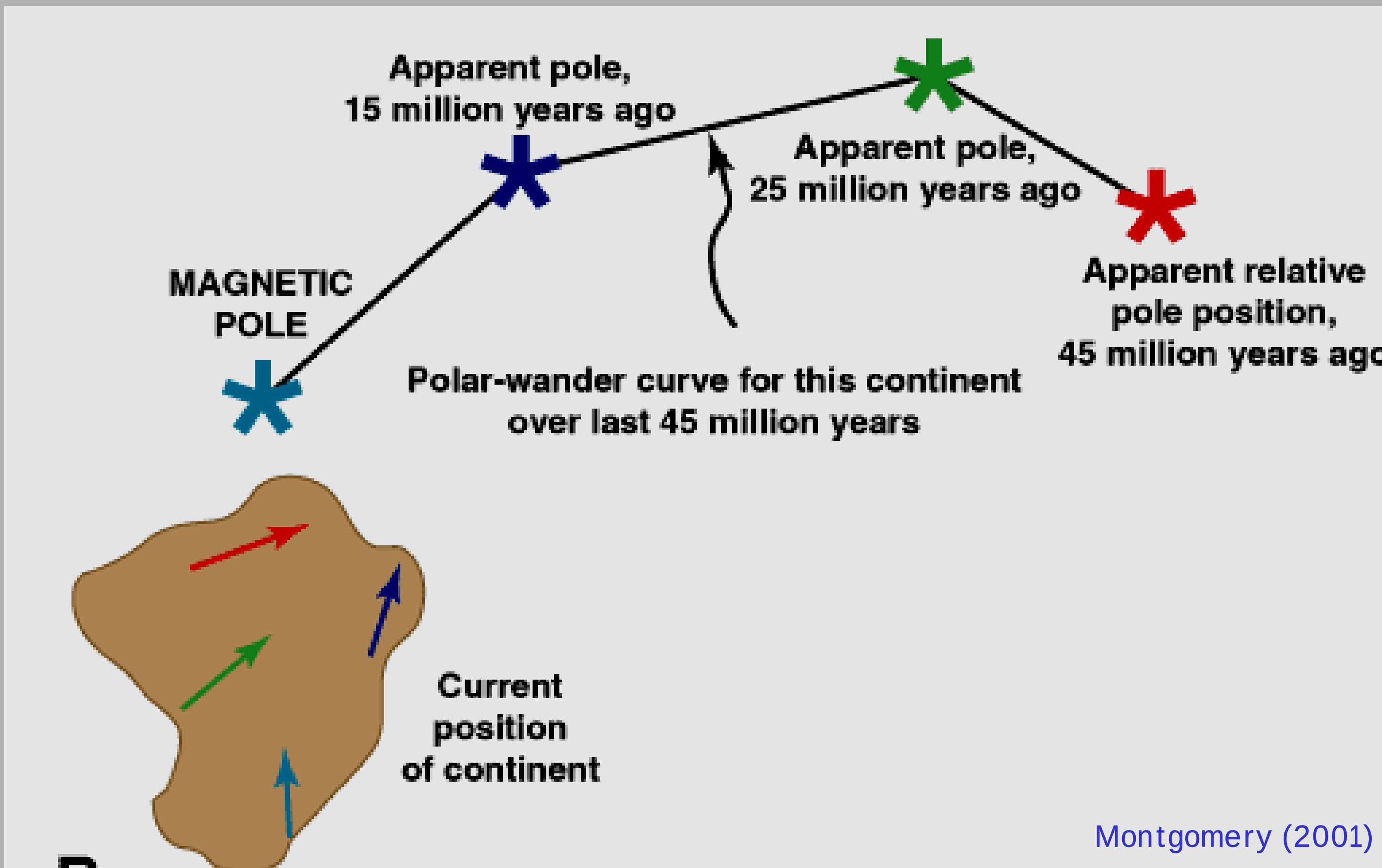
Polar Wandering

Analysis of paleomagnetism in numerous rocks of ages collectively spanning most of Earth's long history suggested the position of the magnet poles have shifted over time (apparent polar wandering).



Wicander and Monroe (2002)

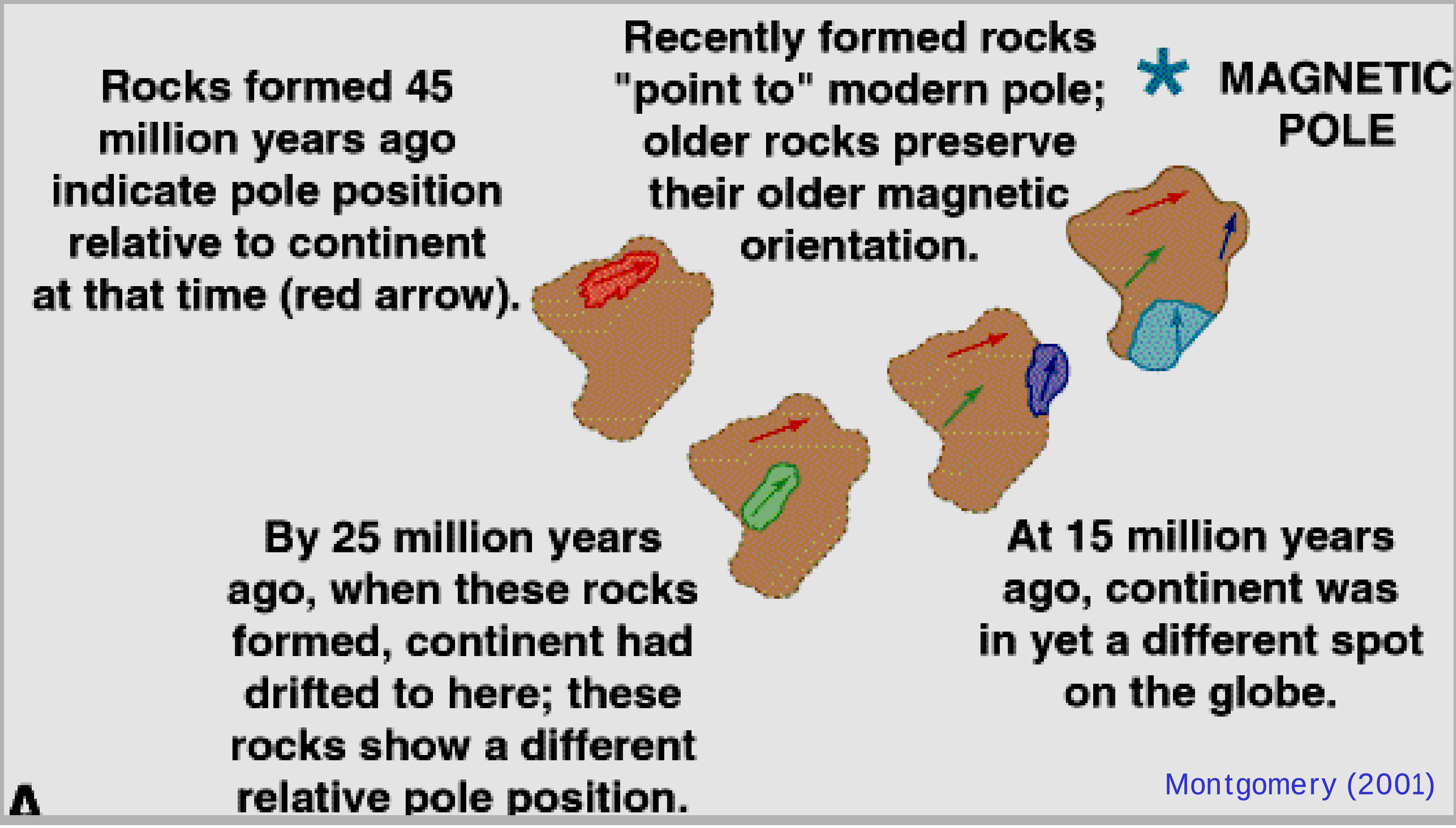
Polar wander curves



Montgomery (2001)

Polar wander curves

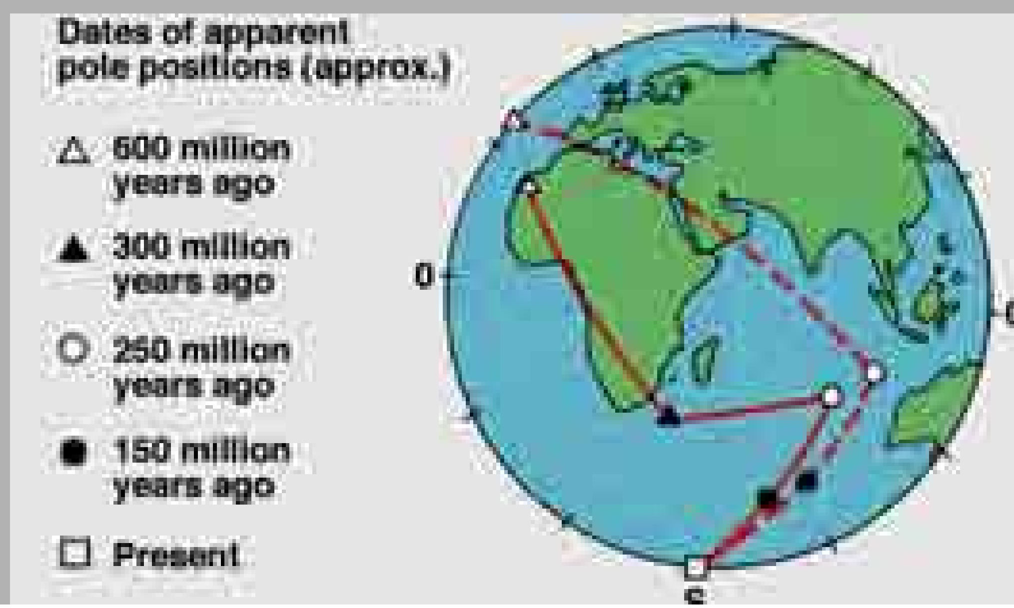
In fact the poles have not moved the continents have



Montgomery (2001)

Polar wander curves

Explained by continents drifting across stationary magnetic poles. Importantly, drift paths recorded by paleomagnetism culminate in the assembly of a supercontinent during the Late Paleozoic. This is consistent with the previously considered evidence for continental drift and validates the hypotheses of Wegener and du Toit.



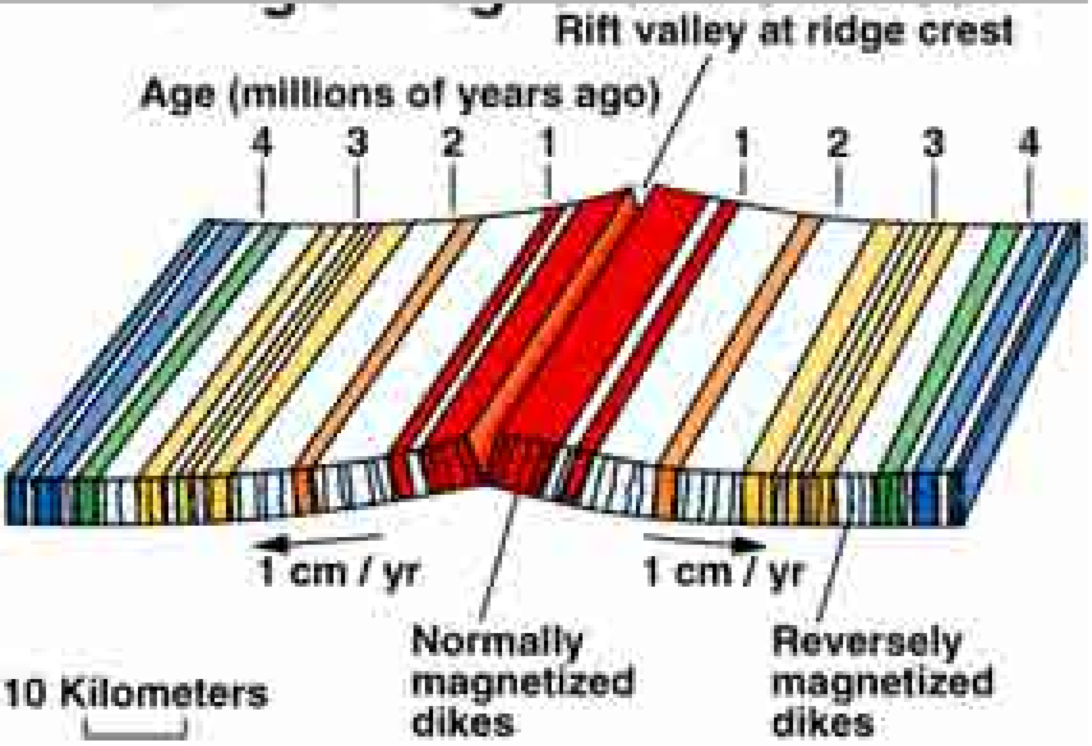
Montgomery (2001)

The final clue

- Although polar wander curves provided strong support for continental drift there was still no good mechanism to split the crust
- In the ‘60s oceanographers started surveying the Atlantic with magnetometers

Magnetic anomalies

- These studies showed that there were alternating bands of magnetic polarity on the ocean floor
- The bands are symmetrical about ocean ridges

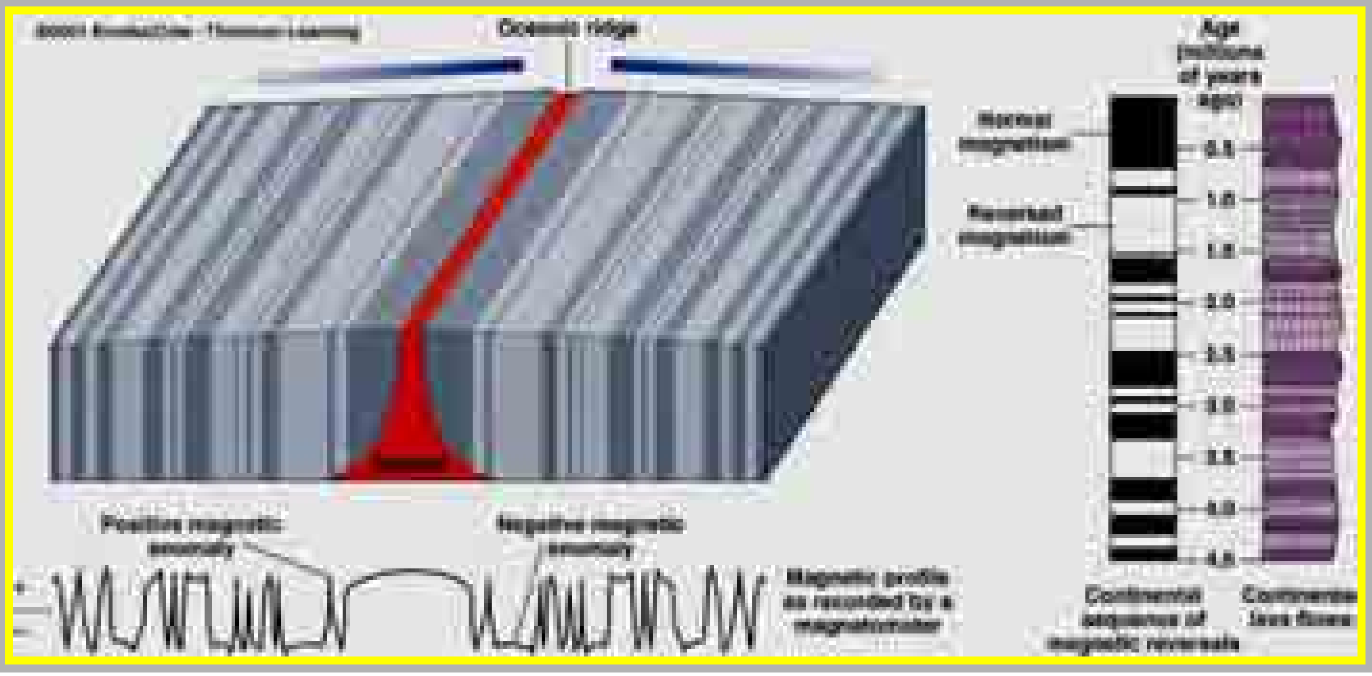


Plummer et al. (2001)

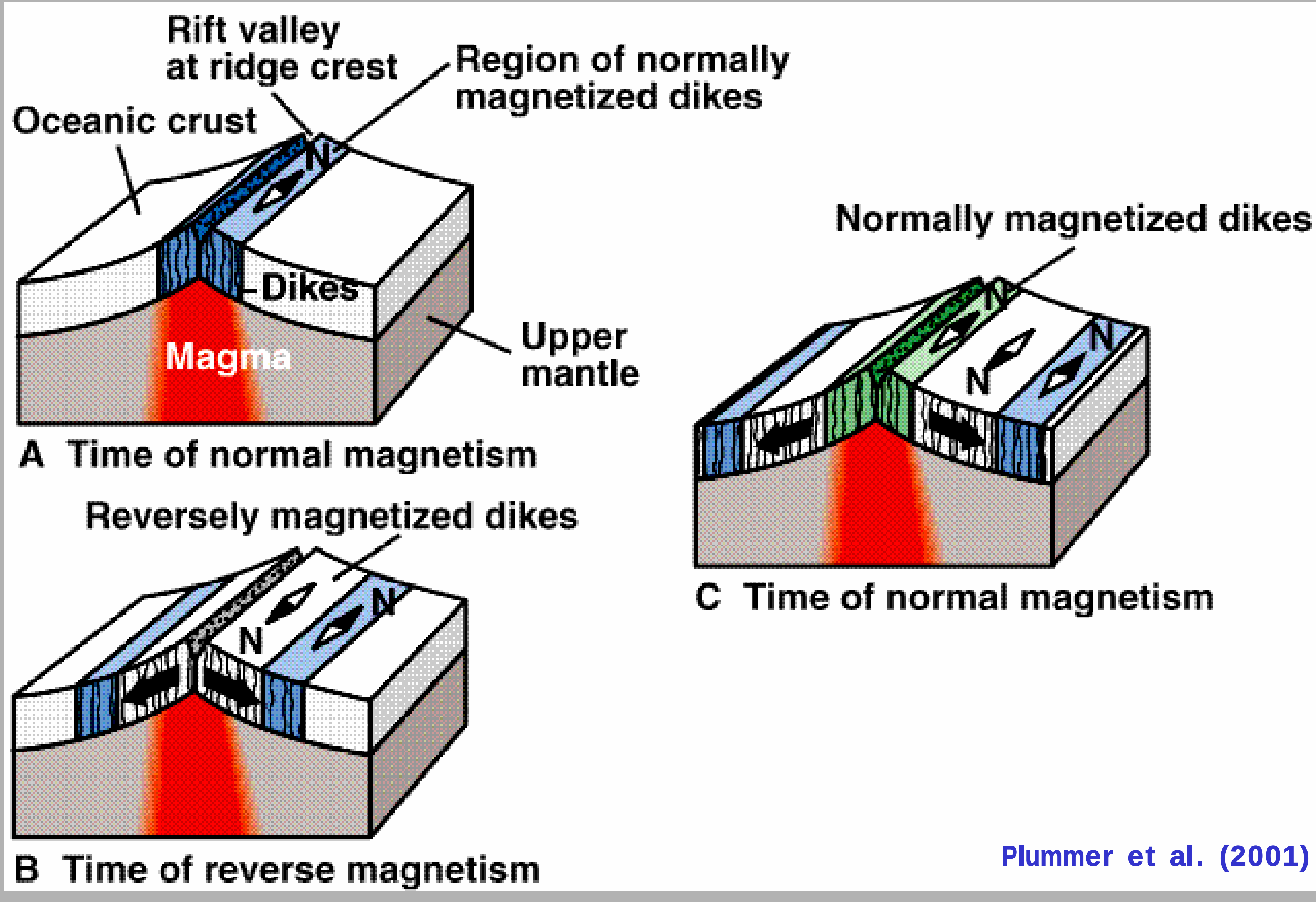
How Do Magnetic Reversals Relate to Seafloor Spreading?

In the early 1960s, oceanographer Harry Hess proposed seafloor spreading. Oceanic crust and continents move together as the seafloor separates along and moves away from mid-ocean ridges where new oceanic crust is created by upwelling magma. Newly-formed igneous rocks of oceanic crust record prevailing magnetic polarity.

