# Economic Geology: Lecture Notes


Assembled by:

Dr. AbdelMonem Soltan

Professor of Applied Mineralogy

E-mail address: abdelmonemsoltan@gmail.com

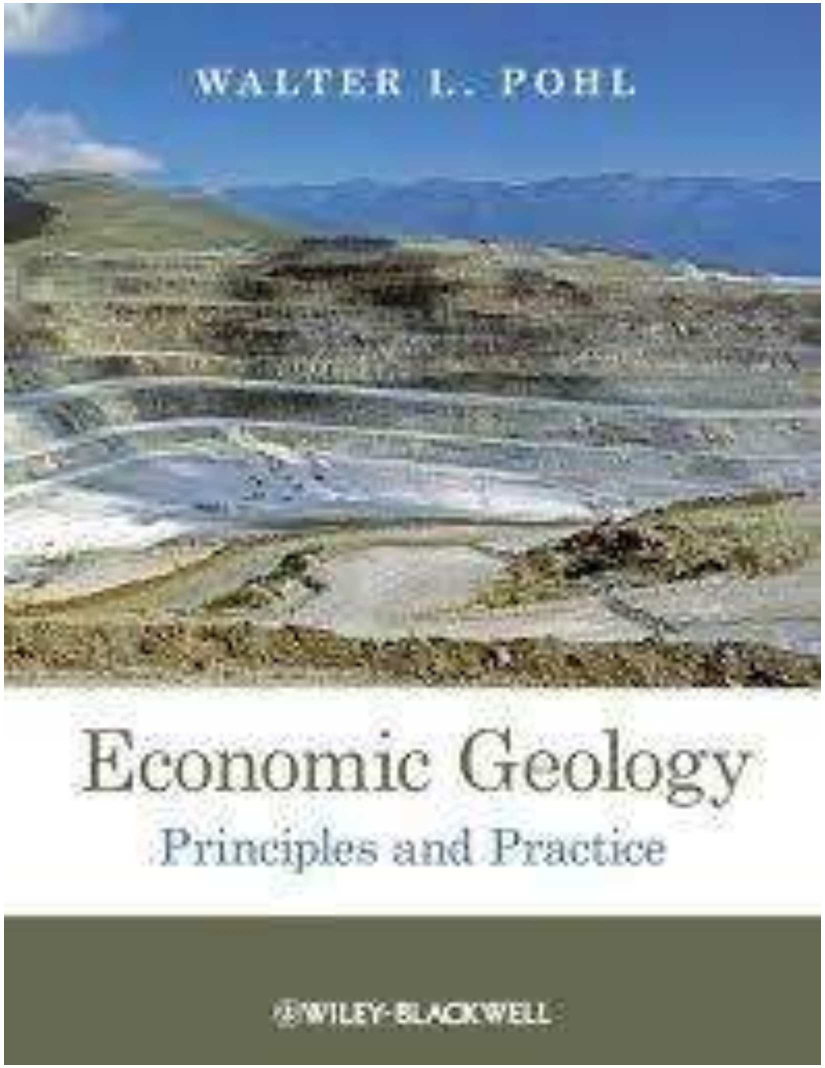
Applied Mineralogy and Building Materials Research Group

Ain Shams University

| Geology of Economic Ores | | |
| --- | --- | --- |
| **Course Code** | G322 | Credit hour system-Level 3 |
| **Teaching Material** | Economic Geology: Lecture Notes | Text book and PPT (available at Researchgate) |
| **Starting Date** | Week begins 09/02/2019 | Lecture Hall |
| **End Date** | Week begins 02/05/2019 | Lecture Hall |

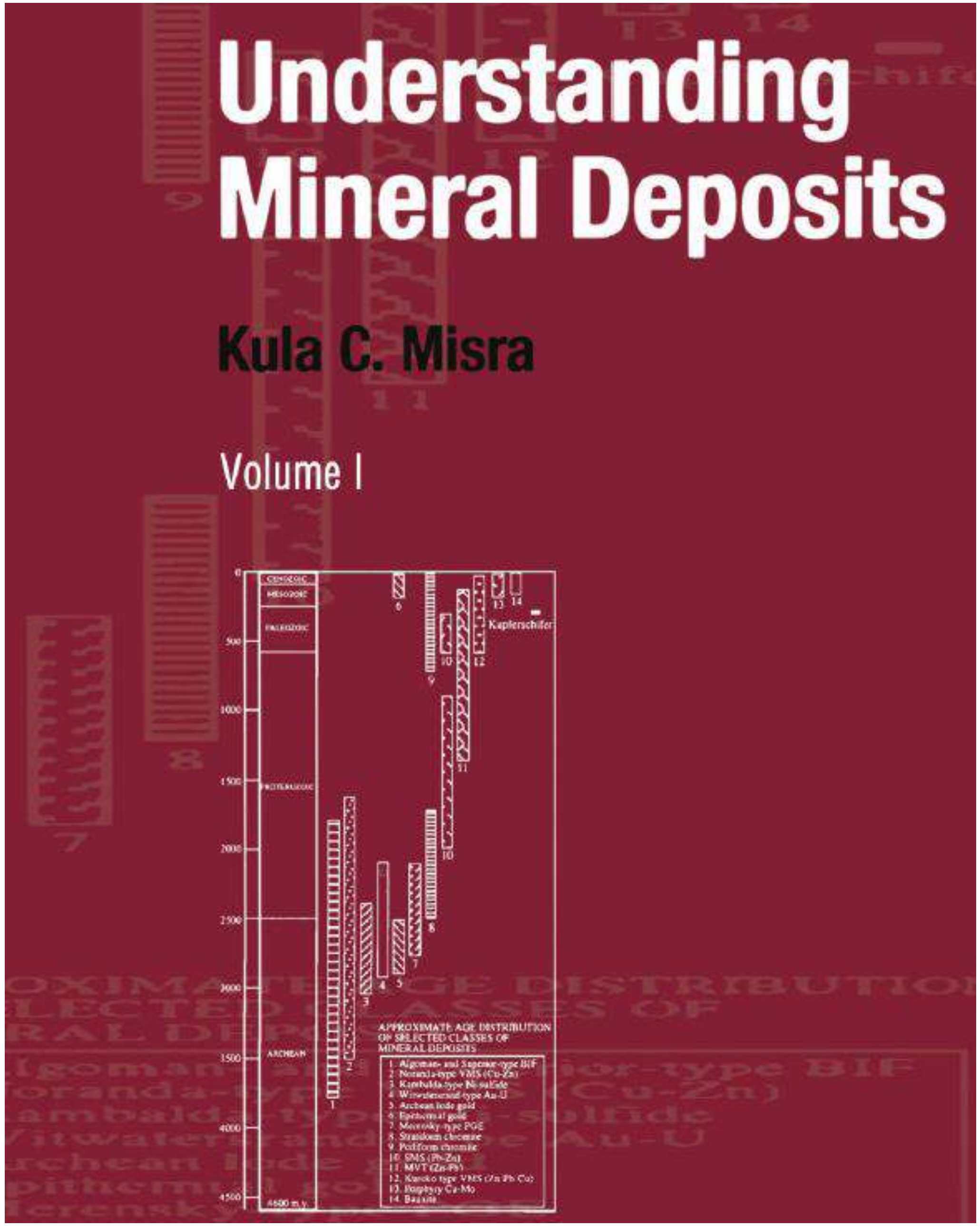
| Course Evaluation | | | |
| --- | --- | --- | --- |
| **Evaluation mode** | **Evaluation Marks** | **Evaluation date** | **Evaluation Procedure** |
| **Semester Work** | 10 | All over the course | • Lecture discussion<br>• Practical discussion<br>• Group work<br>• Quizzes |
| **Oral Examination** | 5 | Week begins 04/05/2019 | Written Sheet |
| **Practical Examination** | 25 | Week begins 04/05/2019 | Sample Identification |
| **Final theoretical written exam** | 60 | Week begins 25/05/2019 | Written Paper Exam |
| **Total** | 100 | | |

# Additional Text Books




***Economic Geology Principles and Practice***

***Metals, Minerals, Coal and Hydrocarbons – Introduction to Formation and Sustainable Exploitation of Mineral Deposits*, *Walter L. Pohl* ©2011 Walter L. Pohl. Published 2011 by Blackwell Publishing Ltd.**




***Understanding Mineral Deposits*, *Kula C. Misra* ©2000 by Springer.**

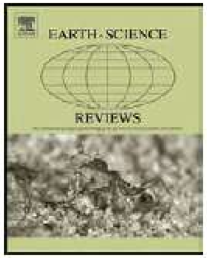
**Harald G. Dill (2010): The “chessboard” classification scheme of mineral deposits: Mineralogy and geology from aluminum to zirconium. Review Article *Earth-Science Reviews, Volume 100, Issues 1–4, June 2010, Pages 1-420***

Earth-Science Reviews 100 (2010) 1–420

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev




# The “chessboard” classification scheme of mineral deposits: Mineralogy and geology from aluminum to zirconium

Harald G. Dill

*Institute of Geosciences, Gem-Materials Research and Economic Geology, Johannes-Gutenberg-University Mainz, D-55099 Mainz, Becherweg 21, Germany*

# Group work

## Group A (Mr. Ahmed Yahia)

| | |
|---|---|
| احمد جميل حامد رفاعي خاطر | 822802 |
| حسام ابراهيم حجازى محمود | 822807 |
| حلمي احمد حلمي حافظ احمد | 822808 |
| سيف الدين حسام محمد فؤاد | 822812 |

## Group B (Ms. Noha Ali)

| | |
|---|---|
| عبدالرحمن احمد فتحي محمد | 822813 |
| عمرو طارق محمد المهدى ابراهيم | 822815 |
| محمود محمد محمود احمد | 822818 |
| مصطفى محمود جميل ابوسنه | 822819 |

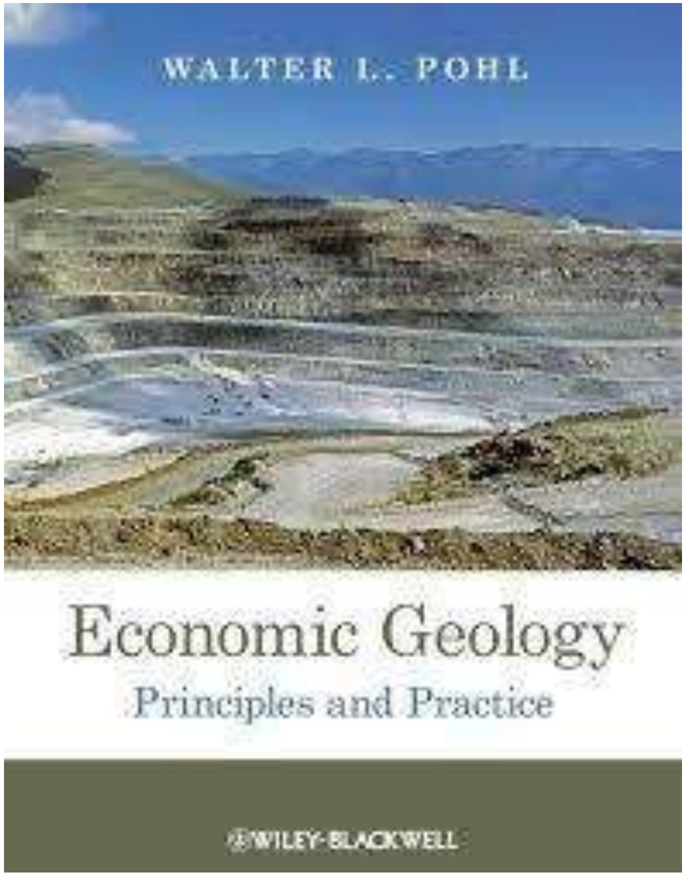
## Group C (Ms. Noha Ali)

| | |
|---|---|
| نورهان جمال احمد متولي احمد | 822822 |
| احمد حسين احمد محمد | 823801 |
| ايناس محى احمد السيد | 823802 |
| ايه مصطفى عبدربه احمد هلال | 823803 |

## Group D (Mr. Ahmed Yahia)

| | |
|---|---|
| طارق عادل ربيع علي | 823804 |
| كيرلس مجدى فهمي ابسخرون | 823805 |
| محمد حسن رمزى ابراهيم | 823806 |
| محمود ناصر محمد محمد منصور | 823807 |

# Group work-1


WALTER L. POHL
Economic Geology
Principles and Practice
WILEY-BLACKWELL

# Group work-2

**Harald G. Dill (2010): The "chessboard" classification scheme of mineral deposits: Mineralogy and geology from aluminum to zirconium. Review Article *Earth-Science Reviews, Volume 100, Issues 1–4, June 2010, Pages 1-420***

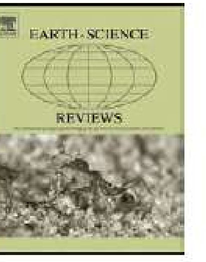
Earth-Science Reviews 100 (2010) 1–420

ELSEVIER

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev




The "chessboard" classification scheme of mineral deposits: Mineralogy and geology from aluminum to zirconium

Harald G. Dill

*Institute of Geosciences, Gem-Materials Research and Economic Geology, Johannes-Gutenberg-University Mainz, D-55099 Mainz, Becherweg 21, Germany*

| Geology of Economic Ores | |
|---|---|
| **Course Objective** | Knowledge of the basic information on Economic minerals and under-standing the concept of ore formation processes and distribution of ores in time and space. Through achieving the followings:<br><br>• Understanding the ore forming processes.<br>• Recognizing the abundance and distribution of minerals deposits related to plate tectonics, the relationship between ore-forming processes and the ore distribution.<br>• Be aware of the behavior of ore-bearing metals during magmatic crystallization, weathering and metamorphism. |

