Ch. 2. Earth Structure & Plate Tectonics

2.1 Earthquakes

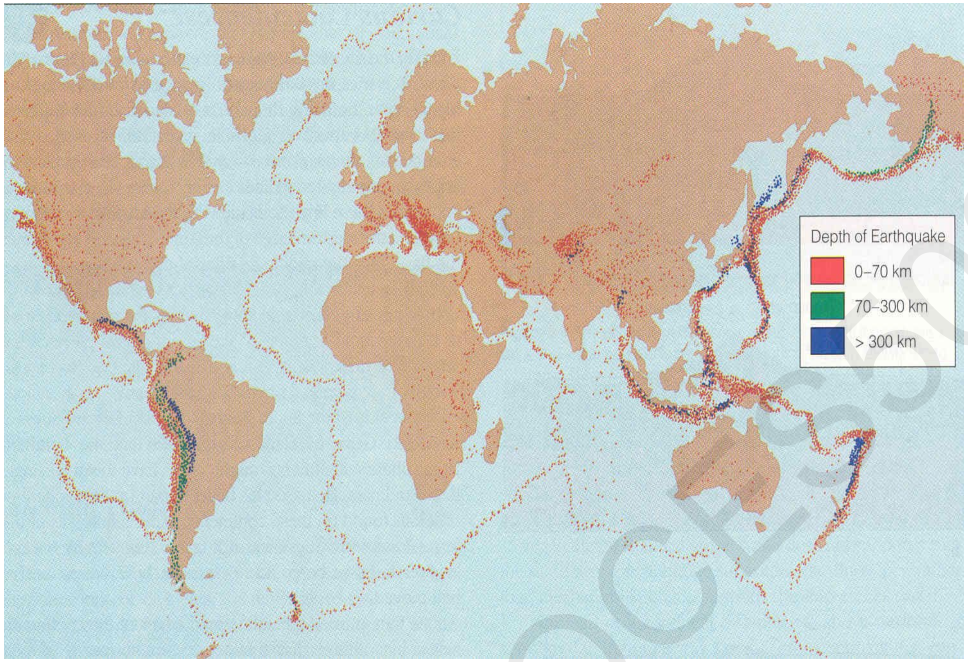
2.2 A Layered Earth

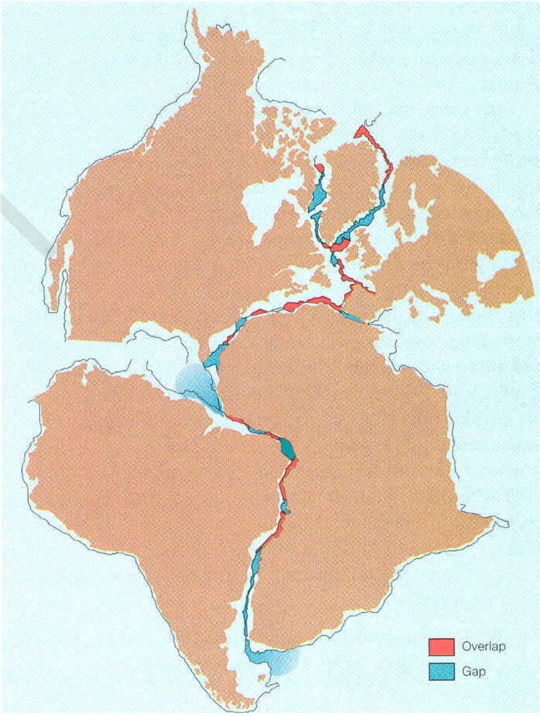
2.3. From Seafloor Spreading to Plate Tectonics

2.4. Confirmation of Plate Tectonics

2.1 Earthquakes

Piece of Earth's Surface Look Like They Once Fit Together

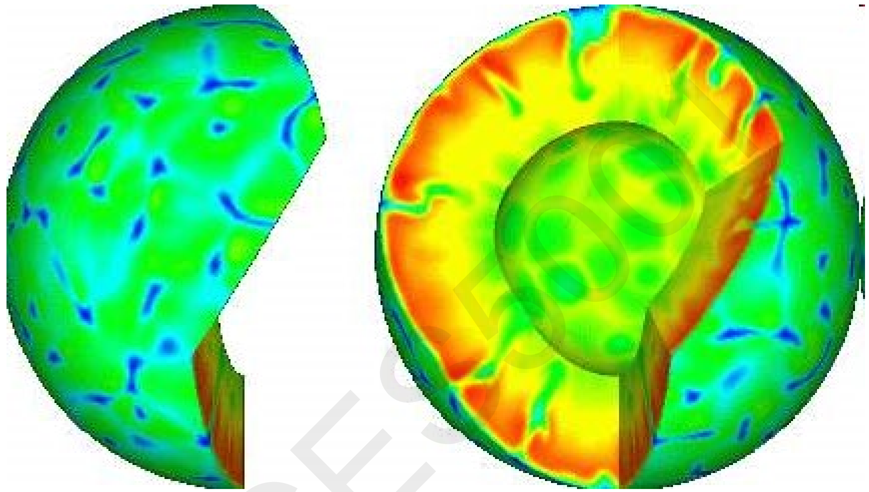




Fit (by computer) of Continents Around the Atlantic at 137 m (Fig 3.8)

Continents and oceans are formed and destroyed where these plates collide, flex and sink: Earthquake

***Geodynamics** is concerned with the physical processes that drive motion like mountain building or plate tectonics in the Earth and planets.*



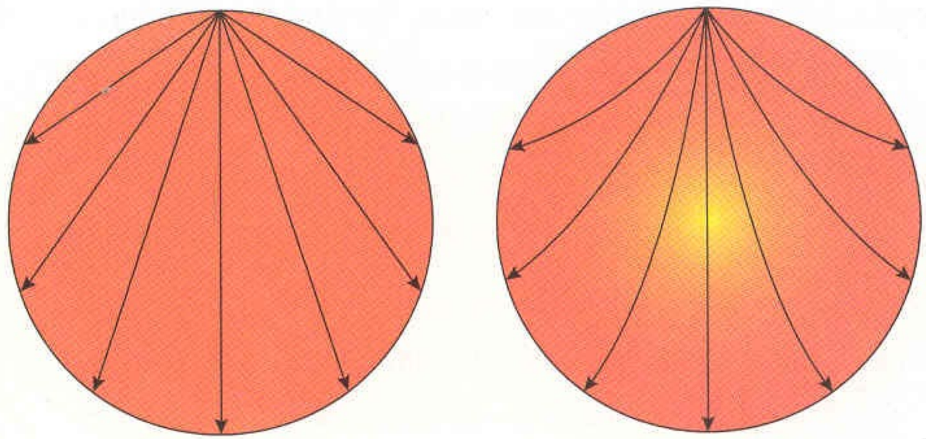
From Hans-Peter, Bunge, Princeton

Earth in cross section showing zones of hot and cooler materials.

1. Earth's interior is layered: study of earthquakes provides the evidence for the layering;
2. Forces acting with and between these layers form the major features of Earth's surface (mountains, seabed, islands, trenches);
3. The forces lead to shock waves associated with distant earthquakes.

Earthquakes and Earthquake Waves

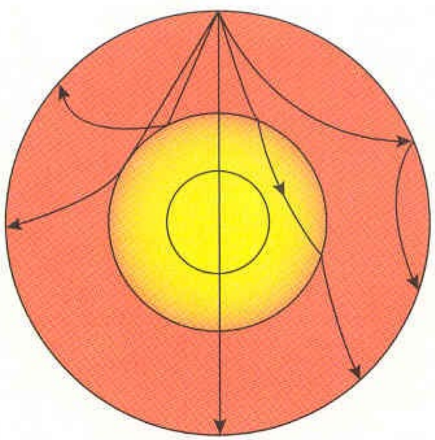
- **Seismic waves** are low frequency pulses of energy, generated by forces that cause earthquakes.
- By determining how the seismic waves travel through the earth's interior, one can determine that the interior is composed of layers: waves speed, strength and frequency are determined by the density (e.g. solid, liquid or partially melted.
- *earthquake*
  A **seismograph** is an instrument that records earthquakes.



a

b

Denser and more rigid with depth in a planet would bend (refract) the wave. Earth is not homogeneous.



c

Paths of Seismic Waves Through the Earth

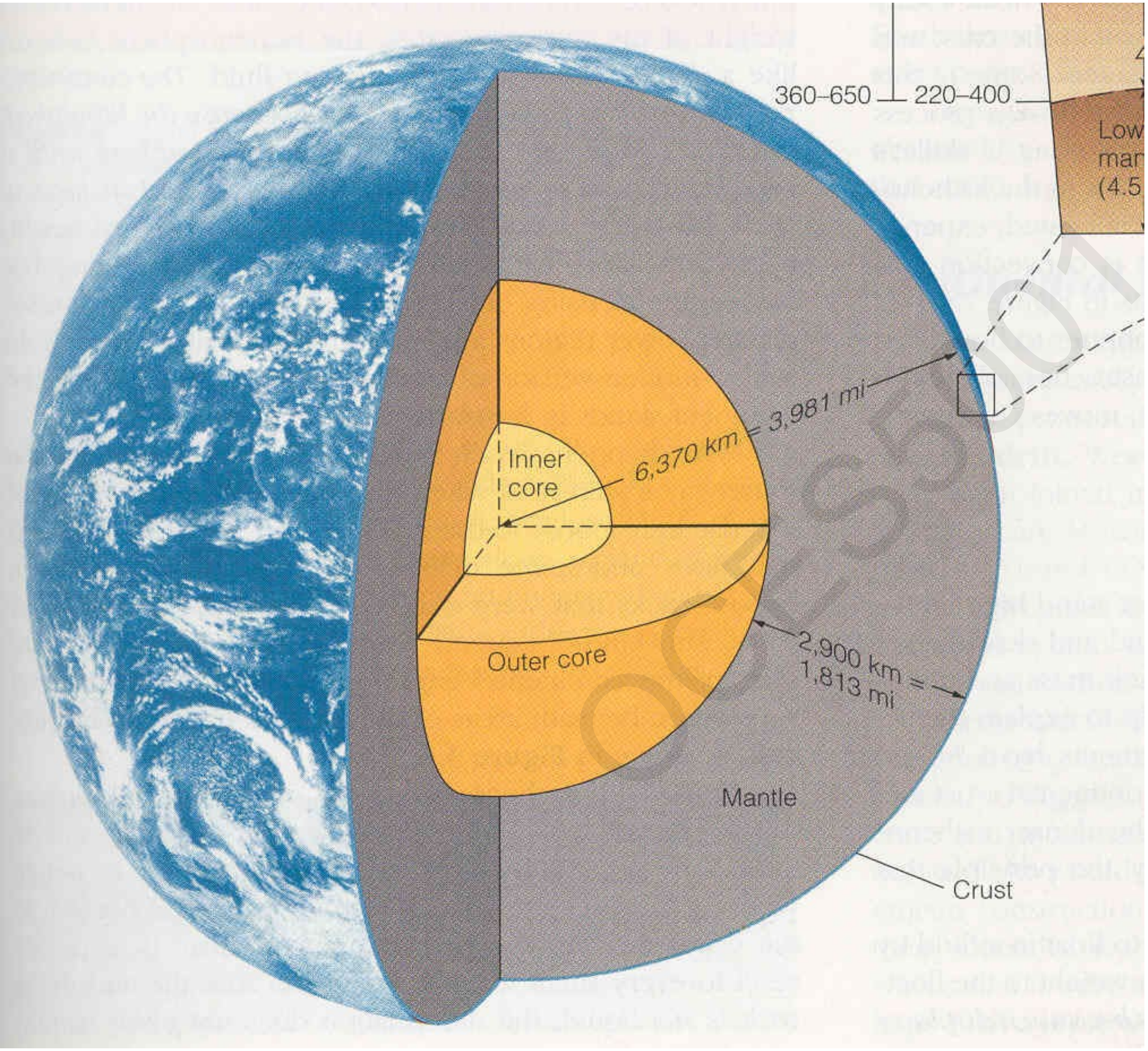
a. **If Earth has uniform composition (homogeneous), waves travel in a straight line**

b. **If density of Earth increases uniformly with depth, wave velocity increases with depth.**

c. **If Earth is layered, some waves striking layer at an angle are reflected at boundaries of layers, while others were bent (Fig 3.2).**

Study of earthquakes (seismic waves) provide information for earth structure: layered

2.2 A Layered Earth



Cross Section of Earth Showing Layers (Fig 3.3)

Earth's Layers:

different chemical and physical characteristics

A) Chemical Classification in Earth's Layers

1) **Crust** – light , brittle, about **70 km** thick; 1% volume and 0.4% of mass
   a) **Oceanic Crust** – basalt* – heavy, dark-coloured – O_2, Si, Mg, Fe
   b) **Continental Crust** – granite – speckled – O_2, Si, Al

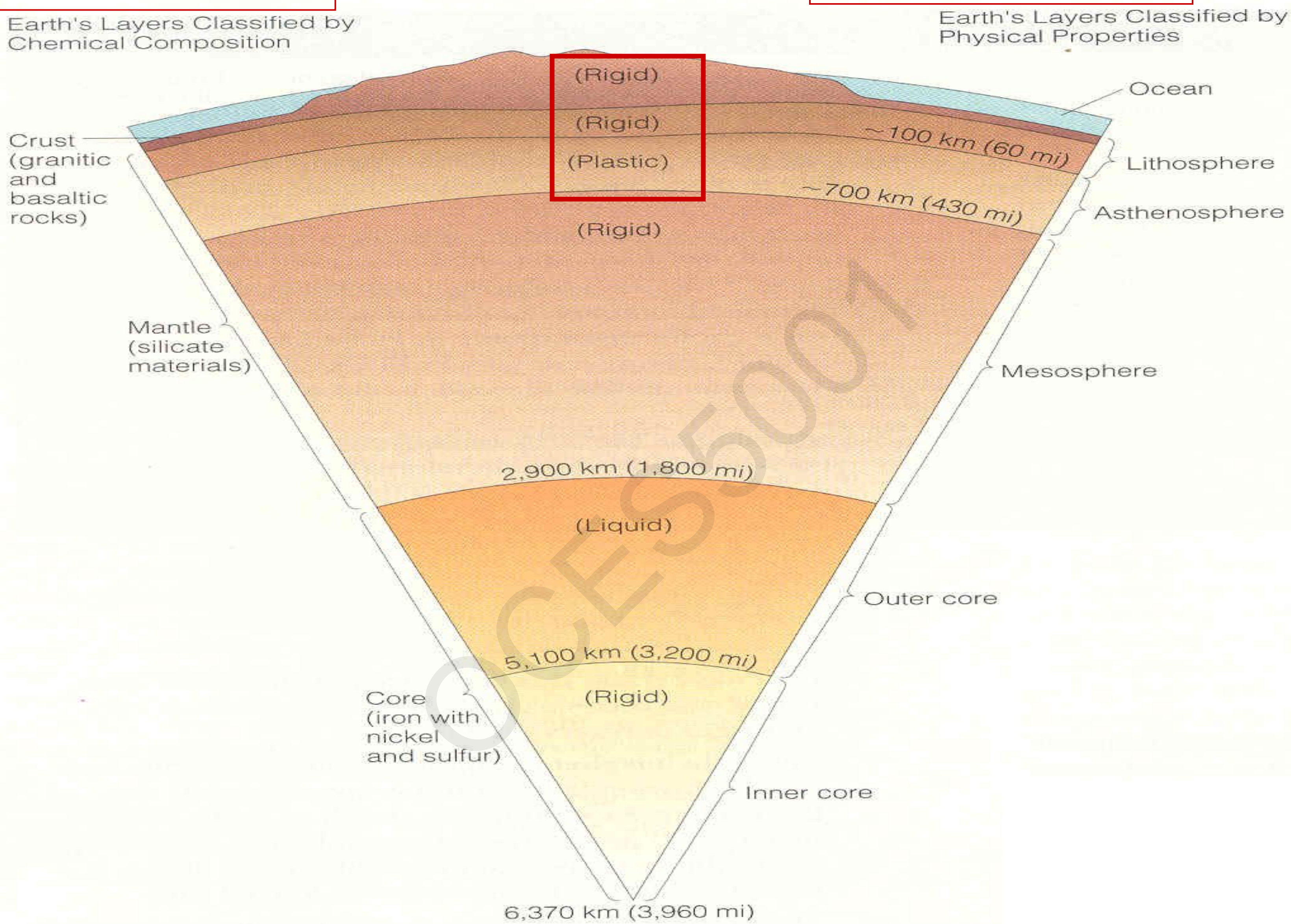
2) **Mantle** – O_2, Fe, Mg, Si – most abundant layer, about **2900 km** thick
   – 85% of Earth's volume; 68% of Earth's mass

3) **Core** – outer and inner core – Fe (90%) and Ni – forms Earth's centre, about **3470 km** thick

**Basalt: a type of dark rock that comes from volcanoes*

Chemical Properties

Physical Properties



Chemical and physical classification of the Earth's layers compared. The lithosphere accounts for only about 1.5% of Earth's radius.

(Garrison, 1996) Fig 3.2

Earth's Layers

B) Physical Classification: **the behaviour of rock is determined by: temperature; pressure and the rate at which a deforming force (stress) is applied.**

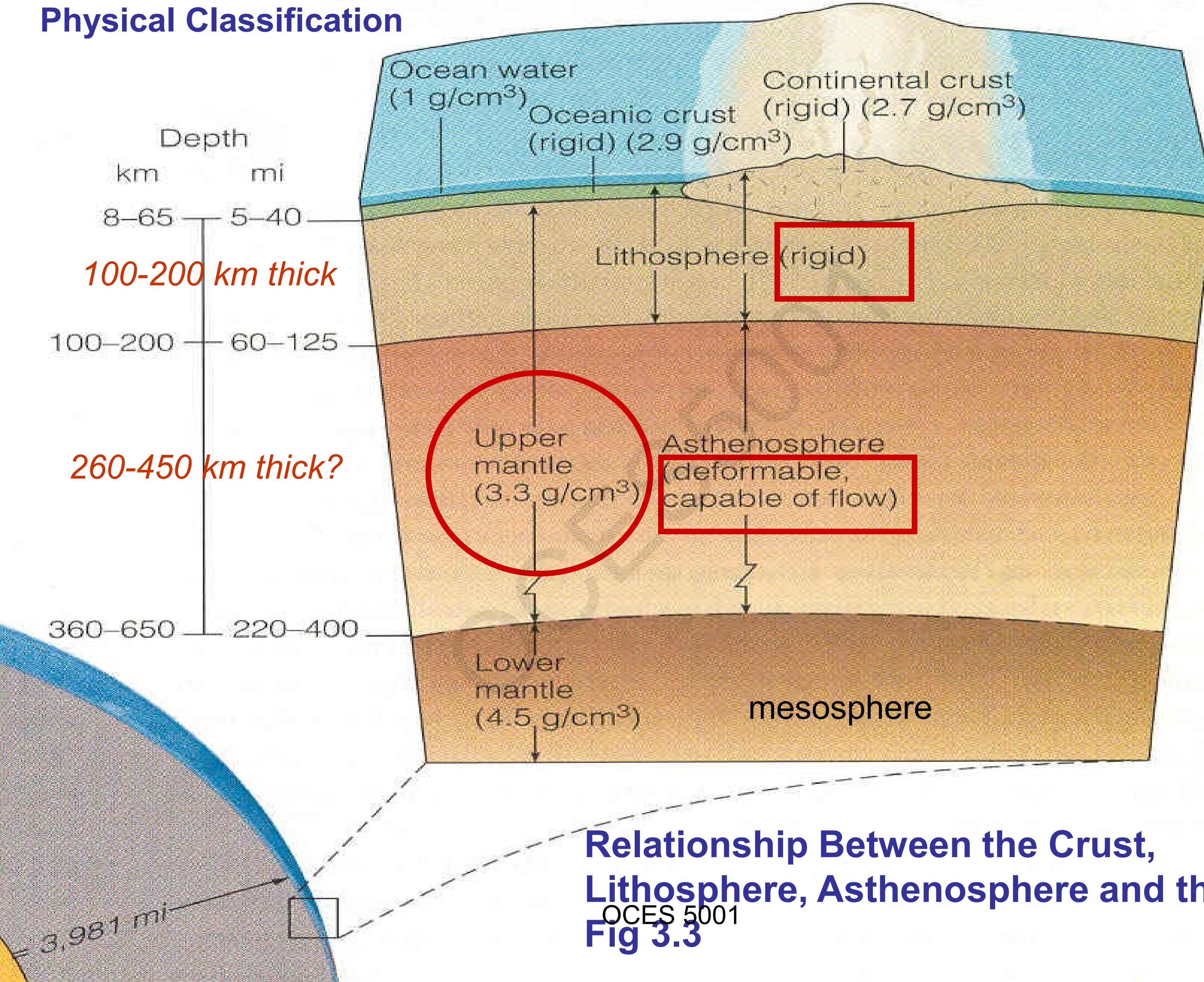
1) **Lithosphere** (lithos=rock): cool, rigid outer layer – 100-200 km thick
   Lithosphere = continent + oceanic crusts
   + outer most cool rigid part of mantle = **Plate.**

2) **Upper Mantle = Lithosphere + Asthenosphere**
   (**Asthenosphere** (asthenes = weak): hot, partially melted
   slowly flows – extend to a depth up to 300-650 km

3) **Lower Mantle**: hotter, denser, flows more slowly

4) **Core** **(two parts)**: Outer – viscous liquid density = 4X crust, 5500℃
   Inner – solid, density = 6X crust, up to 6600℃ (higher than Sun's surface)

Physical Classification



Relationship Between the Crust, Lithosphere, Asthenosphere and the Mantle
Fig 3.3

Characteristics of the Earth's Layers (Table 3.1)

Layer	Depth from Surface	Primary Composition	Average Temperature	Average Density	Proportion of the Earth's Total Mass	Proportion of the Earth's Total Volume
Crust			~500°C (900°F)		0.4%	<1%
Continental crust	From surface to 35 km (22 mi)	Granite (aluminum silicates)		~2.7 g/cm^3		
Oceanic crust	From surface to 11 km (7 mi)	Basalt (magnesium silicates)		~2.9 g/cm^3		
Mantle	From 11 km to 2,900 km (from 7 mi to 1,800 mi)	Iron and magnesium silicates	2,500°C (4,500°F)	4.5 g/cm^3	68.1%	83%
Core					31.5%	16%
Outer core	From 2,900 km to 5,100 km (from 1,800 mi to 3,200 mi)	Liquid iron and nickel	5,000°C (9,000°F)	11.8 g/cm^3		
Inner core	From 5,100 km to 6,370 km (from 3,200 mi to 3,960 mi)	Solid iron and nickel	6,600°C (12,000°F)	16.0 g/cm^3		
Whole earth	6,370 km (3,960 mi)			5.5 g/cm^3		

Lithosphere + Asthenosphere+mesosp

Sources: Kennett, 1982; Bott, 1982

Hotter with depth

Density increases with Depth

or top one get buoyancy from one below

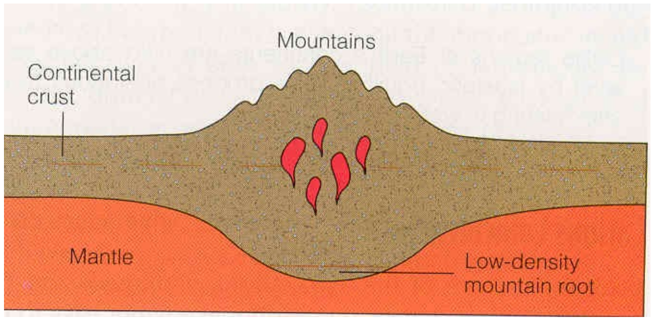
(Garrison, 1996)

Isostatic Equilibrium

- Continental crust stands high above non-rigid and deformable asthenosphere due to buoyancy in which less dense object obtains a force in denser object: *the lithosphere floats on the asthenosphere.*
- **Isostatic equilibrium** – continent is in equilibrium with asthenosphere when a volume of asthenosphere equal in mass to the mountains' mass (buoyancy=densityxvolume)
- Erosion causes weight to decrease and get isostatic uplift and continent rises up: **isostatic readjustment**
- Ice (lower density) melting will cause uplift of a continent.