Wicander and Monroe (2002)

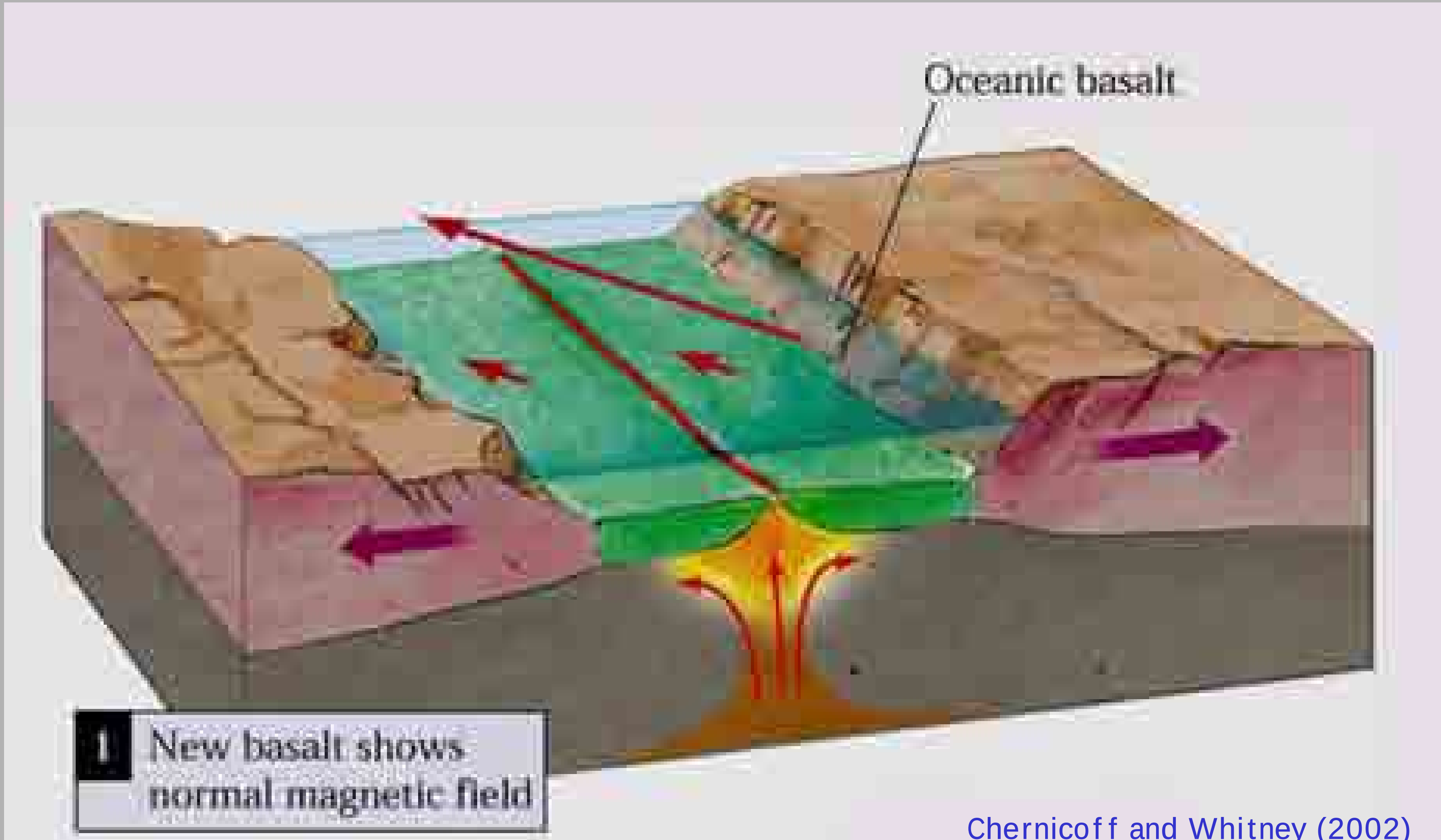


Origin of magnetic anomalies



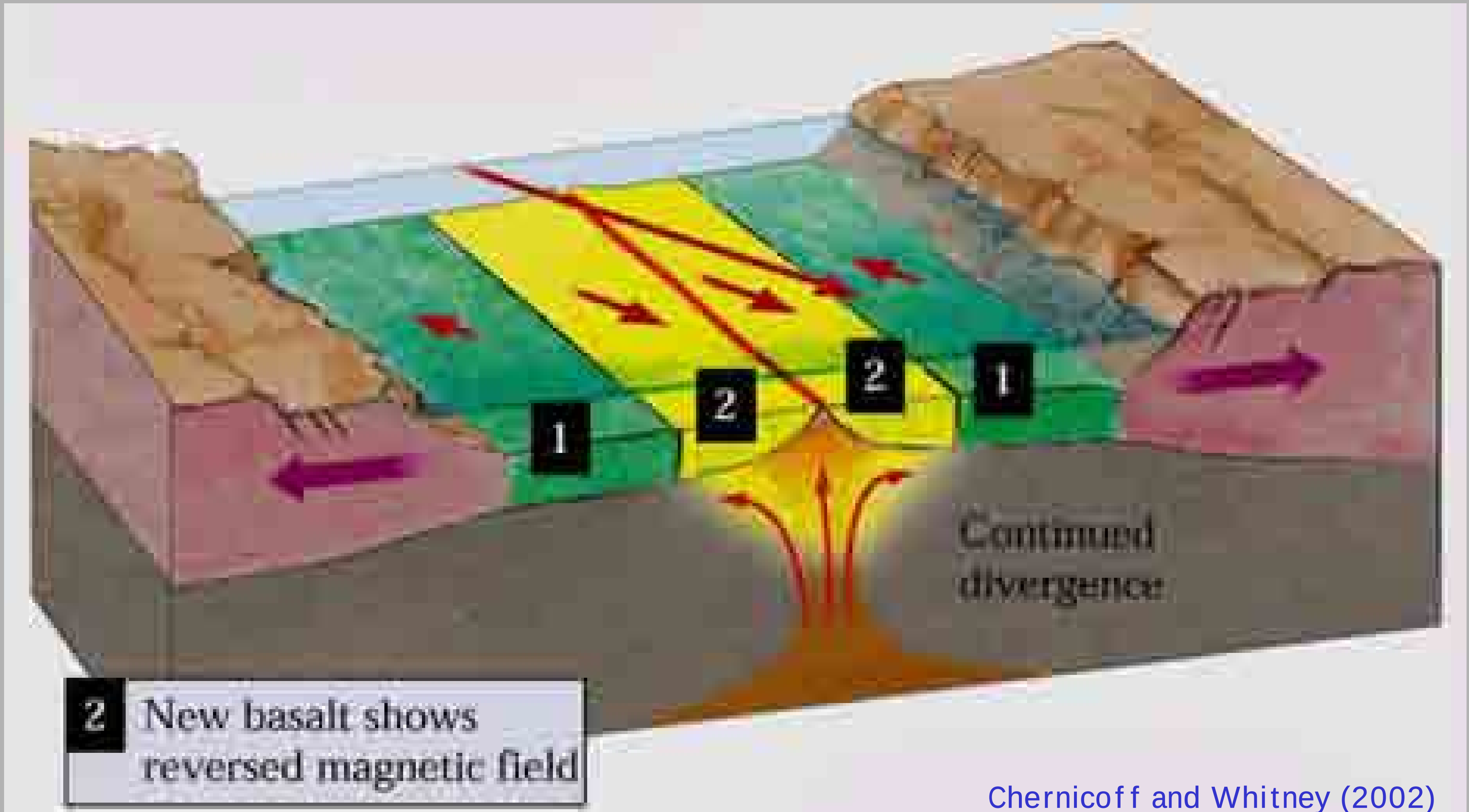
Plummer et al. (2001)

Marine magnetic anomalies



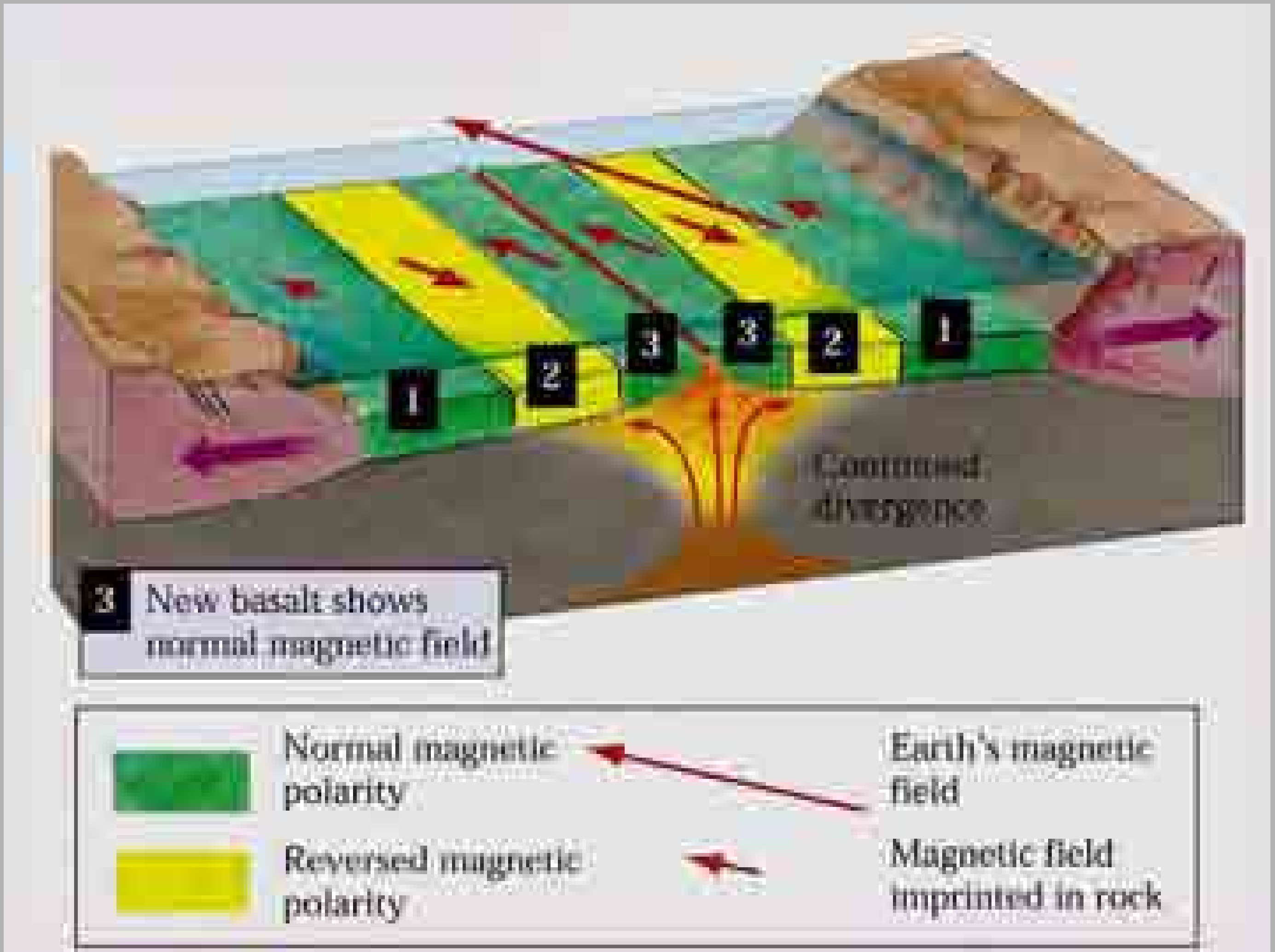
Chernicoff and Whitney (2002)

Marine magnetic anomalies



Chernicoff and Whitney (2002)

Marine magnetic anomalies



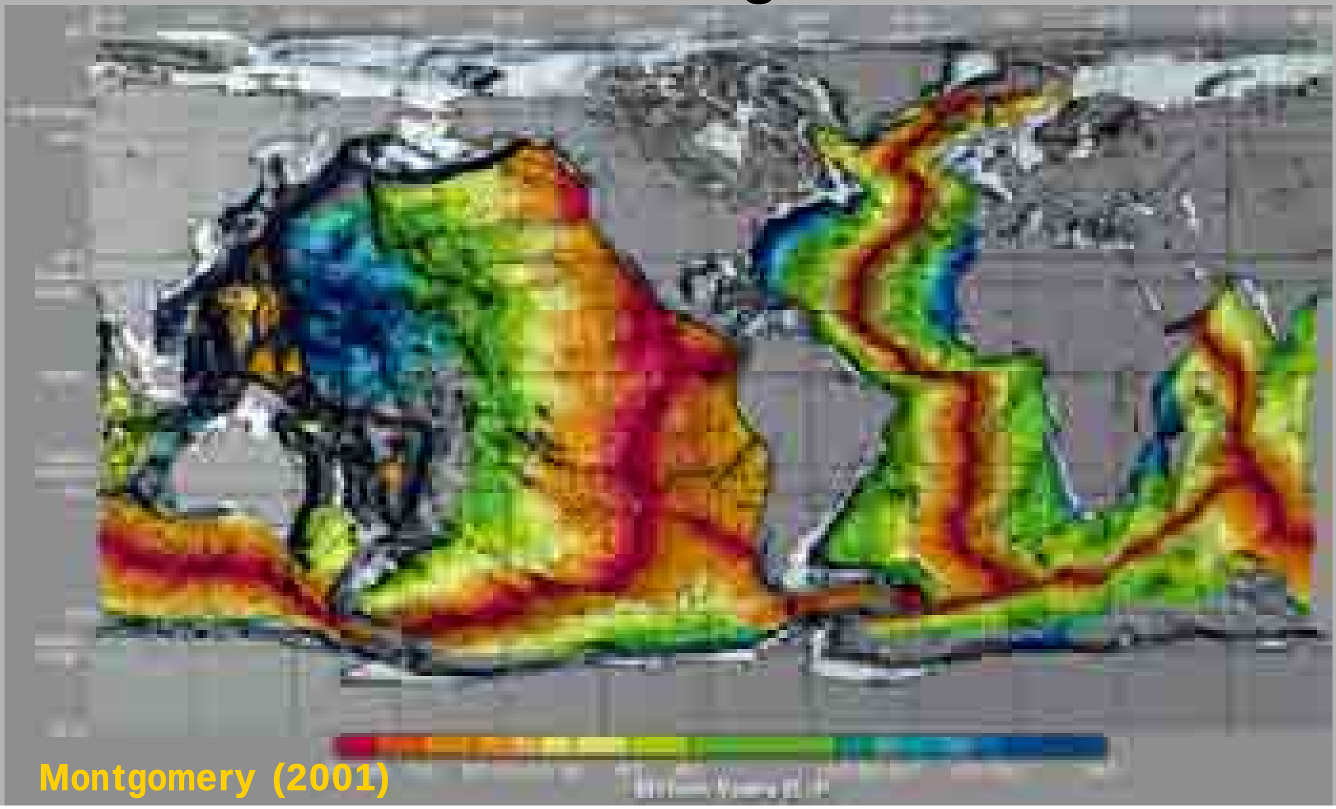
Chernicoff and Whitney (2002)

Seafloor Spreading

- The symmetry of the stripes provides compelling evidence for seafloor spreading
- With the benefit of radiometric dating we now now that the ocean crust also gets older away from the ridges

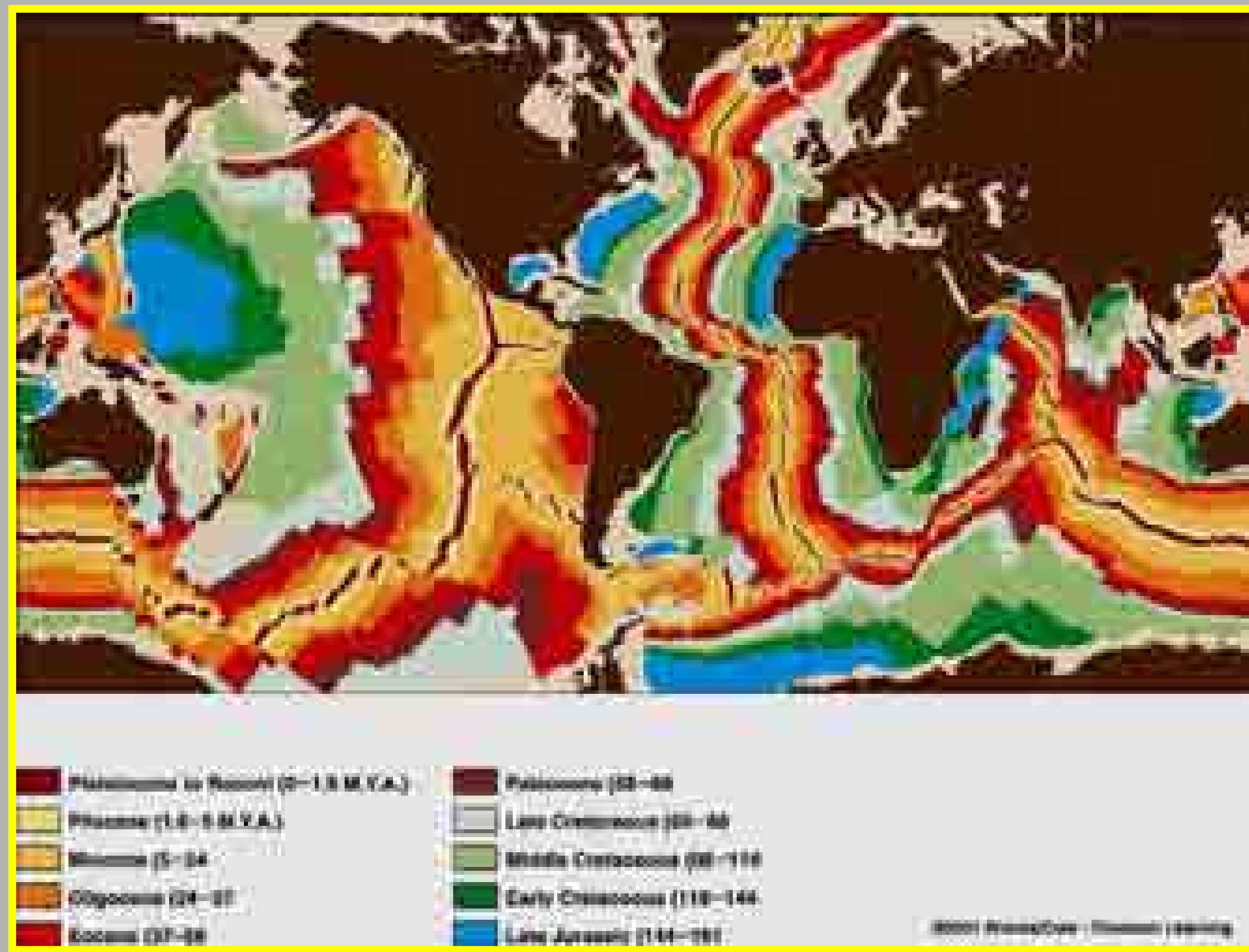
Seafloor Spreading and the Age of Oceanic Crust

The results from radiometric dating reveal that oceanic crust is youngest at mid-ocean ridges, where it was formed, and increases in age with distance from mid-ocean ridges



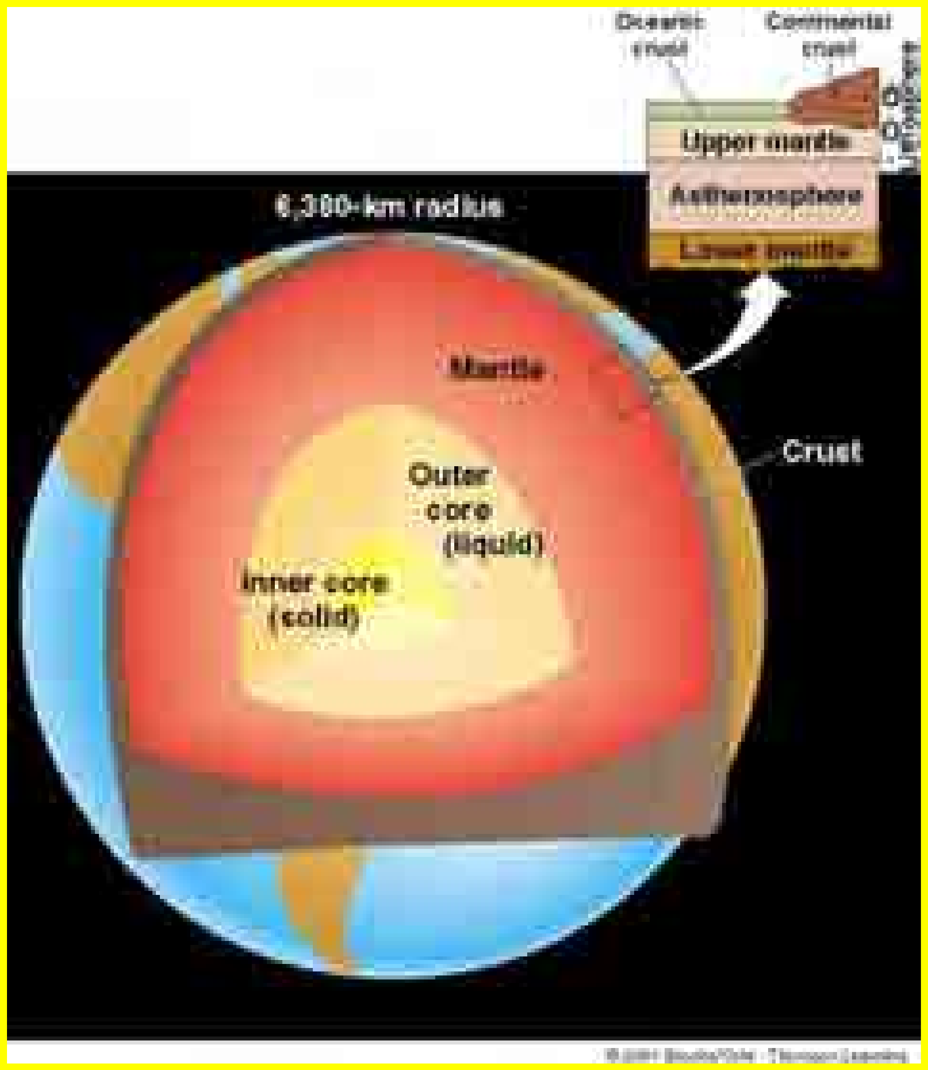
Age of the ocean crust

Interestingly, the oldest oceanic crust is less than 180 million years old, whereas the oldest continental crust is ~ 4 billion years old.