# Our Course

# Our Course

# Lecture One: Basics

# Lecture Contents

I. What is the structure of the Earth?

II. Plate tectonics

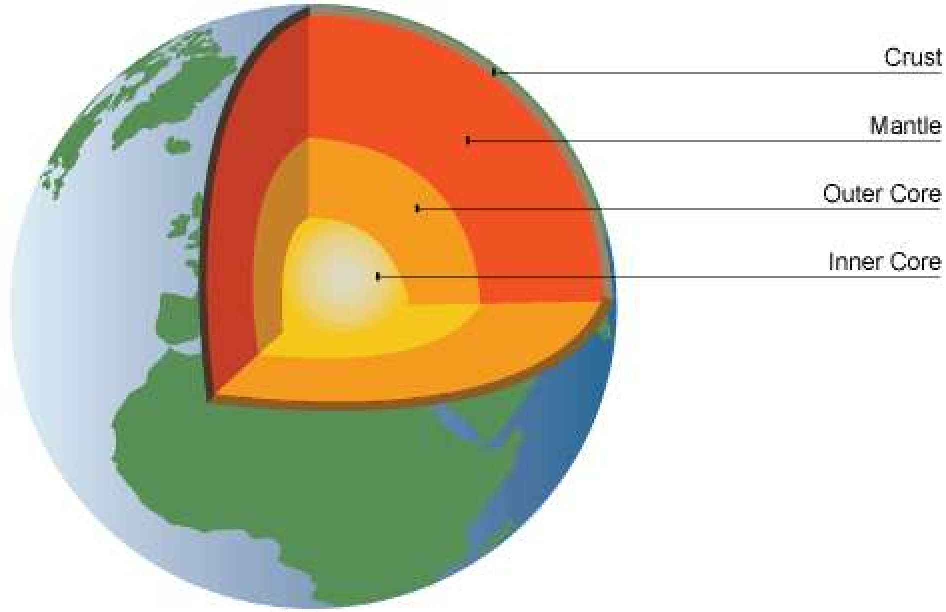
III. Types of Plate Boundary

IV. Plate Tectonics vs. Geological Processes

V. Magma.

# I. What is the structure of the Earth?

The Earth is an irregular sphere, with a radius that varies between 6,356 and 6,378 km. This solid sphere is chemically divided into layers that become less dense from the centre towards the surface.




The three main layers are:

(i) the Core (which comprises an Inner Core and an Outer Core);

(ii) the Mantle, and

(iii) the Crust.

Each layer has a distinctive chemical composition, and a different density.

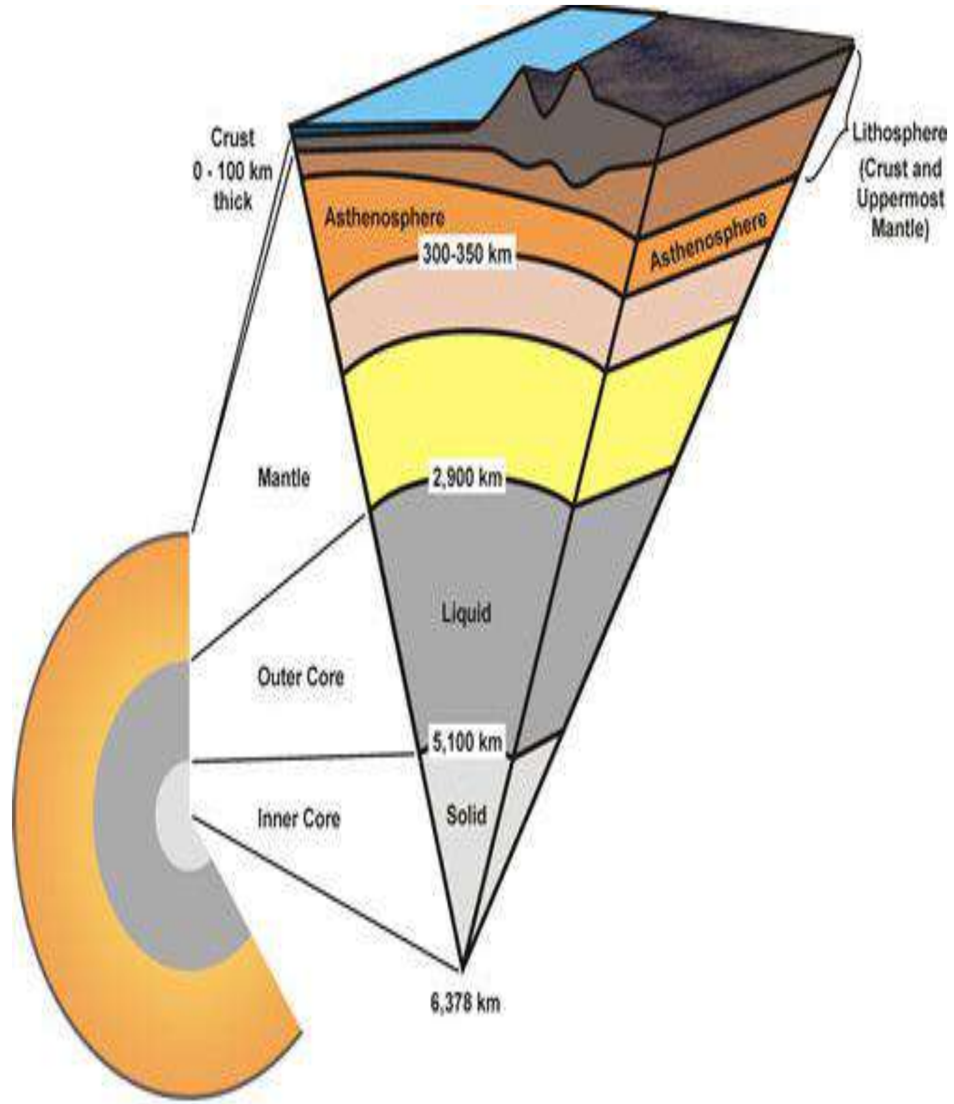
**The core** is primarily solid composed of the **heavy elements iron and nickel.** **The outer core is made of molten iron, which produces the Earth's magnetic field.**

**The mantle is less-dense than the core. The mantle extends to a depth of about 2,900 km. The mantle is rich in iron- and magnesium-bearing silicate minerals.**

**The outer layer of the Earth is termed the crust, which is divided into oceanic crust and continental crust. Overall, continental crust is richer in the element silica, and is less dense, than oceanic crust.**

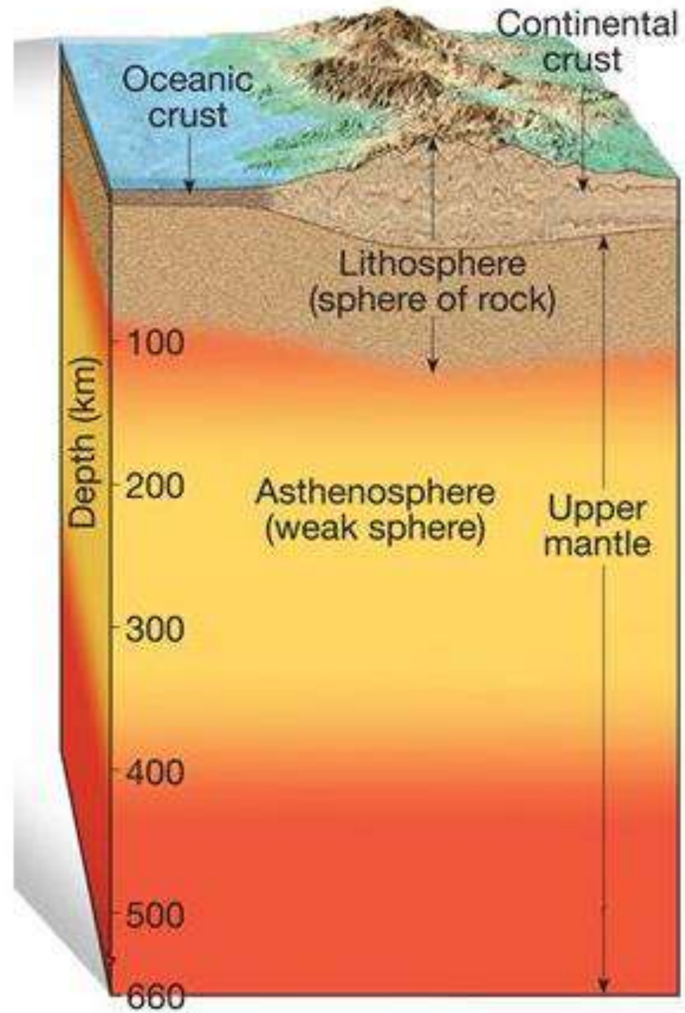
- **Oceanic crust (about 10 km thick) is composed of iron-, magnesium-, calcium-, and aluminium-rich silicate minerals that typically form a dark colored, heavy rock called basalt.**

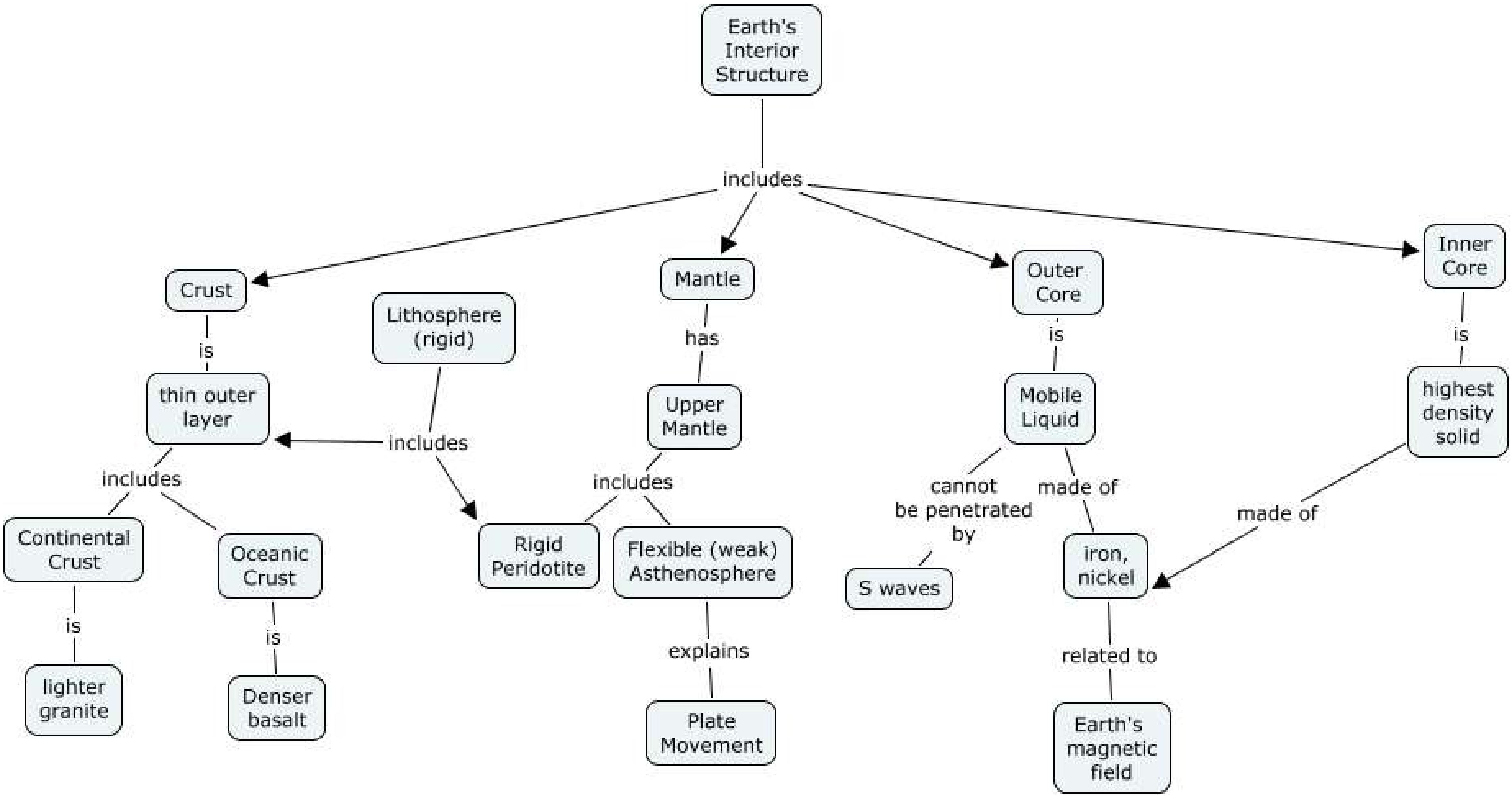
- **Continental crust (about 20 - 60 km thick) is composed of potassium-, sodium-, and aluminium-rich silicate minerals that form a diverse range of rock types such as granite.**