Isostatic Equilibrium

a



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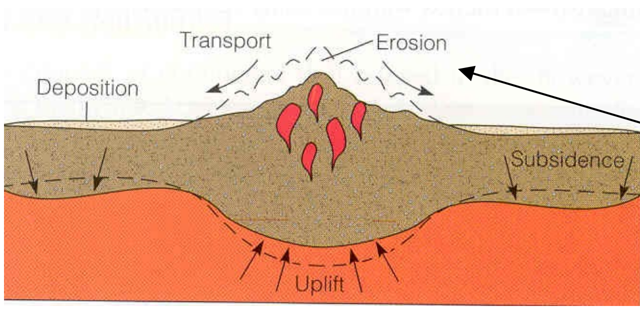
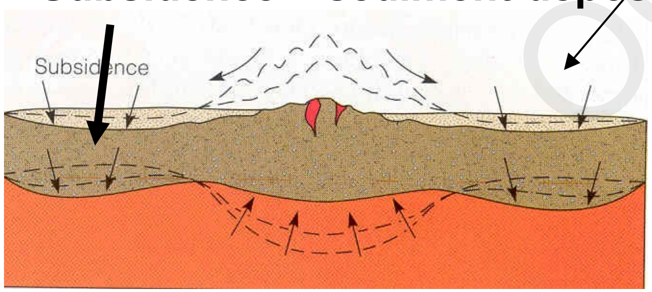


Erosion → Uplift

Deposition → Subsidence

Subsidence – sediment deposition: cause sinking in nearby crust

c



- Continental crust becomes thinner in mountainous region

Erosion & isostatic readjustment

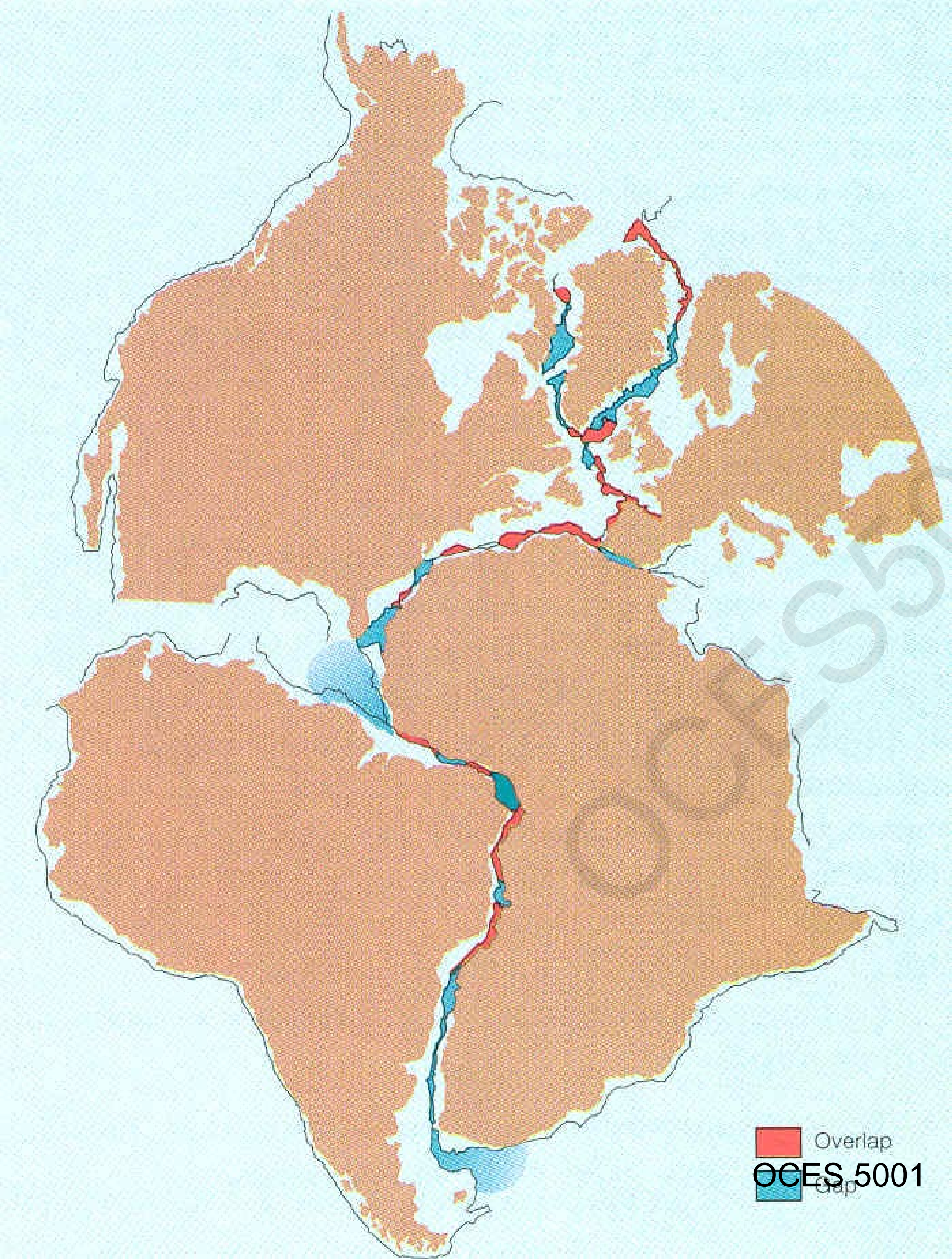
2.3. From Seafloor Spreading to Plate Tectonics

A Fault: In the ocean crust, when the force of the uplift or down bending exceeds the *mechanical strength* of the adjacent rock, the rock will fracture along a plane of weakness.

The sudden adjustment of the crust to isostatic force by fracturing, or faulting, is one cause of earthquakes.

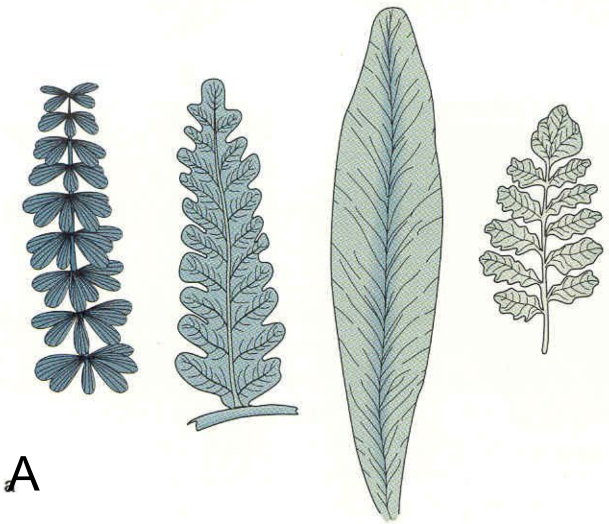
Fitting Continental Coastlines

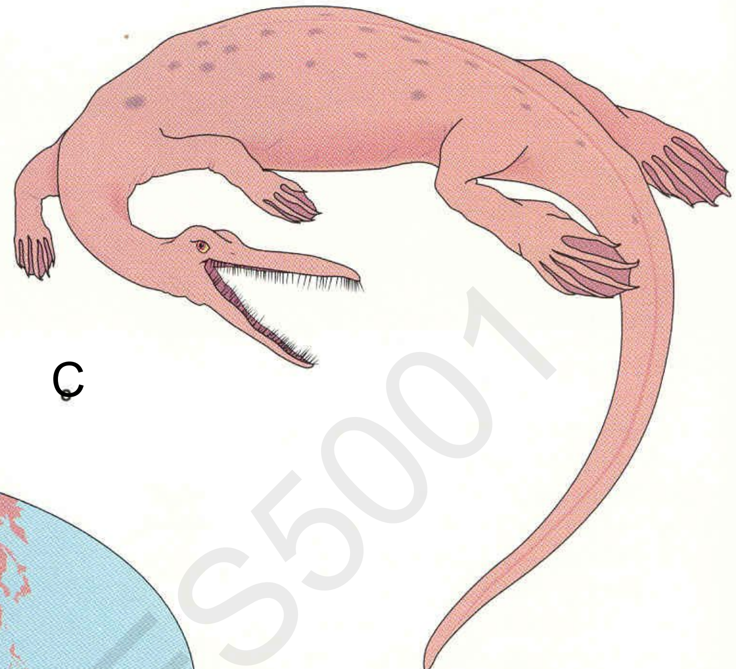
- Coastlines fit well (e.g South America & Africa)
- Edge of continental slopes fit even better
- Could not have fit so well just by chance – must be a mechanism to make continents move apart.

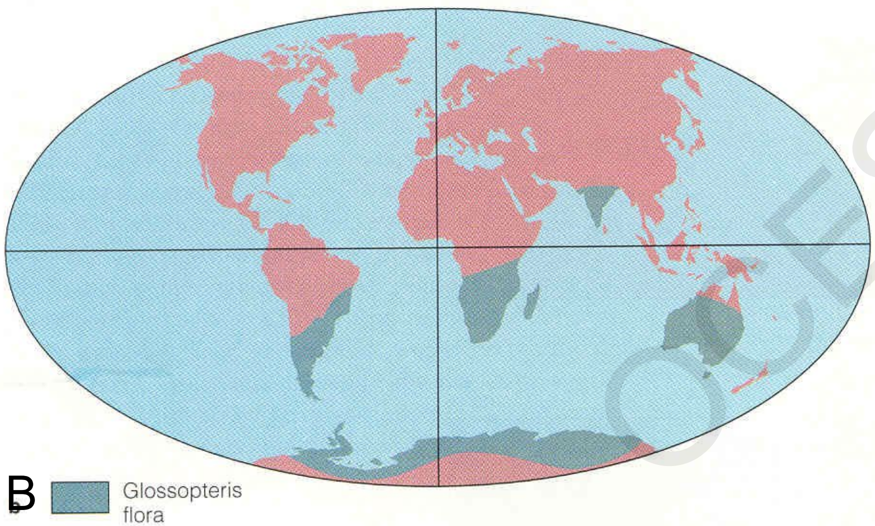


Pangaea (super continent)

Fit of Continents Around the Atlantic at 137 m (Fig 3.9)







Fossils whose distribution supports the existence of Pangaea.

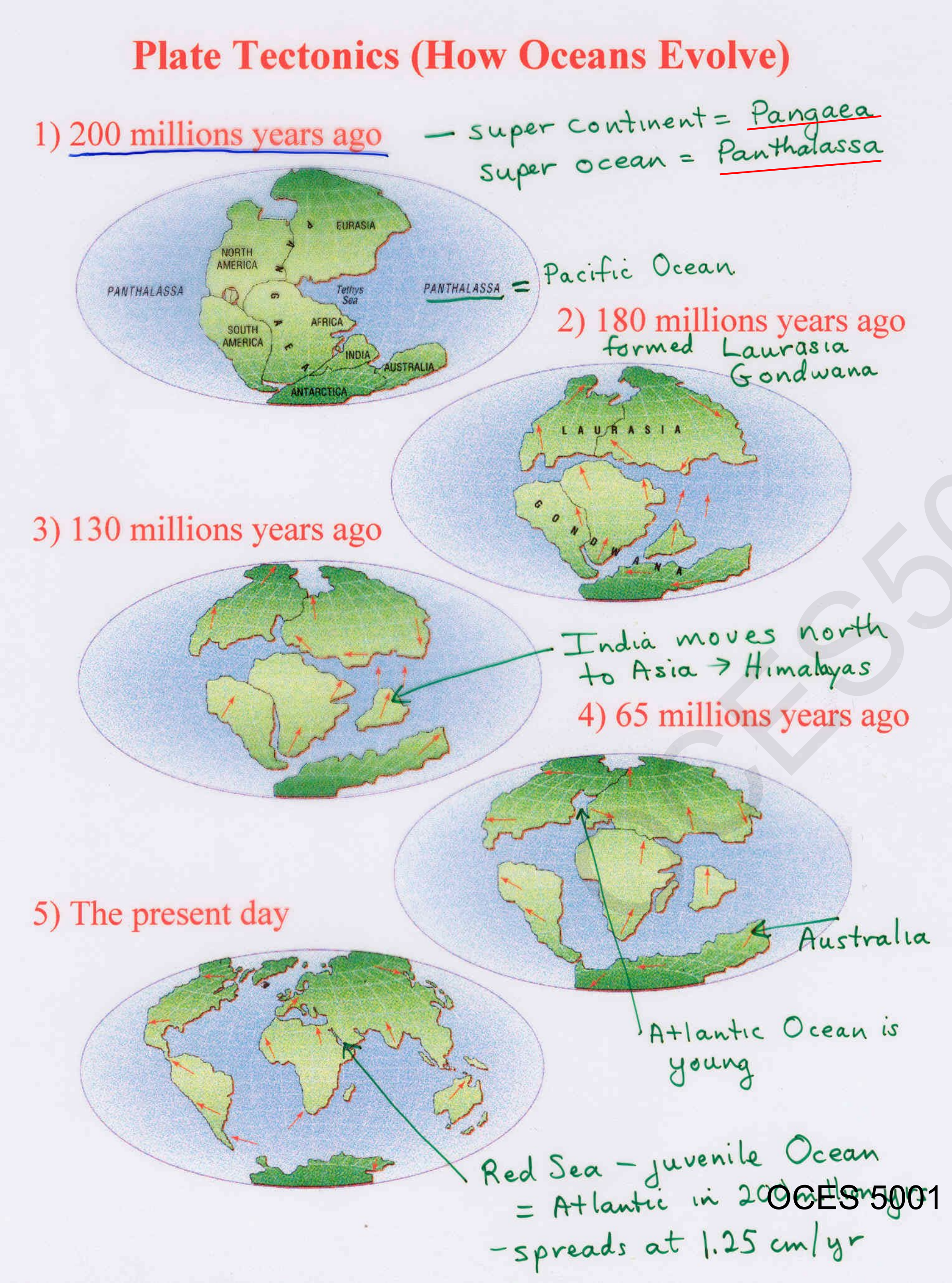
a) Fossil plants found in South America, southern Africa, India, Australia, and Antarctica.

b) The distribution of fossils of *Glos-sopteris* flora (舌羊牙齒植物) strengthens the impression that the continents were once united.

***c)* *Mesosaurus*, a shallow-water reptile whose remains are found only in eastern South America and southwestern Africa. (Fig 3.33)**

Evidence for the Existence of Pangaea (one land mass)

(Garrison,1996)



How The Oceans Evolved by Plate Tectonics

(Day, 1999 p.32)

Continental Drift (proposed by Wegner)

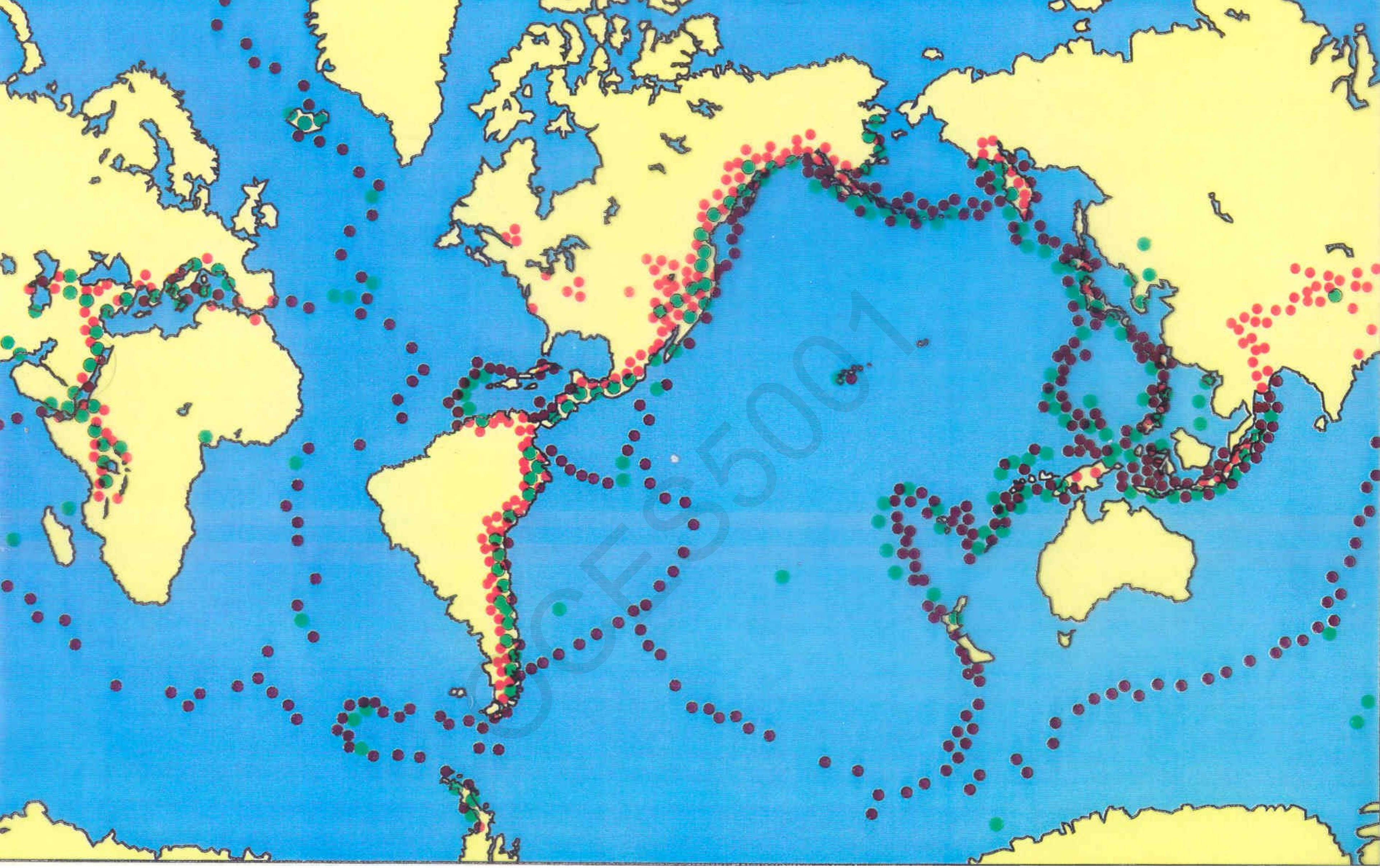
- In the beginning thought only **one** land mass (Pangaea, the super continent) which was surrounded by one ocean (Panthalassa).
- Moved apart about 200 million year ago)
- But geologists **thought that the mantle was solid** and supported the mountains structurally and therefore how could the continents move (drift) apart if the mantle was solid?
- Wagner's theory was not accepted initially.