Wicander and Monroe (2002)

Earth's Internal Structure

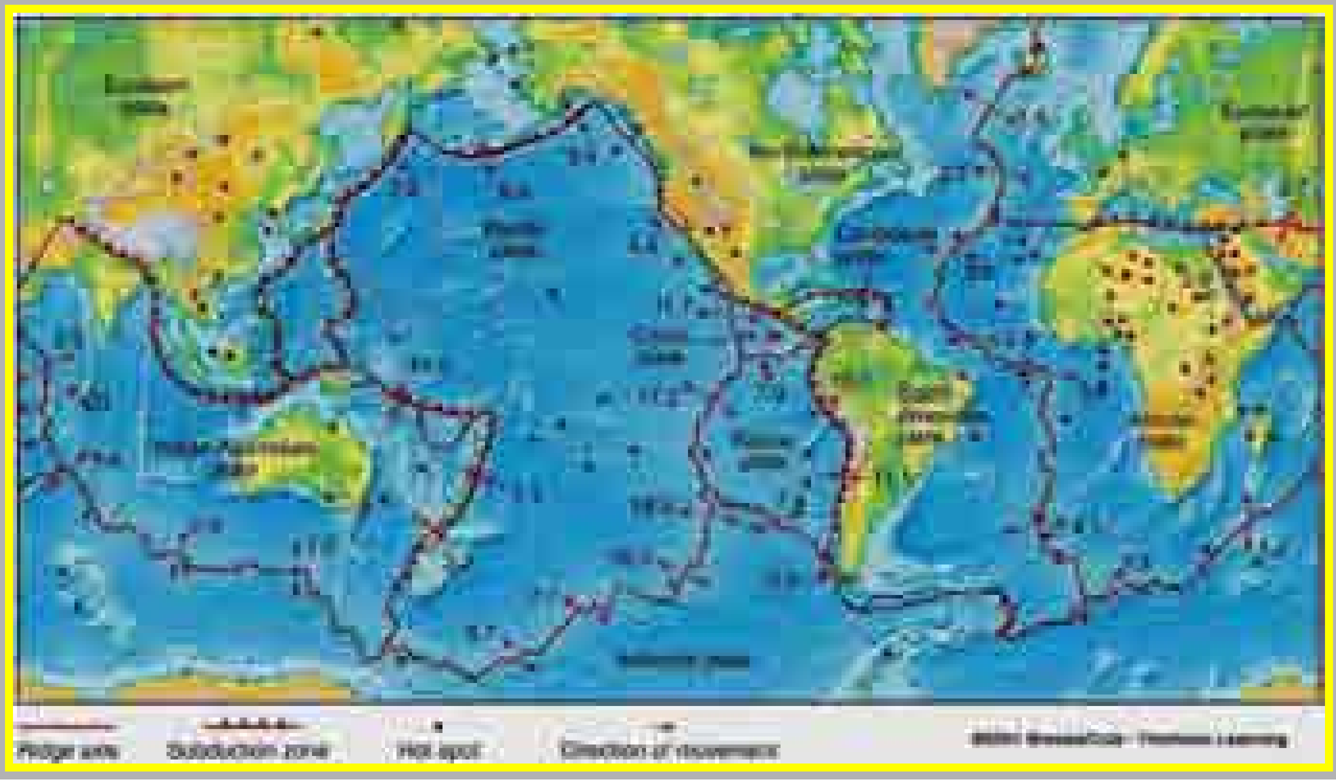


Wicander and Monroe (2002)

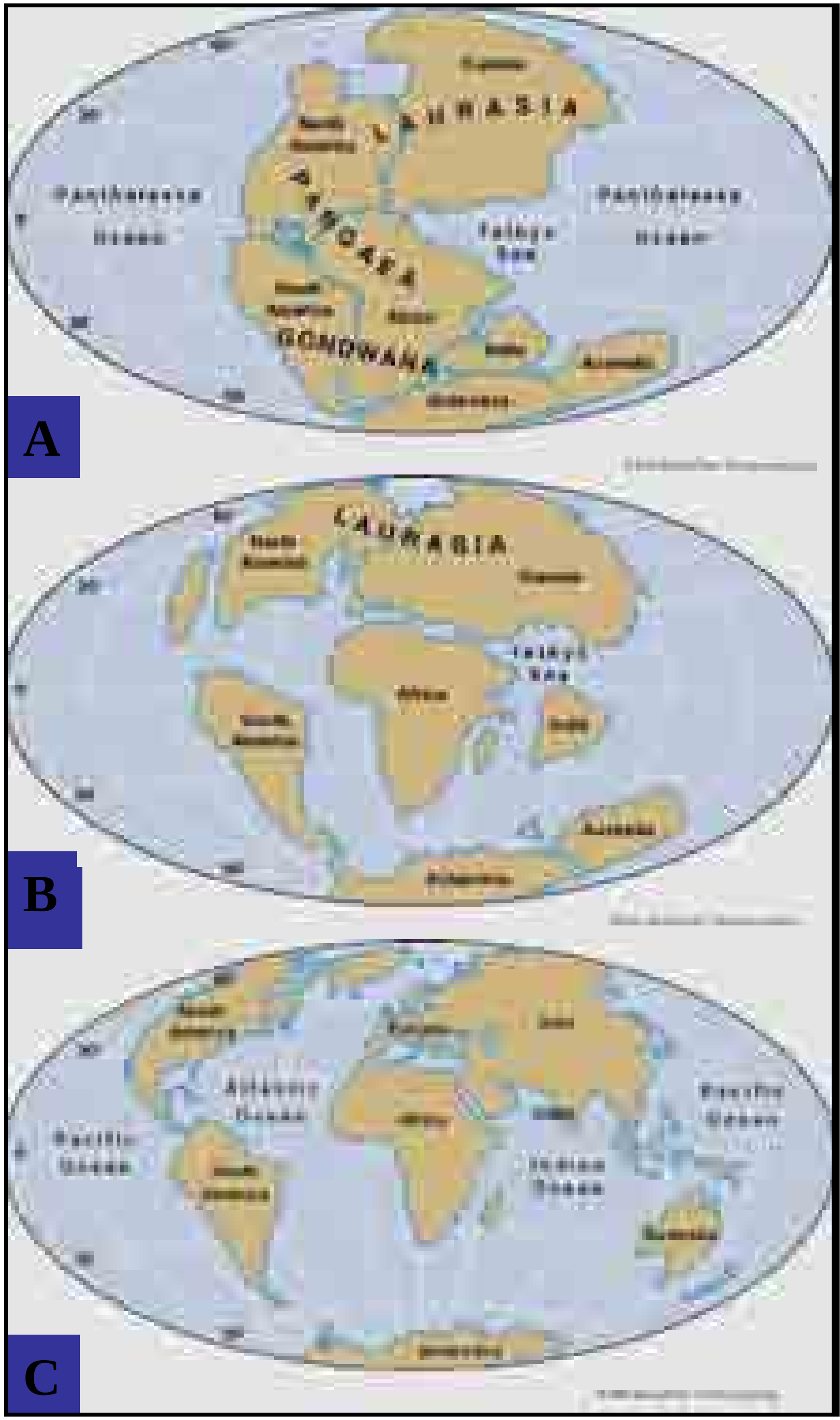
Earth's interior consists of concentric layers with distinct physical and chemical properties. Earth's outer layer, the crust, is of two types: oceanic and continental. Oceanic crust is significantly thinner than continental crust. The crust is welded to the rigid upper mantle and together these layers form the lithosphere. The lithosphere rides on the asthenosphere which is partially molten and behaves semiplastically.

Plate Tectonic Theory

Plate tectonic theory recognizes that the lithosphere is broken into plates, jigsaw-like pieces of various sizes. Plates can include both oceanic and continental lithosphere and drift across Earth’s surface floating on the partially molten asthenosphere.



Wicander and Monroe (2002)



Supercontinent Cycle

- Plate movements led to assembly of Pangaea by the Late Paleozoic Era.
- Fragmentation of Pangaea began in the Triassic Period.
- Continued plate movement has led to the present configuration
- The supercontinent cycle of Tuzo Wilson proposed that super-continents have formed and fragmented repeatedly throughout Earth's history on a cycle of 500 million years.

Wicander and Monroe (2002)

The Wilson cycle

- Evidence from continental geology supports two and possibly as many as five complete opening and closings of all ocean basins
- Spreading rates suggest that crust forms at 2.8km^2/year
- Therefore 310km^2 of ocean crust could have formed in 110 billion years
- Over the past two billion years as many as 20 ocean basins could have been created or destroyed

The Wilson Cycle

Developed by J. Tuzo Wilson (a Canadian!)

Embryonic - Rift valleys of East Africa

Youthful - Red Sea, Gulf of California

Mature - Atlantic Ocean (growing)

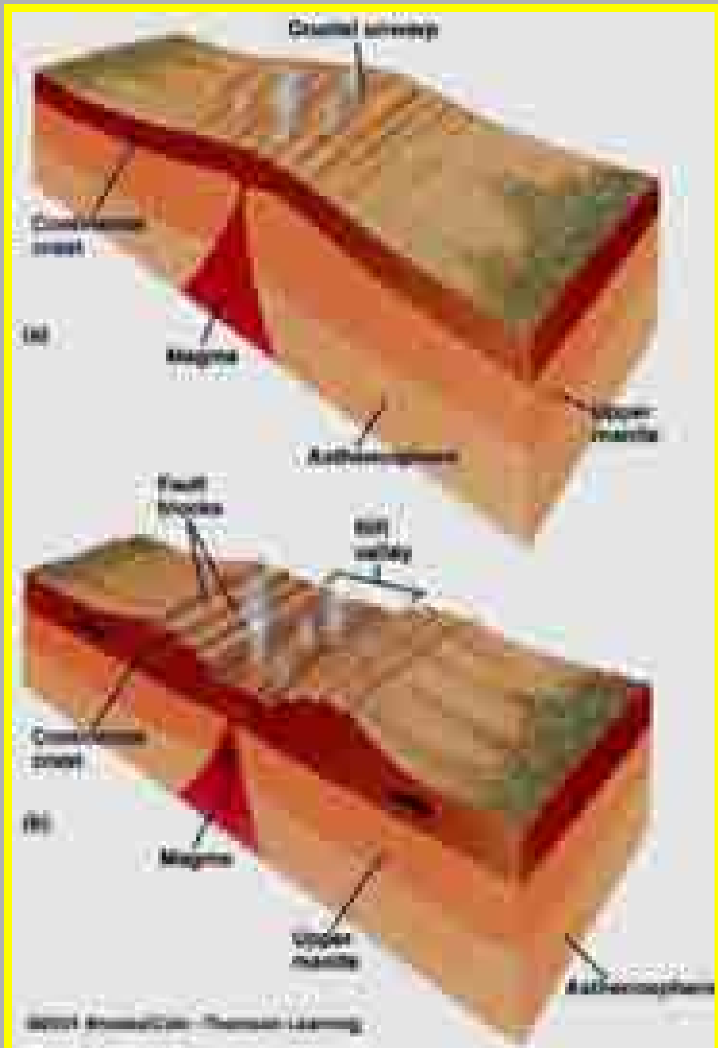
Declining - Pacific Ocean (shrinking)

Terminal - Mediterranean (closing)

Three Types of Plate Boundaries
A review…

- Plate tectonics has had a profound affect on Earth’s geologic and biologic history.
- Interaction of plates along their boundaries controls the distribution of most earthquakes and volcanoes as well as the formation of mountain ranges.
- Geologists recognize three major types of plate boundaries based on their mode of interaction: divergent, convergent, and transform plate boundaries.
- Oceanic crust is created at divergent, consumed at convergent, and conserved at transform boundaries.

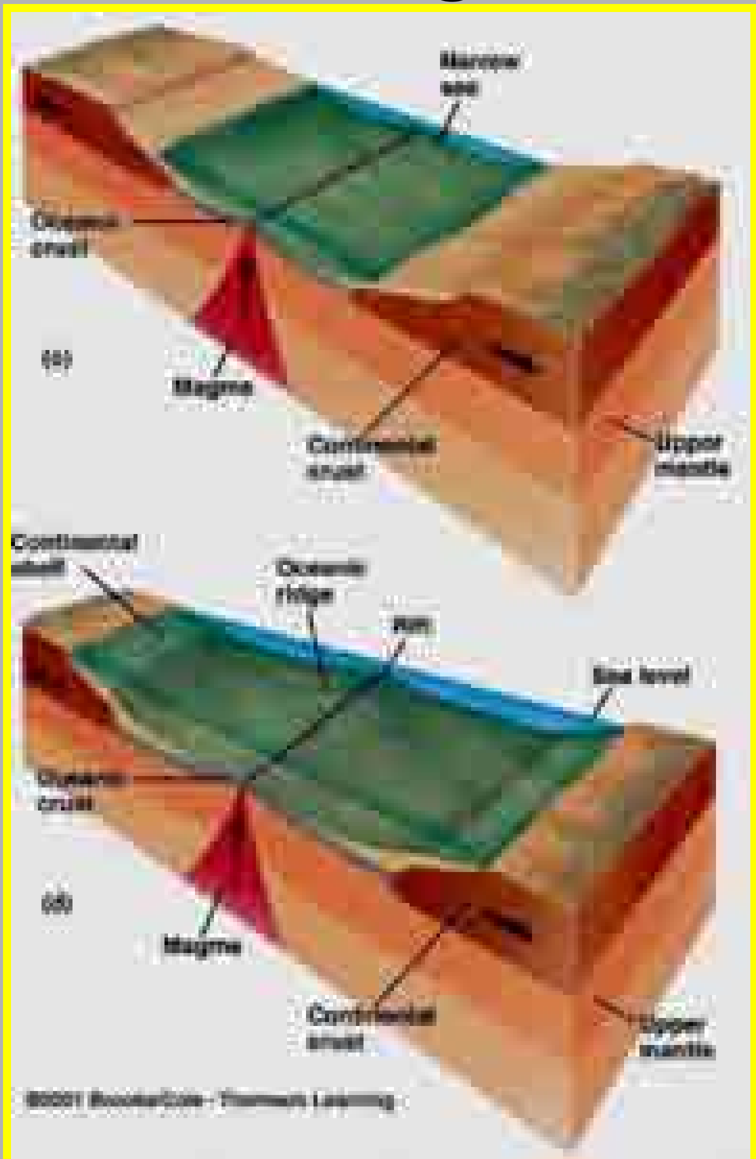
Divergent boundaries



- These begin formation within continents. Upwelling magma causes uplift stretching and fracturing of the overlying continental crust.
- As stretching continues, crustal blocks slide downward to form a rift valley. Magma intrudes and rises along fractures and out onto the valley floor. The East African rift is an excellent example of this phase of divergent boundary formation.

Wicander and Monroe (2002)

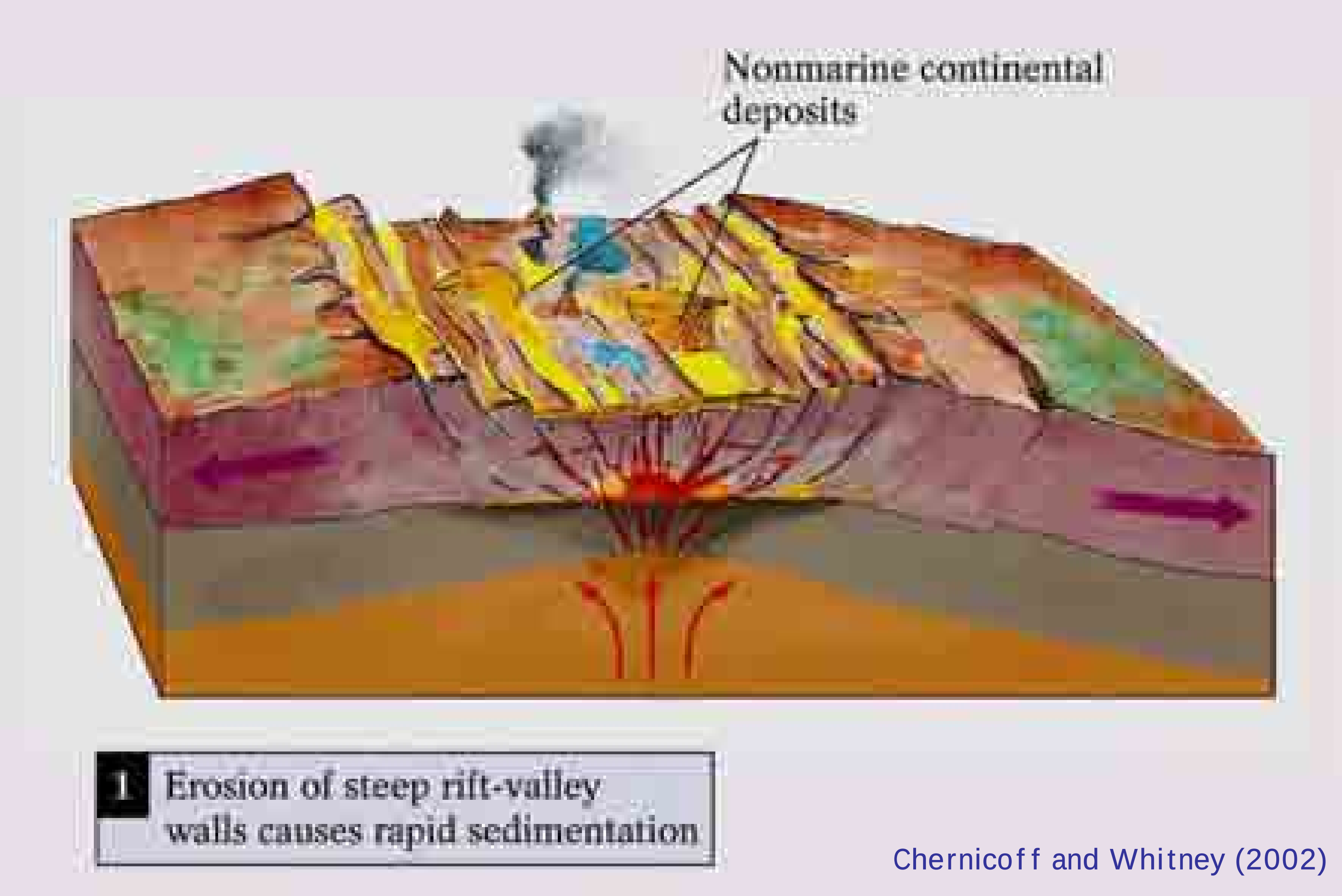
Divergent Boundaries



- As spreading continues, the rift valley deepens and lengthens to intersect the edge of the continent allowing the sea to flood the rift valley. Narrow seaways, such as the Red Sea, are formed. Rising magma reaches the seafloor and cools to form new oceanic crust.
- If spreading continues, the newly formed sea grows wider as ever more oceanic crust is created along the divergent boundary. A broad ocean basin like the Atlantic Ocean is formed.