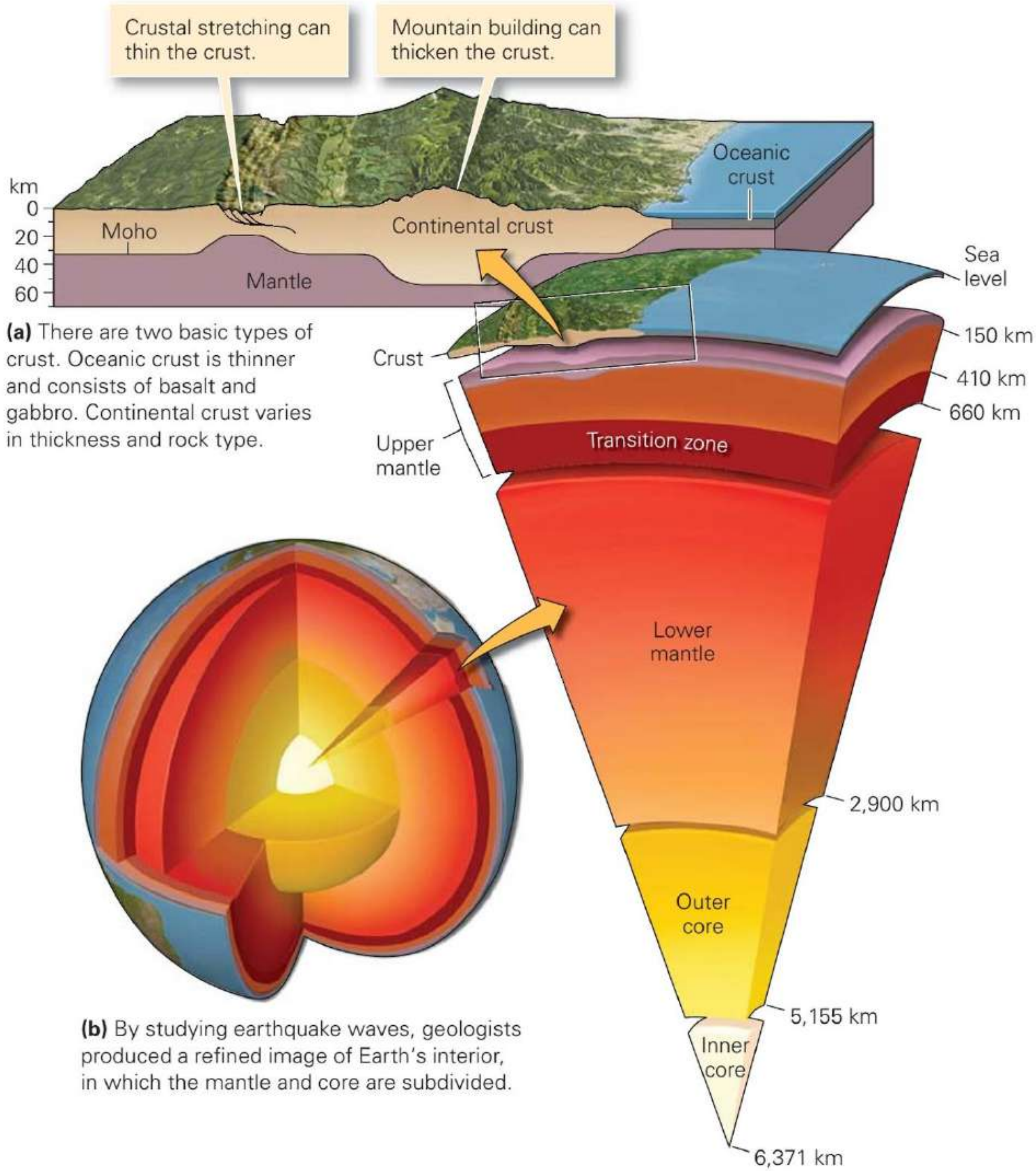



**The layers of the Earth.**

- Oceanic Crust
  - primarily basalt
  - 4-7 km thickness (thin relative to continental crust)
  - denser (heavier) than continental crust
- Continental Crust
  - primarily granite
  - 20-70 km thickness
  - less dense (will not undergo subduction)




Earth's Interior Structure
includes
Crust
Mantle
Outer Core
Inner Core
is
thin outer layer
Lithosphere (rigid)
includes
has
Upper Mantle
is
Mobile Liquid
is
highest density solid
includes
Continental Crust
Oceanic Crust
Rigid Peridotite
includes
Flexible (weak) Asthenosphere
cannot be penetrated by
S waves
made of
iron, nickel
made of
is
lighter granite
is
Denser basalt
explains
Plate Movement
related to
Earth's magnetic field




**(a)** There are two basic types of crust. Oceanic crust is thinner and consists of basalt and gabbro. Continental crust varies in thickness and rock type.

**(b)** By studying earthquake waves, geologists produced a refined image of Earth's interior, in which the mantle and core are subdivided.

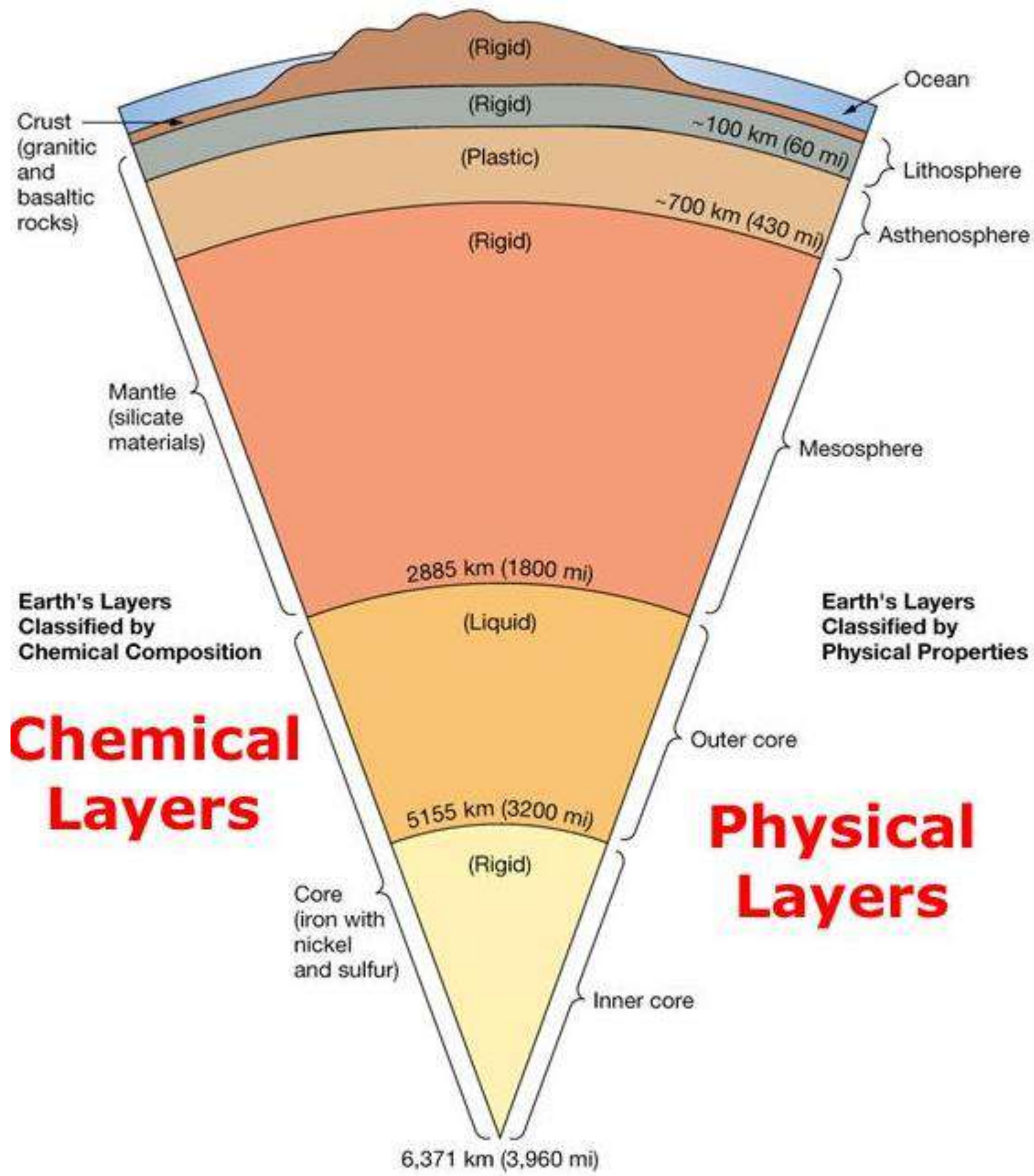
# Dynamic Structure of the Earth

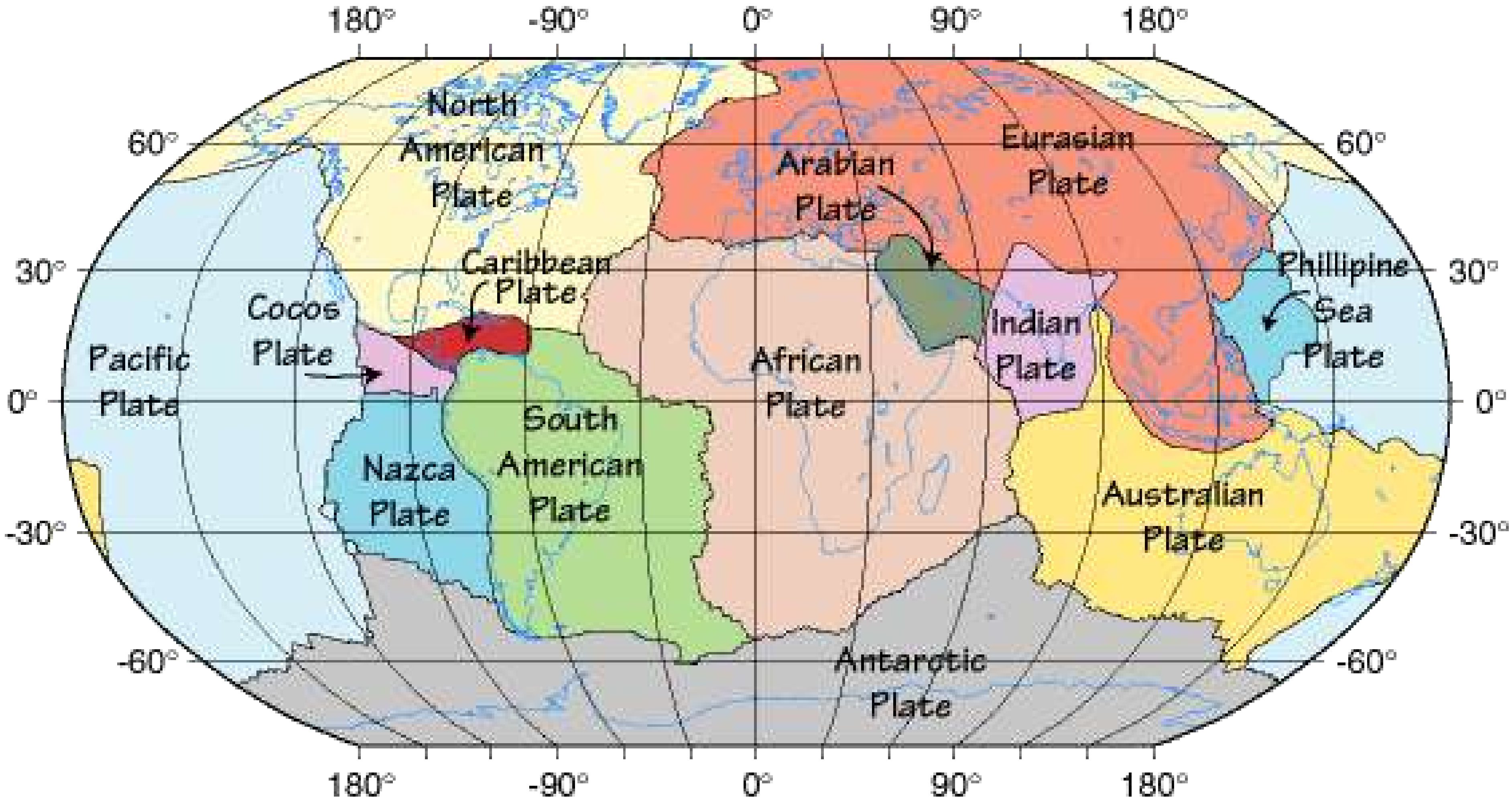
The Earth consists of series of concentric layers which differ in chemical and physical properties.

The crust and upper part of the mantle of the Earth is further subdivided into the lithosphere and the asthenosphere.