Plate Tectonics (板塊構造)- Questions

1. Plotted earthquakes at edge of Pacific → Pacific Rim of Fire. Why are earthquakes concentrated along lines? Why was earth's crust divided into sections? How could these sections **slide on the molten upper mantle?**

2. Radiometric dating of sediments and rocks indicated ocean floor was <200 million years old and = 4% of Earth's age. **Why was the oceanic crust so young?**

Plate = crust + lithosphere (called lithosphere plates)



• Volcanoes • Earthquakes

Earthquakes and volcanoes along plate boundaries

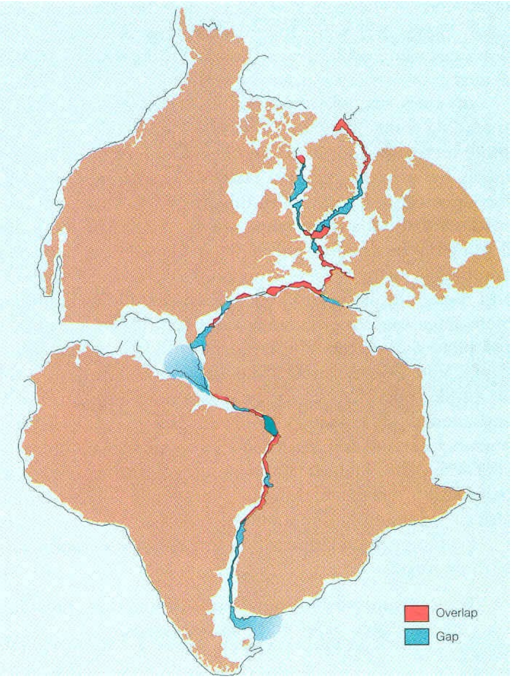
Evidence for Plate Tectonics

1. Echo Sounding – revealed the mid-Atlantic ridge and overall shape = shorelines on either side of Atlantic

2. Submerged continental outlines fit together well.

3. Mantle studies – layer in upper mantle was **not solid** because the velocity of the seismic waves **decreased** as they passed through the mantle.

What was the energy source that moved the continents apart?



Breakthrough:

- In 1960, Harry Hess and Robert Dietz suggested that new seafloor develops at the ocean ridges and then spreads outward from this line of origin.

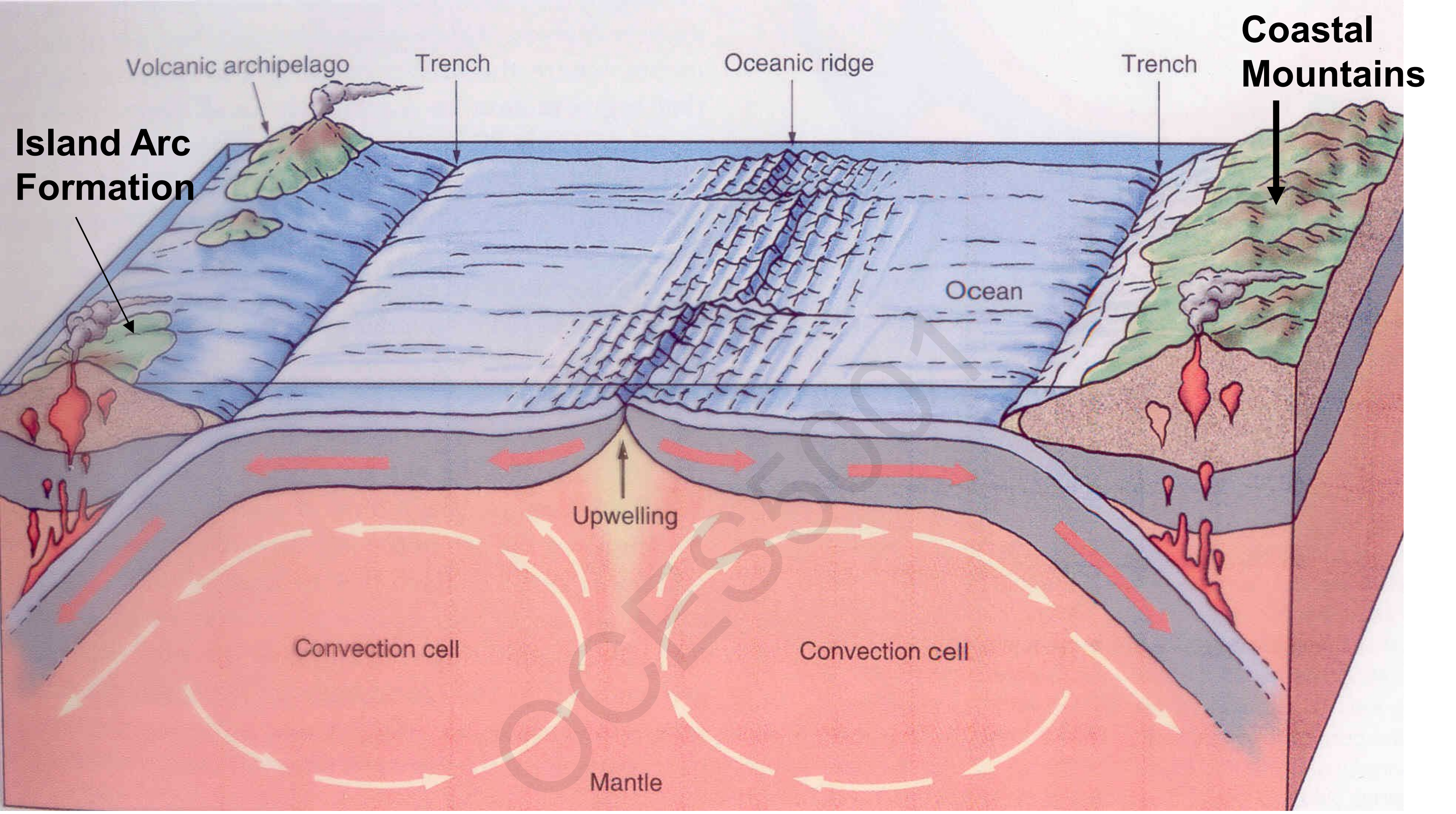


Plate Tectonics (Sea Floor Spreading)

showing the oceanic ridge, trenches, subduction of the oceanic plate at the trench produces island arc formation by volcanic activity and subduction at the edge of the continent forms coastal volcanic mountains.

Convection currents move the oceanic crust.

Seafloor Spreading/Plate Tectonics (new concepts of continental drift)

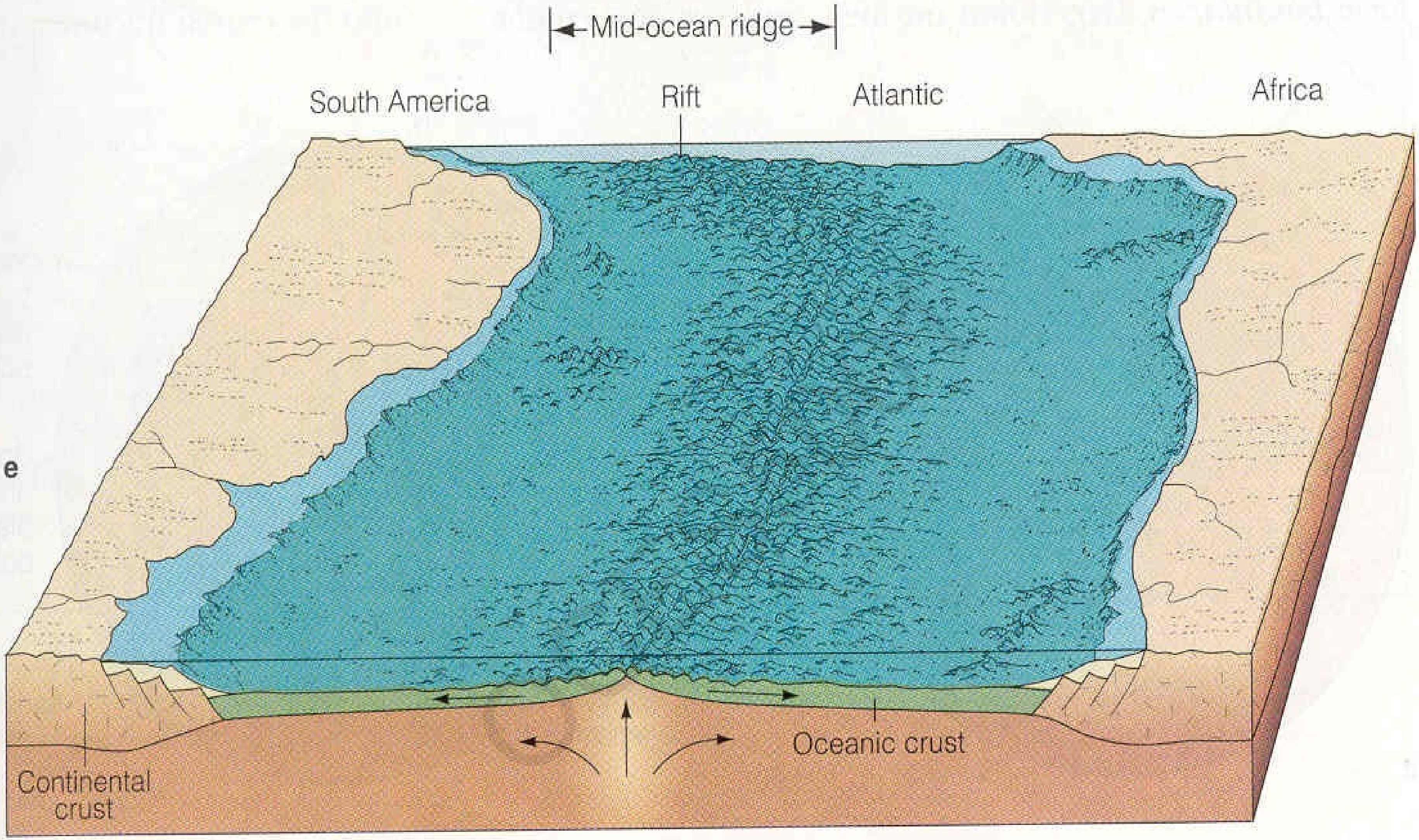
1. Spreading motion is due to *convection currents* in the asthenosphere that new seafloor develops at the mid-ocean ridge and spreads outward;

2. Mid-ocean ridges are spreading centers: the new hot ocean floor from asthenosphere cooled and were shrink , the ocean is deeper away from the ridge; sediments at the edges of the ocean basin is thicker.

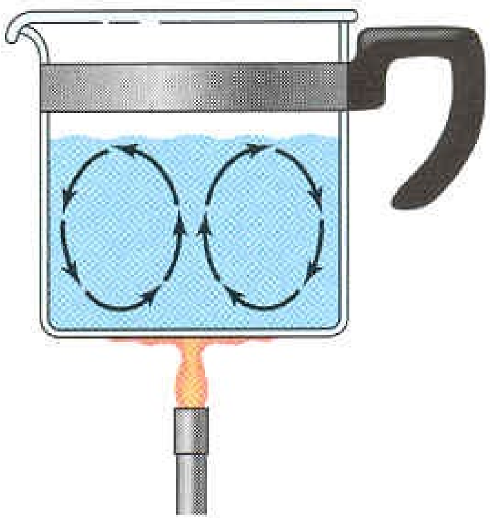
3. A cycle of new crust formation, crust movement (spreading) and crust subduction (sinking) occurs. **Subduction:** the crust plunges down into the mantle: preventing Earth continuously expands. Region of crust formation and subduction is earthquake-active zone.

4. Ocean is like a conveyor belt, so ocean floor/crust is not very old (~200 million years old).

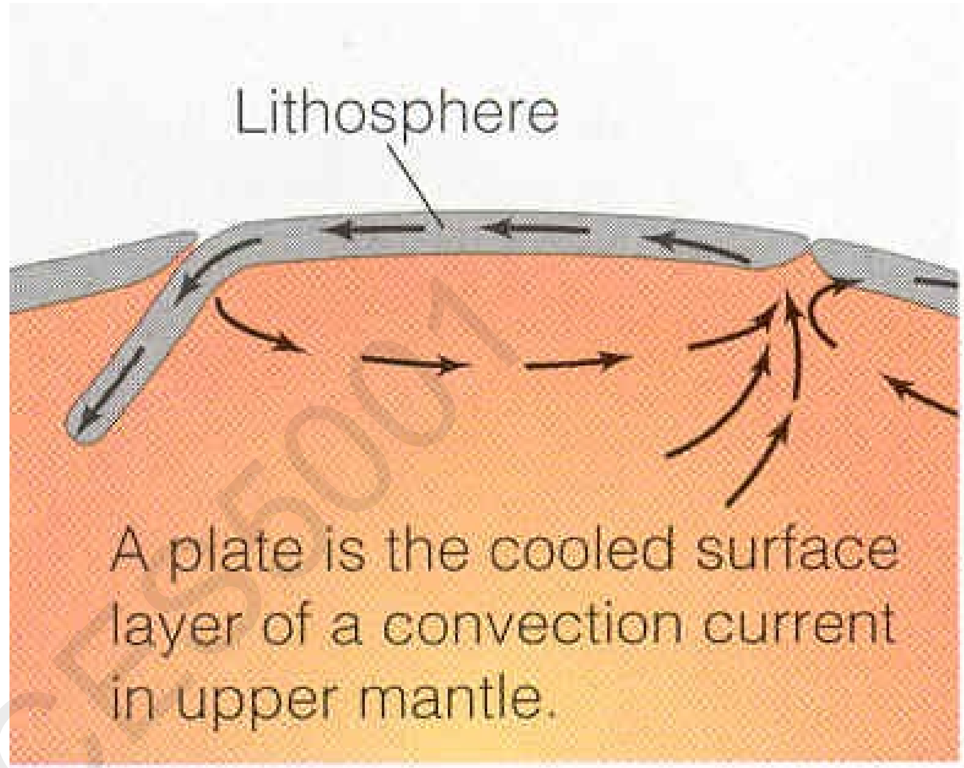
5. Oceanic crust sinks and is melted and recycled at the trenches.



South Atlantic Rift Valley and Mid-Atlantic Ridge



a) Convection in a boiling pot of water



b) Tectonic plate movement by sliding off raised mid-ocean ridge and pulled into trench and mantle by gravity

Plate Tectonics (John Tuzo Wilson, 1965): integrated the ideas of continental drift and seafloor spreading

- Earth's outer layer consists of about a dozen lithospheric plates floating on the asthenosphere;

- When heated from below, the deformable asthenosphere expands, reduces density and rises;

- Move aside in lithosphere and drags the plates laterally until it turns under again.

Three forces that drive plate movement:

1: The outward push by the spreading;

2: Friction of mantle convection currents against the bottom of a plate;

3: The downward pull of a descending plate’s dense leading edge

Or plate motion is driven by slow, heat-generated convection currents flowing in the mantle. Most of *the heat is generated by the decay of radioactive elements inside Earth*

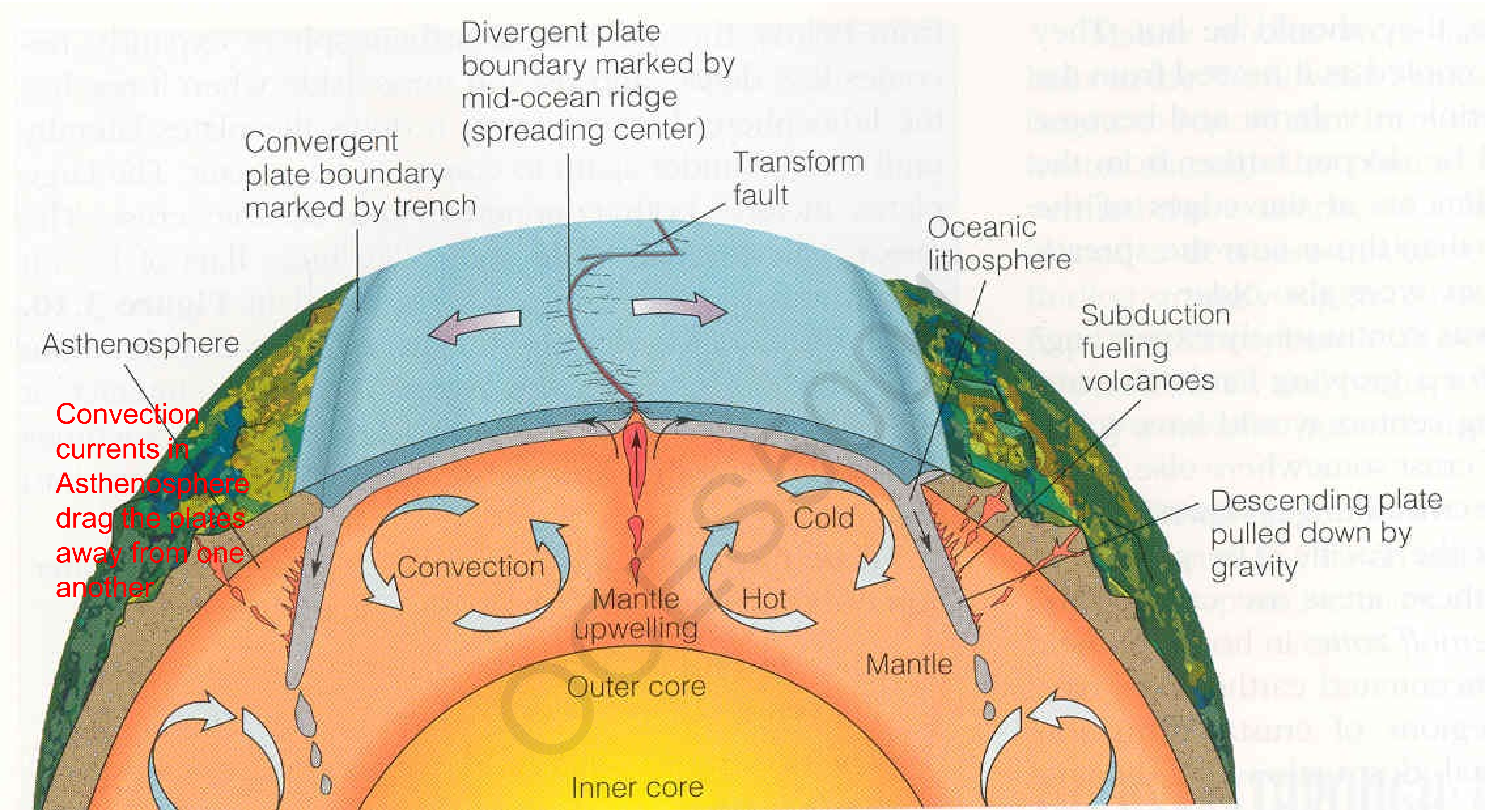
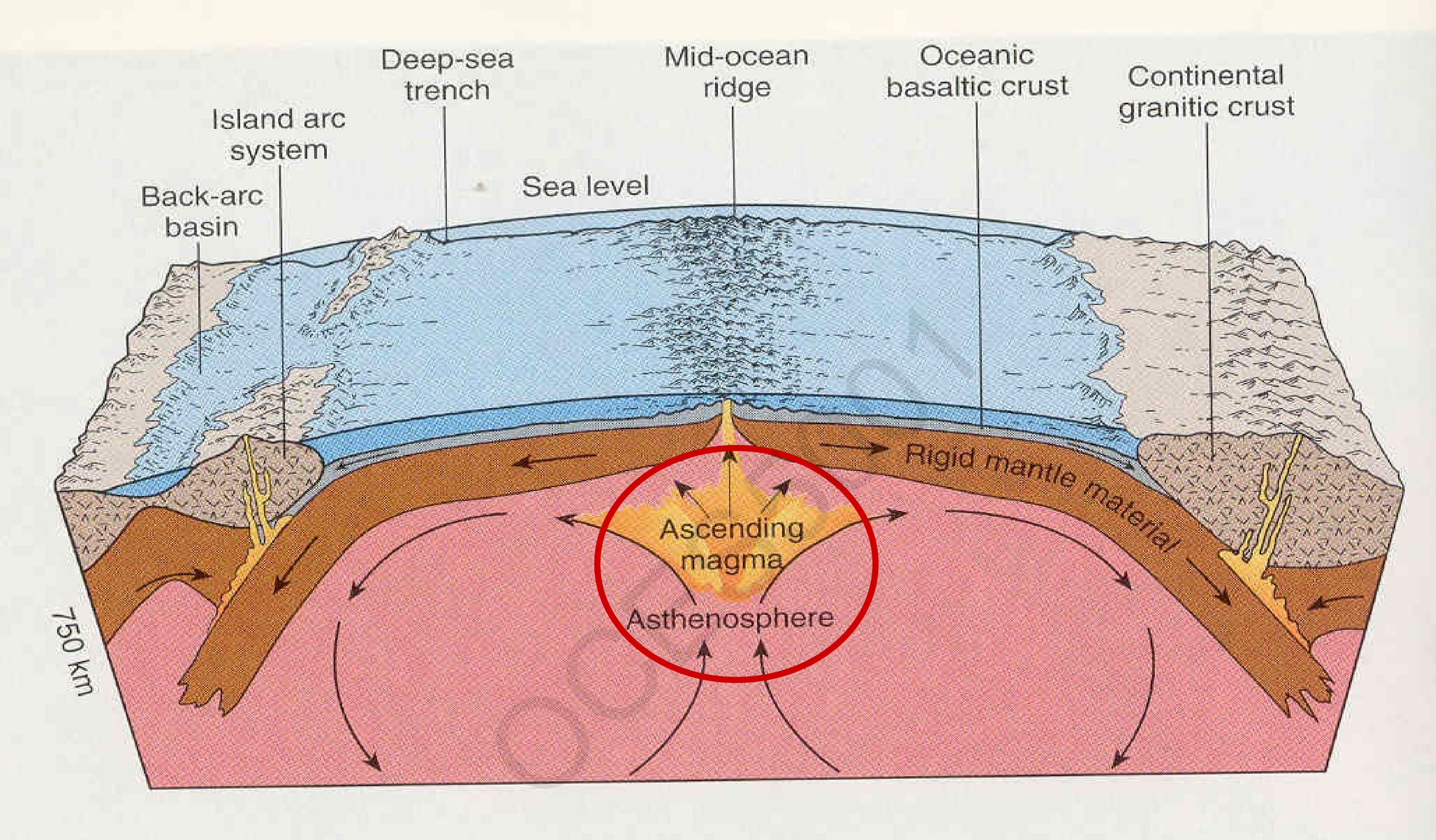


Plate motion driven by heat-generated convection currents in mantle.