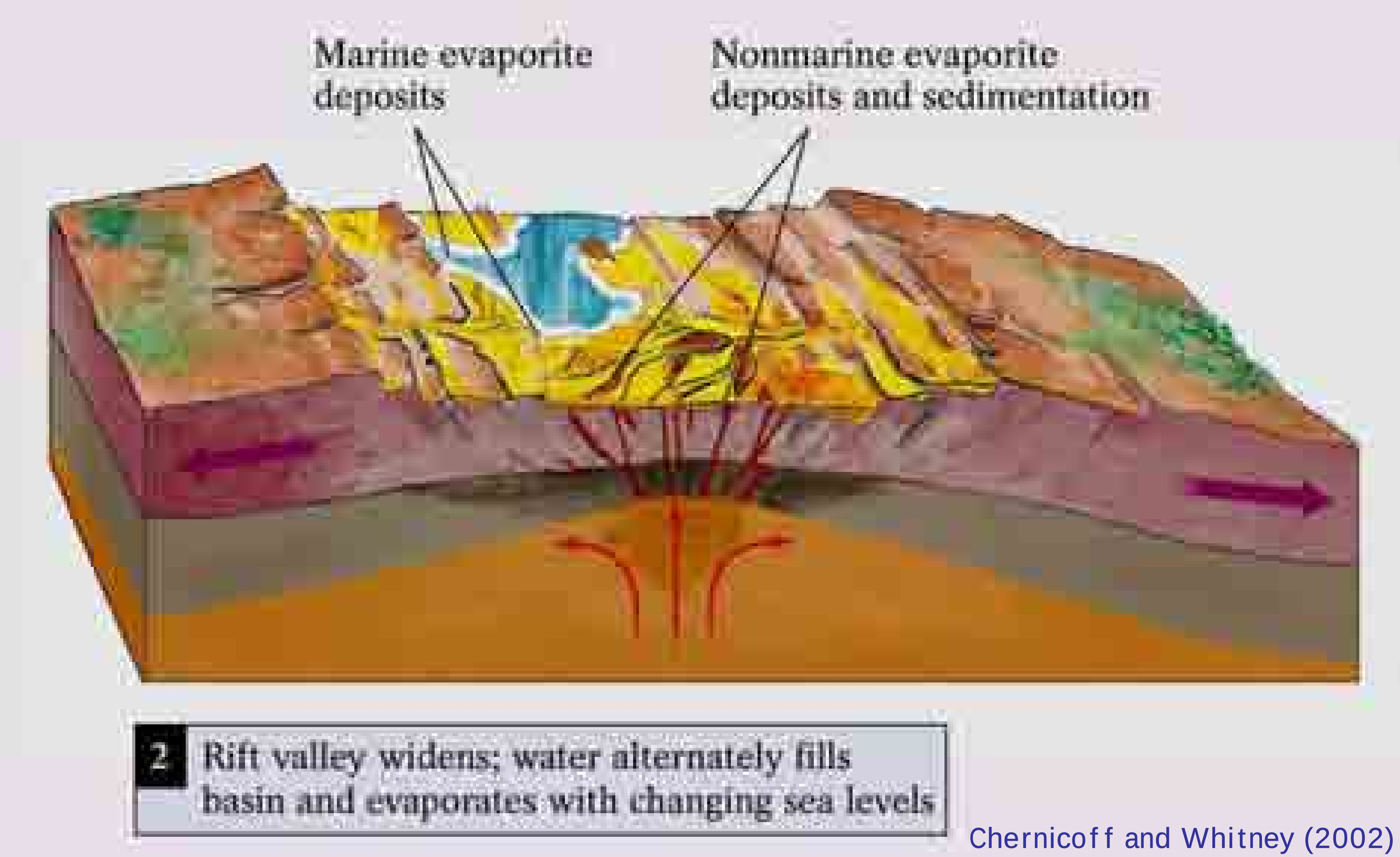
Wicander and Monroe (2002)

The growth of oceanic basins



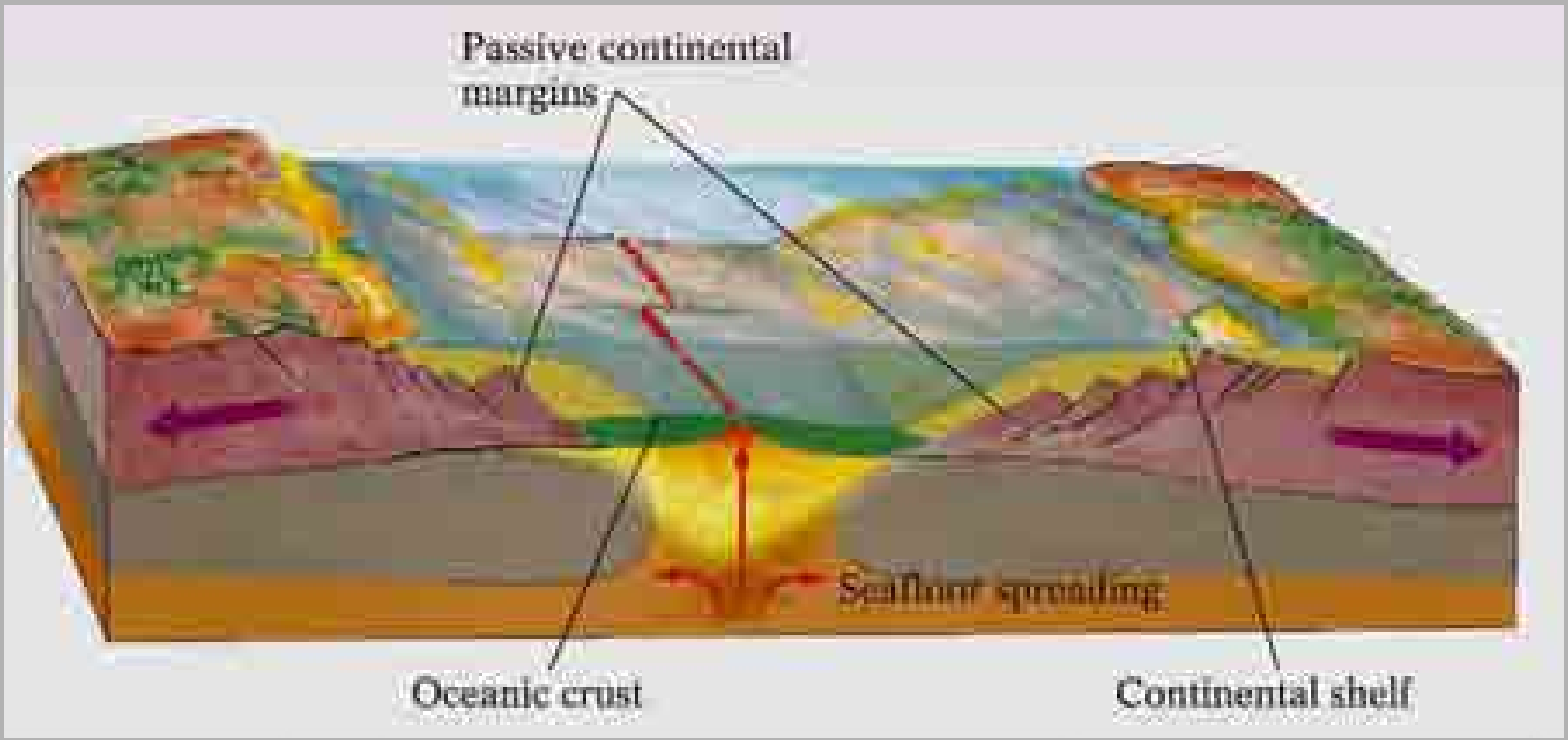
Chernicoff and Whitney (2002)

The growth of oceanic basins



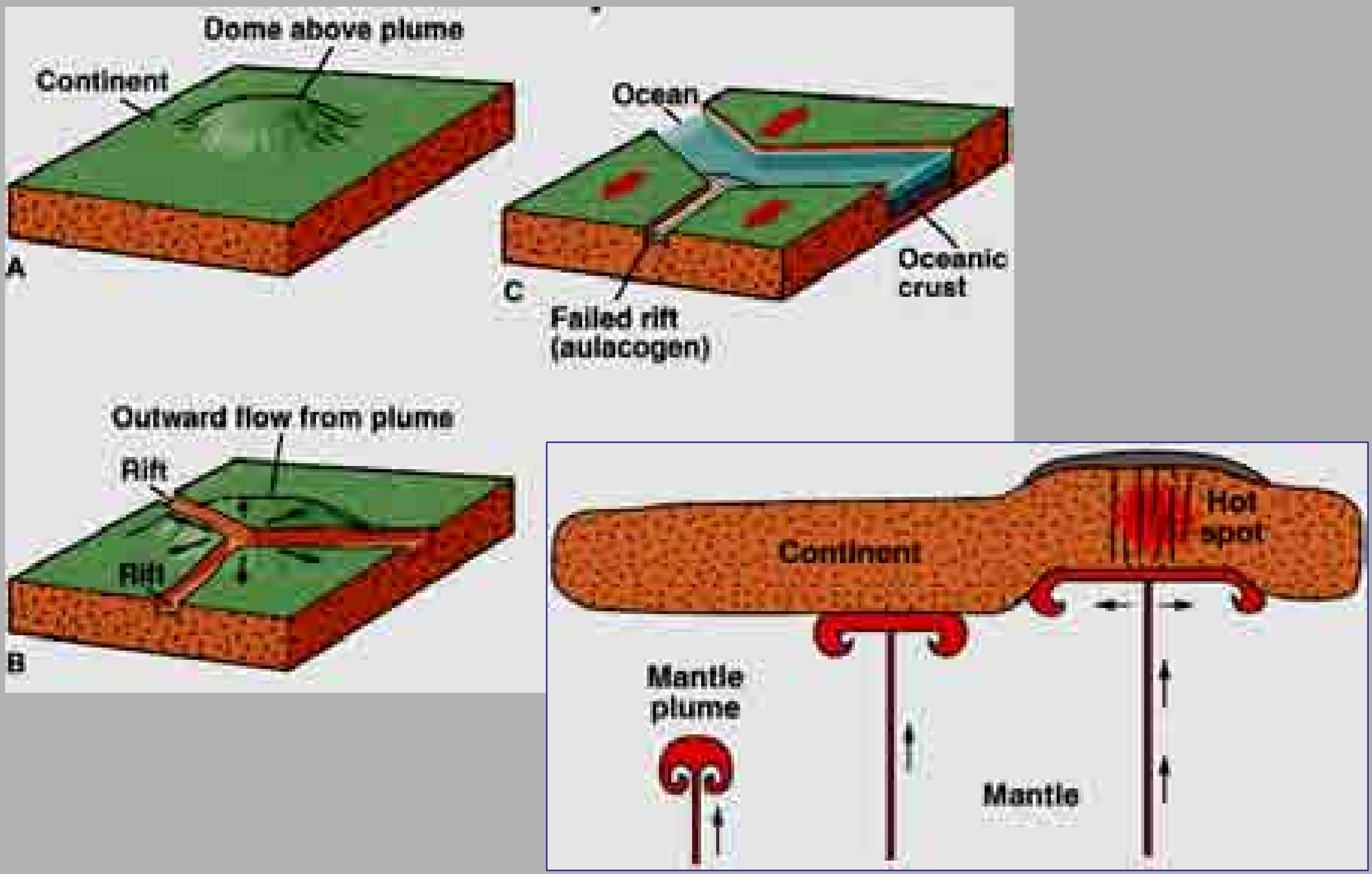
Chernicoff and Whitney (2002)

The growth of oceanic basin



Chernicoff and Whitney (2002)

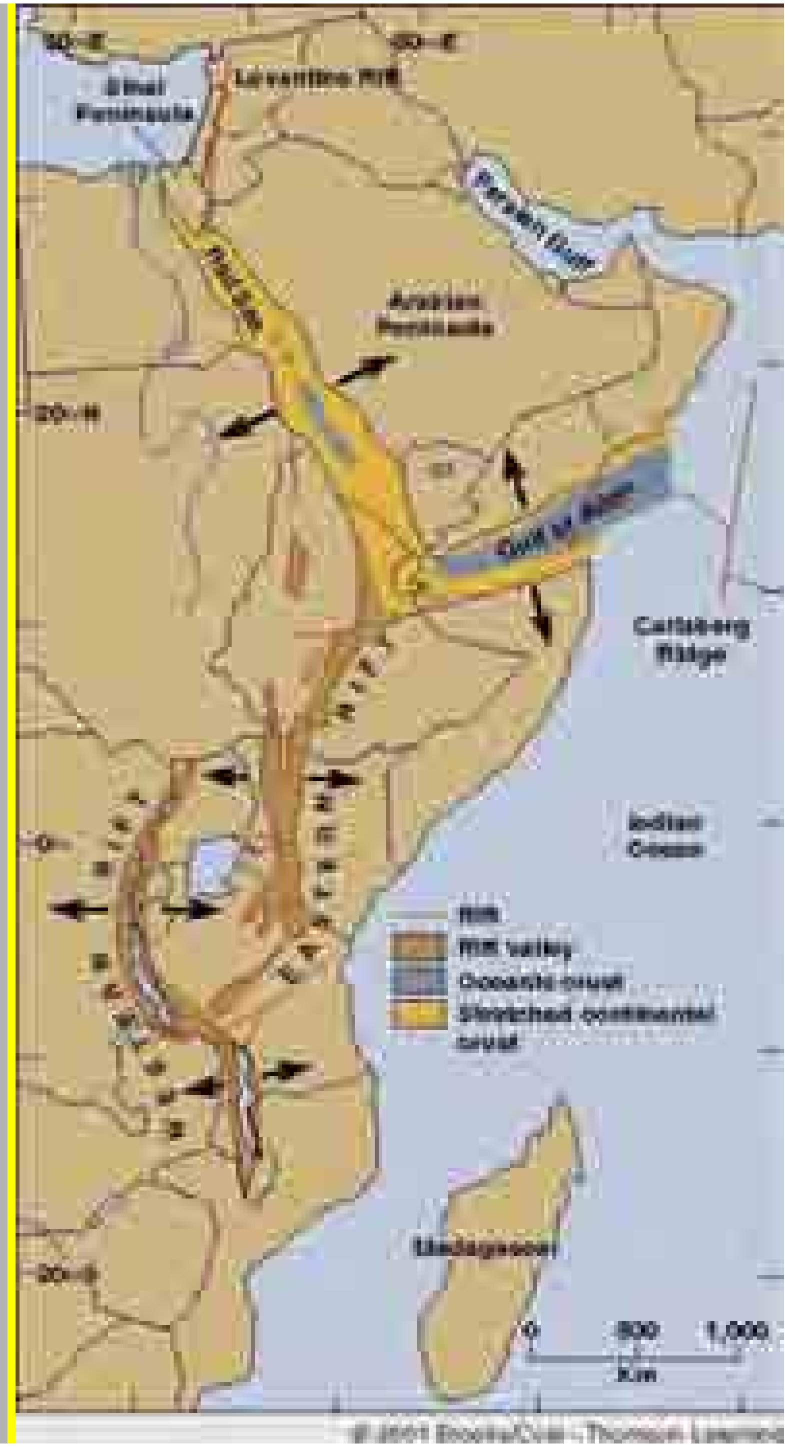
Active rifting.



Plummer et al. (2001)

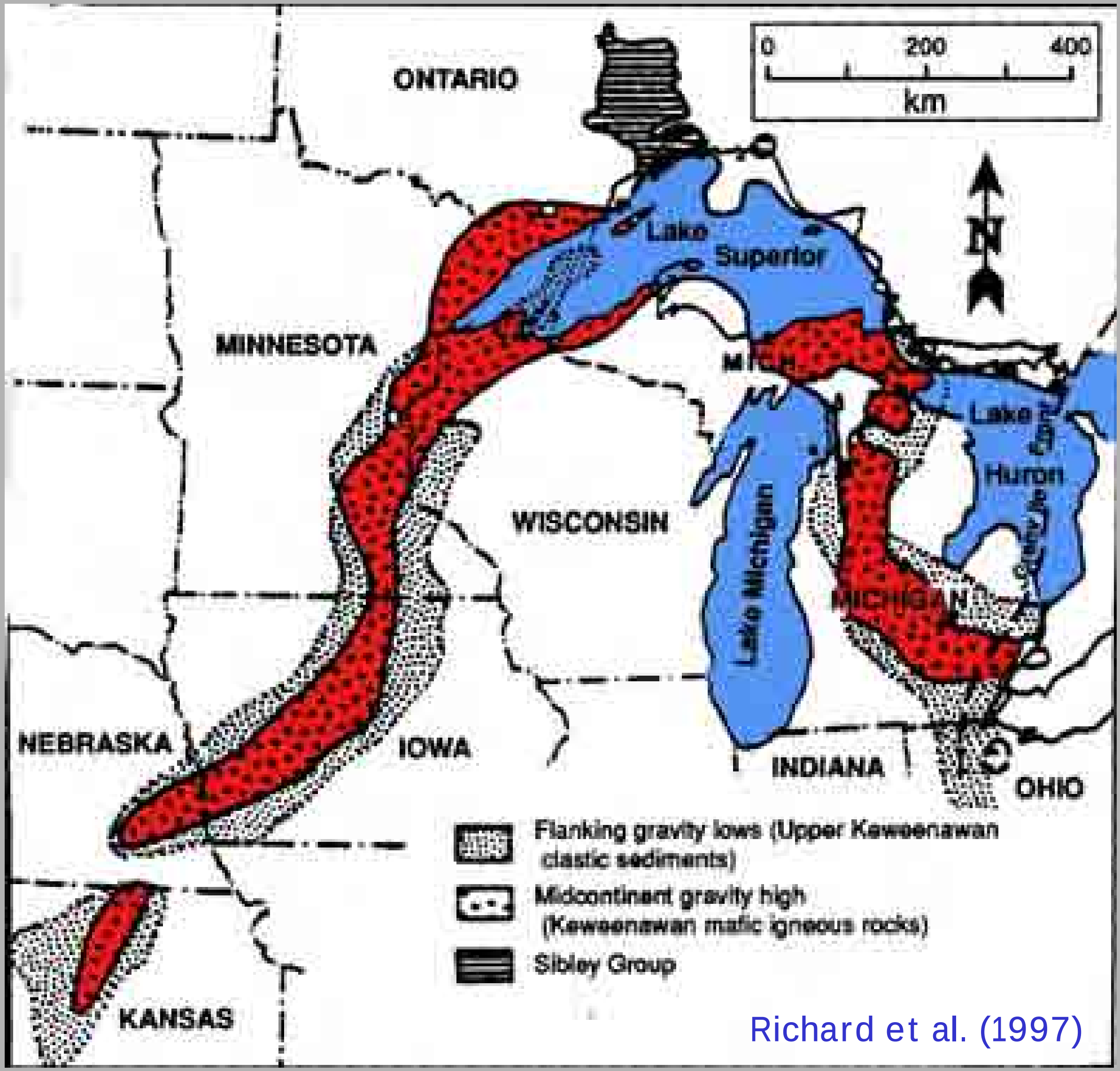
Divergent boundaries

This map of Africa and the Arabian Peninsula shows a divergent margin forming in continental crust (East African rift) and a newly formed narrow seaway (Red Sea and Gulf of Aden) where new oceanic crust is being created.