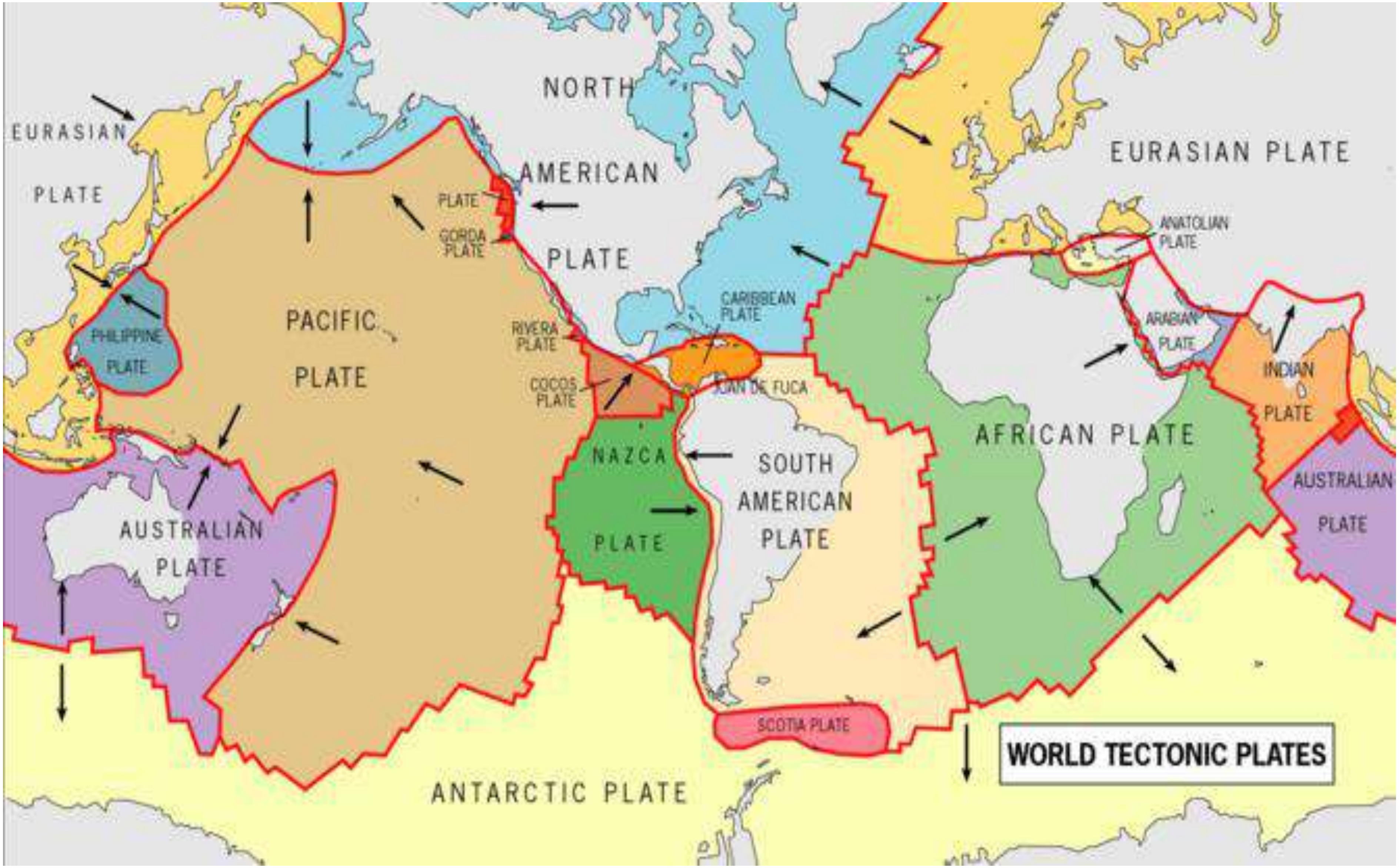
The lithosphere is a strong layer, extending to a depth of 100 to 150 km, that comprises the crust and part of the upper mantle (the upper rigid part). The lithosphere is separated into seven large plates, and several smaller plates.

These plates, which terminate at different types of plate boundary, move over the underlying asthenosphere.

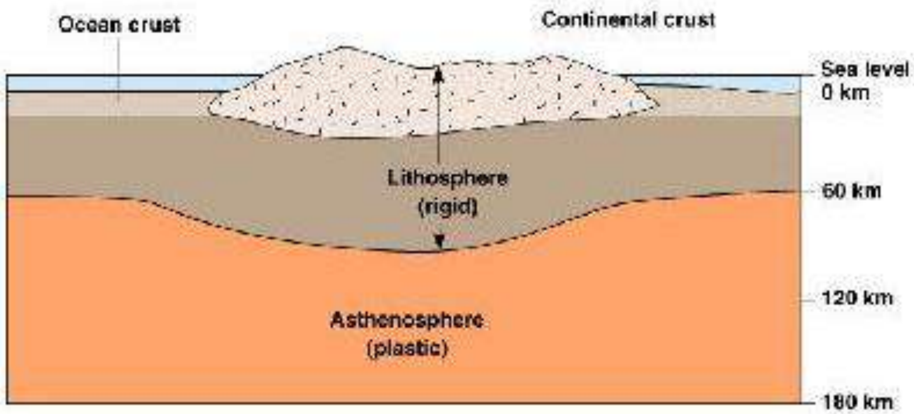


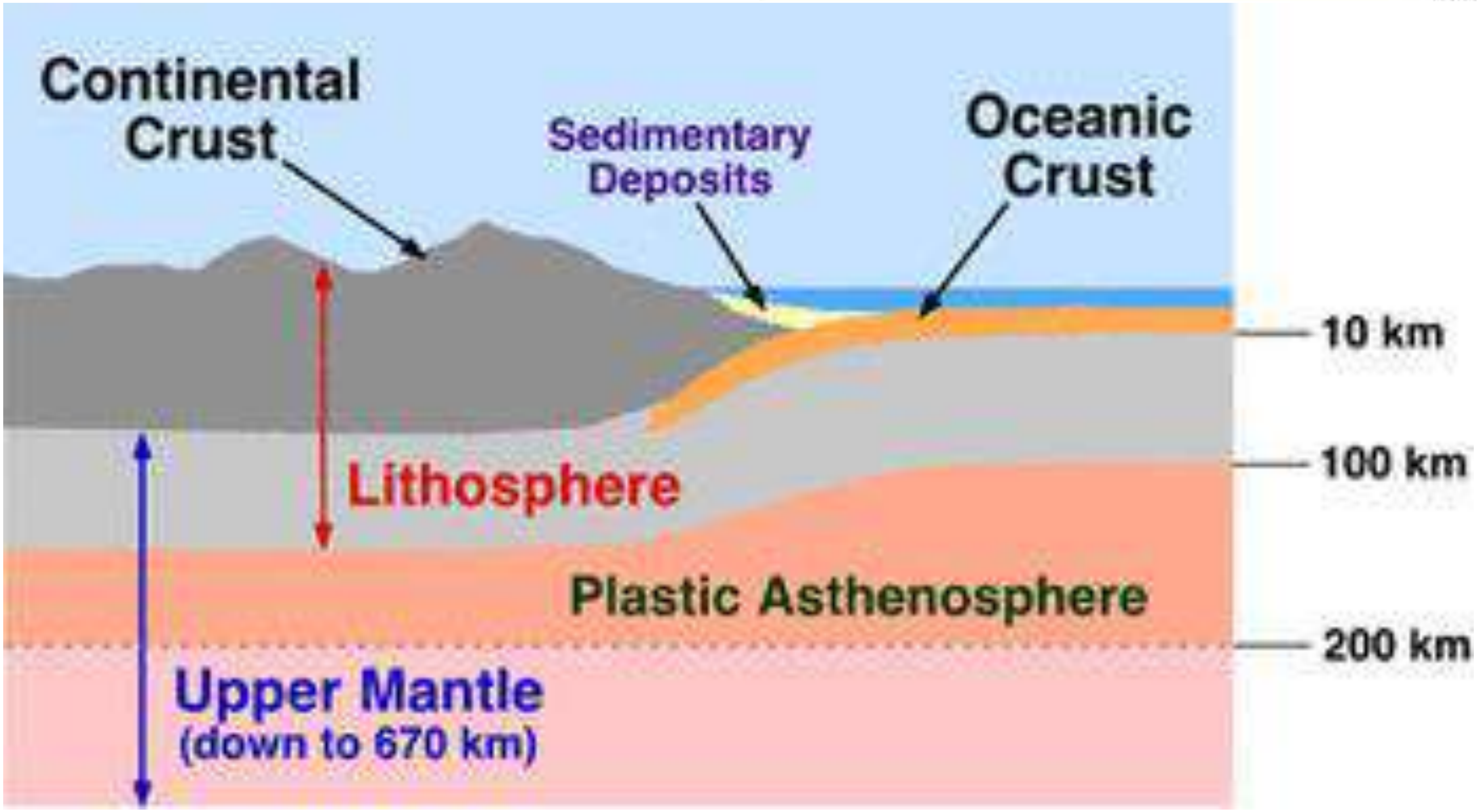


180°
-90°
0°
90°
180°
60°
30°
0°
-30°
-60°
North American Plate
Eurasian Plate
Arabian Plate
Caribbean Plate
Phillipine Sea Plate
Cocos Plate
Indian Plate
Pacific Plate
African Plate
South American Plate
Nazca Plate
Australian Plate
Antarctic Plate

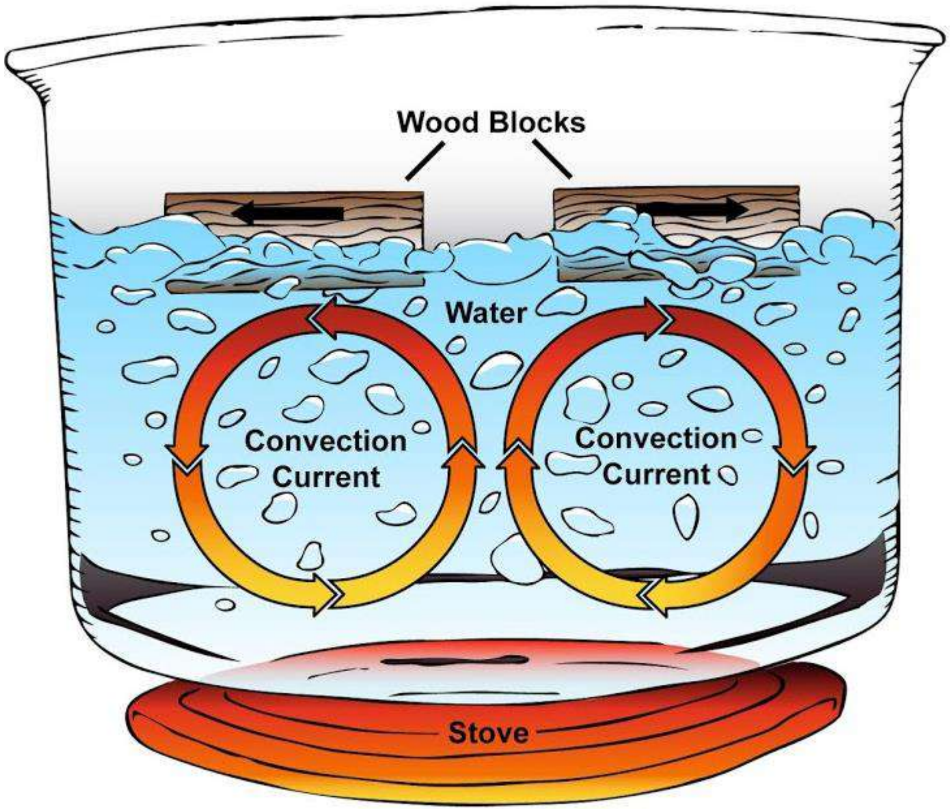

EURASIAN PLATE
NORTH AMERICAN PLATE
EURASIAN PLATE
PLATE
GORDA PLATE
ANATOLIAN PLATE
PACIFIC PLATE
PHILIPPINE PLATE
CARIBBEAN PLATE
RIVERA PLATE
COCOS PLATE
ARABIAN PLATE
INDIAN PLATE
JUAN DE FUCA
AFRICAN PLATE
NAZCA PLATE
SOUTH AMERICAN PLATE
AUSTRALIAN PLATE
AUSTRALIAN PLATE
SCOTIA PLATE
WORLD TECTONIC PLATES
ANTARCTIC PLATE

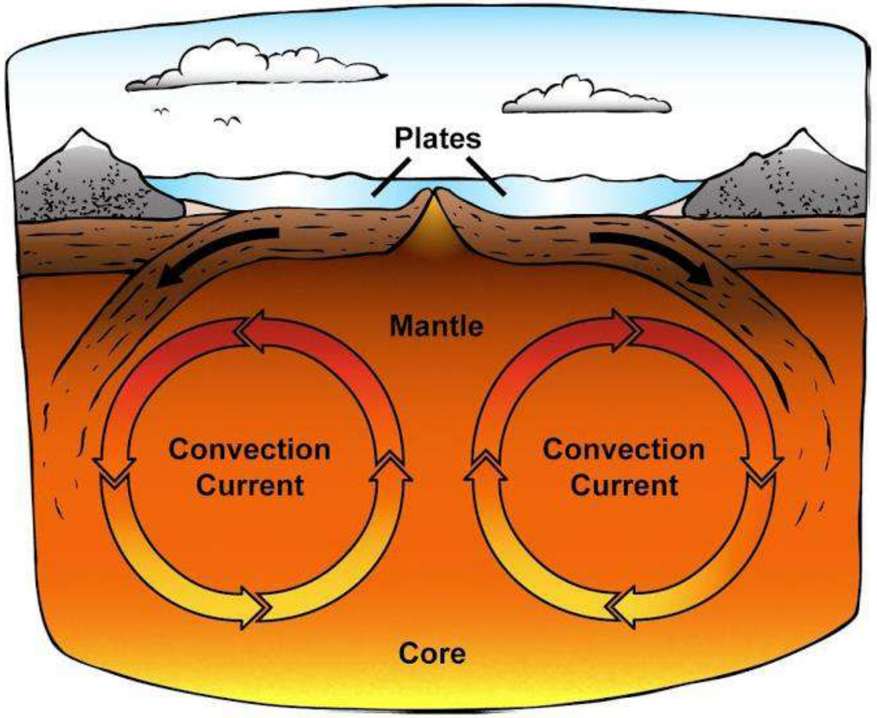
The asthenosphere (the middle part of the mantle - plastic, i.e., semi-liquid and ductile) is a weaker layer, upon which the lithospheric plates move, and from which magmas that form the oceanic crust are derived.



Heat from the Earth's core creates circulation patterns (i.e., convection currents) in the mantle drive the motions of the overlying plates. The slow movement of the lithospheric plates over the mobile asthenosphere is known as plate tectonics, a process that maintains the surface of the Earth in a dynamic and active state.