Cool, rigid lithosphere fragmented into plates and floats on mantle.



Seafloor Spreading creates new crust at mid-ocean ridges and loses old crust in deep-sea trenches. Seafloor spreading is driven by convection currents in the asthenosphere.

(Duxbury & Duxbury, 1999 Fig 3.7)

Plate Tectonic Cycle

- Molten magma in asthenosphere rises and breaks through crust at the oceanic ridges as molten lava.

- New ocean crust is formed at the mid-ocean ridge.

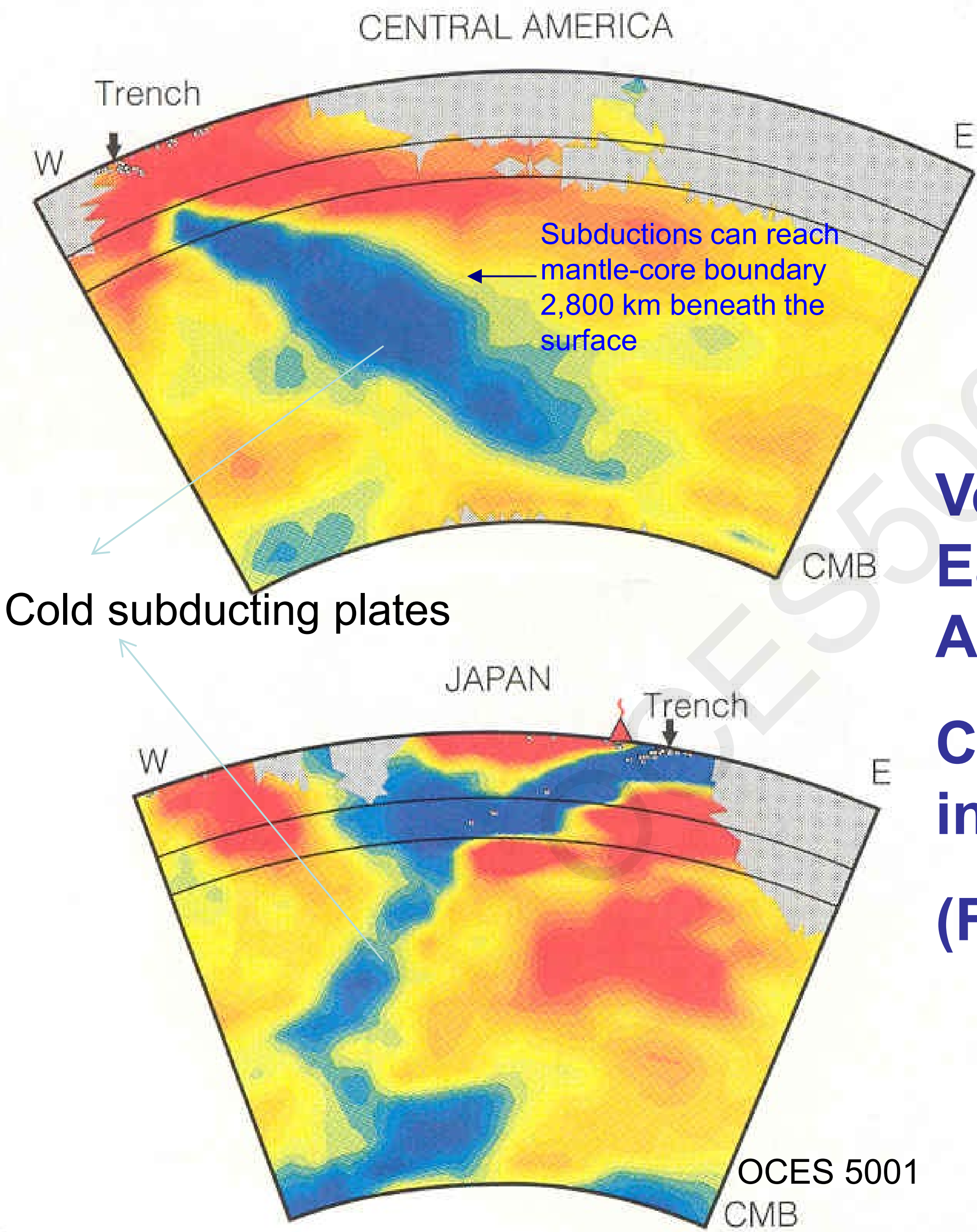
- New crust moves away from the ridge in either direction (~5-18 cm/yr - finger nail growth rate) and crust gets covered with sediment.

Plate Tectonic Cycle - Subduction

- At the trenches, oceanic crust sinks (subducts) into the mantle at oceanic trenches (e.g. Japan), or at the edge of continents (e.g South America).

- Sediment and crust melts as it enters the trench and forms magma which rises and produces underwater volcanoes which grow and form islands and an island arc system (e.g. Japan islands).

- Similarly, at the trenches of the edge of continents (e.g. South America) the sediment and oceanic crust melts, forming magma that rises and forms the volcanic Andes Mountains.

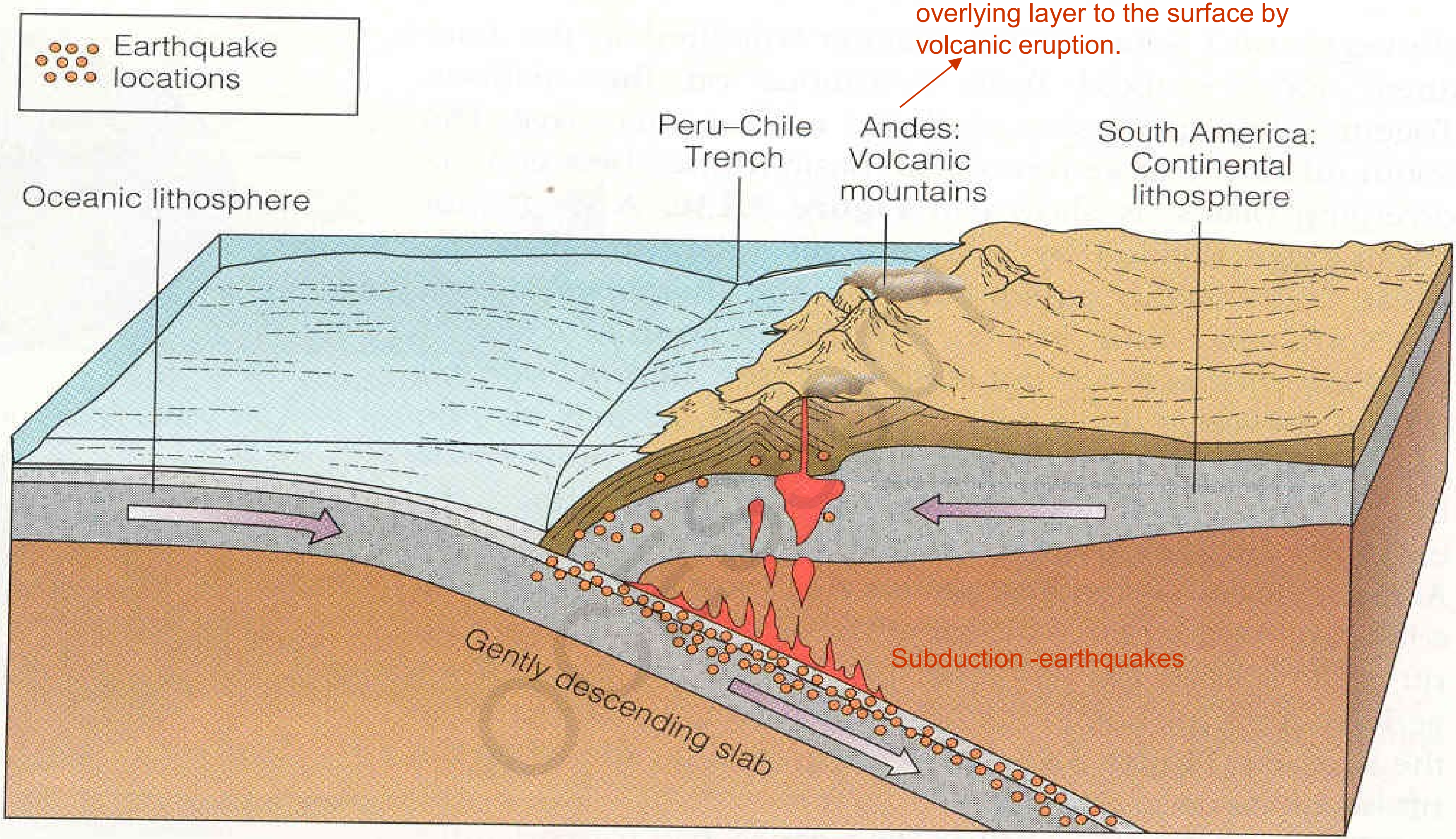


Vertical slice through Earth's mantle off Central America and Japan.

Colder material (blue color) indicates subducting plate

(Fig 3.16)

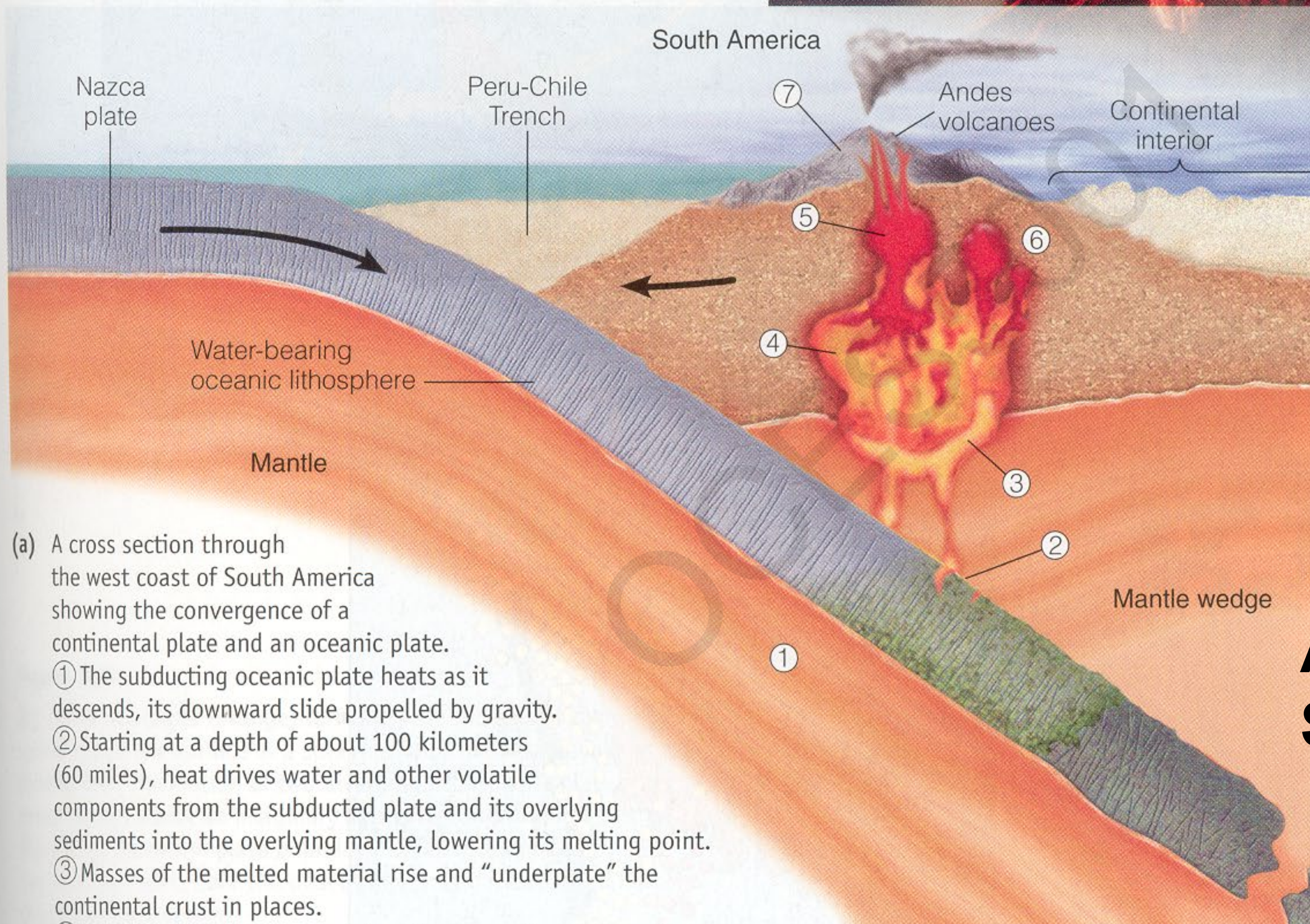
Plate Boundaries



Convergence of Continental and Oceanic Plates, Plate Subduction, and the Formation of Volcanic Mountains (Andes) along the Coast of South America   Note location of earthquakes (Fig 3.15)

Figure 3.20

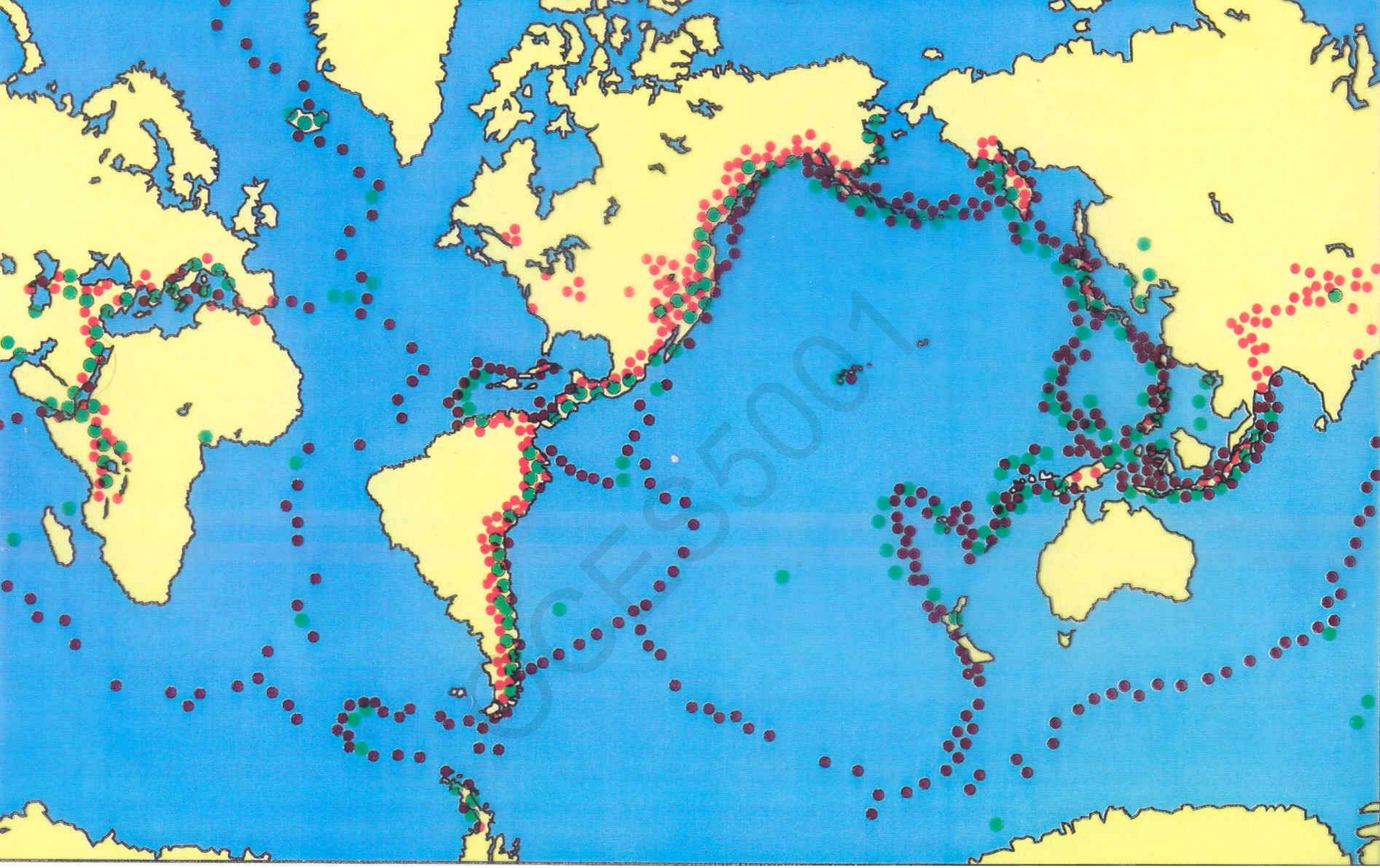
(b) An Andean volcano in full blast in 2006. The 5,000 meter (16,400 foot) high volcano Tungurahua, located in Ecuador, becomes active roughly every 90 years.



(a) A cross section through the west coast of South America showing the convergence of a continental plate and an oceanic plate.
① The subducting oceanic plate heats as it descends, its downward slide propelled by gravity.
② Starting at a depth of about 100 kilometers (60 miles), heat drives water and other volatile components from the subducted plate and its overlying sediments into the overlying mantle, lowering its melting point.
③ Masses of the melted material rise and "underplate" the continental crust in places.
④ Heat from the rising material melts the continental crust and ⑤ mixes with it.
Some of this mixture solidifies in place ⑥,
but some can rise to the surface and power Andean volcanoes ⑦.

Andes Mountains South America

CENTRAL AMERICA



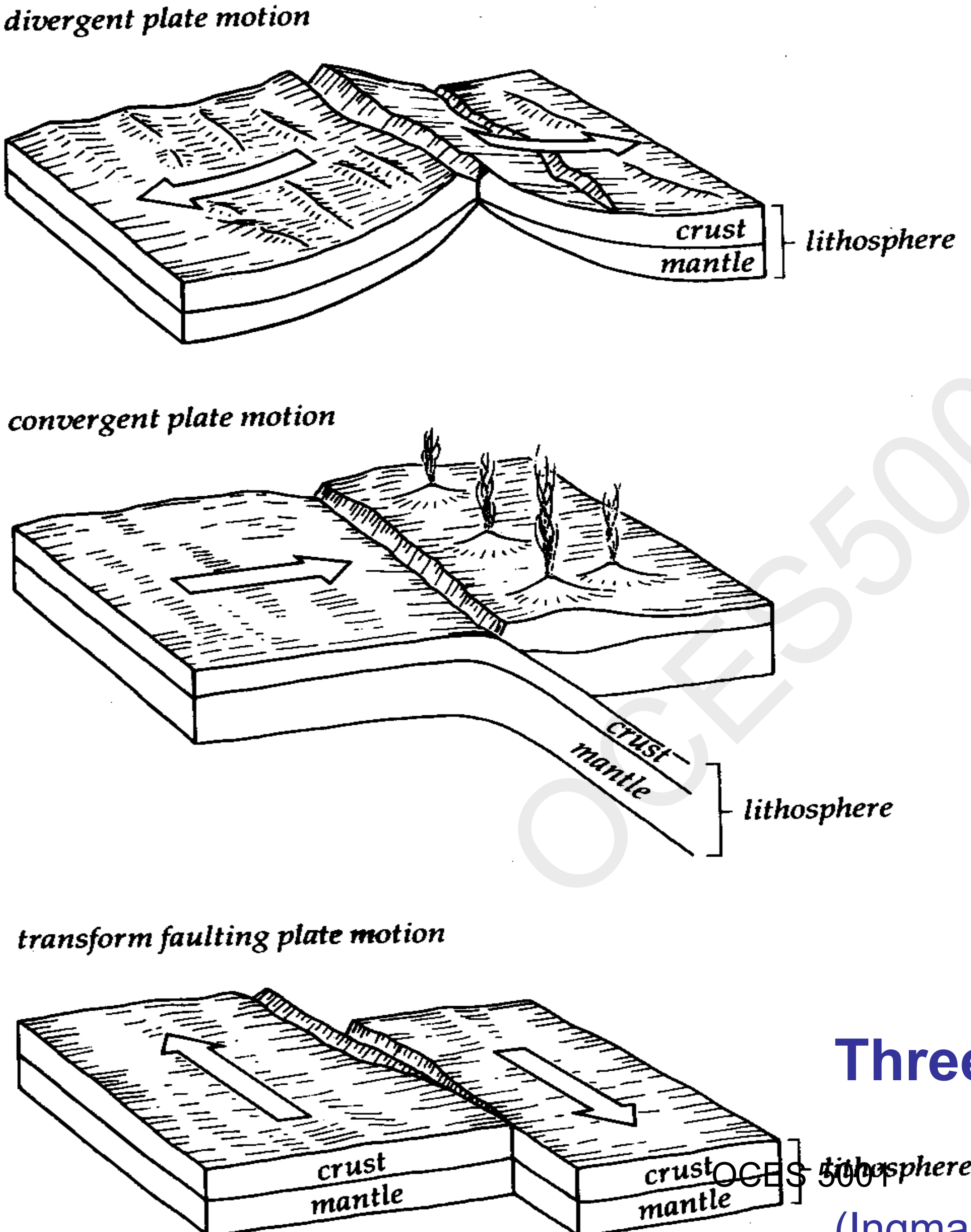
• Volcanoes • Earthquakes

Earthquakes and volcanoes along plate boundaries

Earthquakes – Shallow and Deep

Earthquakes occur at:

1) Crustal formation site (spreading centres/mid-ocean ridges). They are shallow earthquakes from underwater volcanic eruptions.
2) Crustal destruction sites (subduction zones at oceanic trenches or trenches at edge of continents). The earthquakes are shallow (near the surface) and deep (deep part of plate subduction).
3) Transformed faults as plates slid by each other. These earthquakes are shallow.