Wicander and Monroe (2002)

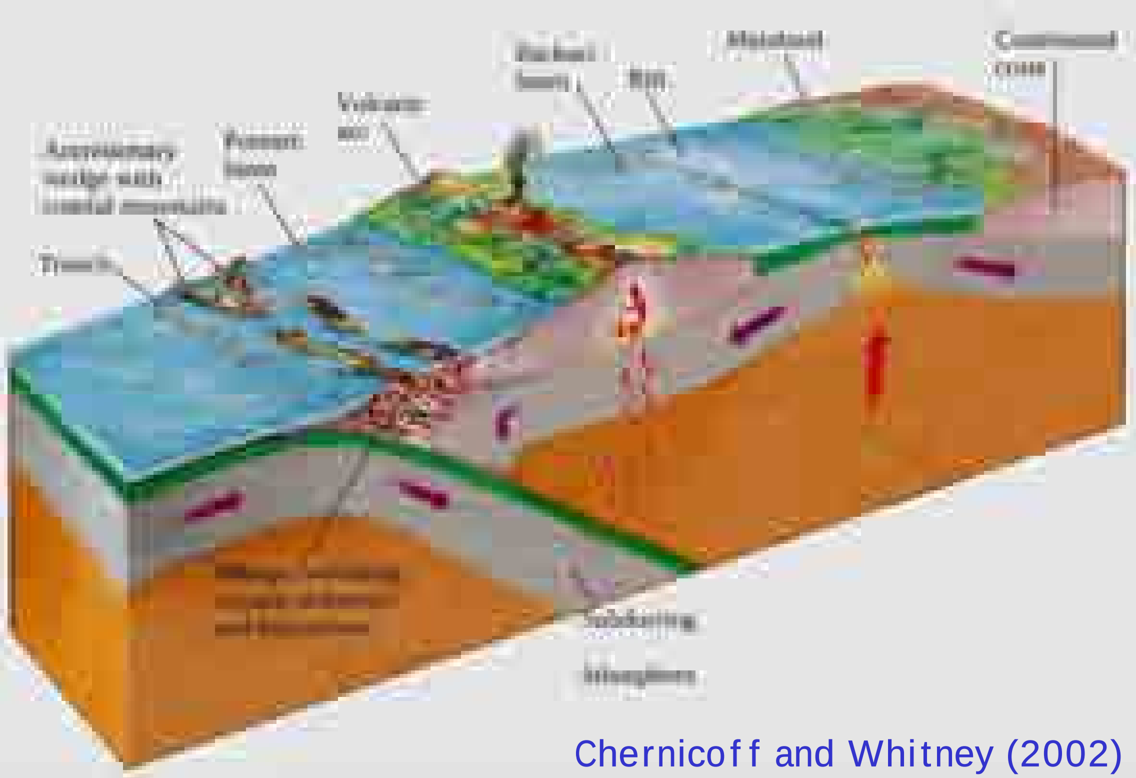
Divergent boundary



Richard et al. (1997)

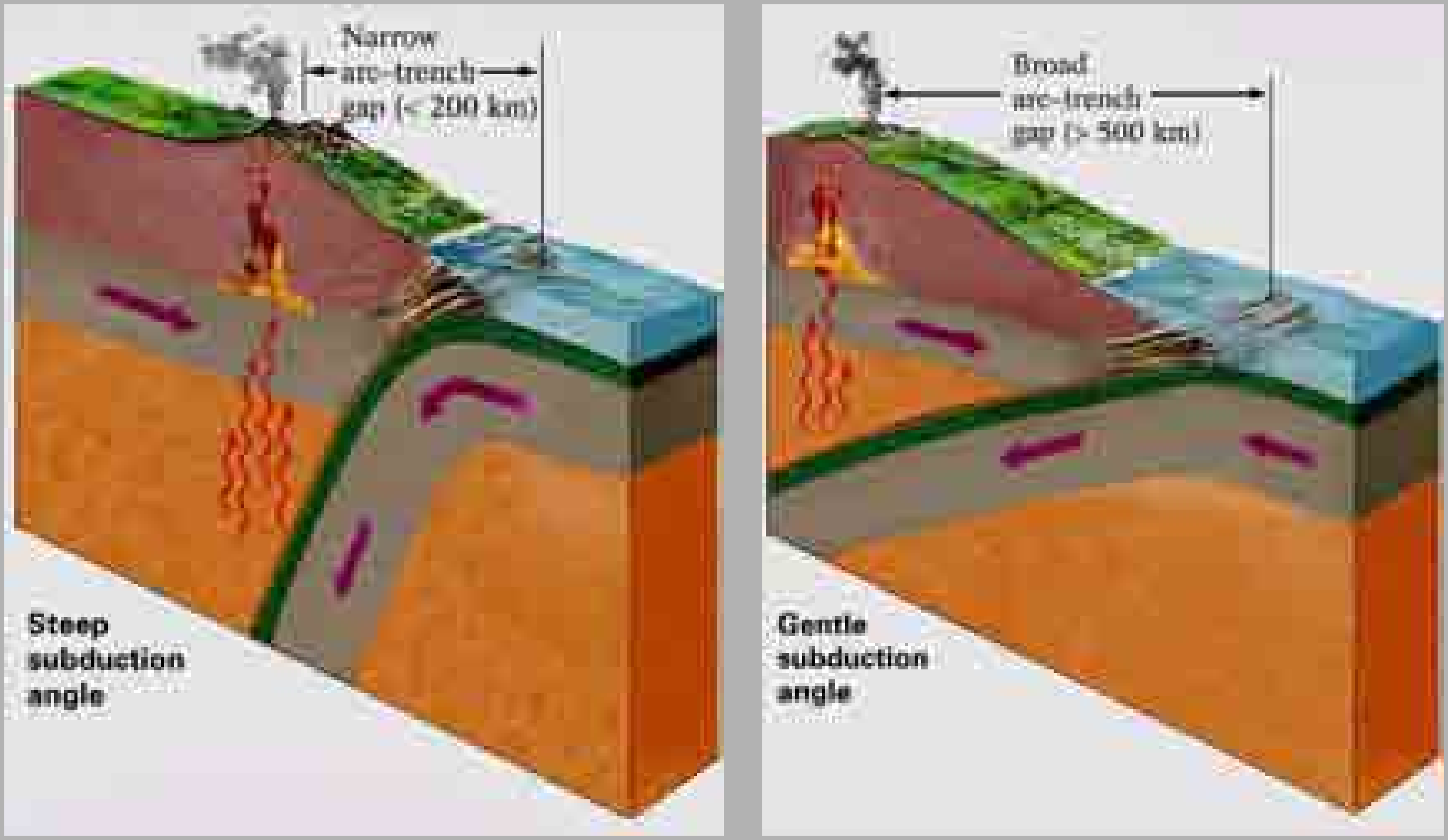
Convergent Boundaries

Plates collide along a convergent boundary and the leading edge of one plate is subducted beneath the margin of the other plate. An ocean trench marks the plate boundary. The subducted plate descends into the asthenosphere where it melts to form magma that is less dense than the magma of the asthenosphere. The lighter magma rises and melts through the over-riding plate to form volcanoes.



Chernicoff and Whitney (2002)

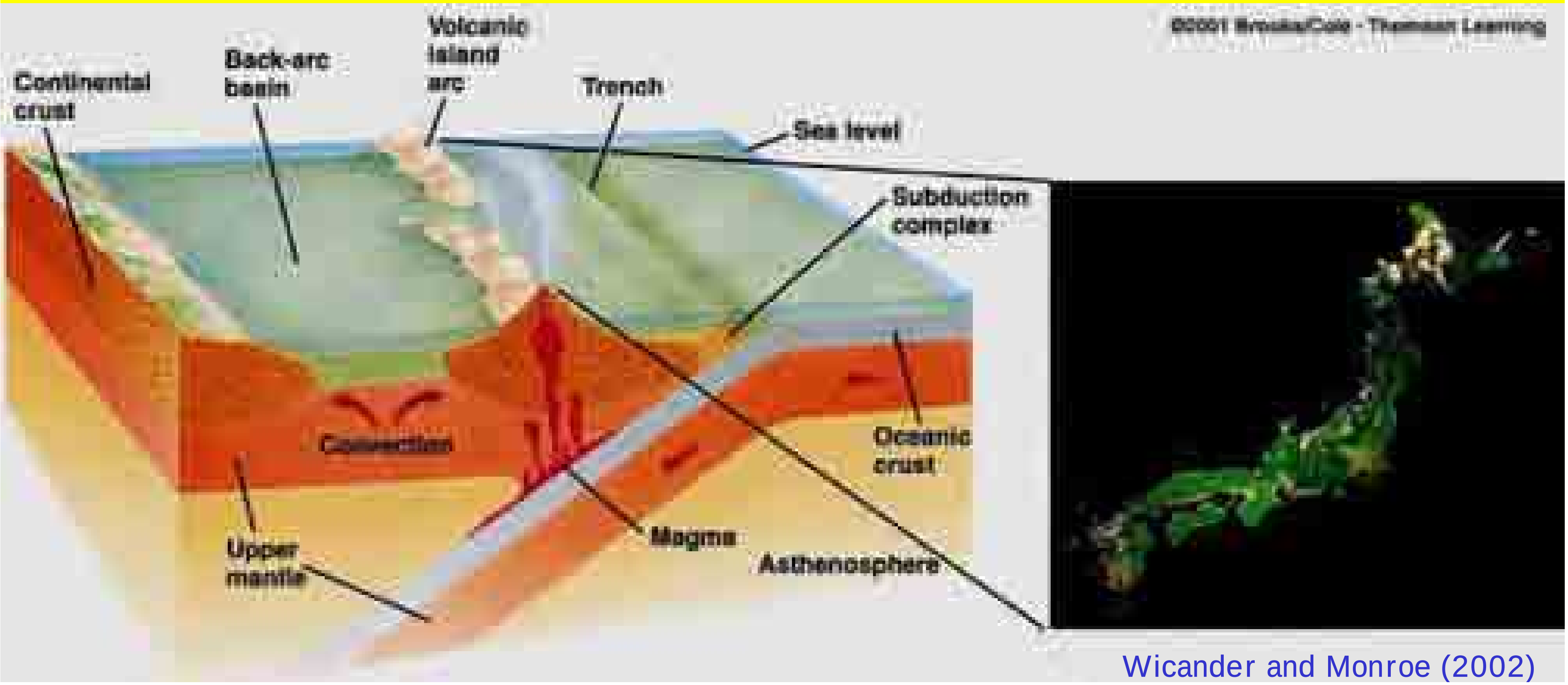
Subduction angle



Chernicoff and Whitney (2002)

Convergent Boundaries

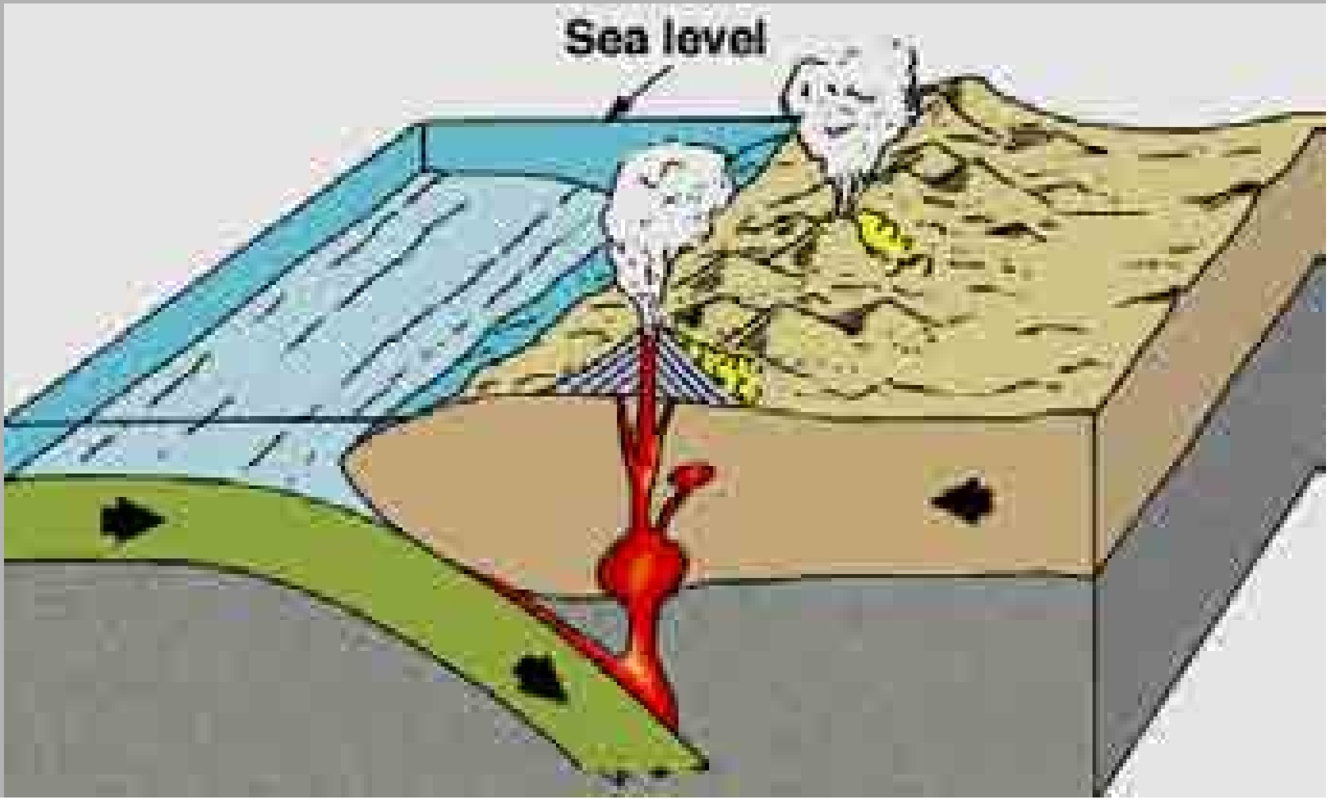
At an oceanic-oceanic plate boundary volcanoes form a chain, a volcanic island arc, paralleling the plate boundary. Japan is an example of a volcanic island arc.



Wicander and Monroe (2002)

Convergent Boundaries

When oceanic crust collides with continental crust along an oceanic-continental plate boundary, the denser oceanic crust is subducted beneath the lighter continental crust. As with oceanic-oceanic plate boundaries, a chain of volcanoes forms on the over-riding plate

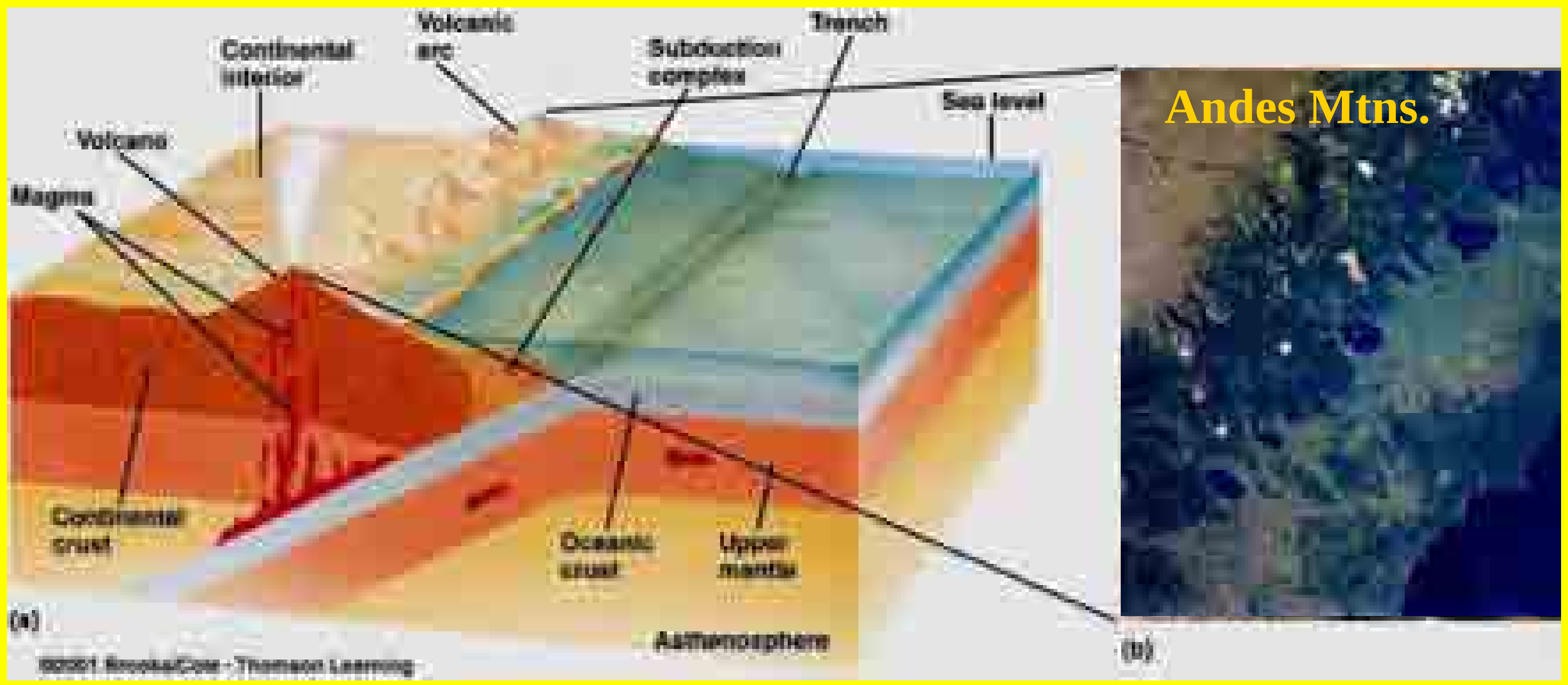


Montgomery (2001)

Convergent Boundaries

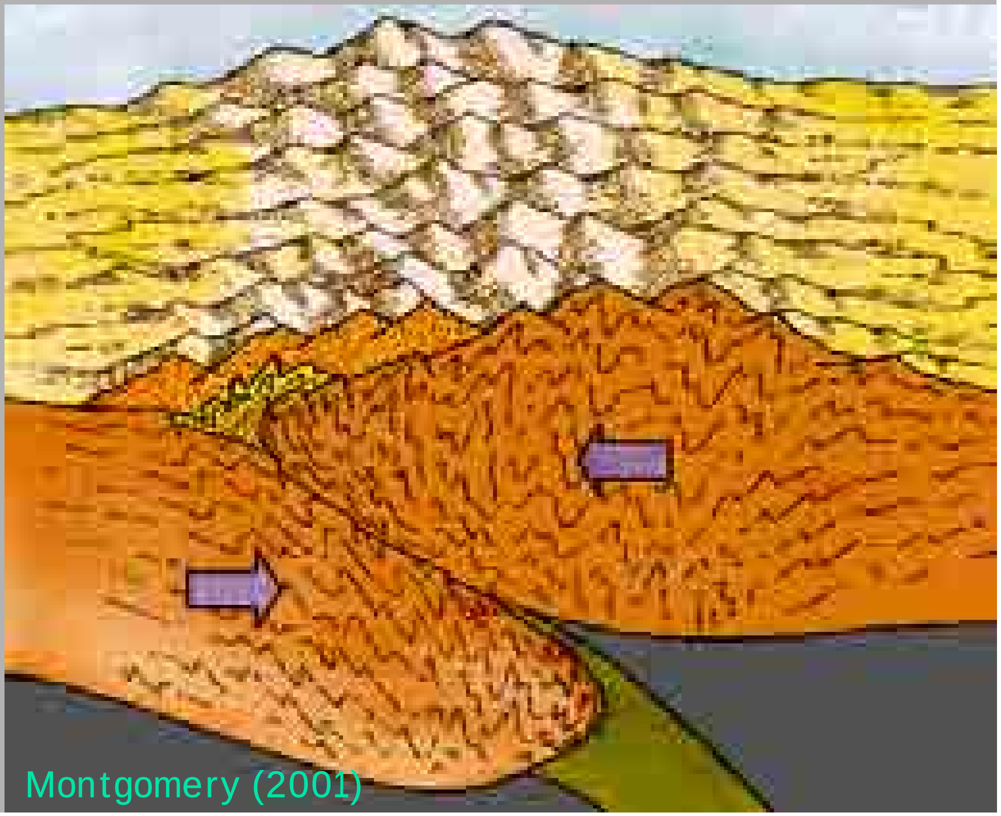
The Andes are an excellent example of this type of mountain chain known as a volcanic arc. The Peru-Chile trench marks the boundary between the South America and the oceanic Nazca plate which lies off the western edge of South America.

Wicander and Monroe (2002)



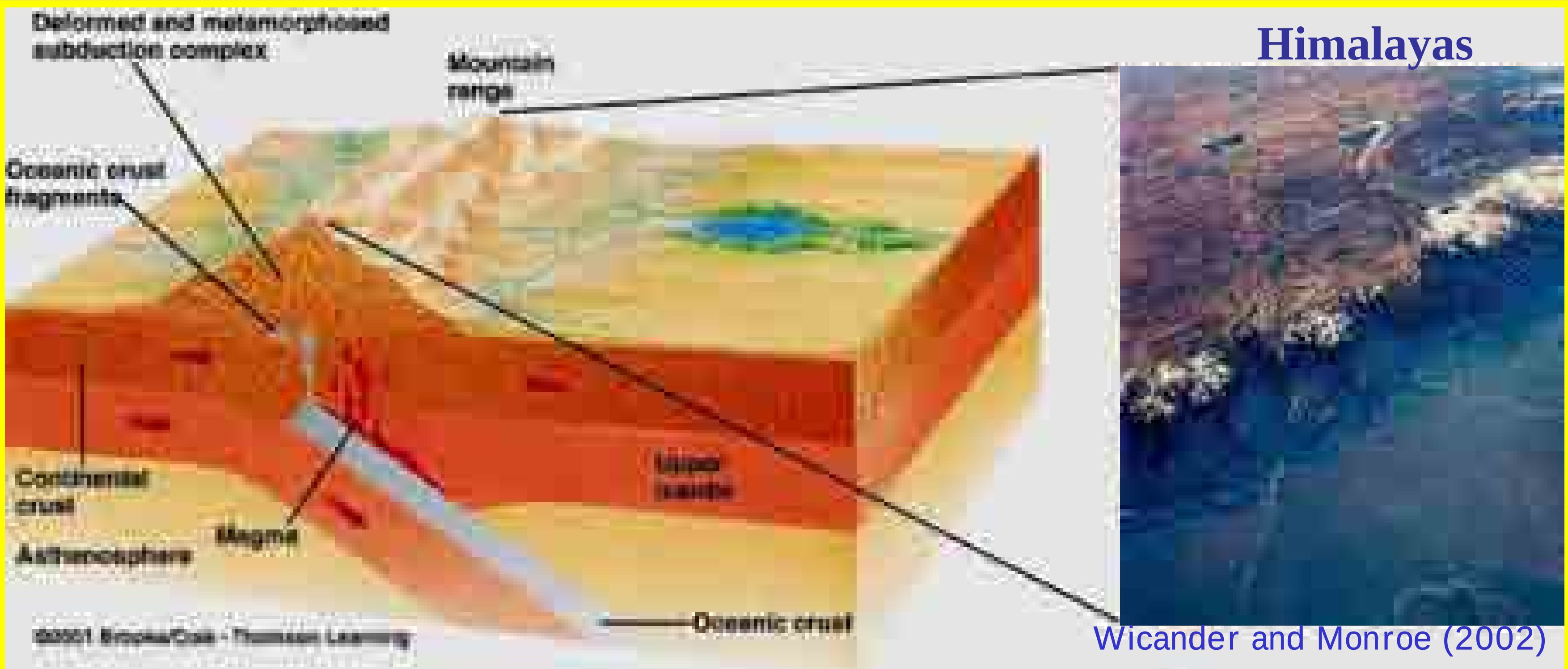
Convergent Boundaries

When oceanic crust flooring an ocean basin is subducted, continents formerly separated by an intervening ocean basin collide along a continent-continent plate boundary. Continental crust is too light to subduct into the asthenosphere, but may slide a short distance beneath an adjacent continent. Colliding continents become welded together along the plate boundary.