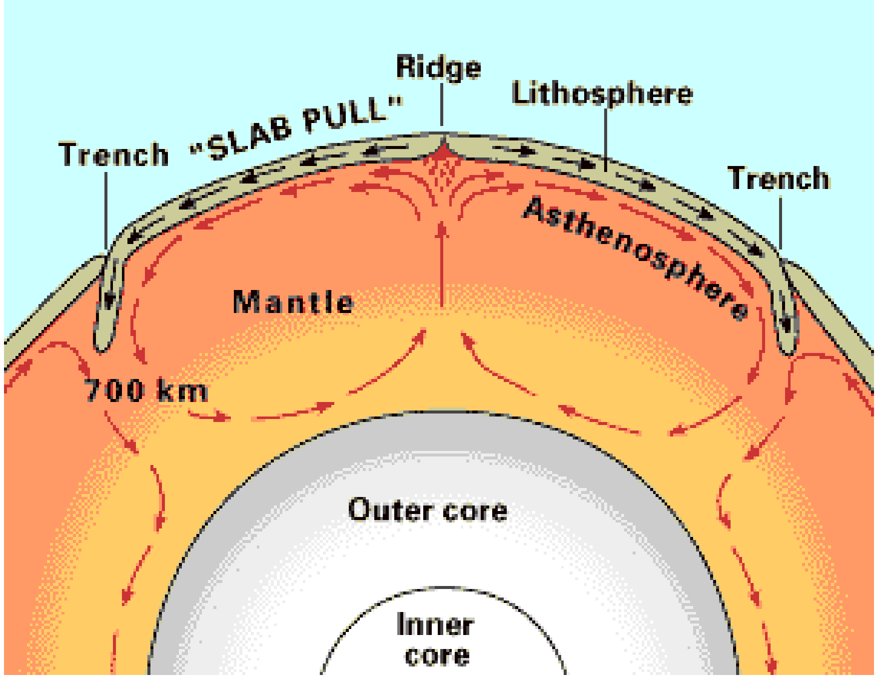


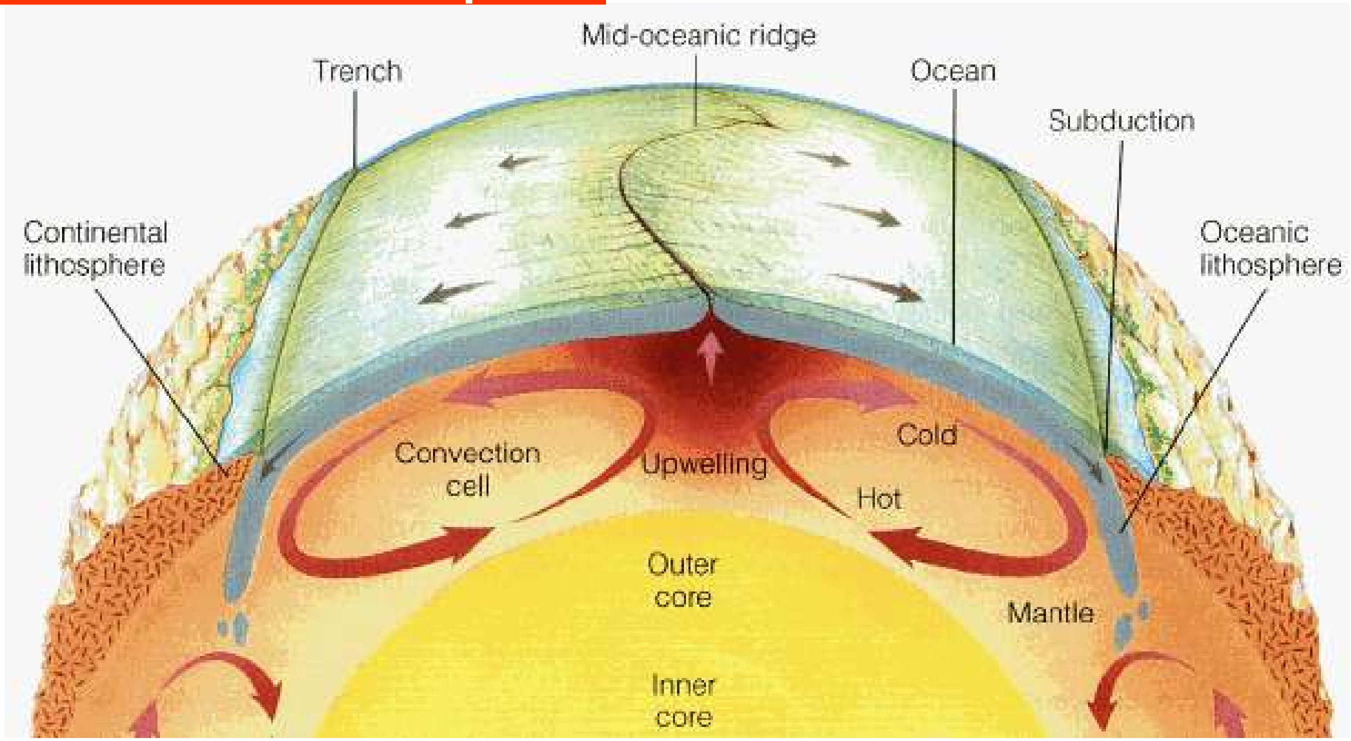



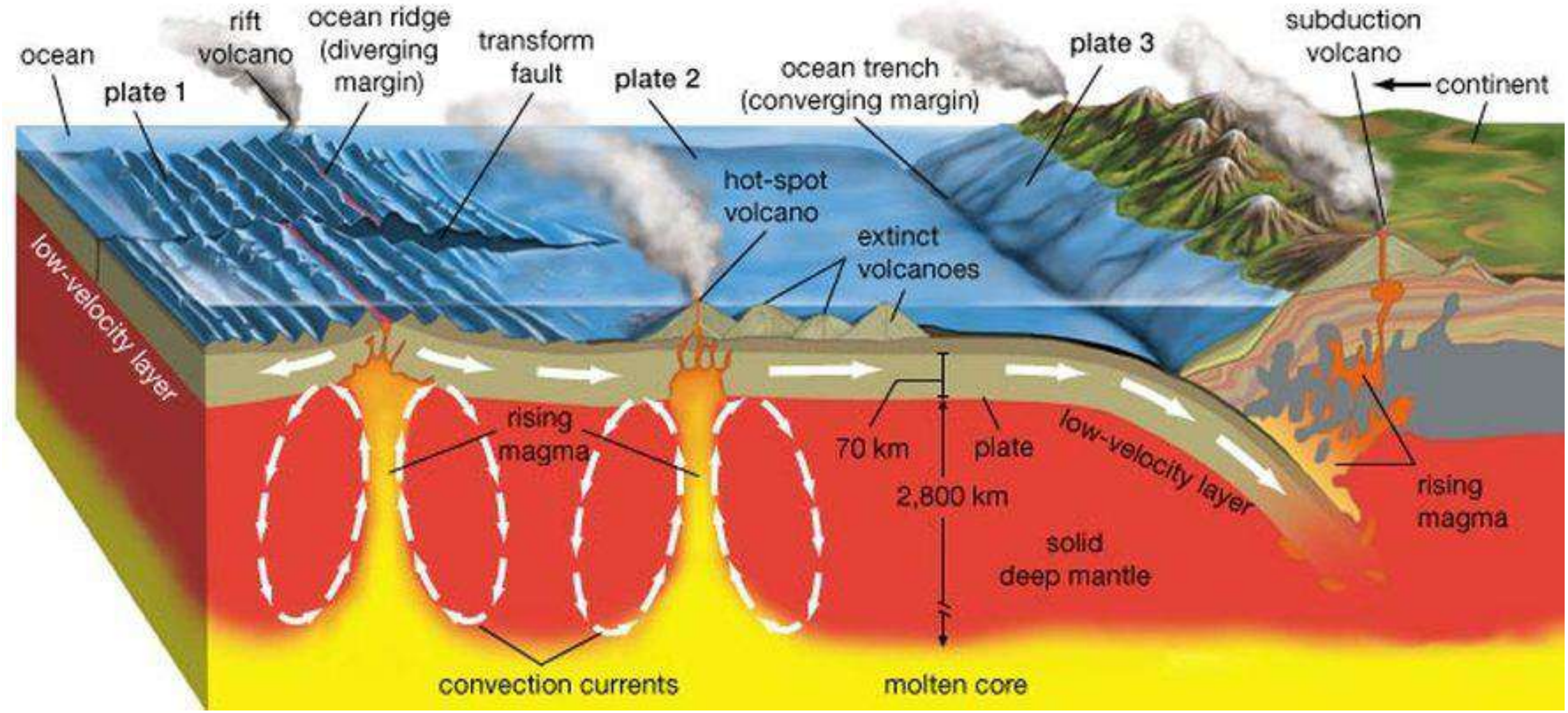

Convection: is the process in which energy is transferred through a material with any bulk motion of its particles. Convection is common in fluids.

**Convection currents** in the asthenosphere transfer heat to the surface, where **plumes of less dense magma break apart the plates** at the **spreading centers**, creating **divergent plate boundaries.**

As the plates move away from the **spreading centers**, they cool, and the higher density **basalt rocks** that make up ocean crust get consumed at the ocean trenches/subduction zones. **The crust is recycled back into the asthenosphere.**






**Because ocean plates are denser than continental plates, when these two types of plates converge, the ocean plates are subducted beneath the continental plates. Subduction zones and trenches are convergent margins. The collision of plates is often accompanied by earthquakes and volcanoes.**

# INSIDE THE EARTH

# II. Plate tectonics

**Plate tectonics (previously known as continental drift) originated from the geographical observation that the coastal profiles of South America and Africa seem to fit one another.**

**First proposed by Alfred Wegener in the 1920s, the crust was imagined to be made up of continent-sized slabs that "float" on a liquid layer and thus "drift" around.**