Three kinds of Plate Motion

(Ingmanson & Wallace, 1994 Fig 5.11

Plate Boundary		Plate Movement	Seafloor	Events Observed	Example Locations
Divergent plate boundaries	Ocean–ocean	Apart	Forms by seafloor spreading.	Ridge forms at spreading center. Ocean basin expands, plate area increases. Many small volcanoes and/or shallow earthquakes.	Mid-Atlantic Ridge; East Pacific Rise
	Continent–continent		New ocean basin may form as continent splits.	Continent spreads, central rift collapses, ocean fills basin.	East African Rift Valley, Red Sea
Convergent plate boundaries	Ocean–continent	Together	Destroyed at subduction zones.	Dense oceanic lithosphere plunges beneath less dense continental. Earthquakes trace path of downmoving plate as it descends into asthenosphere. A trench forms. Subducted plate partially melts. Magma rises to form continental volcanoes.	Western South America, Cascade Mountains in western U.S.
	Ocean–ocean			Older, cooler, denser crust slips beneath less dense crust. Strong quakes. Deep trench forms in arc shape. Subducted plate heats in upper mantle, magma rises to form curving chains of volcanic islands.	Aleutians, Marianas
	Continent–continent		N.A.	Collision between masses of granitic continental lithosphere. Neither mass is subducted. Plate edges are compressed, folded, uplifted; one may move beneath the other.	Himalayas, Alps
Transform plate boundaries		Past each other	Neither created nor destroyed.	A line (fault) along which lithospheric plates move past each other. Strong earthquakes along fault.	San Andreas Fault; South Island, New Zealand

Plate Boundaries and Movements (Table 3.1)

(Garrison, 2002)

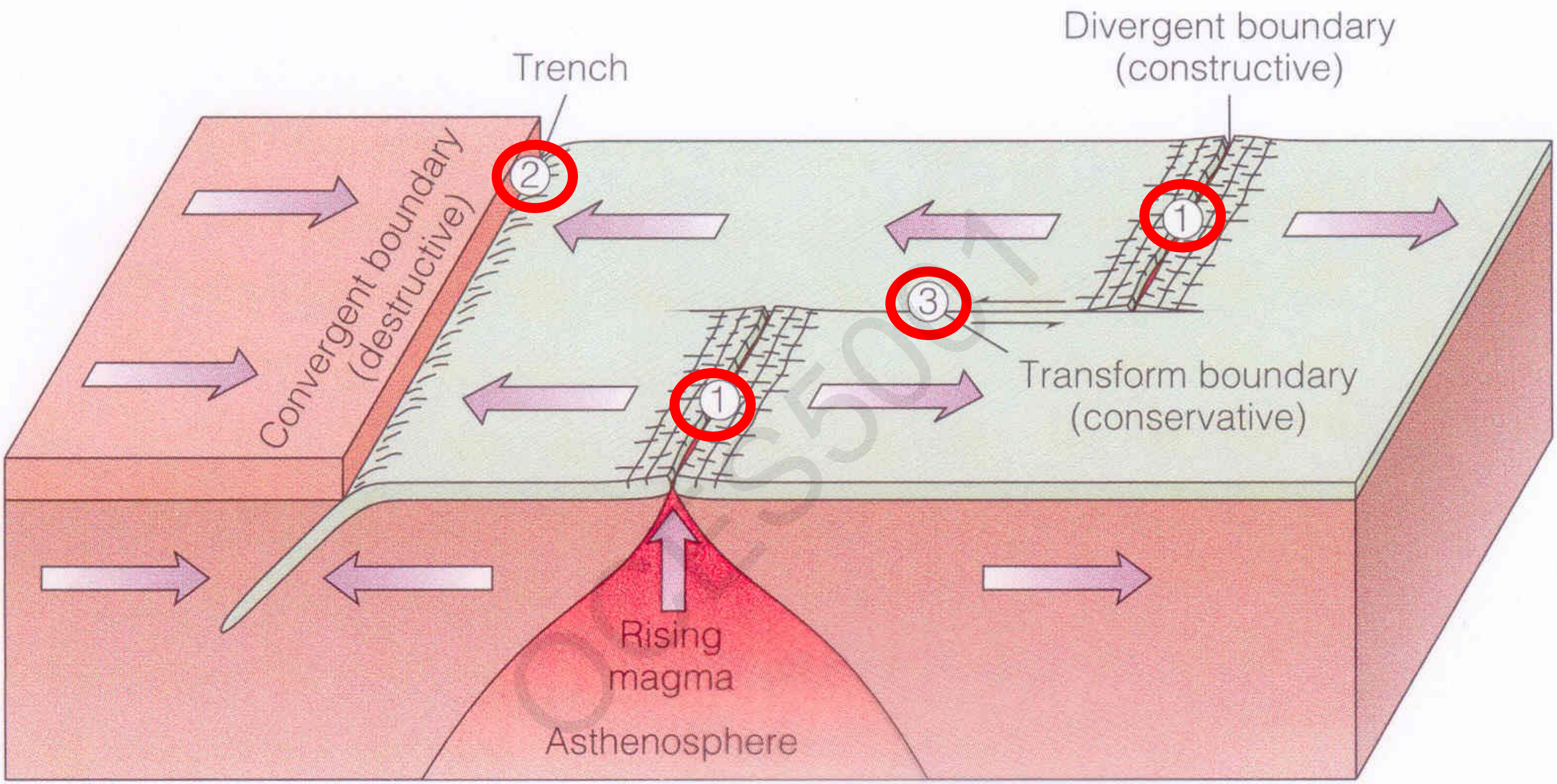
Plate Movements

1) Divergence of plates

a) Divergent oceanic crust e.g. mid-Atlantic ridge – plates move apart and new oceanic crust forms.

b) Divergent continental crust – heat causes asthenosphere to expand, rises and causes fracture → split in lithosphere → rift valley (e.g. East Africa rift valley). Magma or water may flow into the crustal fracture (e.g. Red Sea).

Magma = lava (above ground)



Divergent (ocean ridge) and convergent (subduction at trench) plate movements and transform fault (boundary) along the ocean ridge.

Stages of formation of Atlantic:

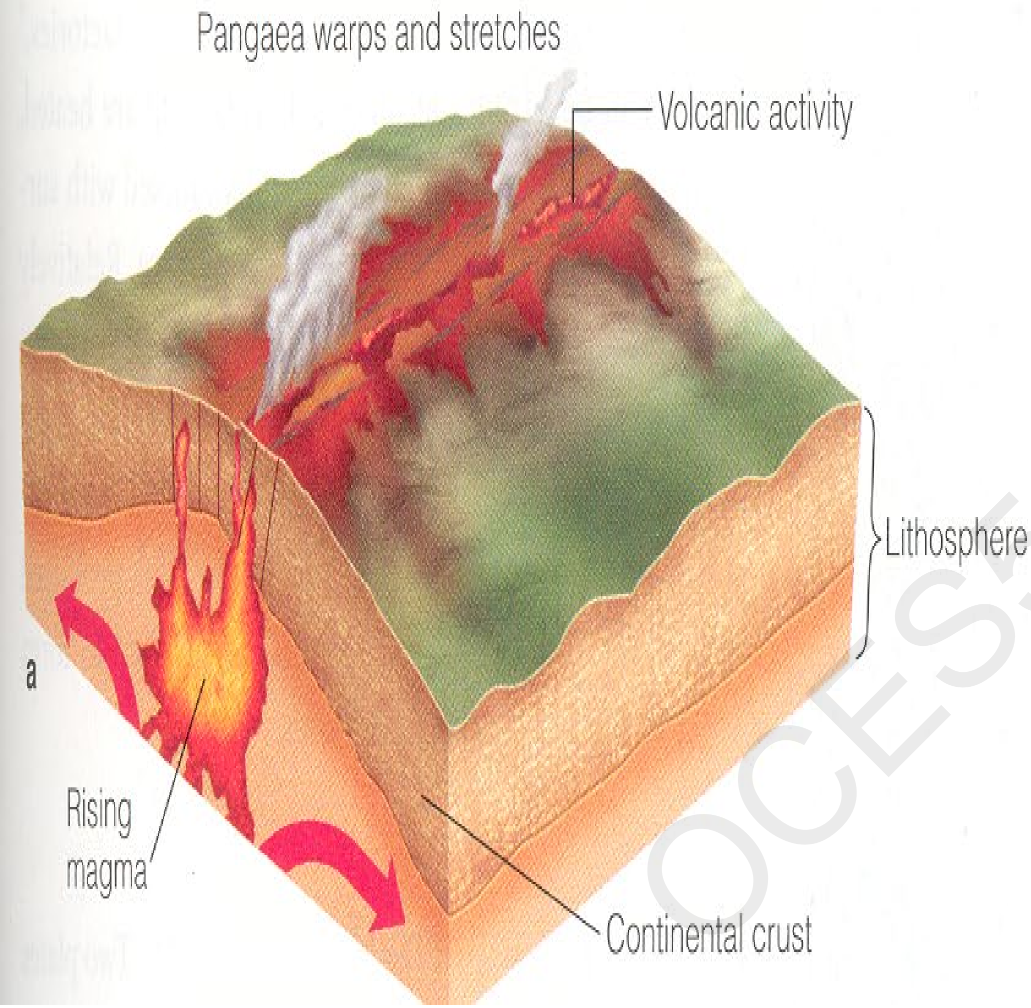
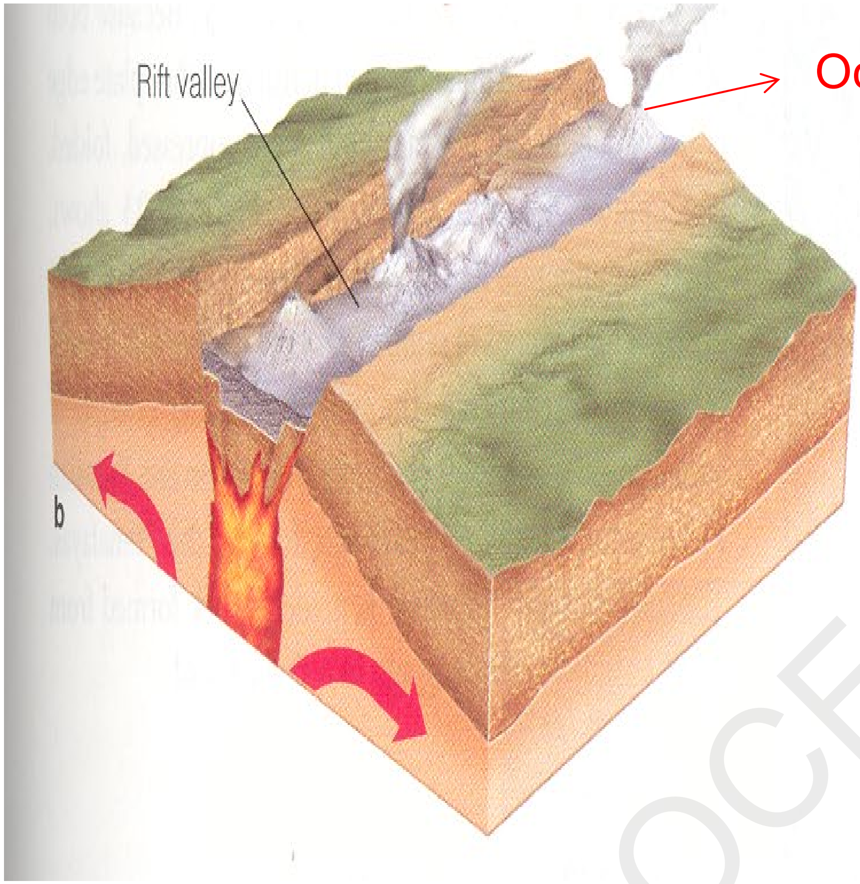


Figure 3.16

A model for the formation of a new plate boundary: the breakup of Pangaea and the formation of the Atlantic.

(a) As the lithosphere began to crack, a rift formed beneath the continent, and molten magma began to rise to form a new basaltic ocean floor.

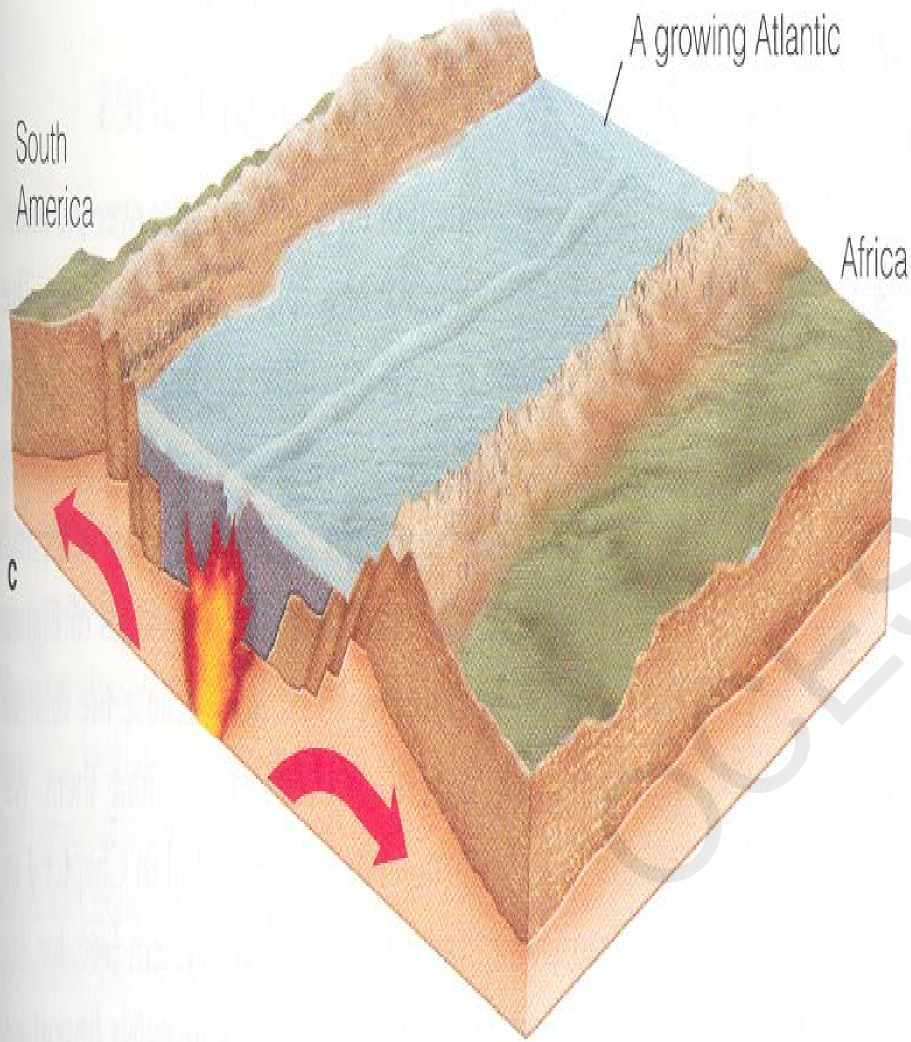
First Stage of Formation:crack



Ocean basin and mid-ocean ridge

(b) As the rift continued to open, the two new continents were separated by a growing ocean basin. Volcanoes and earthquakes occur along the active rift area, which is the mid-ocean (mid-Atlantic) ridge. The East African Rift Valley, though not yet submerged, currently resembles this stage.

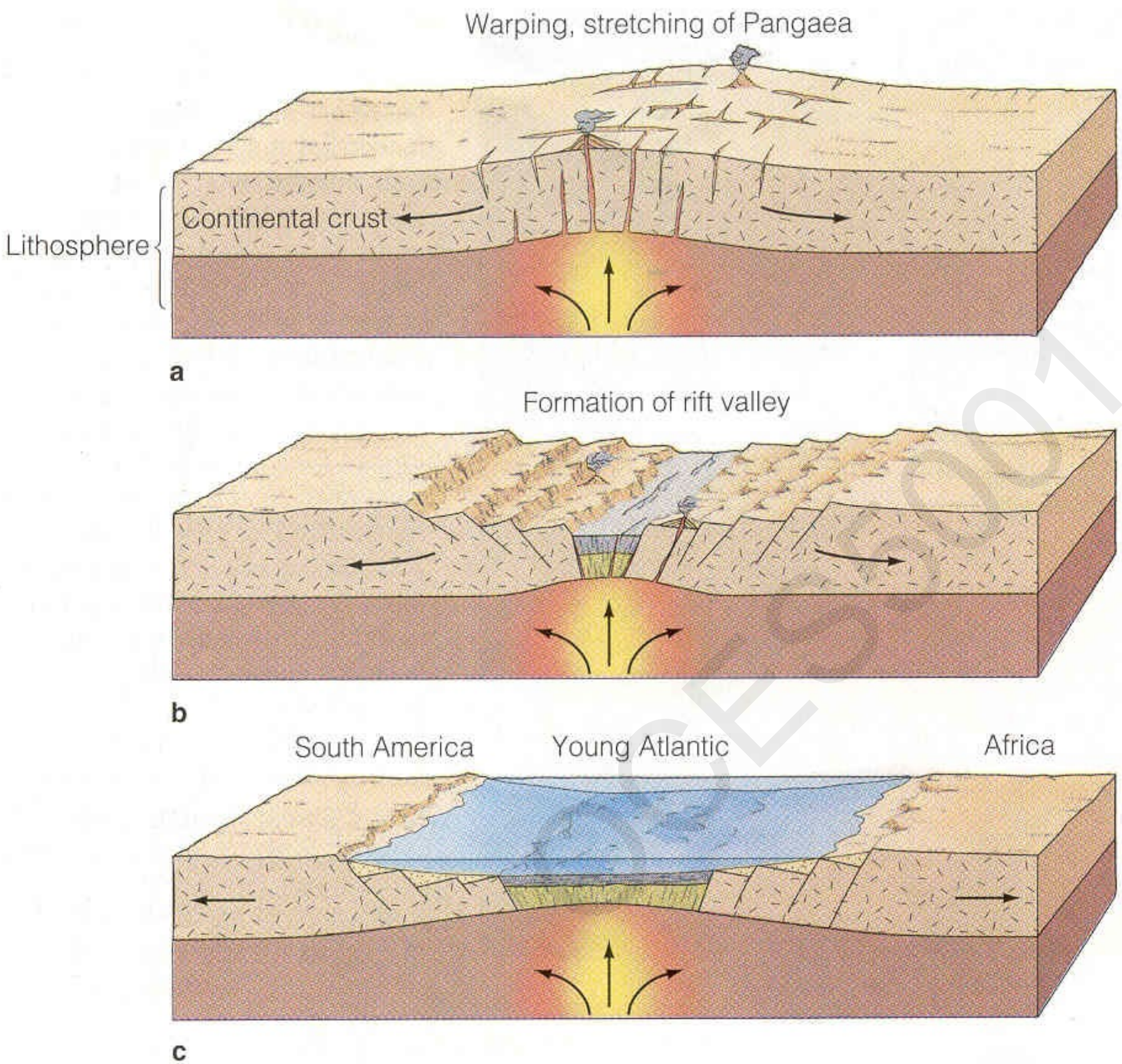
Second Stage
– Formation of A Rift Valley



(c) A new ocean basin forms beneath a new ocean.

The Red Sea (d) currently resembles this stage. Note the remarkable saw-tooth configuration of the peaks on the horizon, and their similarity to the diagram.