Convergent Boundaries

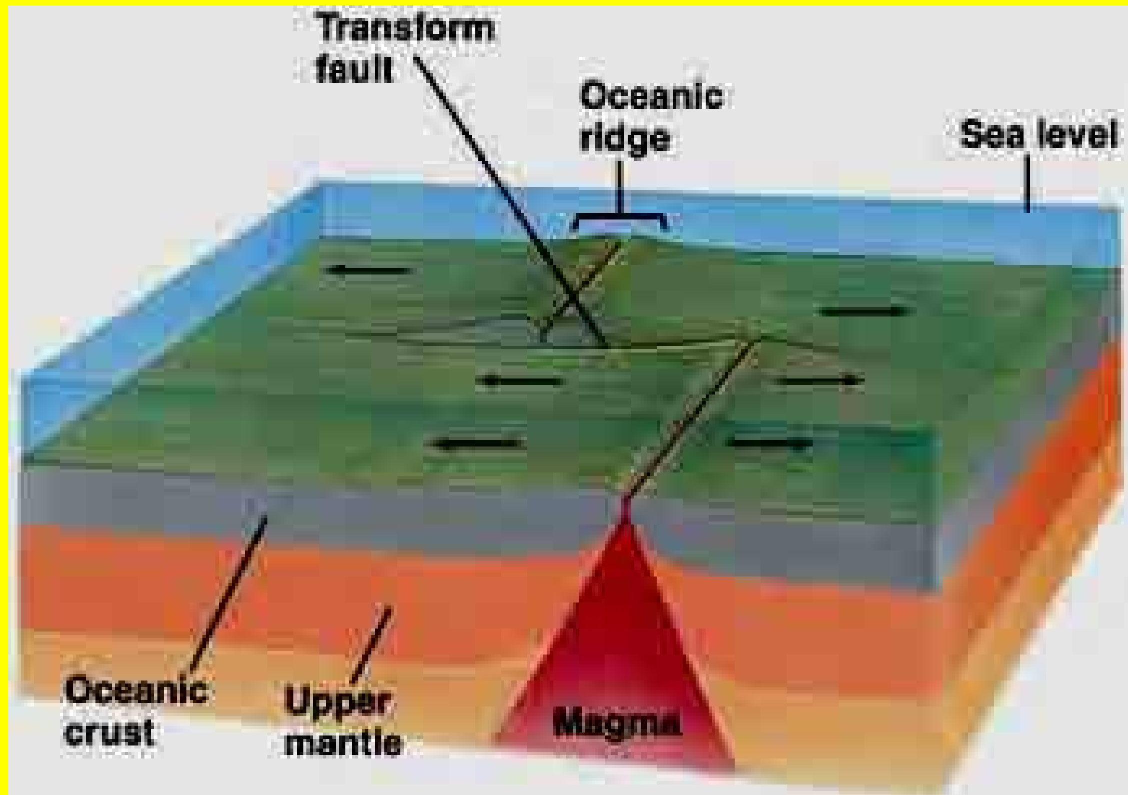
The collision produces an interior belt of mountains consisting of uplifted, folded, and broken rocks. The Himalayas of northern India formed when India collided with Asia.



Wicander and Monroe (2002)

Transform Boundaries

At transform plate boundaries, plates slide laterally past one another. Most are in oceanic crust where they connect two segments of mid-ocean ridges, producing a stair-step appearance.



Wicander and Monroe (2002)

Transform boundaries

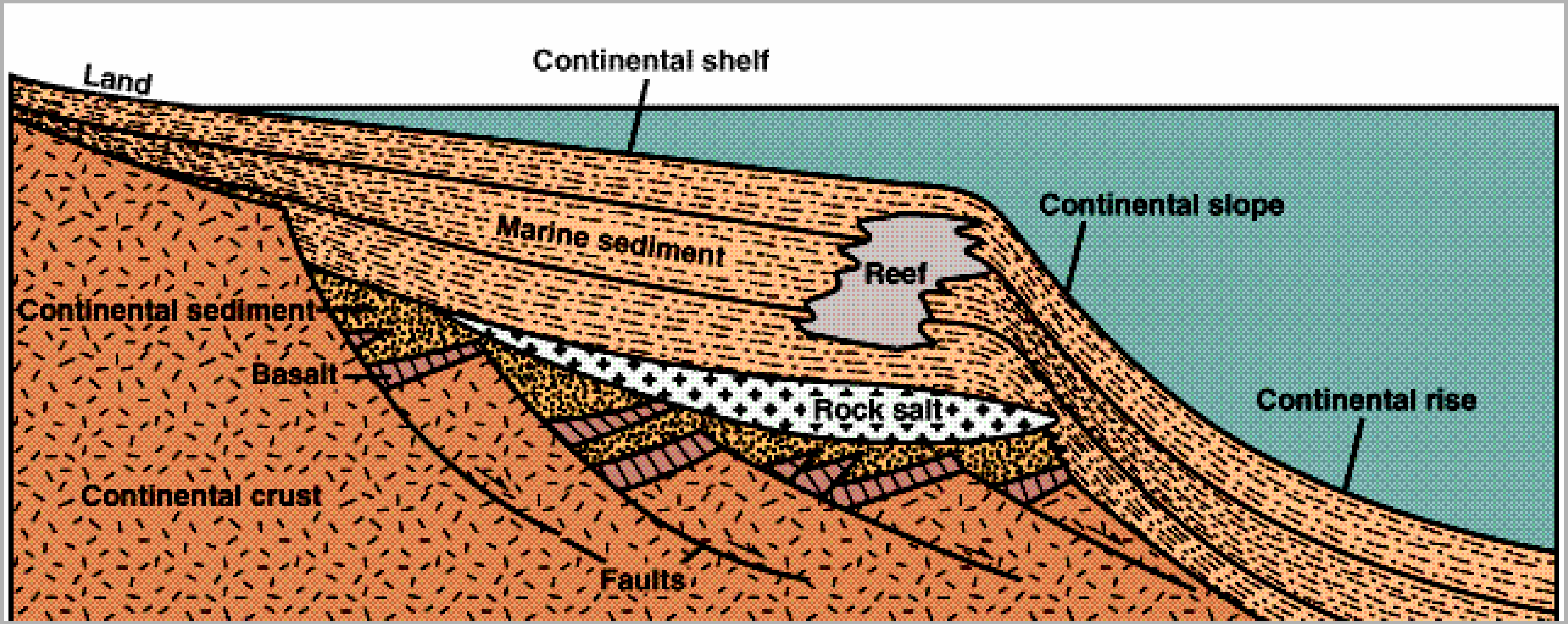
Transforms

Some transform plate boundaries, such as the San Andreas Fault of California, are located in continental crust. Los Angeles lies west of this plate boundary and is situated on the Pacific plate, whereas the rest of North America is part of the North American plate. Many of California's earthquakes result from the plates slipping past one another along this transform fault.

Wicander and Monroe (2002)

The fourth margin type

Passive margins form where there is no active tectonic process



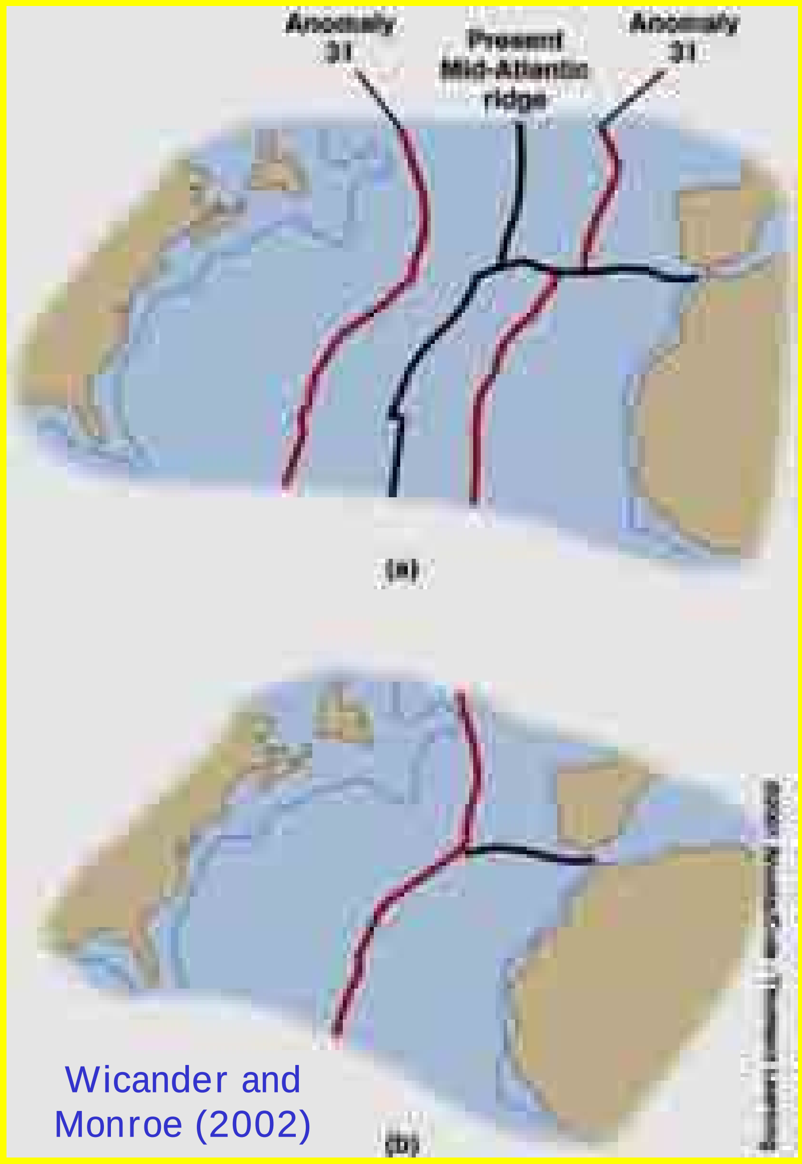
Plummer et al. (2001)

How Are Plate Movement and Motion Determined?

- Magnetic anomalies
- Matching crustal features and anomalies
- Direct measurement
- Hot spots

New pahoehoe lava moves slowly across a black sand beach in Harry K. Brown Park, Kalapana, Hawaii. http://hvo.wr.usgs.gov

Magnetic anomalies

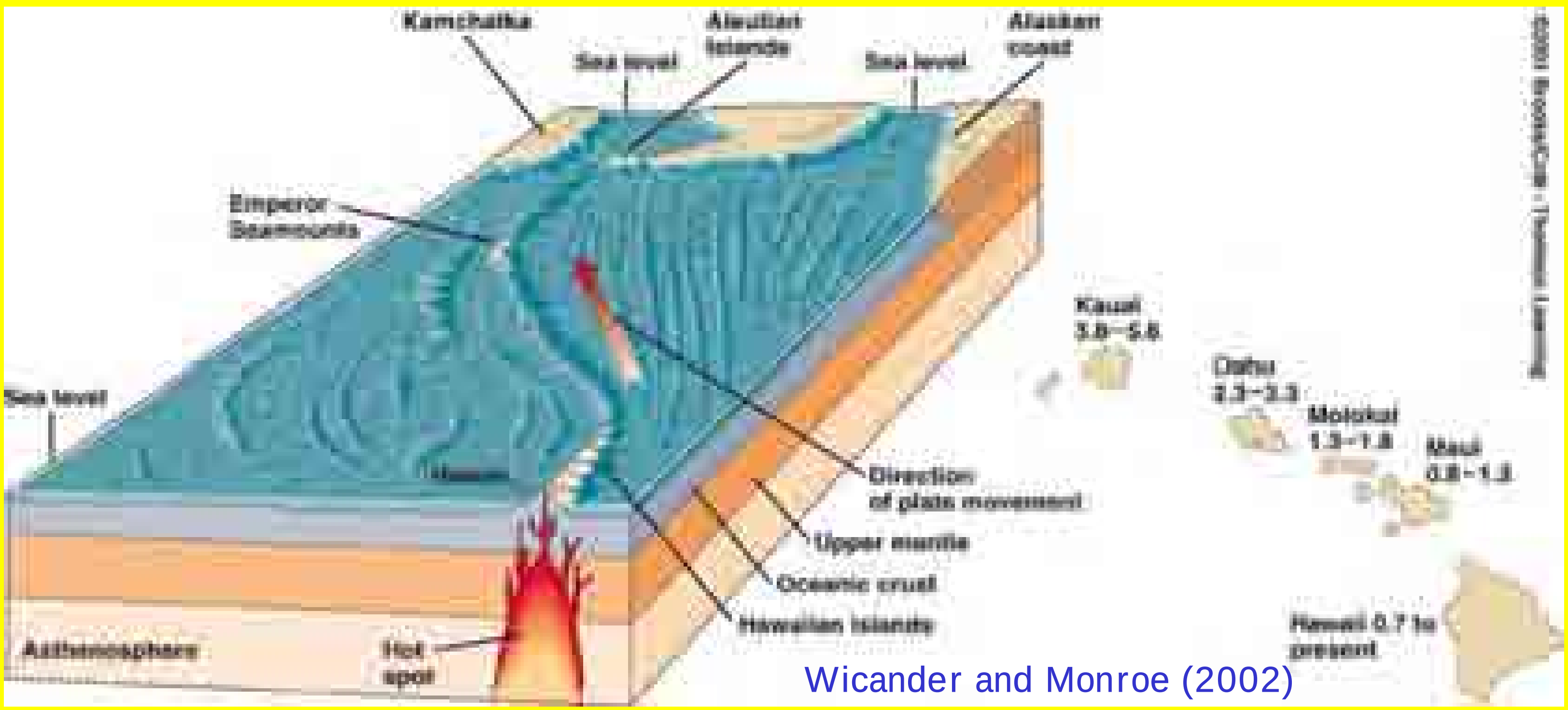


Wicander and Monroe (2002)

- Average rate of plate movement can be determined by dividing the age of a magnetic anomaly in oceanic crust by the distance between that anomaly and the present mid-ocean ridge.
- The motion of one continent relative to another can be assessed by moving matching anomalies on either side of the present ocean ridge back together along the present ocean ridge.

Hot spots

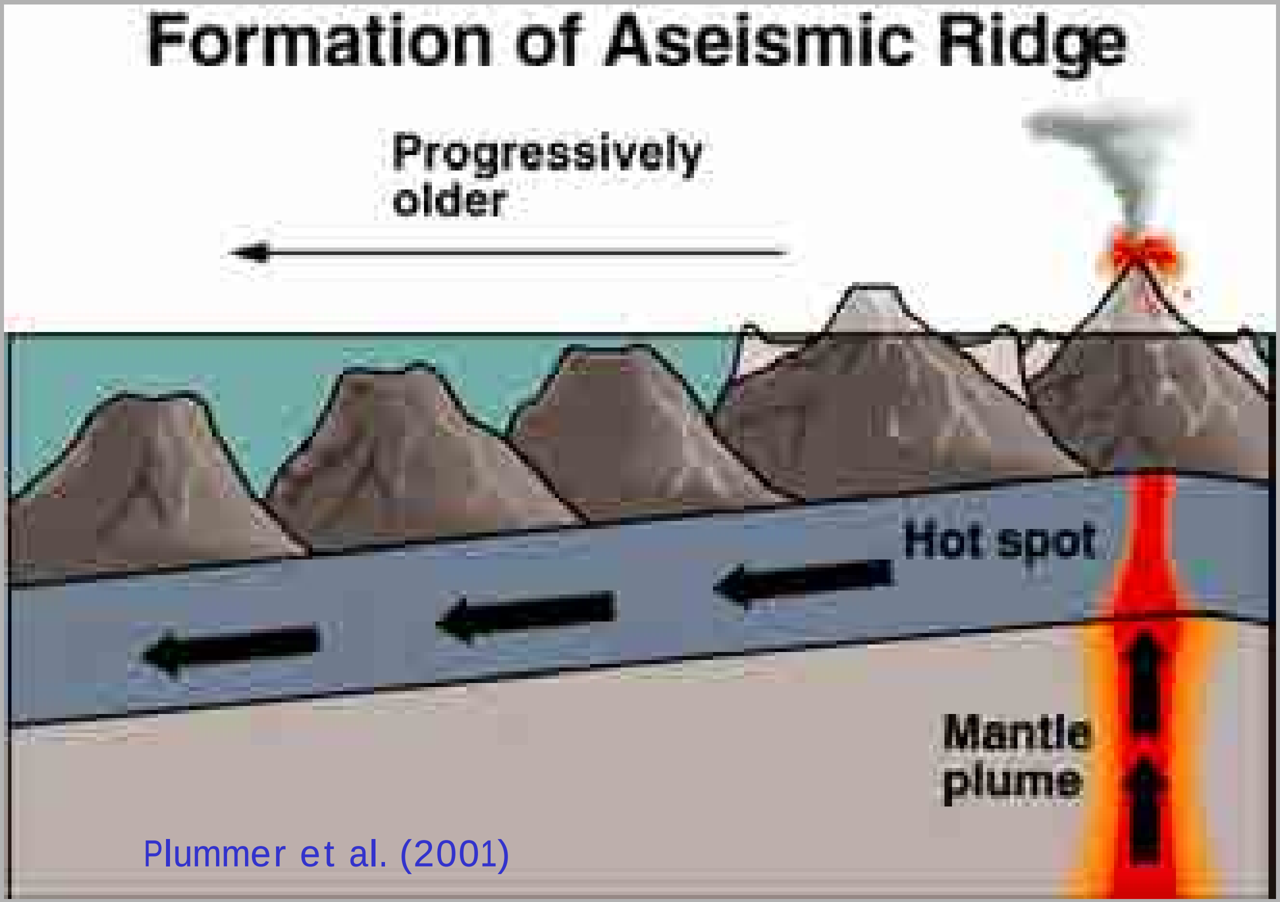
A fixed reference point is required to determine absolute motion of a plate. A hot spot such as lies beneath the island of Hawaii is a stationary plume of rising mantle material.