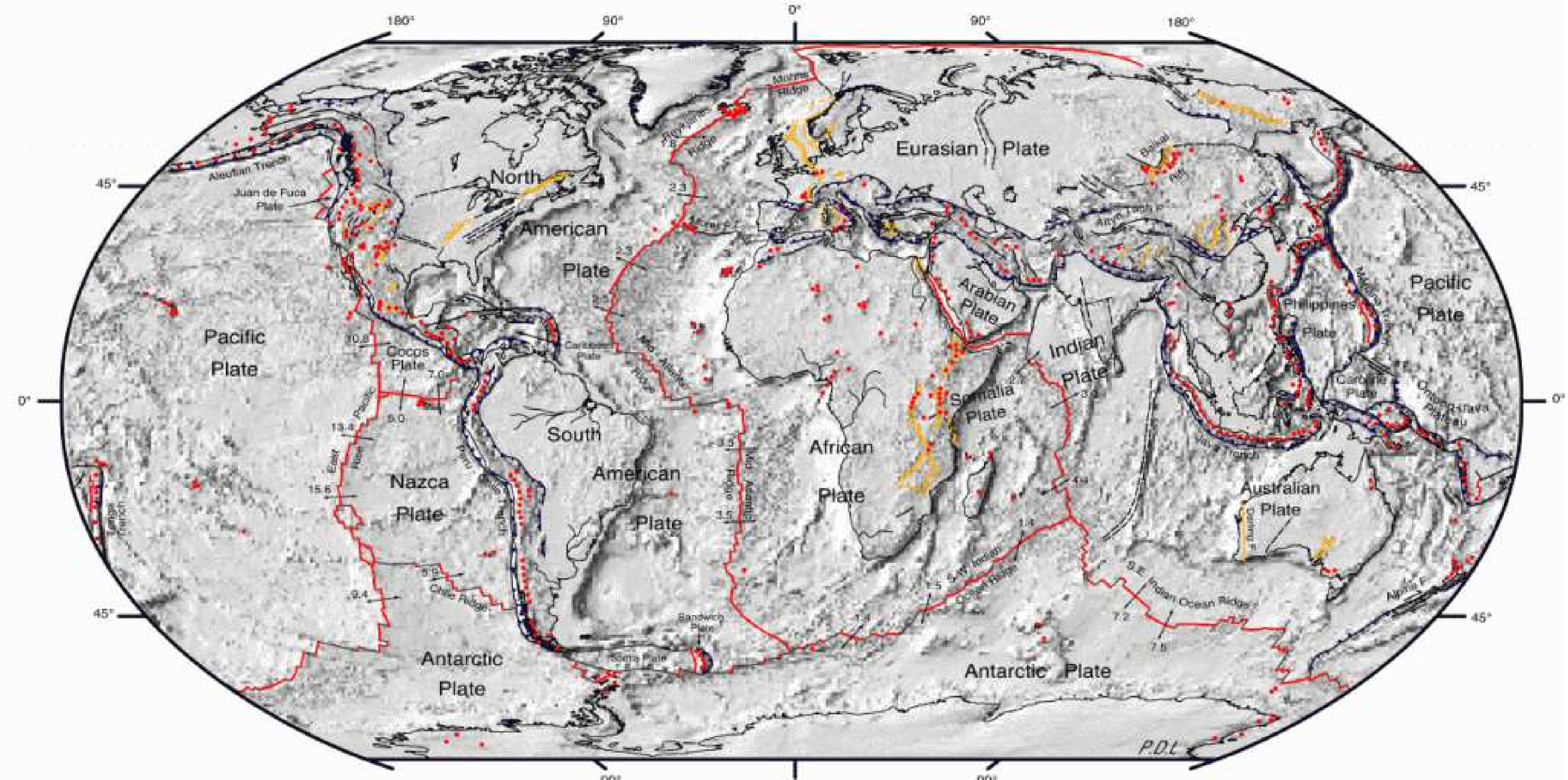
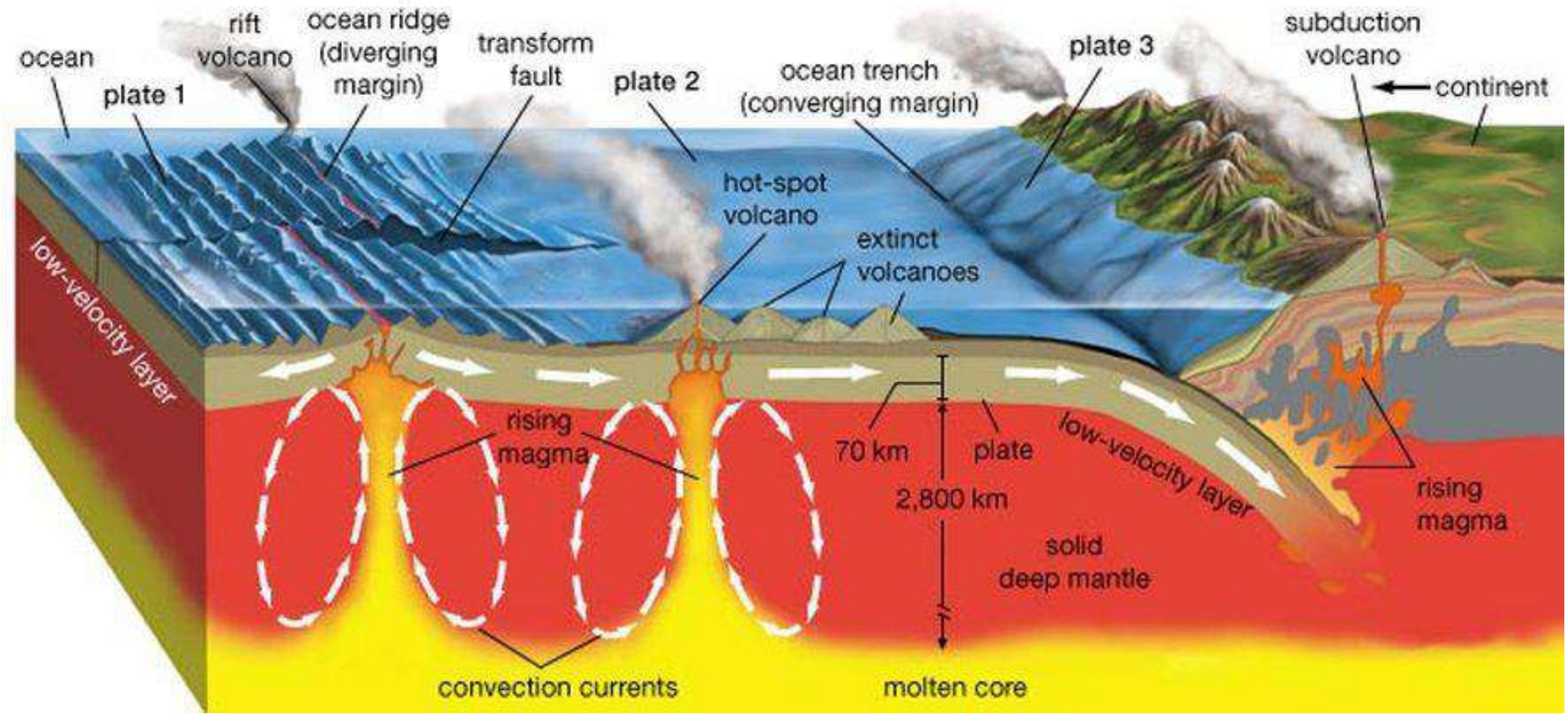
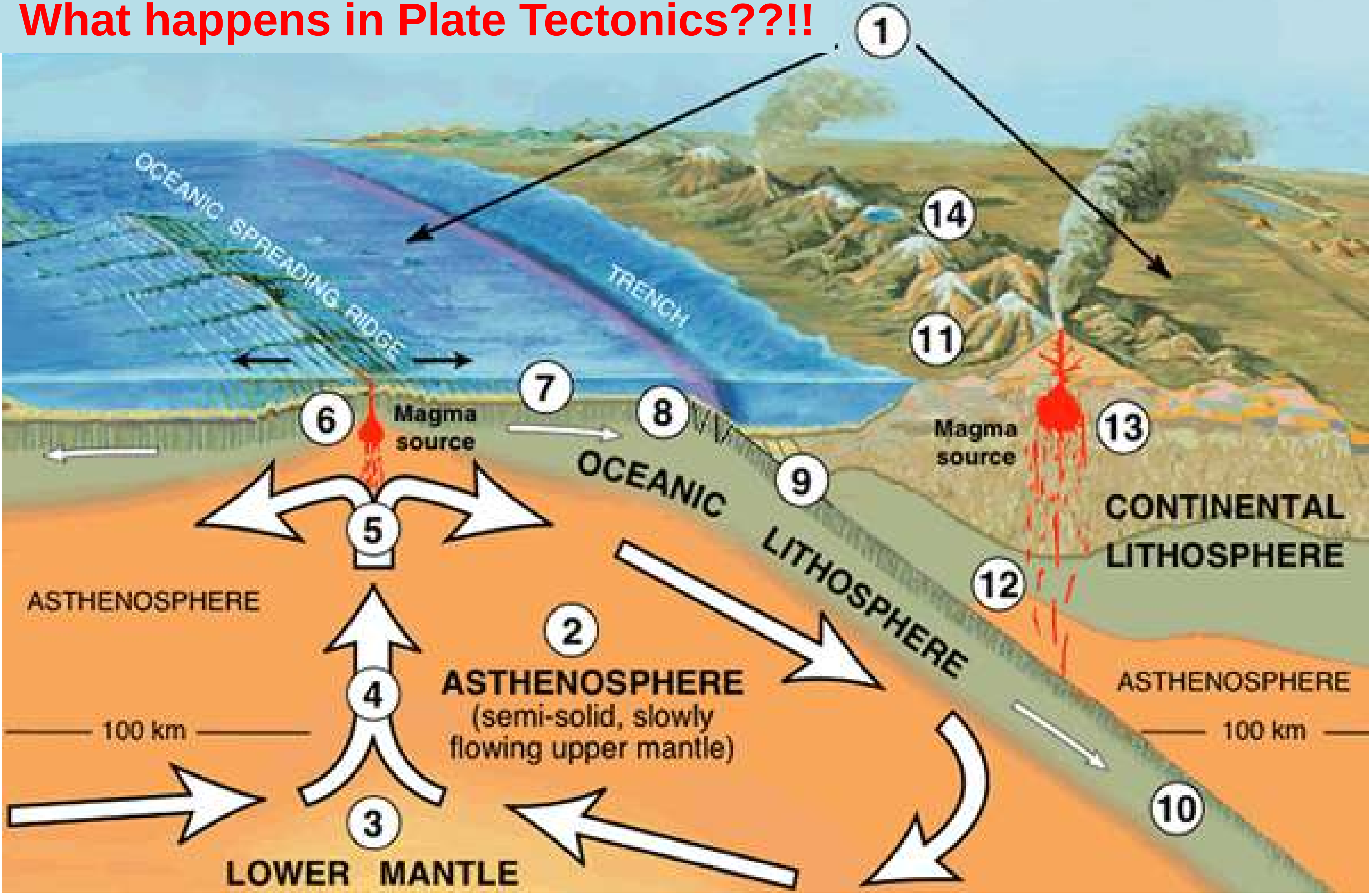


Plate tectonics, appeared in the 1960s when the mid-Atlantic ridge was discovered, along which injection rock material caused "spreading" and consequently leaving parallel north-south trending stripes of injected rock, the youngest of which was adjacent to the injection ridge and the oldest farthest from it.

The plate tectonics solution to the seafloor spreading dilemma was the proposition that new crustal mass created by injection must be compensated by "subduction", the diving of ocean crust (more dense) under opposing continental plates (less dense). Subduction zones and trenches are convergent margins. The collision of plates is often accompanied by earthquakes and volcanoes.

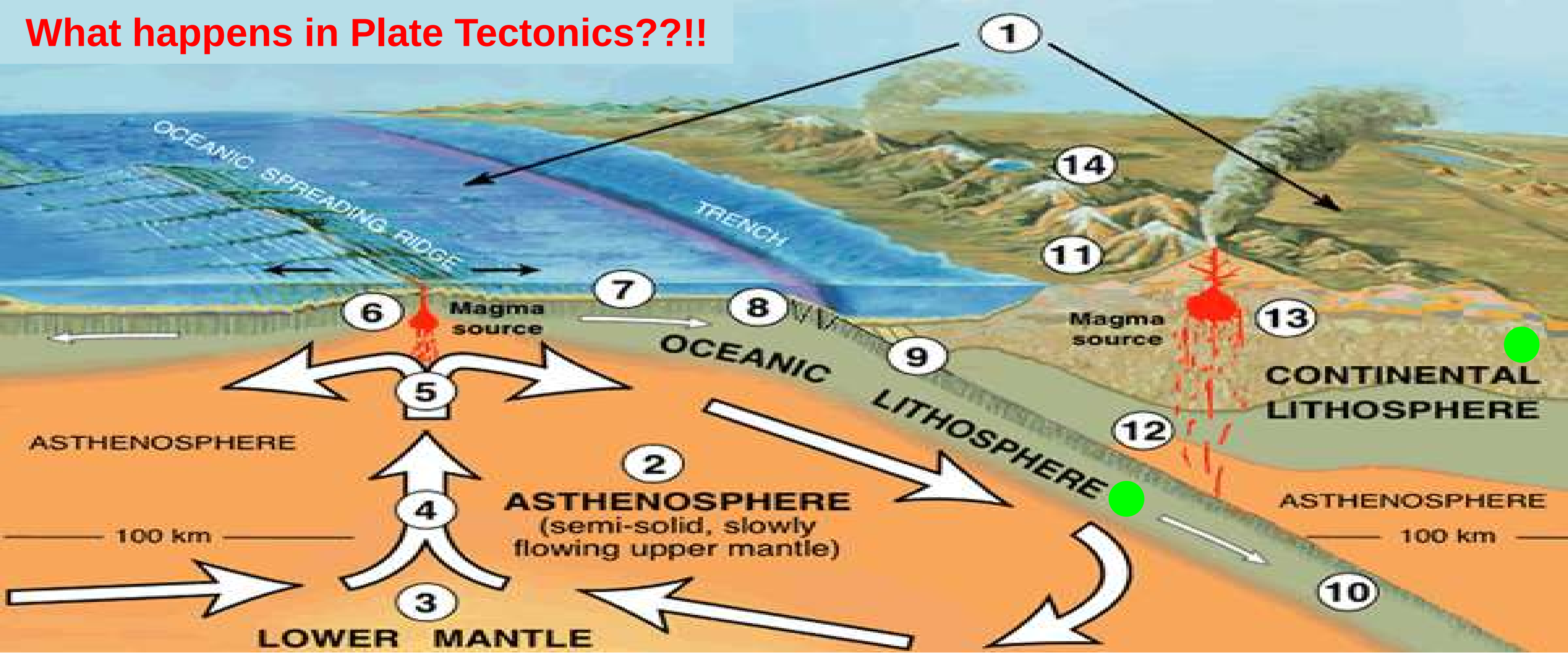


# What happens in Plate Tectonics??!!

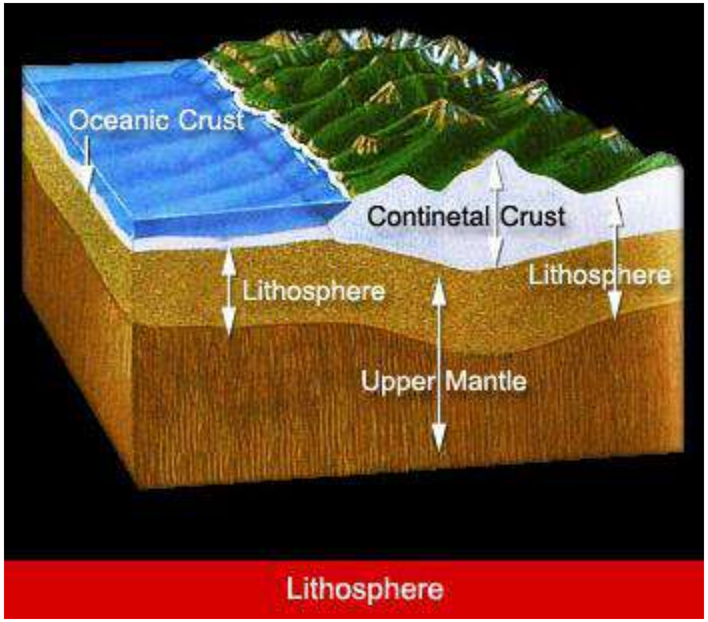



**This diagram shows the interaction between continental and oceanic plates, the processes illustrated generally apply for the interaction between two oceanic plates.**

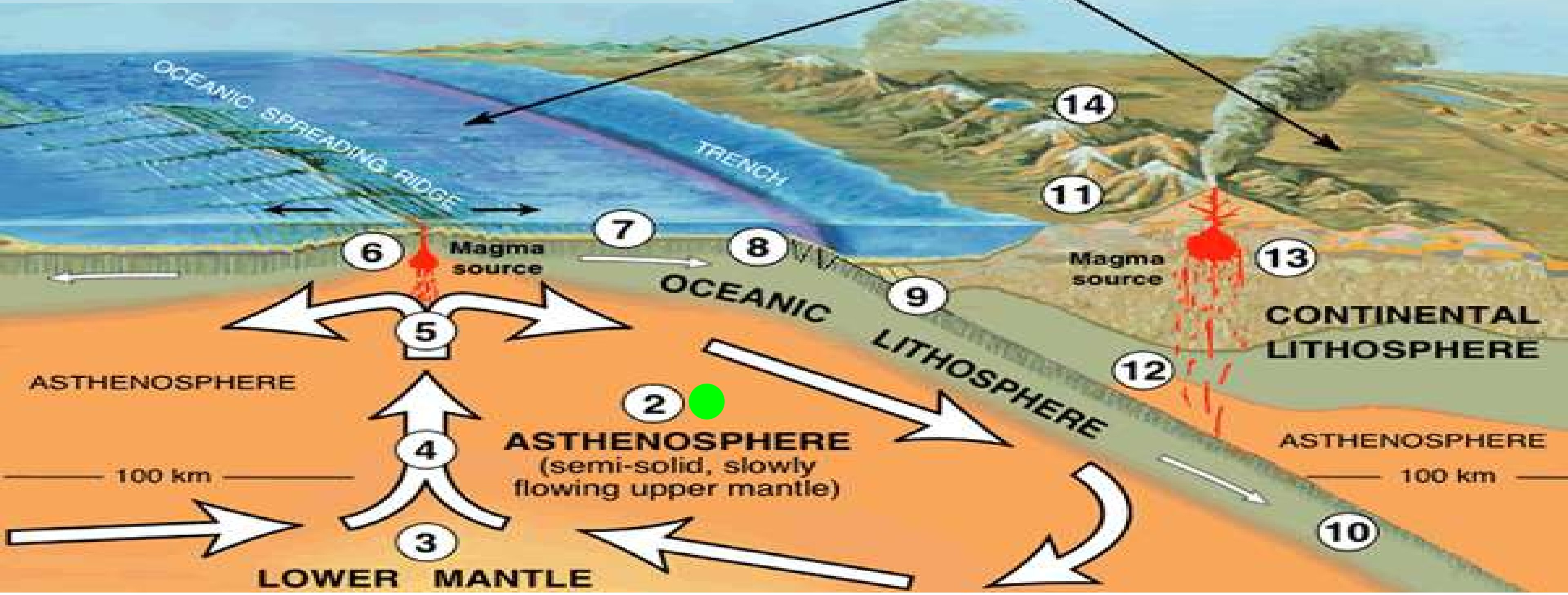
# What happens in Plate Tectonics??!!