Final Stage – Formation of a new Ocean



Divergent Plates

Formation of new plate boundary, break up of Pangaea, and formation a rift valley and the Atlantic Ocean (Fig 3.13)

Plate Movements

2) Convergence of plates – plates move towards each other

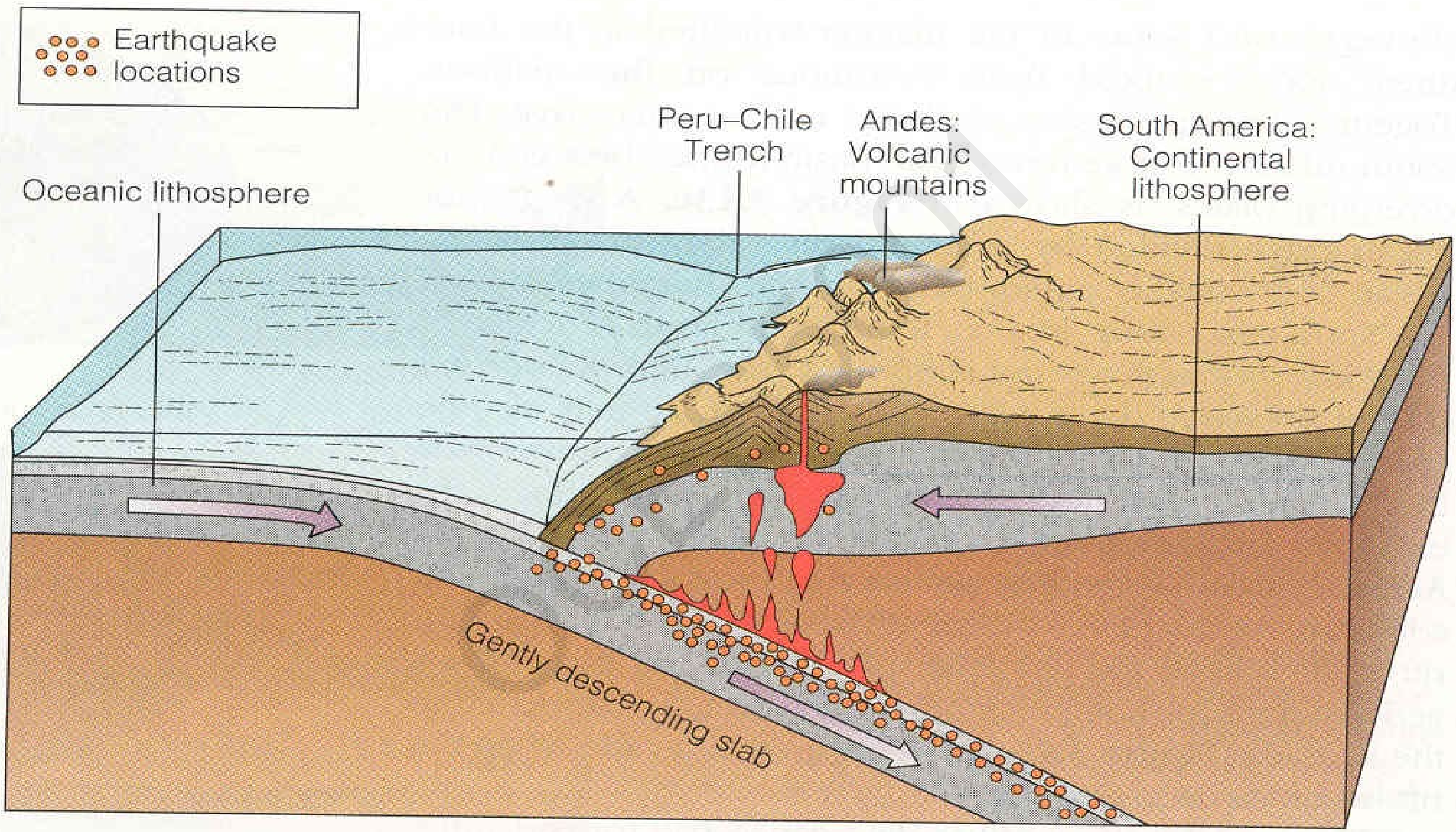
- Thick, light continental lithosphere rides up over heavier oceanic lithosphere and the oceanic crust is subducted at the trench.

- Some of oceanic crust and sediment melt → magma which rises to form volcanoes (e.g Andes Mountains in South America). Therefore, the oceanic plate is recycled as it eventually melts in the mantle.

- Plate movement in the Pacific (max.) ~18 cm/yr > Atlantic

Example 1:

- **Continental crust meets oceanic crust**
  – west coast of South America where heavier oceanic crust subducts under lighter continental crust.

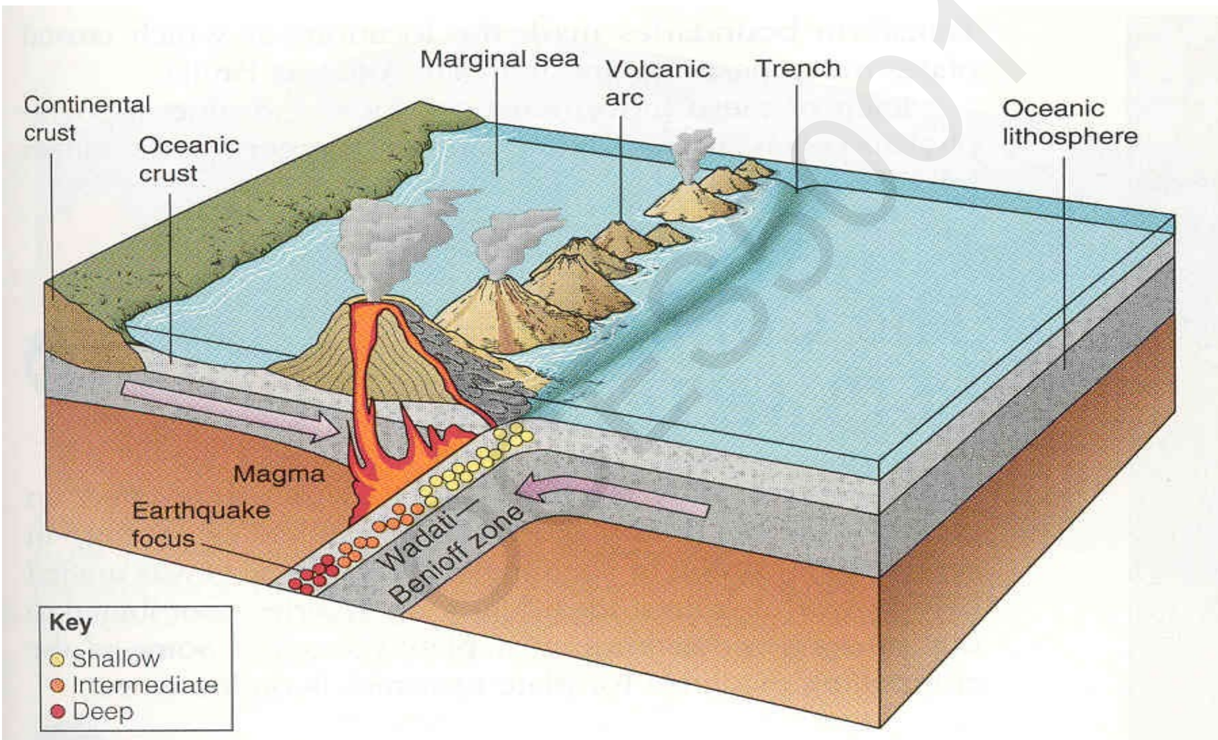


Convergence of Continental and Oceanic Plates, Plate Subduction, and the Formation of Volcanic Mountains (Andes) along the Coast of South America (Fig 3.15)

Example 2:

Oceanic crust meets oceanic crust

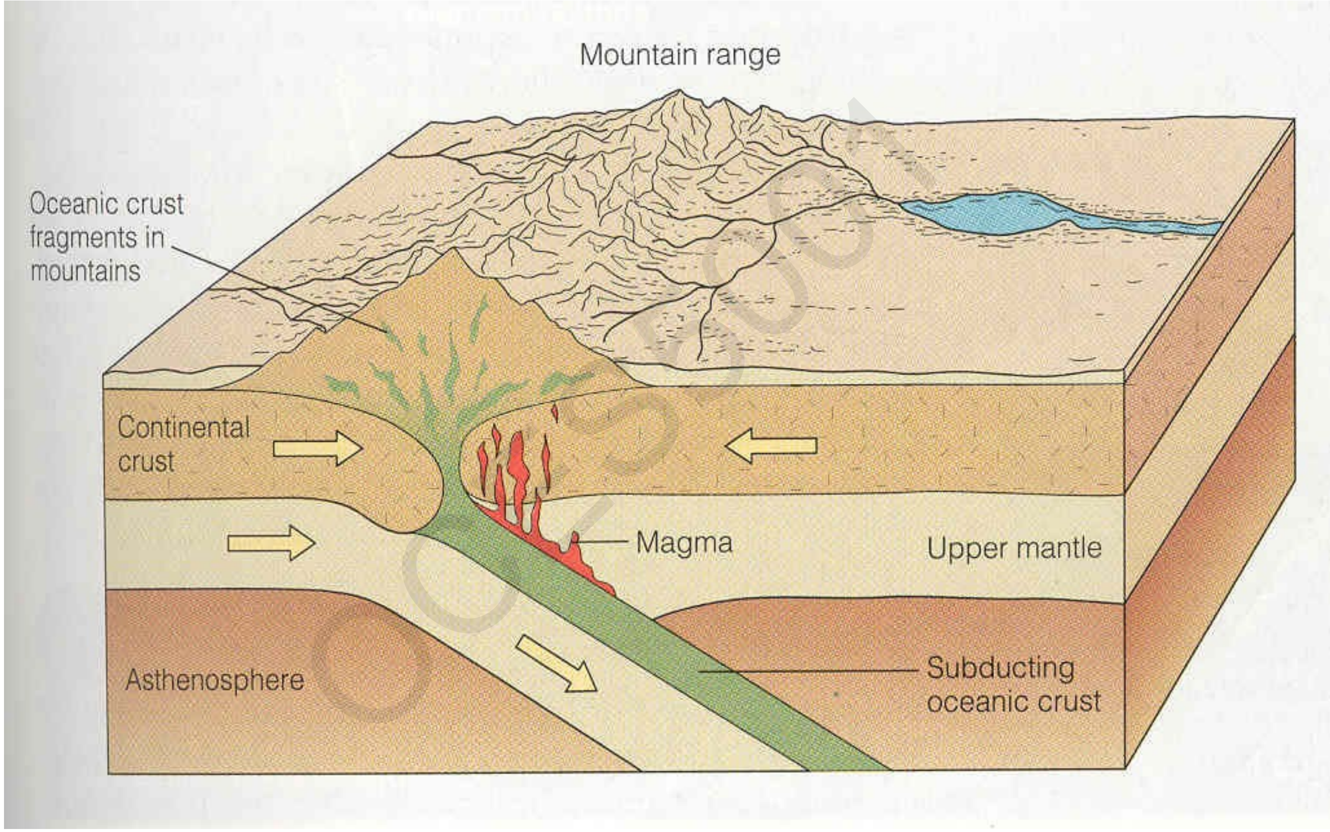
- older, denser crust subducts
- many volcanoes emerge from the seafloor rather than the continent.
- When they rise above the sea surface, they may form island arcs which may coalesce to form larger continental masses.
- The Japanese Islands were formed this way.



Formation of an Island Arc Along a Trench as 2 Oceanic Plates Converge. Example: Japanese Islands. Note the different depths of the earthquakes. (Fig 3.17a)

Example 3:

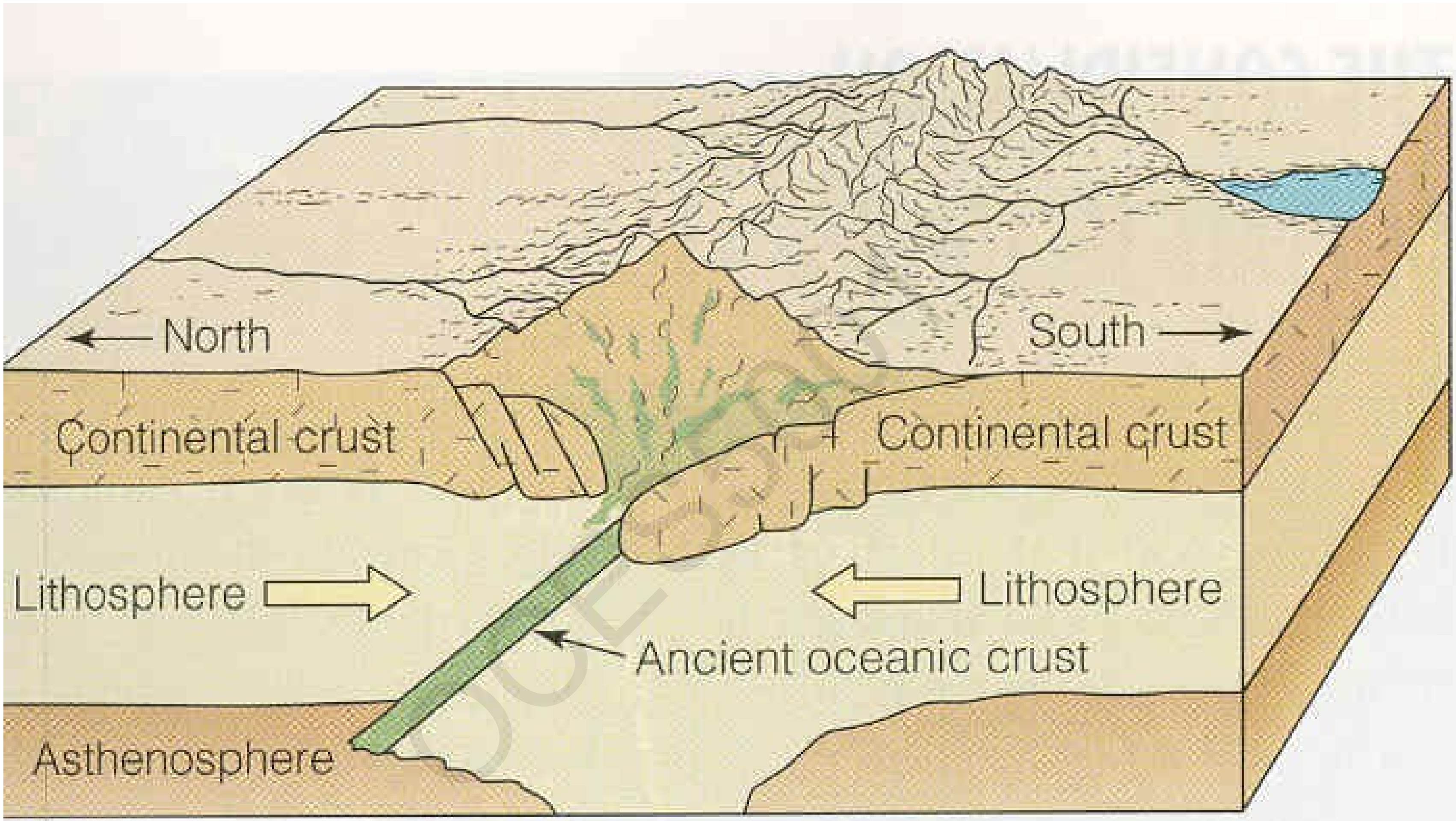
- **Continental crust meets continental crust**
  (get collision, compression, folding, uplifting)
  - Himalayas – Mt Everest formed from sediments from shallow sea.



Convergence of Two Continental Plates.

Compression and folding, uplift the plate edges to form mountains

(Fig 3.18)



Southern China. Convergence of two continental plates.

Plates collide, compress, uplift forming Himalayas.

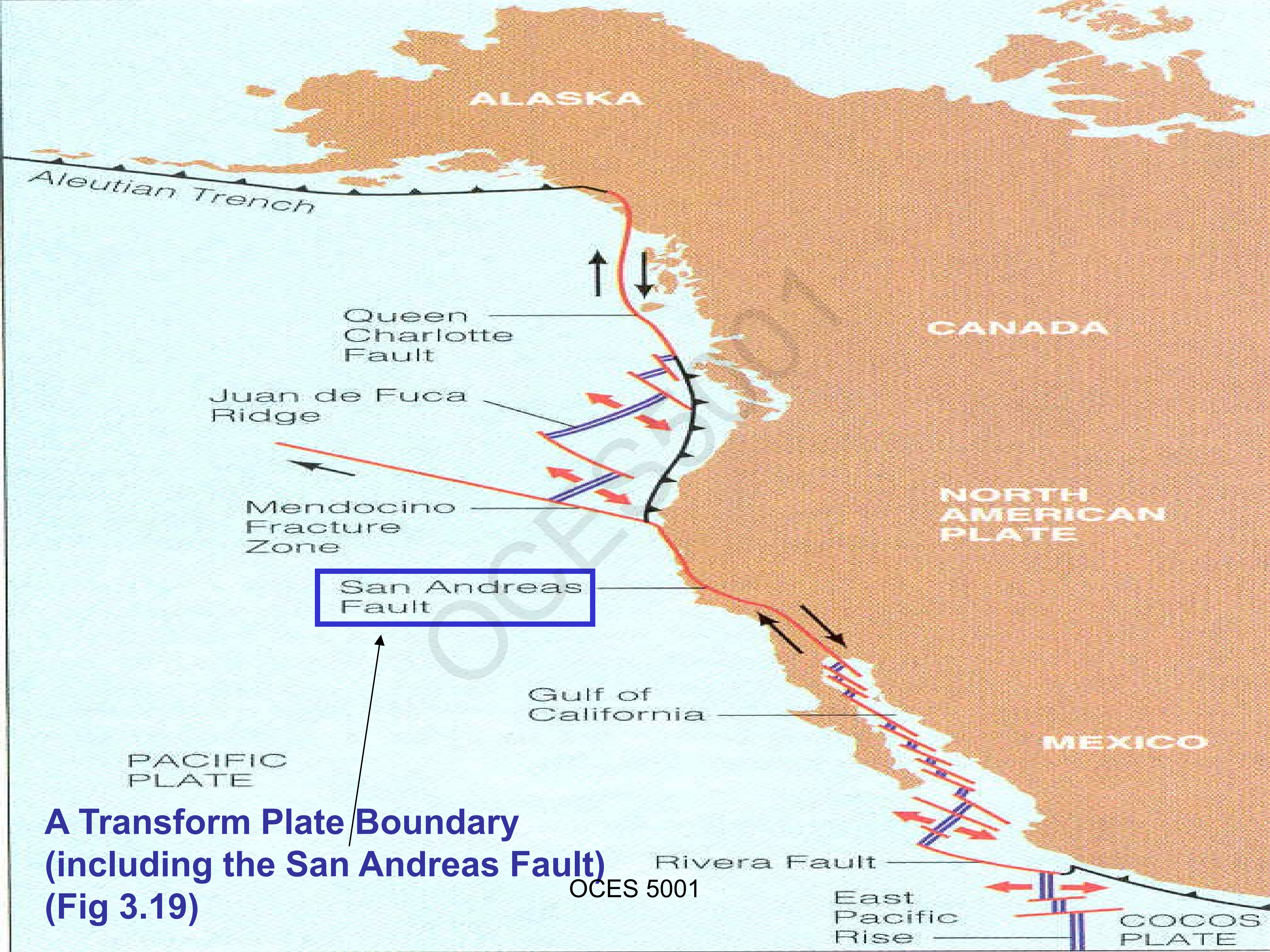
Plate Movements

3. Transform Plate Boundaries

- Crustal plates move laterally past one another → shallow earthquake areas.

  e.g. eastern boundary of Pacific plate – long transform fault system

  e.g. California – San Andreas fault – west part of California (Pacific Plate) is sliding north to the Aleutian trench.



A Transform Plate Boundary (including the San Andreas Fault) (Fig 3.19)

Hotspots

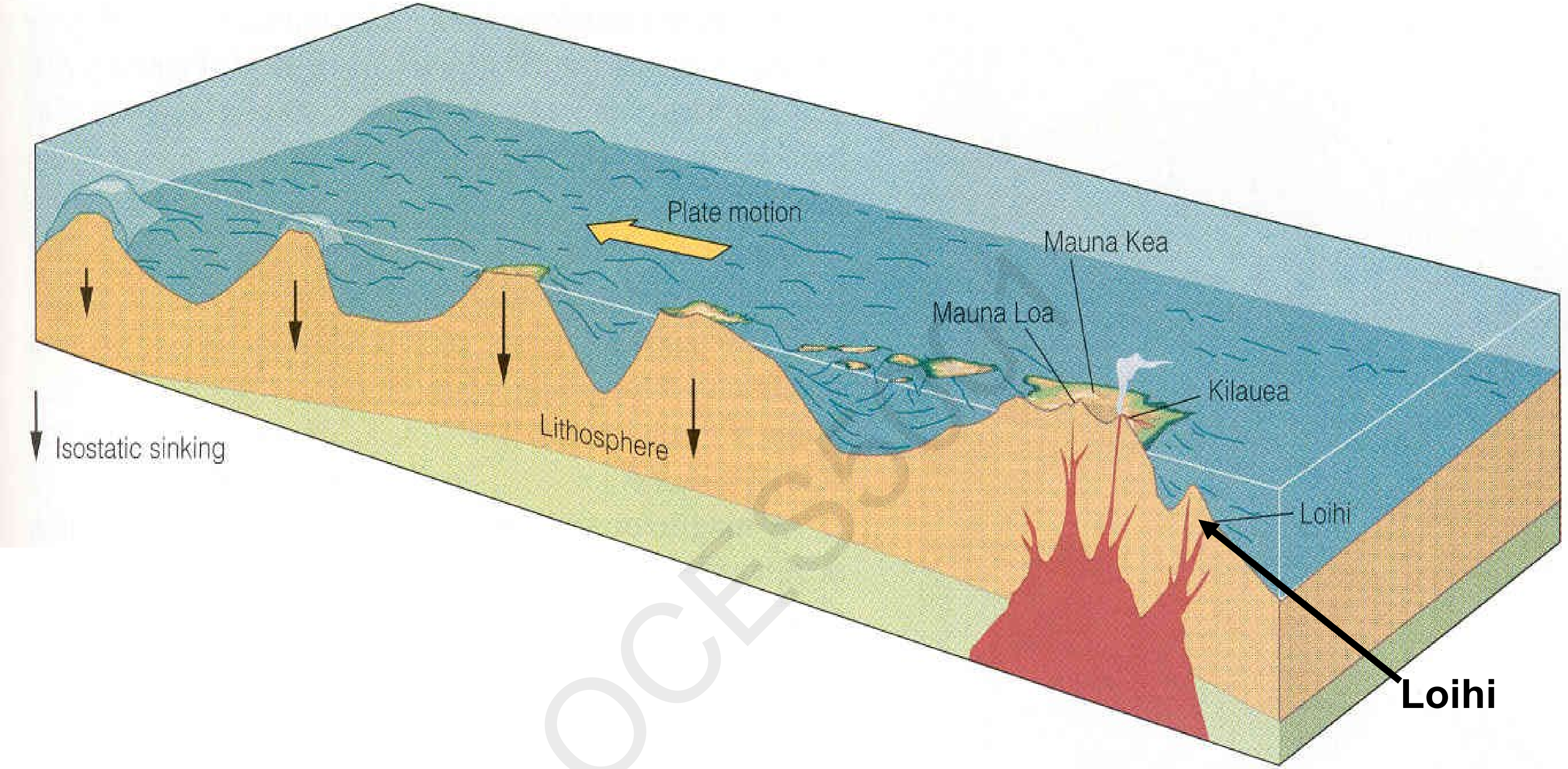
– a stationary source of heat in the mantle (see next slide).