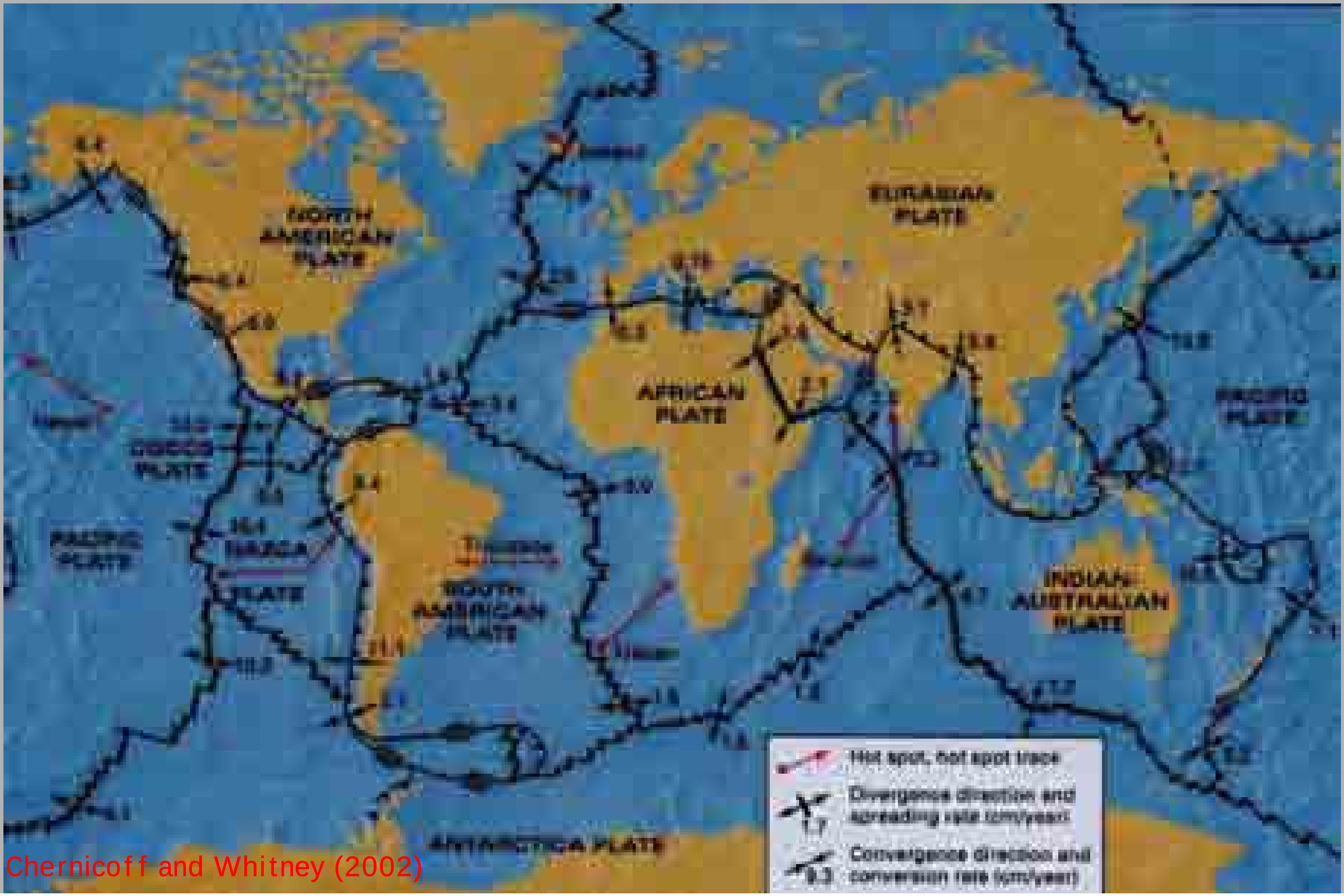
Wicander and Monroe (2002)

What is a hot spot?

Drift of the Pacific plate across the hot spot produced the Hawaiian Islands and Emperor Seamounts.



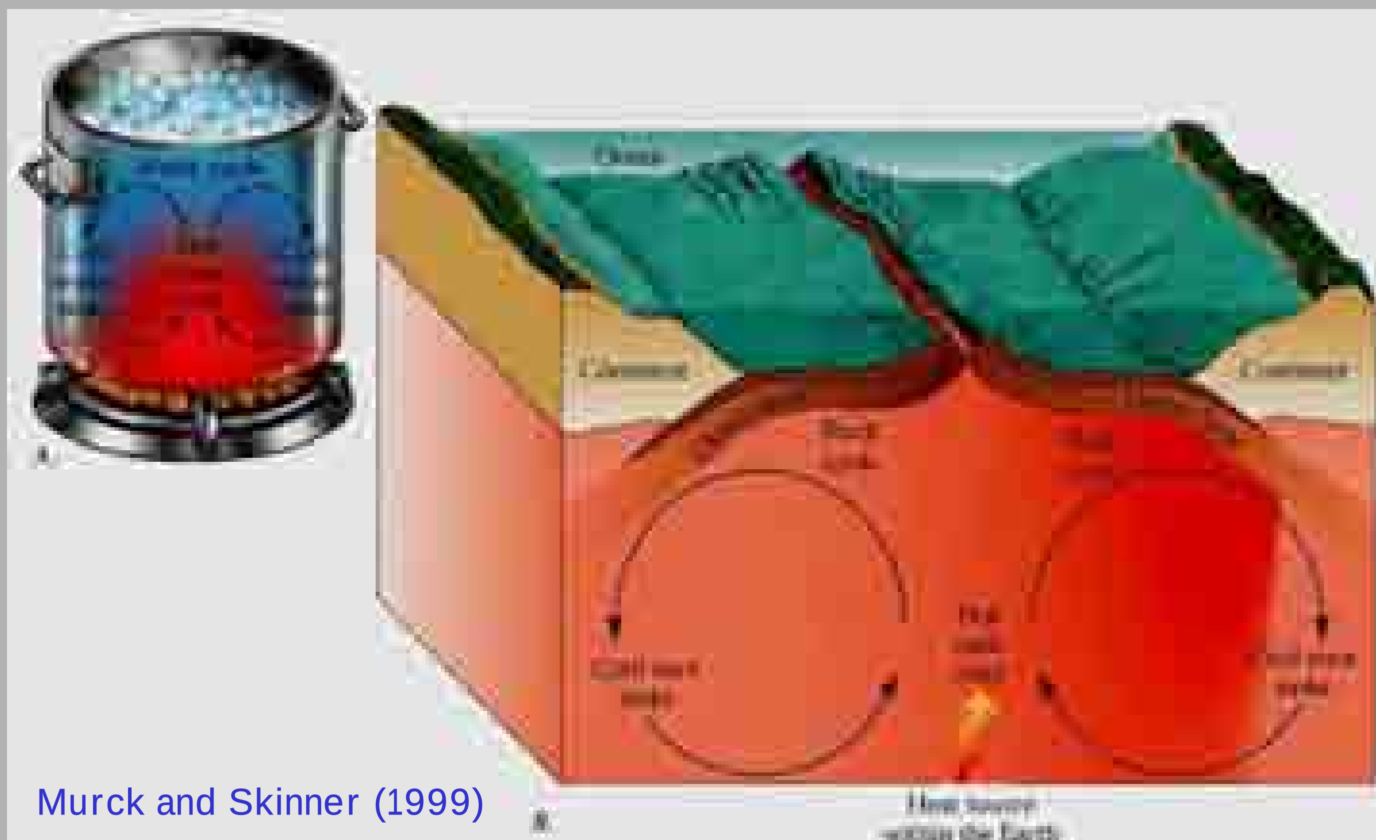
Directions & rates of movement.



Chernicoff and Whitney (2002)

What Is the Driving Mechanism?

The uneven distribution of heat in Earth ultimately drives plate tectonics through the process of convection



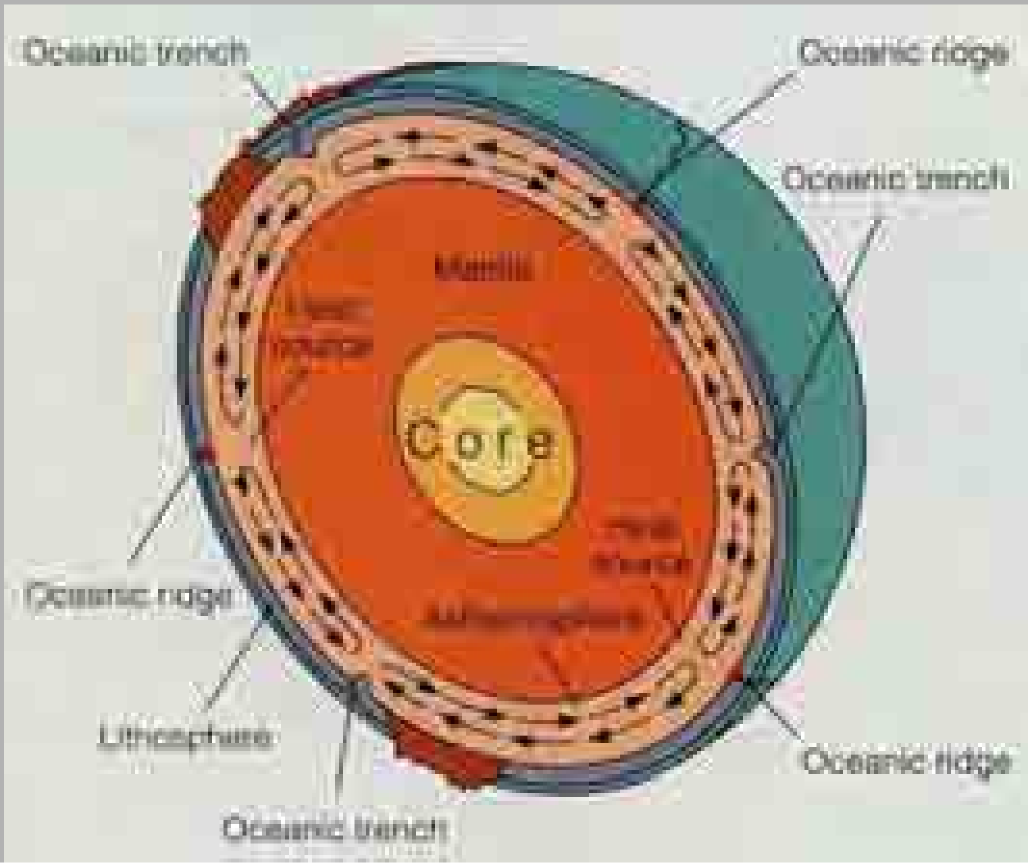
Murck and Skinner (1999)

What Is the Driving Mechanism?

- Two models, both of which entail rotating thermal convection cells, have been proposed.

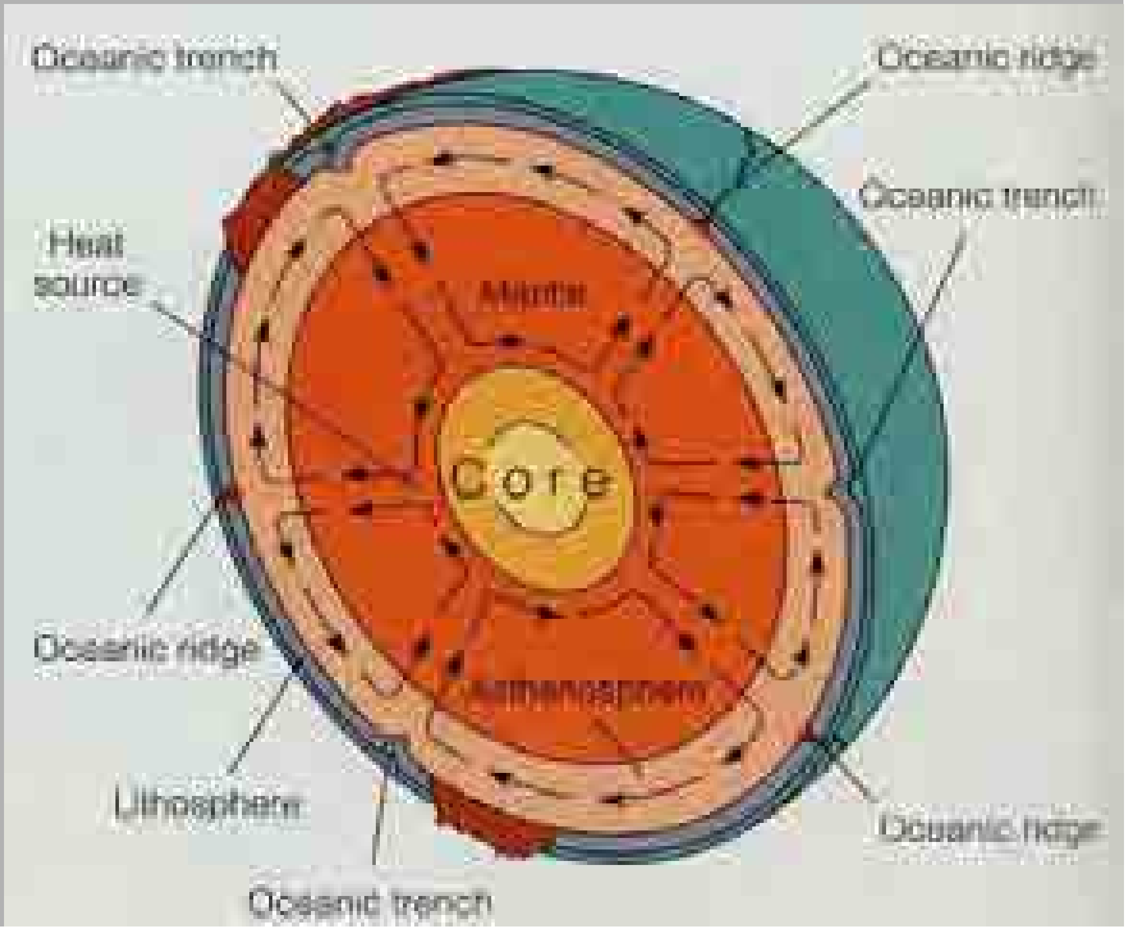
- **In one model the convection cells are restricted to the asthenosphere**

Wicander and Monroe (2002)



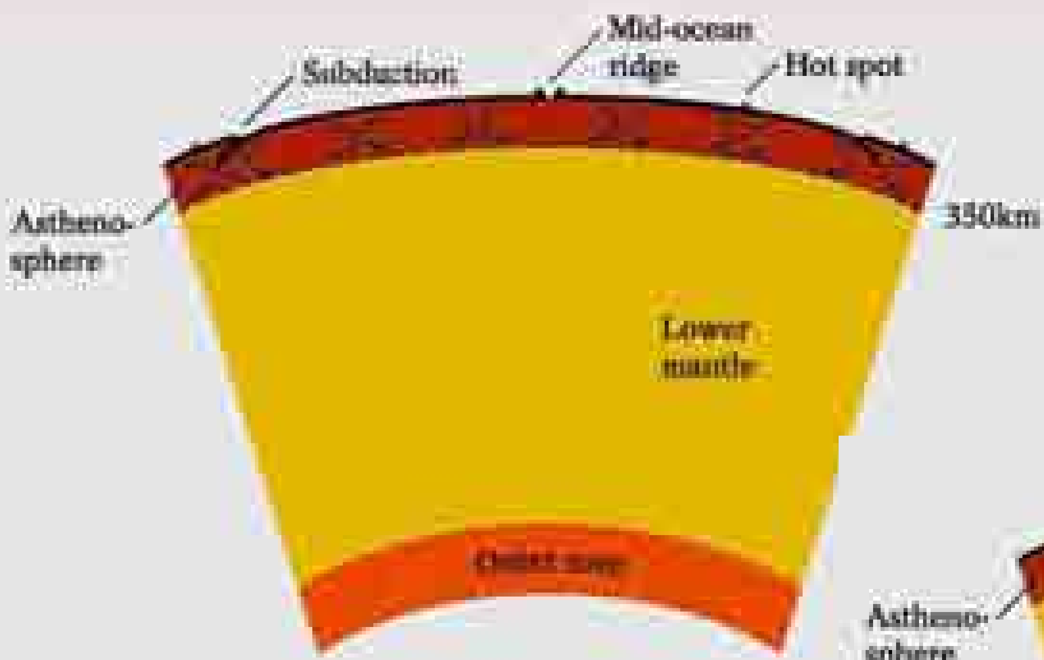
What Is the Driving Mechanism?

- In the other model the convection cells involve the entire mantle.



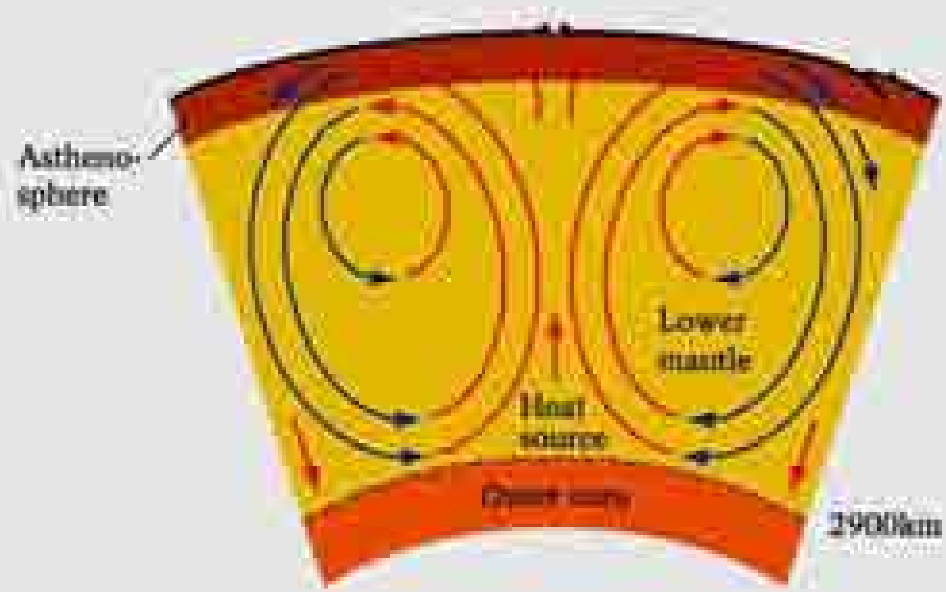
Wicander and Monroe (2002)

Convection cells.



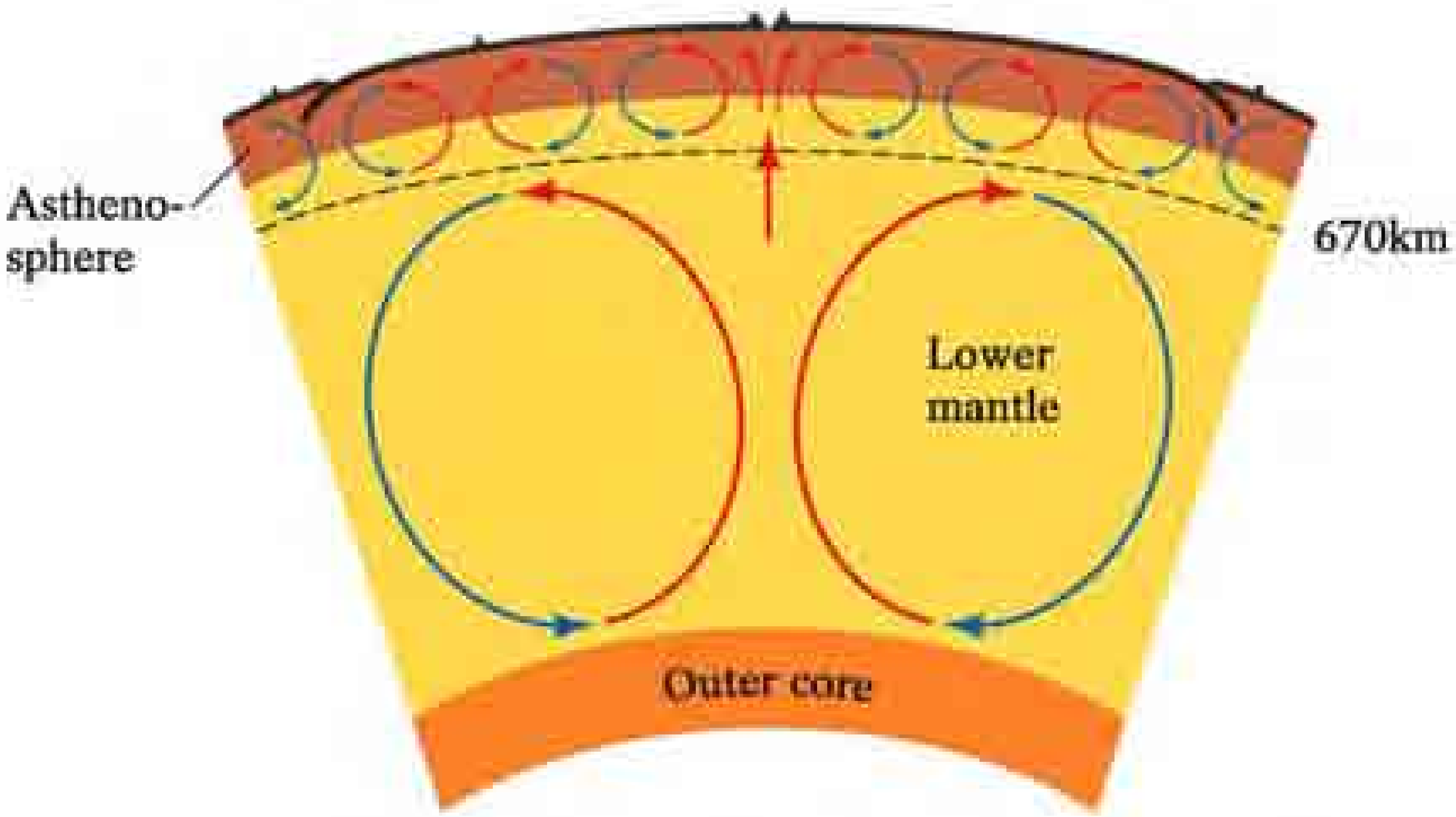
(a) Shallow convection-cell hypothesis

Chernicoff and Whitney (2002)