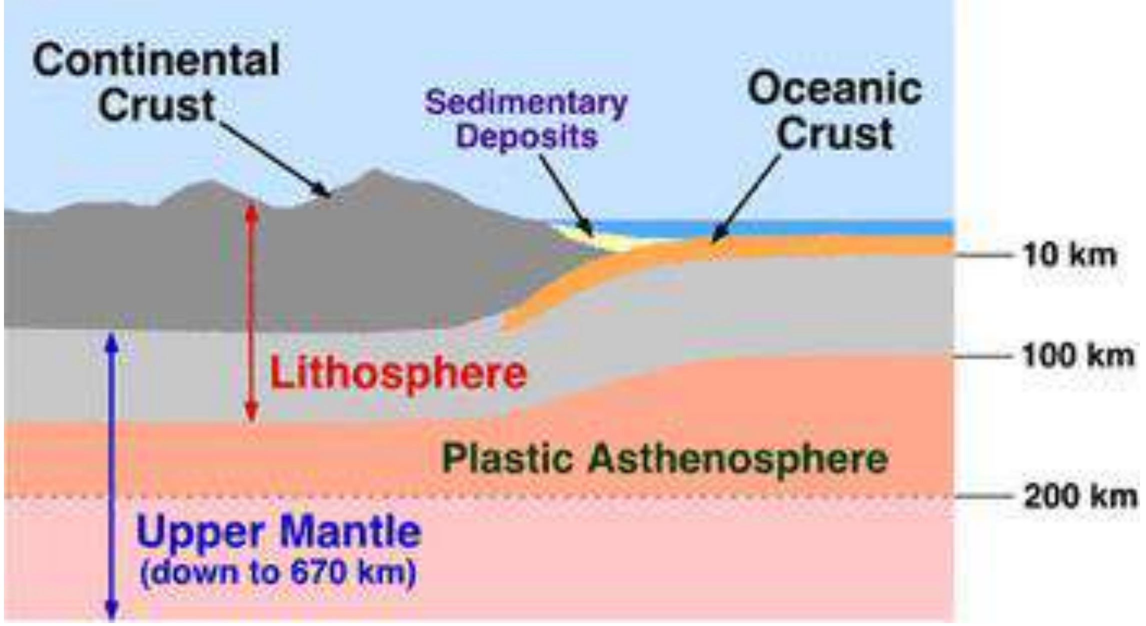

1. There are two basic types of LITHOSPHERE: **CONTINENTAL lithosphere** has a low density because it is made of relatively light-weight minerals. **OCEANIC lithosphere** is denser because it is composed of heavier minerals. **A plate may be made up entirely of oceanic or continental lithosphere, but most are partly oceanic and partly continental.**



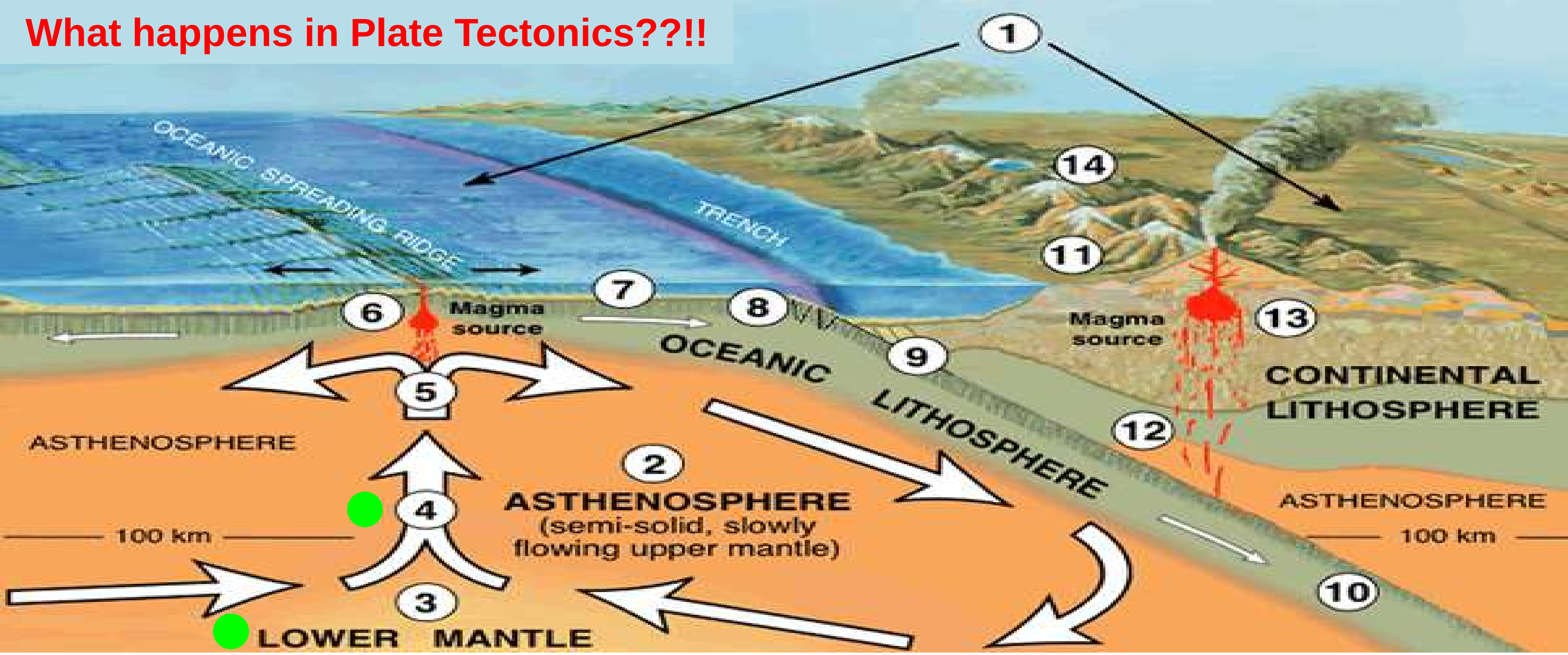
# What happens in Plate Tectonics??!!




2. Beneath the lithospheric plates lies the ASTHENOSPHERE, a layer of the mantle composed of denser semi-solid rock. Because the plates are less dense than the asthenosphere beneath them, they are floating on top of the asthenosphere.

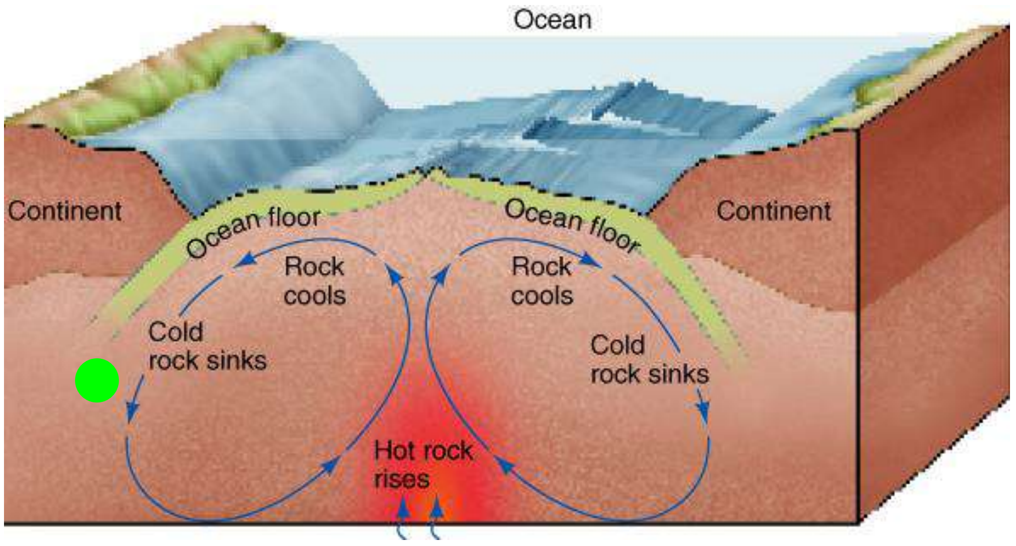


# What happens in Plate Tectonics??!!

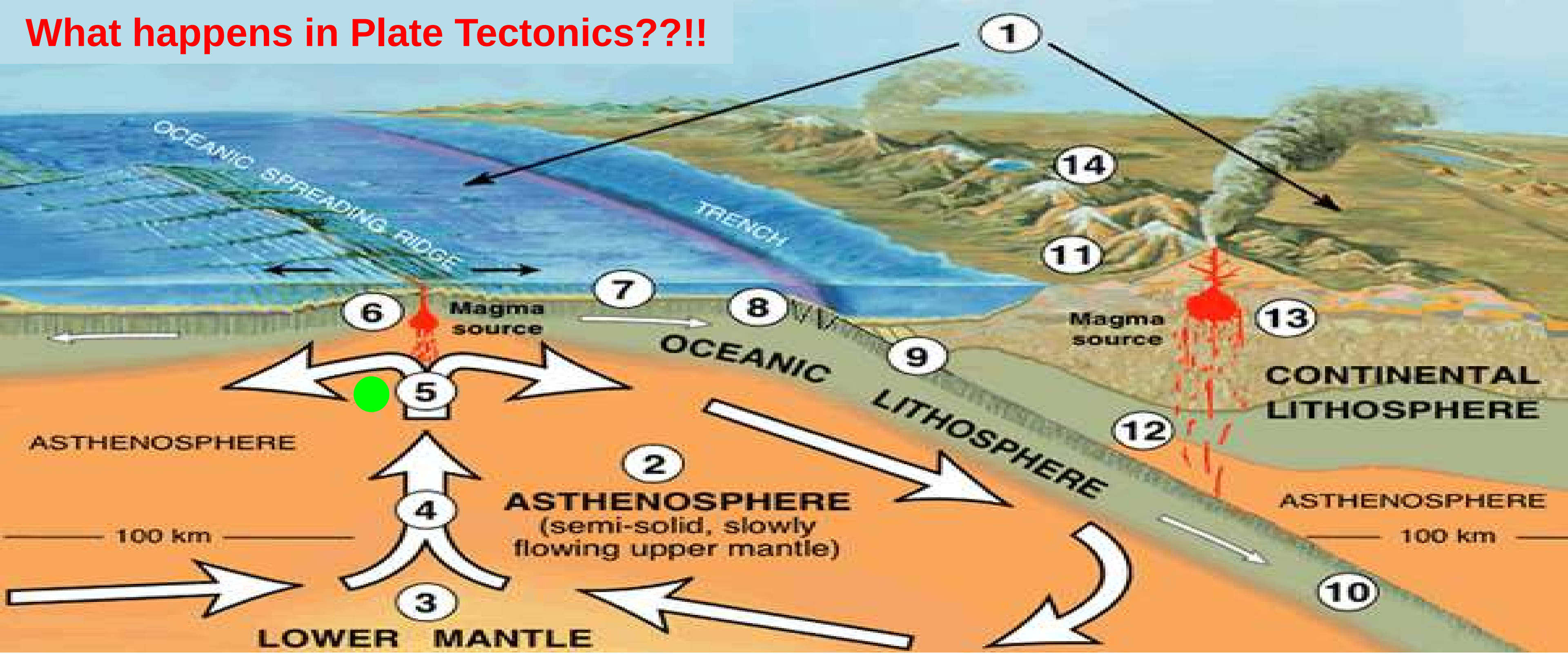



**3. Deep within the asthenosphere the pressure and temperature are so high that the rock can soften and partly melt. The softened dense rock can flow very slowly. Because of the temperature instabilities near the core/mantle boundary, slowly moving convection currents are formed within the semi-solid asthenosphere.**