- A series of volcanos forms over the hot spot in a line, but since plate is moving, volcano is carried beyond the hot spot and it becomes inactive and subsides (isostatic equilibrium), and then a new volcano forms over the hot spot.

- This process leads to the formation of a chain of volcanic islands (e.g. Hawaii).

- The first formed Hawaiian islands moved north, now northwest.

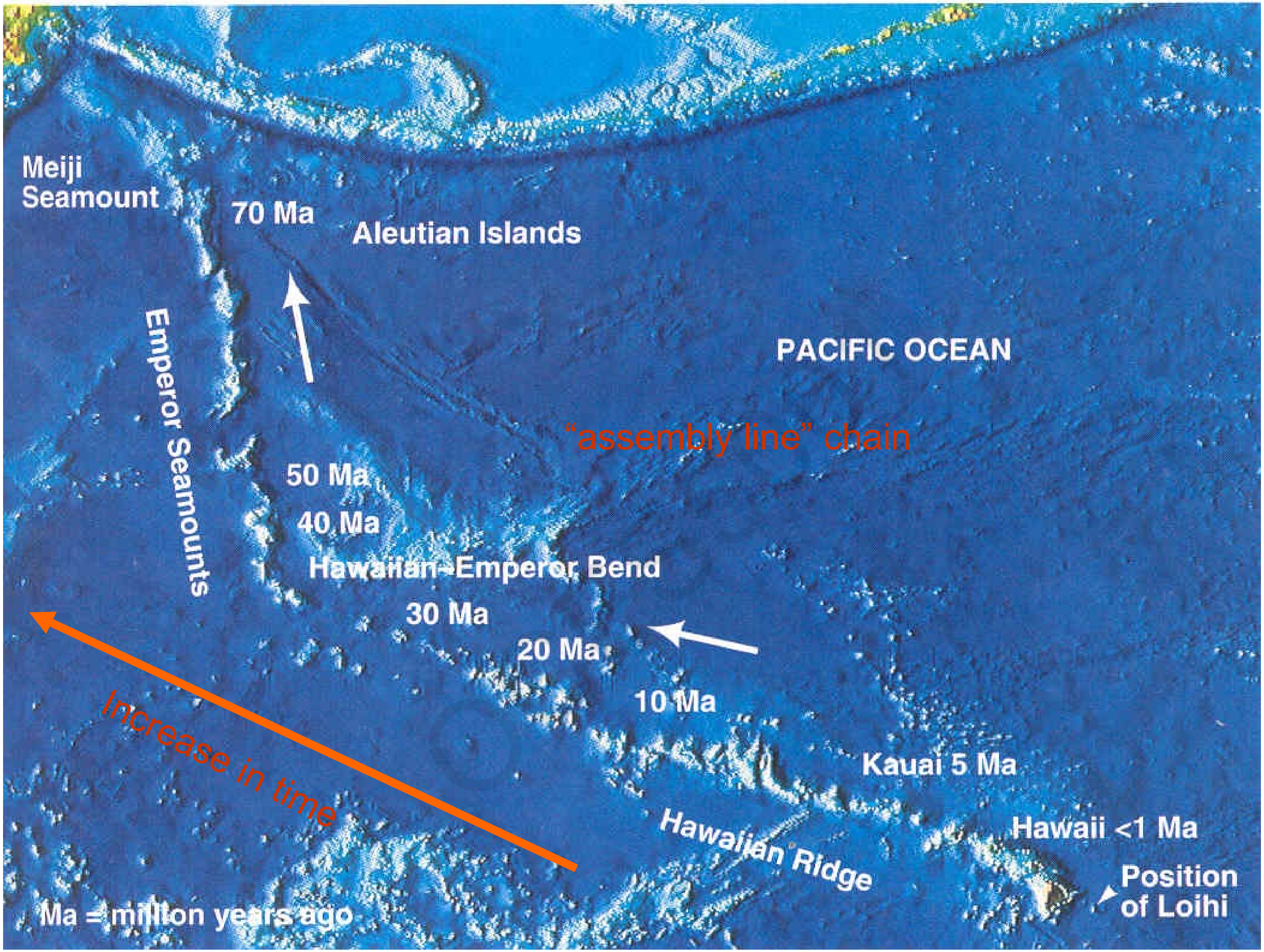
- Loihi (new Hawaiian island) is 100 m below the surface and estimated to reach the surface of the water in 30,000 years.



Formation of a volcanic island chain by the movement of an oceanic plate over a stationary mantle plume and hot spot.

The age of the islands increases towards the left.

New islands -like Loihi will continue to form over the hot spot. (Fig 3.20)

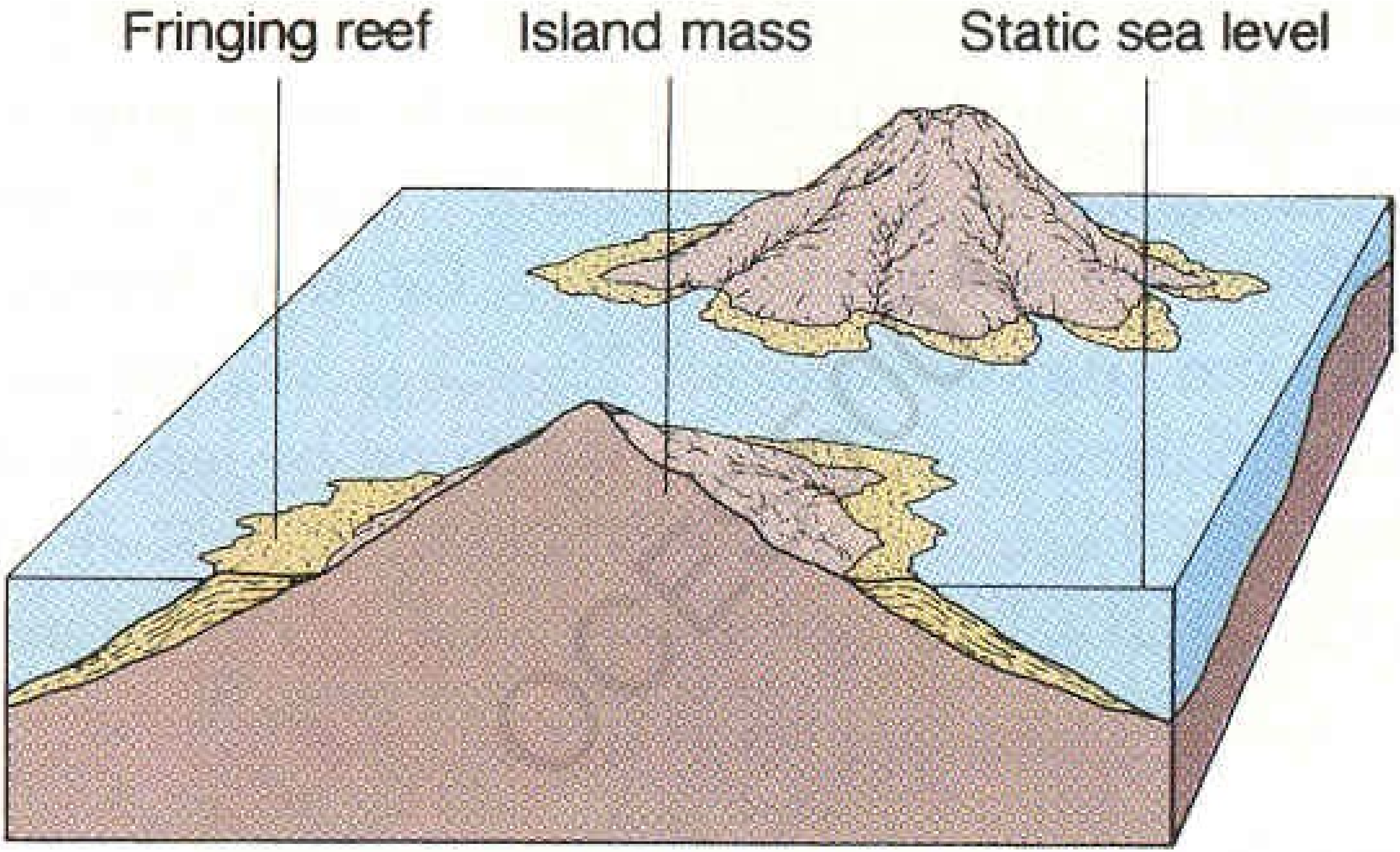


Hawaiian Islands Formed as Plate Slid Over a Hot Spot (Fig 3.21)

Fringing and Barrier Reefs and Atolls

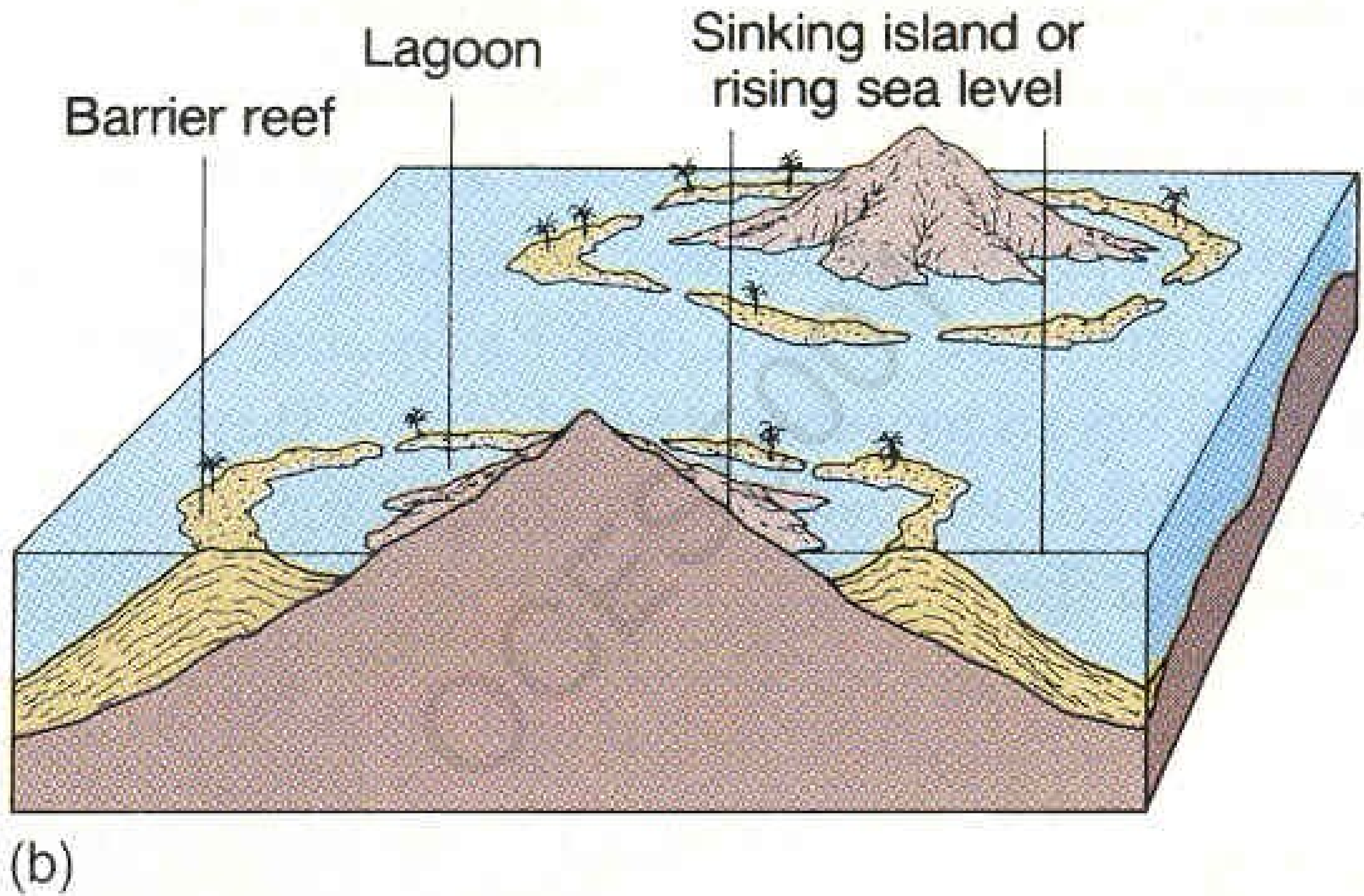
- are ring-shaped islands of coral reefs around a submerged inactive volcano.
- if coral growth is high, then that plate/volcano subsides due to the increased weight of the corals, and then get deep coral structures.

Volcano

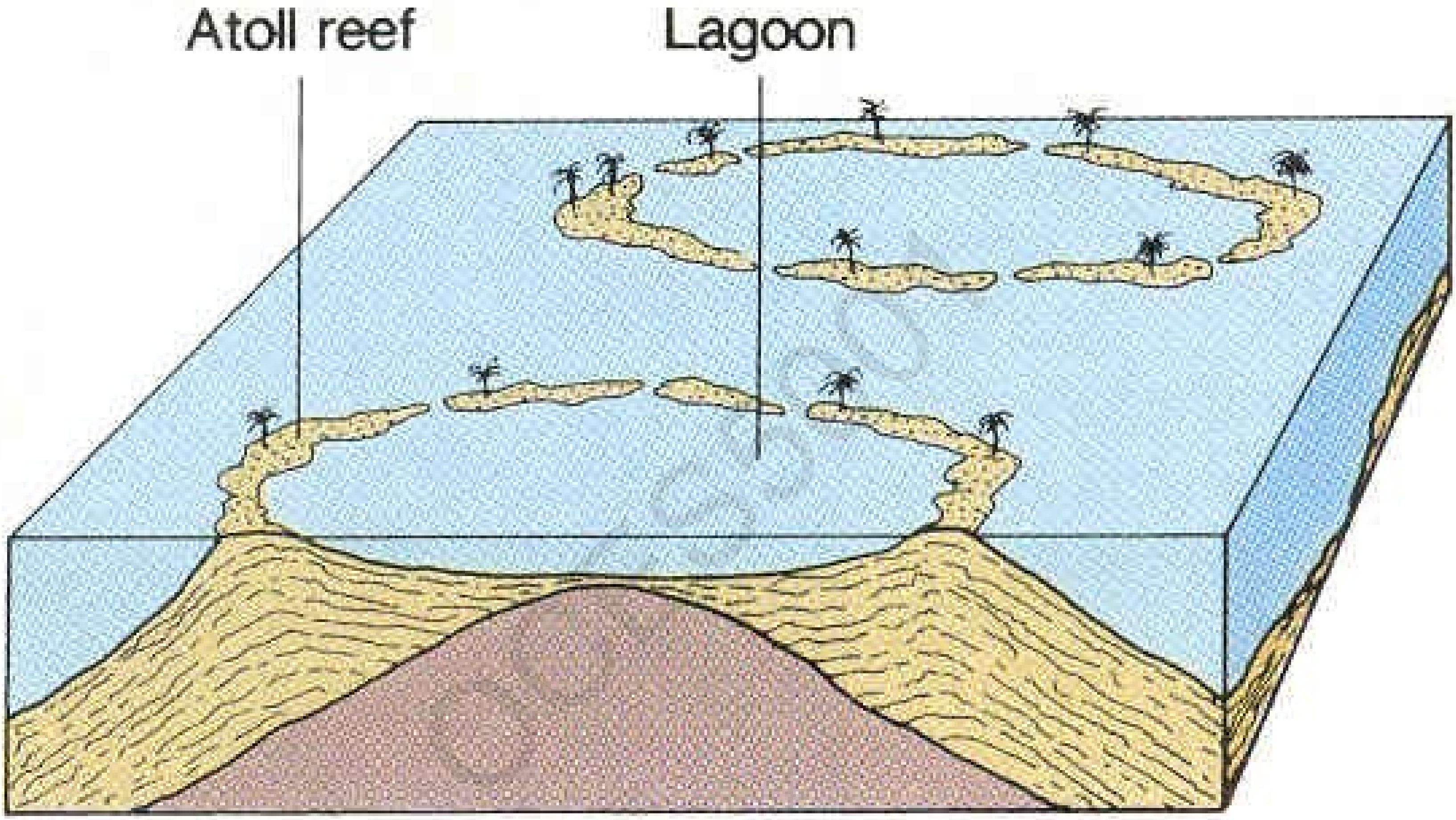


(a)

Fringing Coral Reef

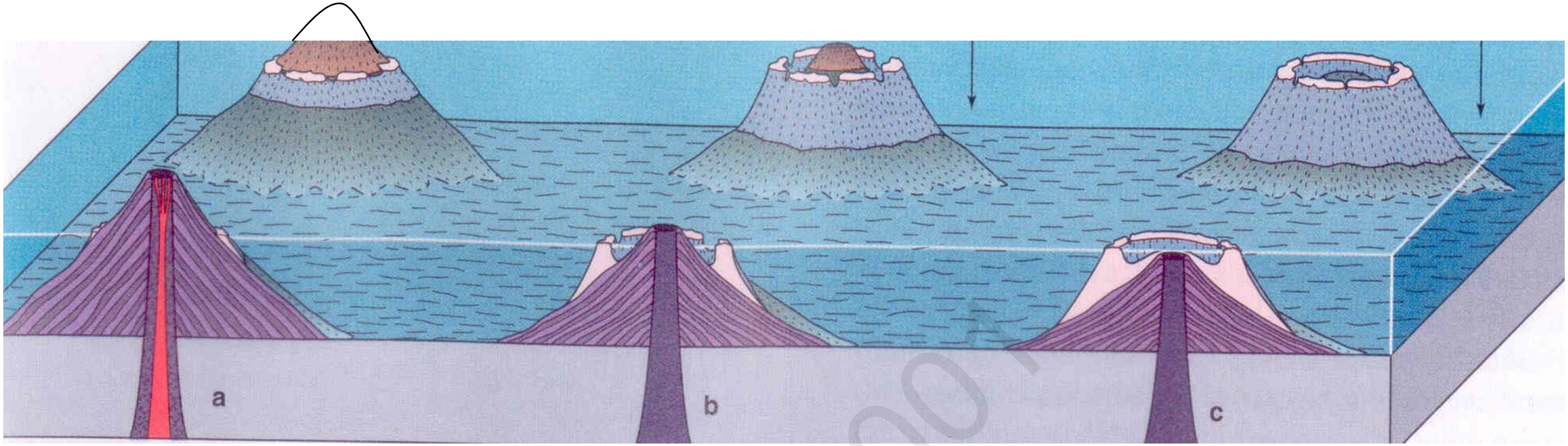


Barrier Coral Reef and lagoon are formed due to sinking island (isostatic equilibrium)



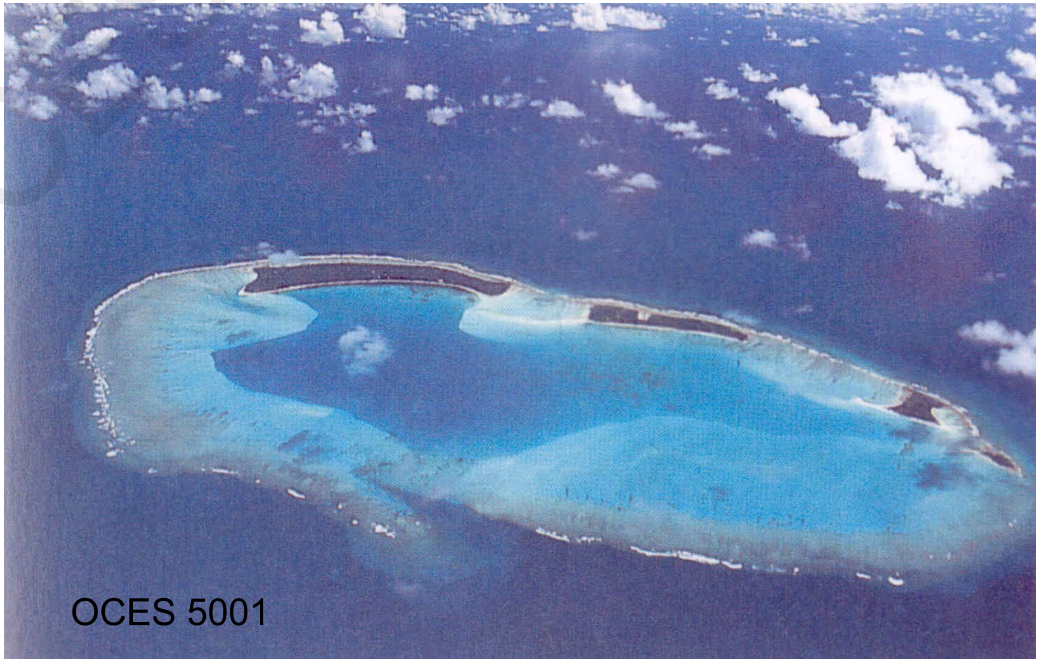
(c)

Atoll and Full Lagoon is formed when island sinks due to weight of coral.