(b) Deep convection-cell hypothesis

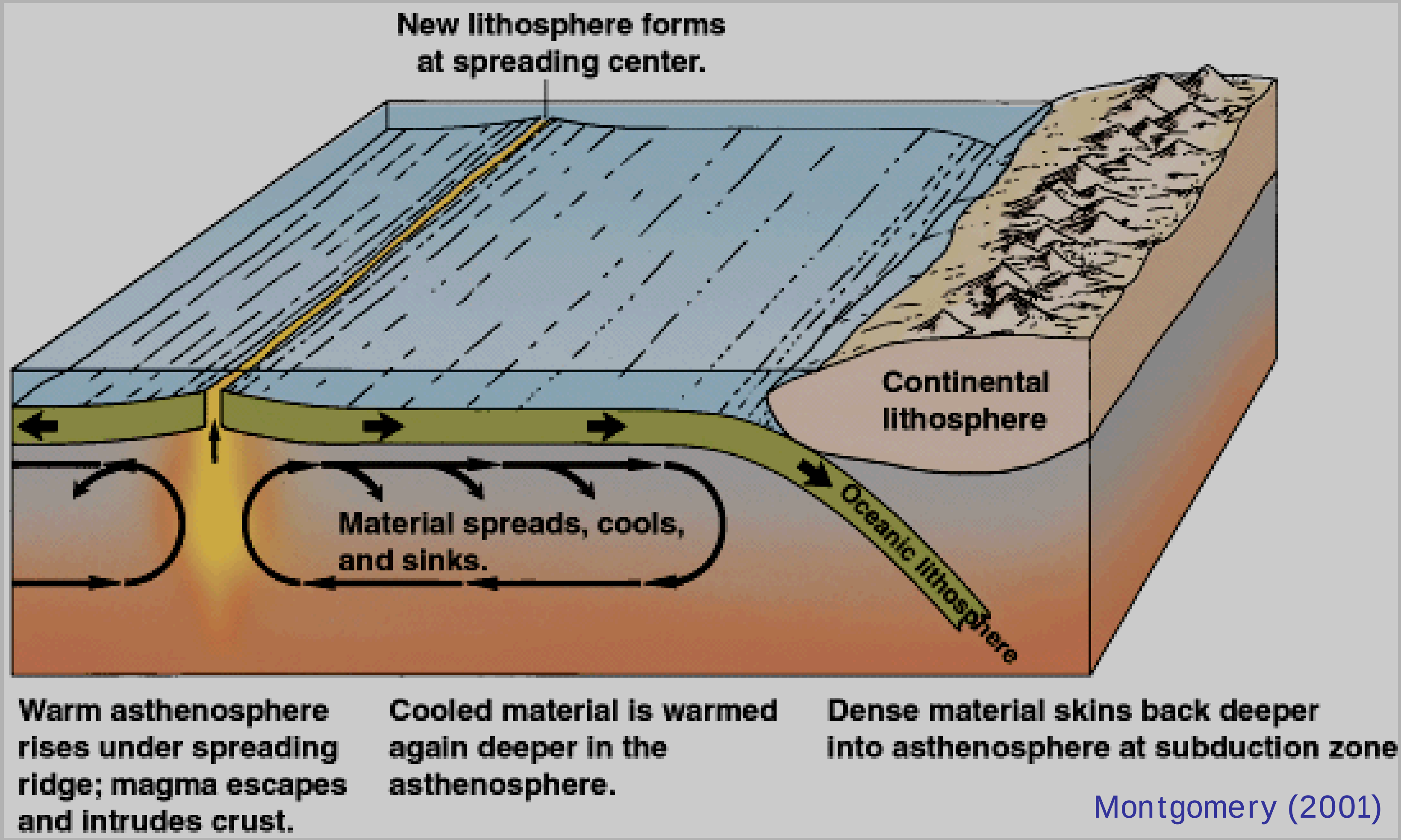
A compromise?



(c) Two-tiered convection-cell hypothesis

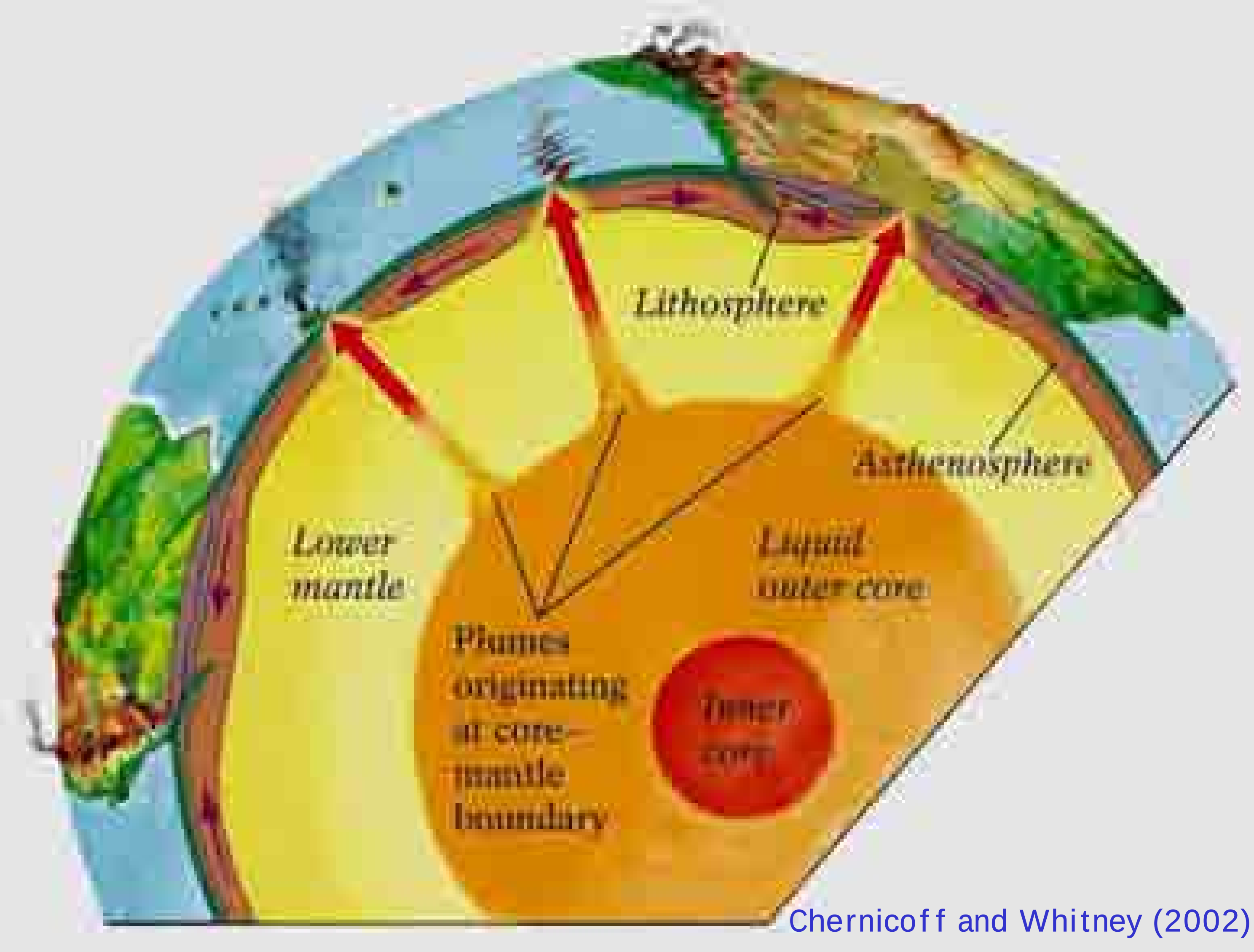
Chernicoff and Whitney (2002)

Mantle convection



Montgomery (2001)

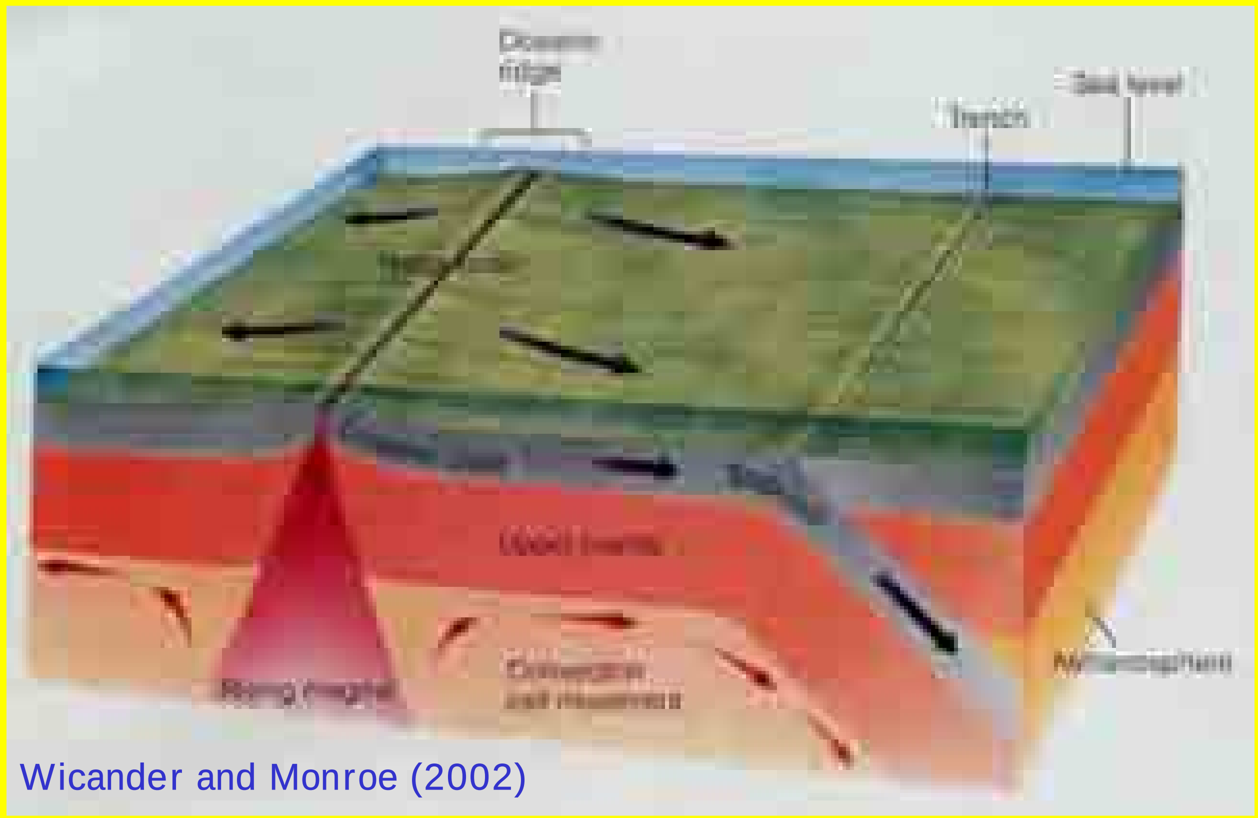
Convection & thermal plumes



Chernicoff and Whitney (2002)

Other Mechanisms?

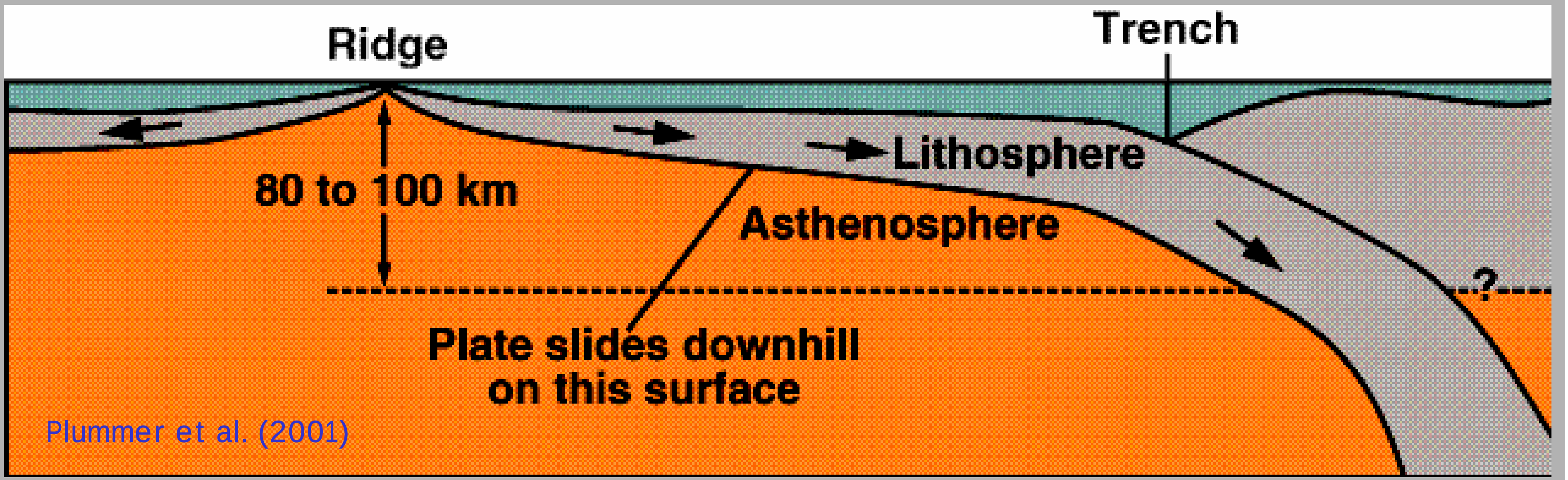
Most geologists accept one of the thermal convection models, but some favor additional drive mechanisms.



Wicander and Monroe (2002)

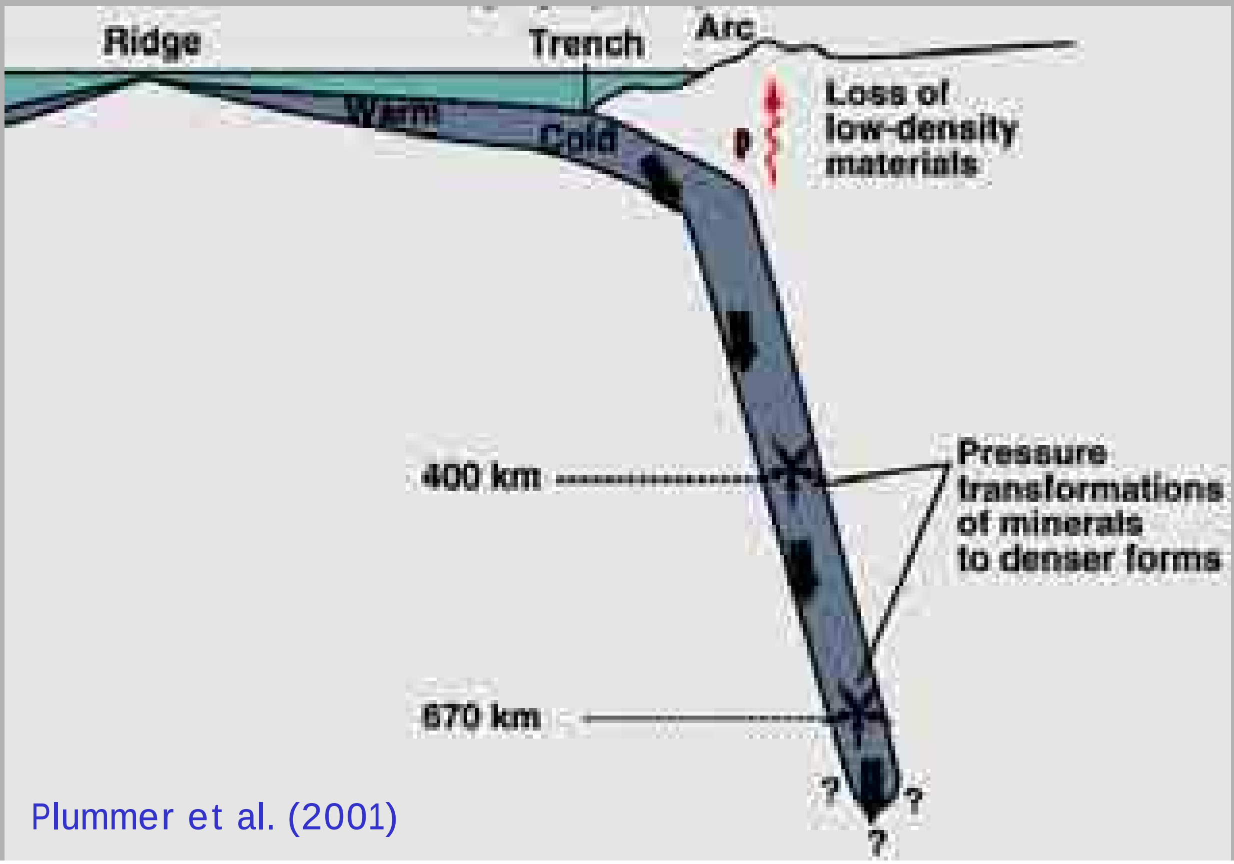
Ridge push

Ridge-push results as magma intruding along divergent margins pushes plates apart.



Slab pull

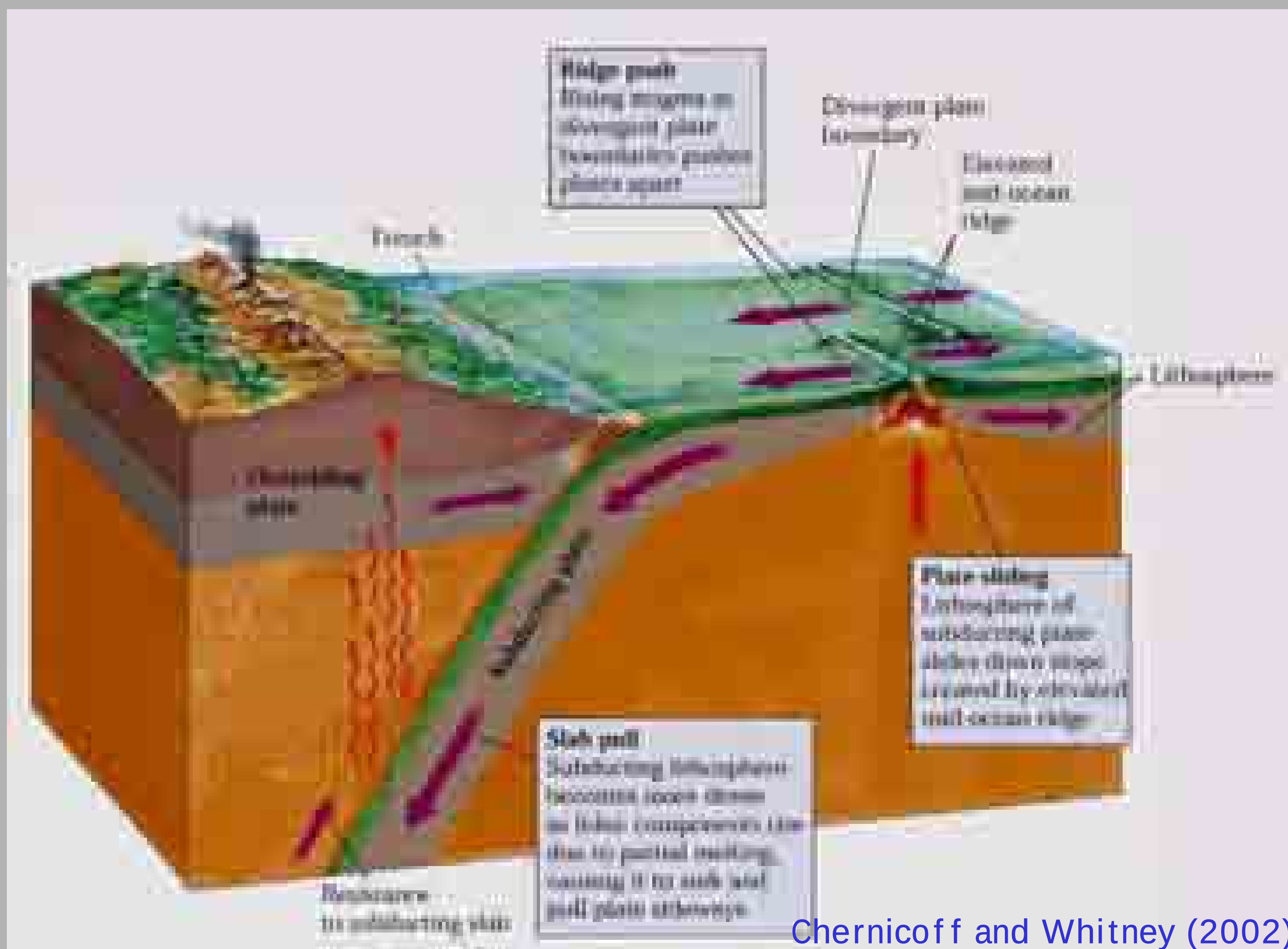
Slab-pull is thought to result as a plate undergoing subduction pulls the rest of the plate along.



Plummer et al. (2001)

The driving mechanism

It’s likely that all three play a role



Chernicoff and Whitney (2002)