Fringing Reef **Barrier Reef** **Atoll**

Time Series of Fringing & Barrier Reefs & Atolls



South Pacific Atoll – lagoon in centre

Dongsha atoll in the South China Sesa

Evidence for Plate Tectonics

Paleomagnetism:

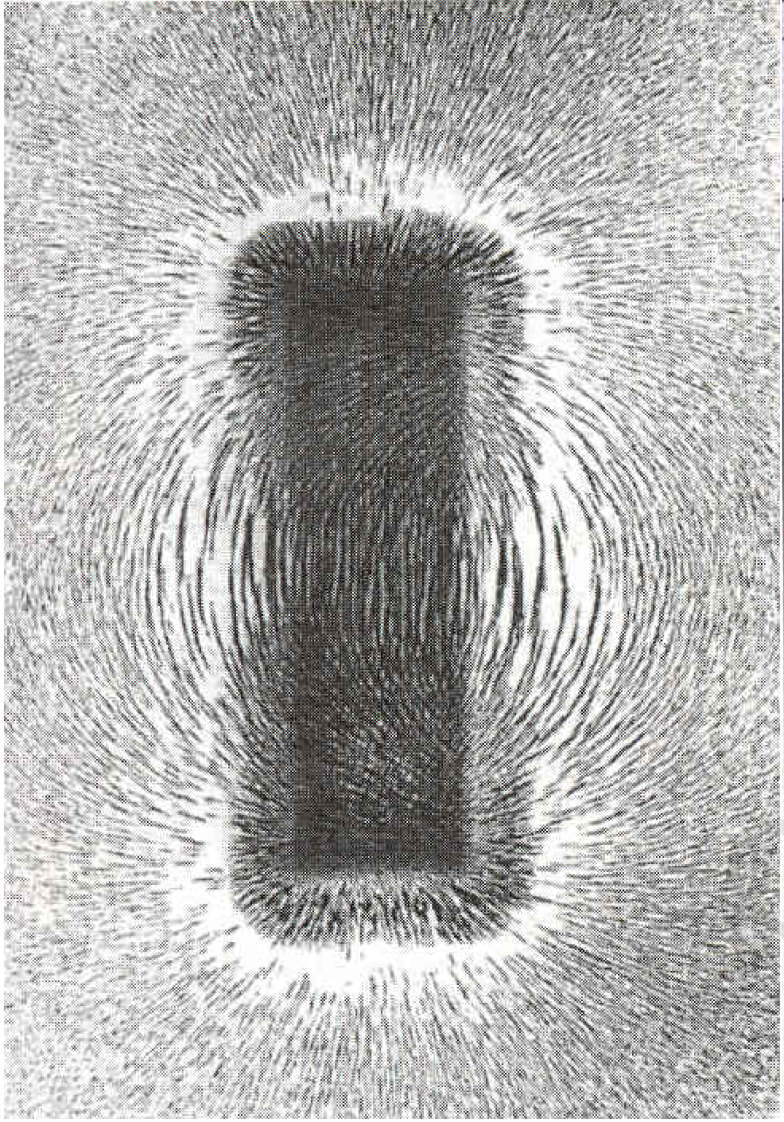
- a compass needle points north – aligned with the Earth's magnetic field.

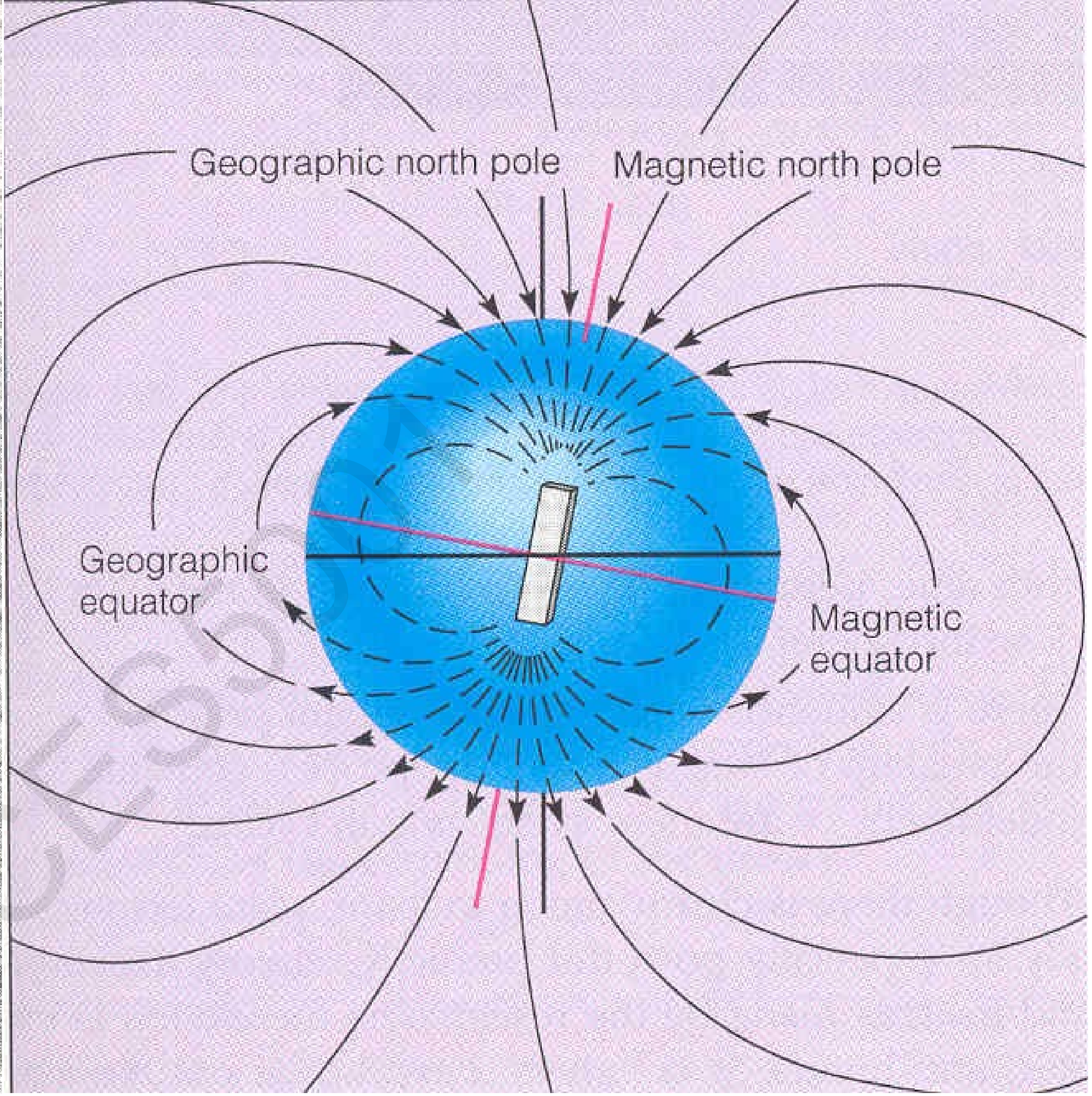
- tiny particles of Fe-bearing magnetic minerals are found in basaltic magma (like mini compass needles).

- as particles erupts at mid-ridges, cool, the magnetic fields of magnetic minerals align with the Earth's magnetic field.

- this 'fossil" magnetic field = **paleomagnetism** (paleo=ancient)

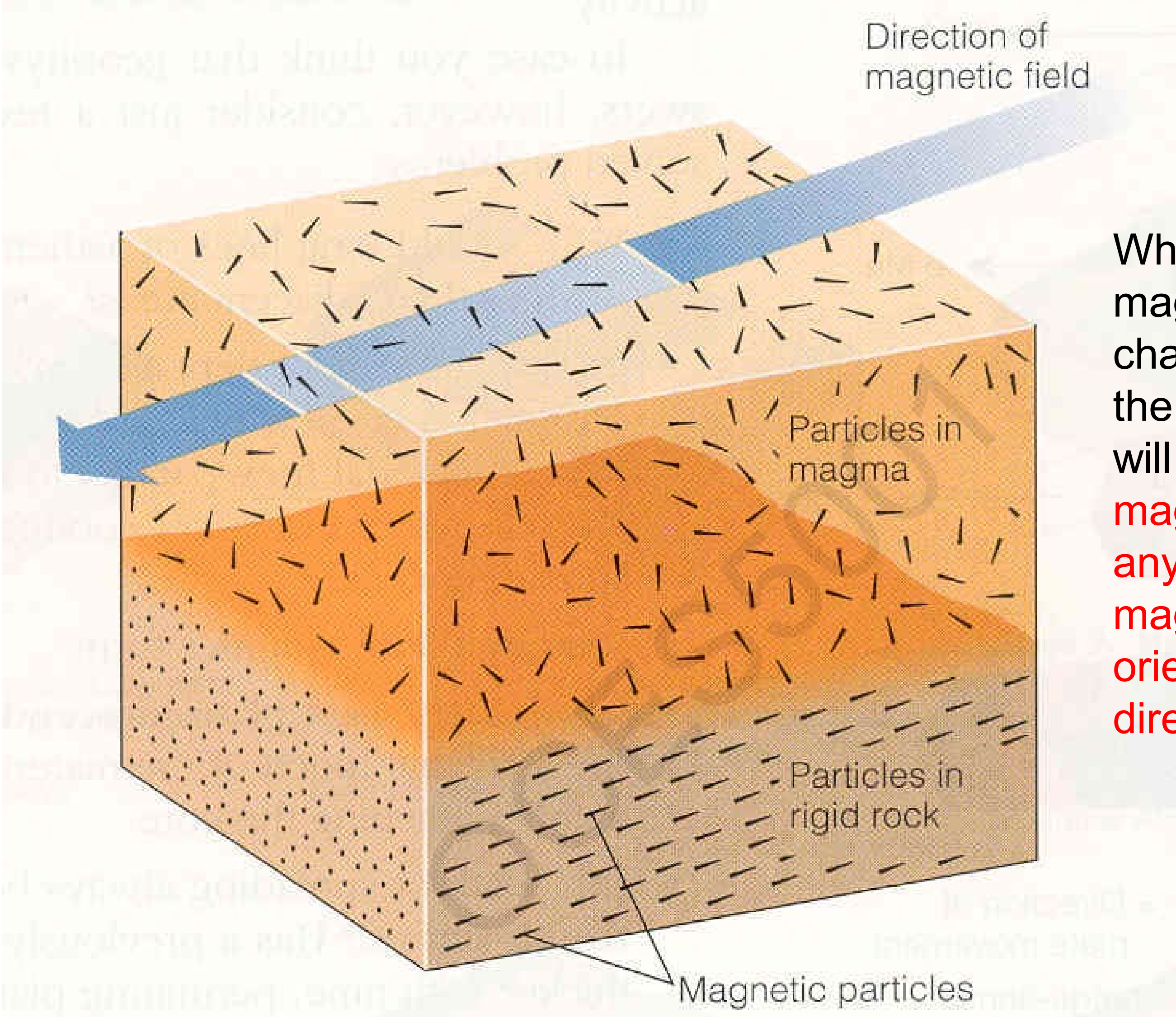
**Earth's persistent magnetic field is caused by the movement of molten metal in the outer core.





Magnetic Field Pattern of a Bar Magnet (Fig. 3.23a)

Earth's Magnetic Field (Fig 3.23b)



When earth's magnetic field changes direction, the "locked" particles will not respond, but magnetic particles in any new form (hot) magma above will orient to the new field direction.

Particles of iron-bearing magnetite in magma. Magma cools forming new seabed and magnetic particles locked into magnetic orientation of Earth's prevailing magnetic field.

Evidence for Plate Tectonics

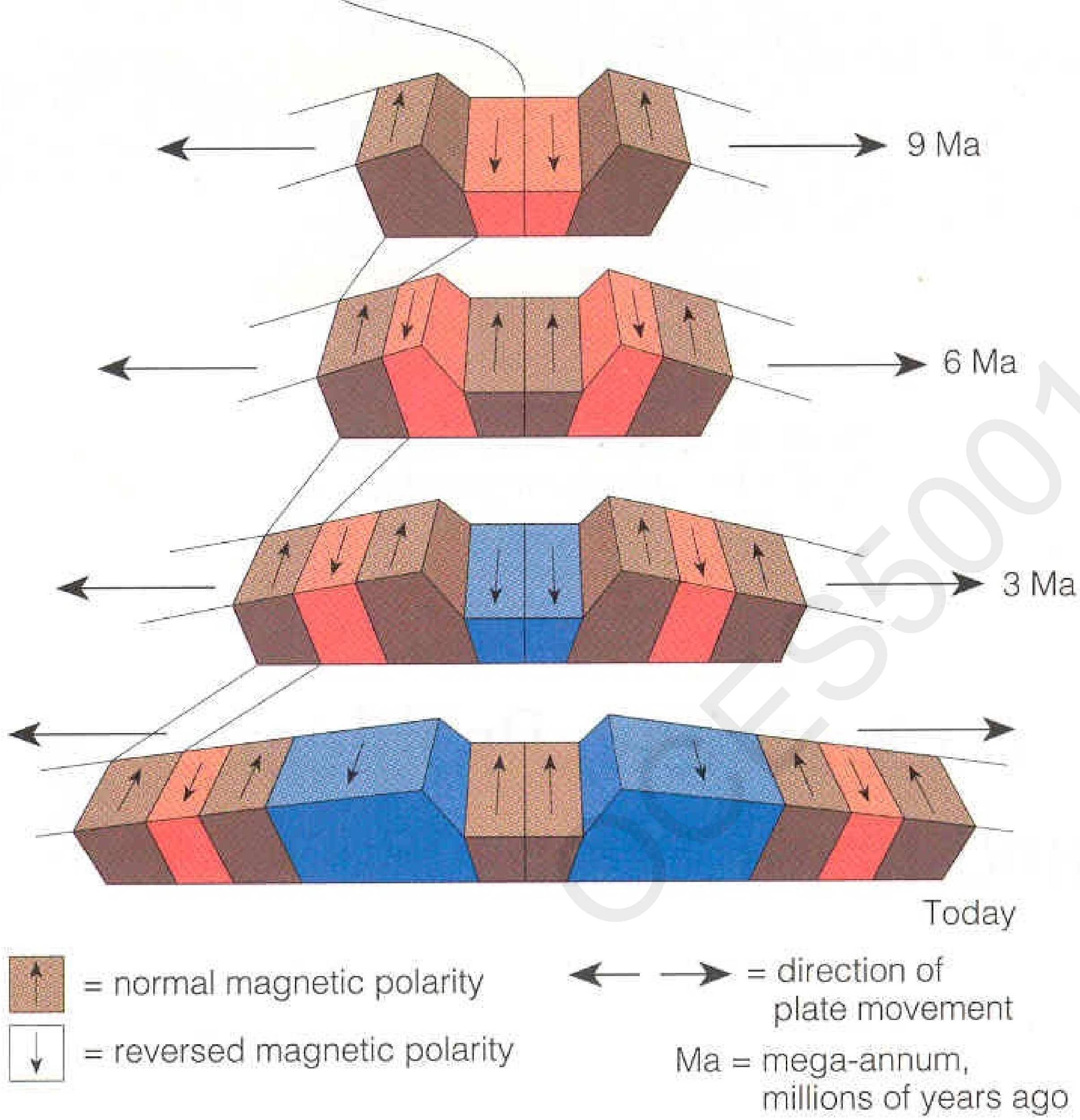
3) Paleomagnetism:

Earth's magnetic field reverses at irregular intervals (~1000s of years).

These reversals are due to the difference in rotation rates between the Earth's inner and outer cores.

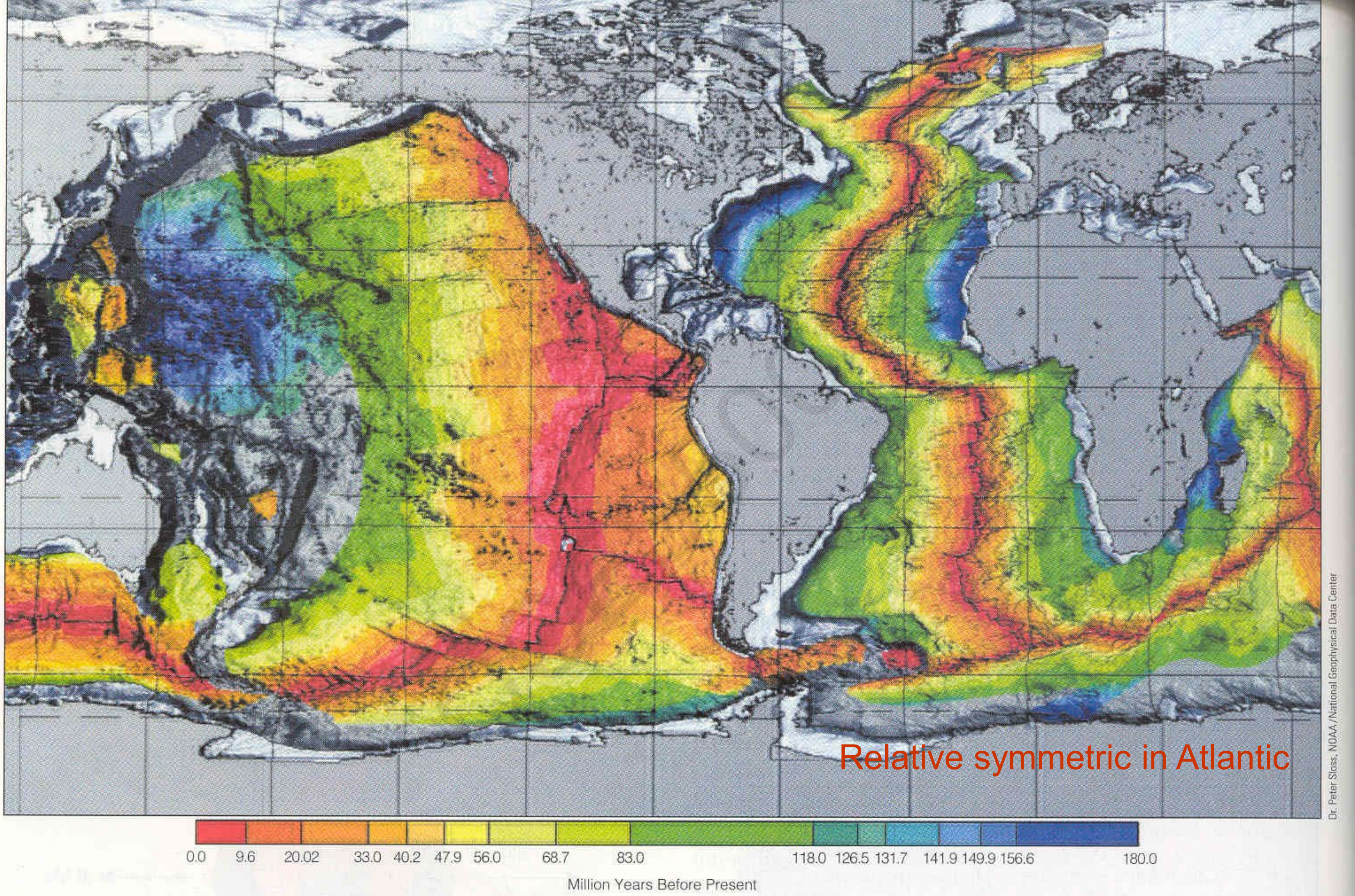
A reversal means that a compass needle points south.

These reversals are detected by using an underwater paleomagnetometer.



- Earth's magnetic field reverses at irregular intervals of a few hundred thousand years,
- The molten rocks forming at the spreading center take on the polarity of the planet when they are cooling
- They then move slowly in both directions from the center,
- When Earth's magnetic field reverses, the polarity of newly formed rocks changes, creating symmetrical bands of opposite polarity.
- The magnetized minerals contained in the rocks in some bands add to Earth's present

Symmetrical Patterns of Paleomagnetism (Fig 3.24b)



Age of the Ocean Floors and Seafloor Spreading in last 200 million year as revealed by paleomagnetic patterns (Fig 3.25)