**4. Once formed, convection currents bring hot material from deeper within the mantle up toward the surface.**

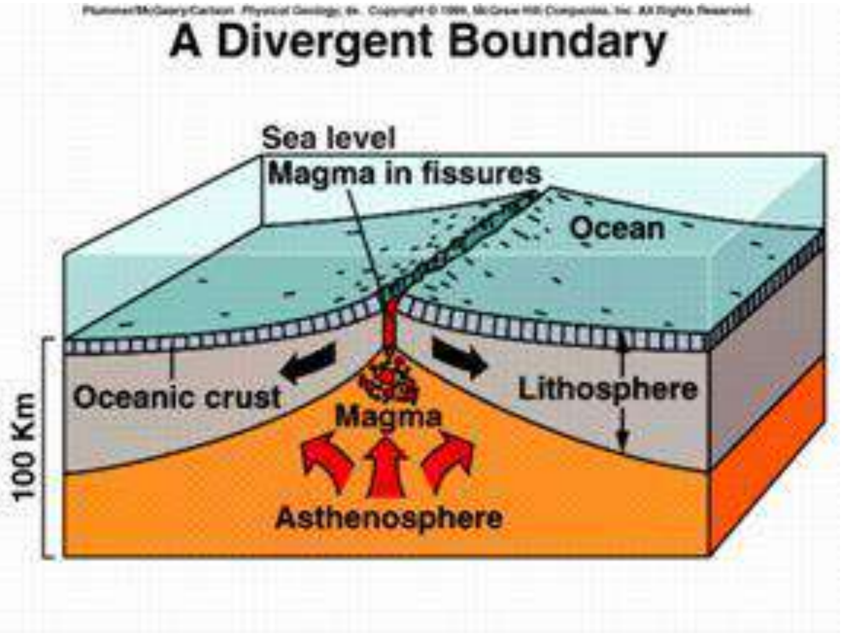


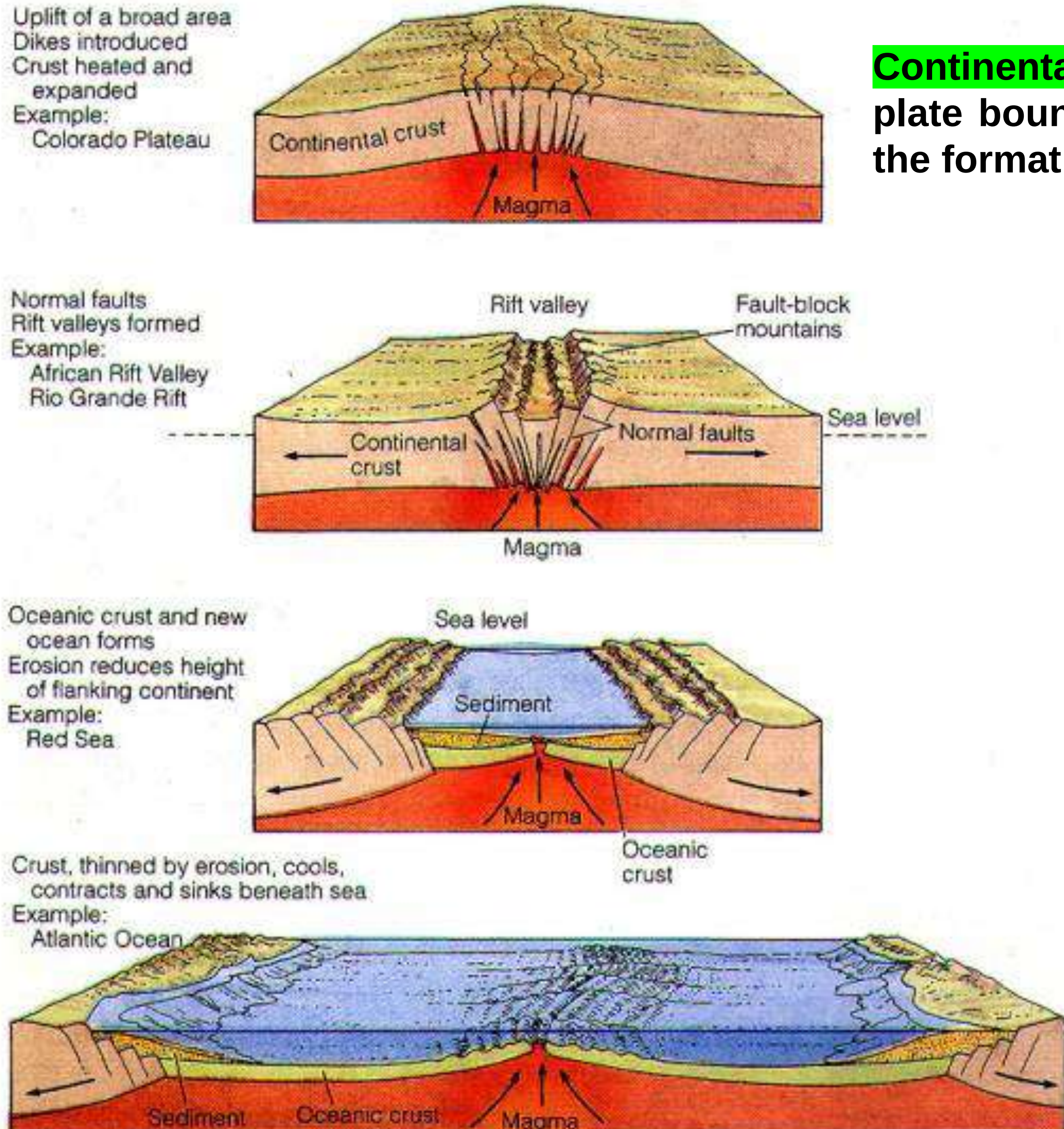
# What happens in Plate Tectonics??!!




5. As they rise and approach the surface, convection currents diverge يفلق/يمزع at the base of the lithosphere. The diverging currents exert a tension or "pull" on the solid plate above it.

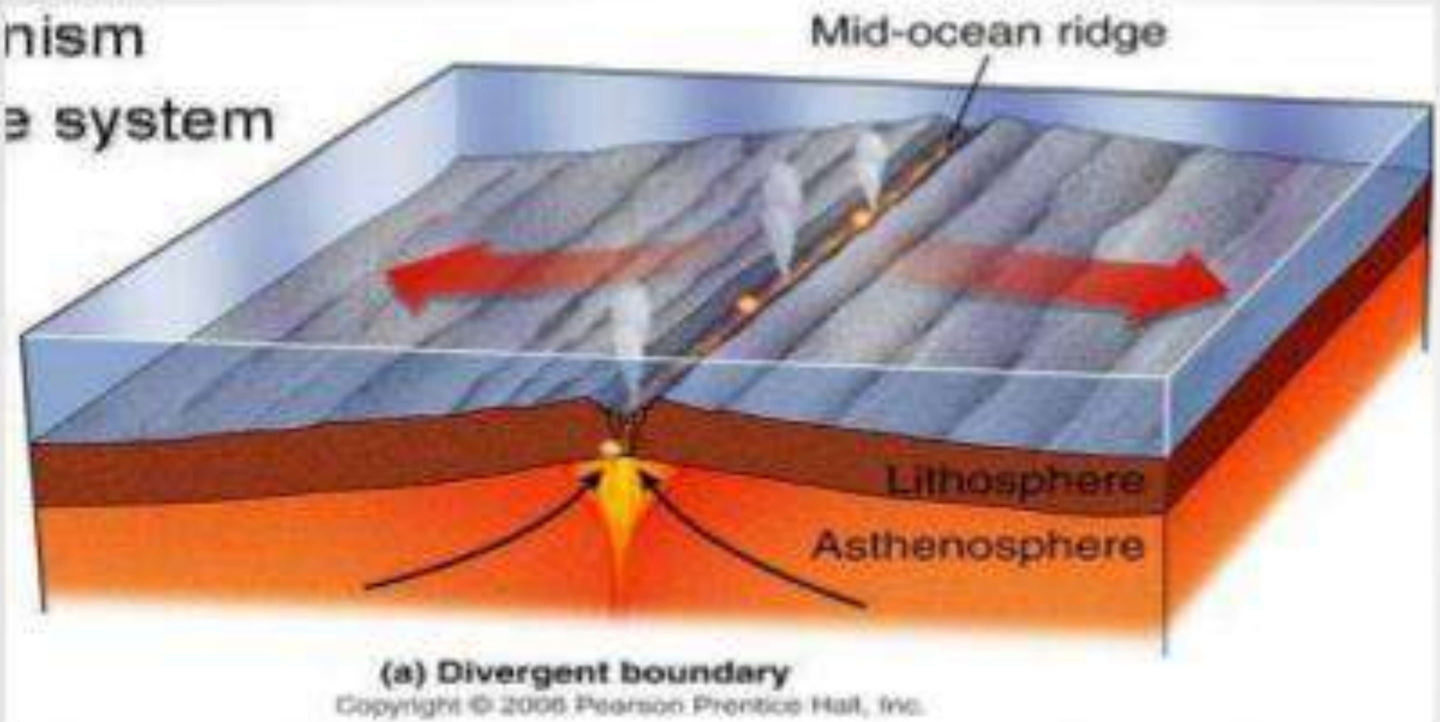
Tension and high heat flow weakens the floating, solid plate, causing it to break apart. The two sides of the now-split plate then move away from each other, forming a DIVERGENT PLATE BOUNDARY.





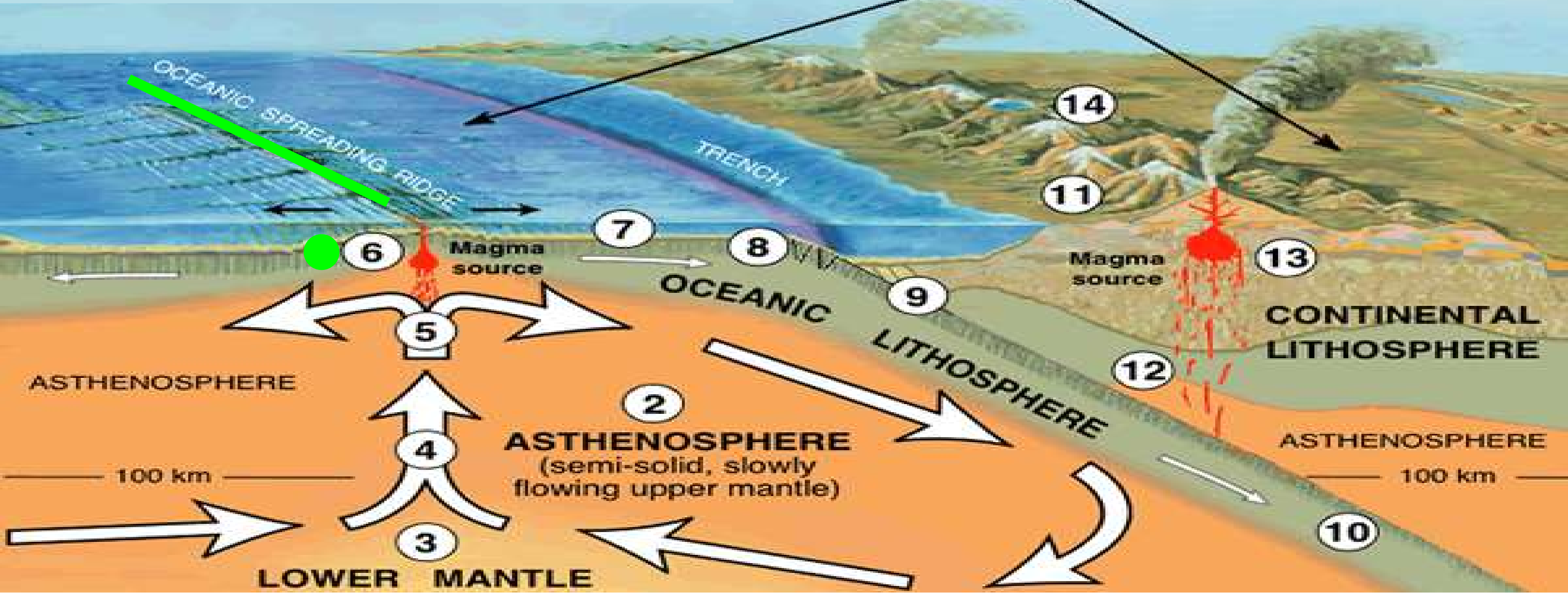

**Continental divergent plate boundary leads to the formation of rift.**

# Oceanic - Oceanic

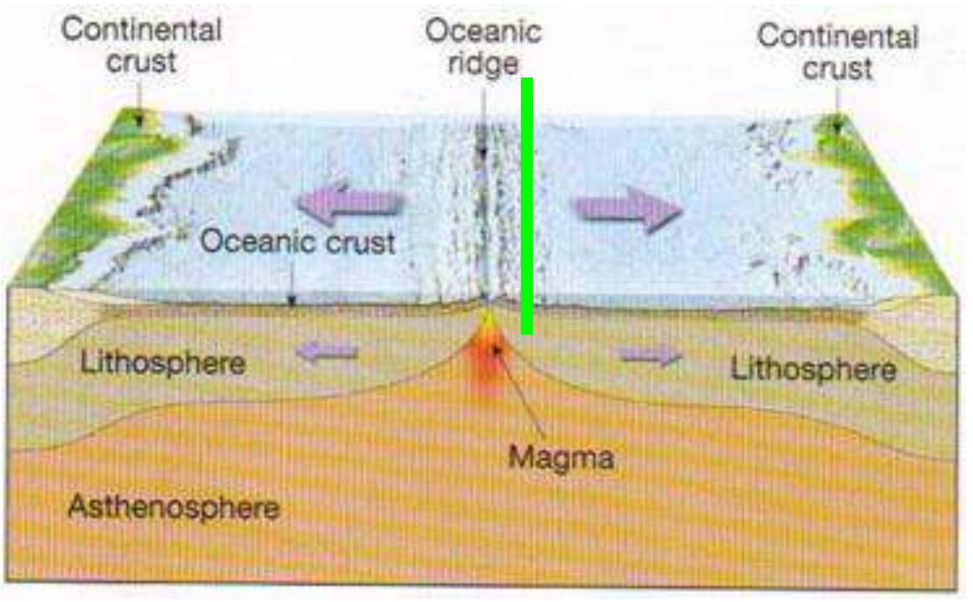



oceanic - oceanic divergent plate boundary form Mid ocean ridge

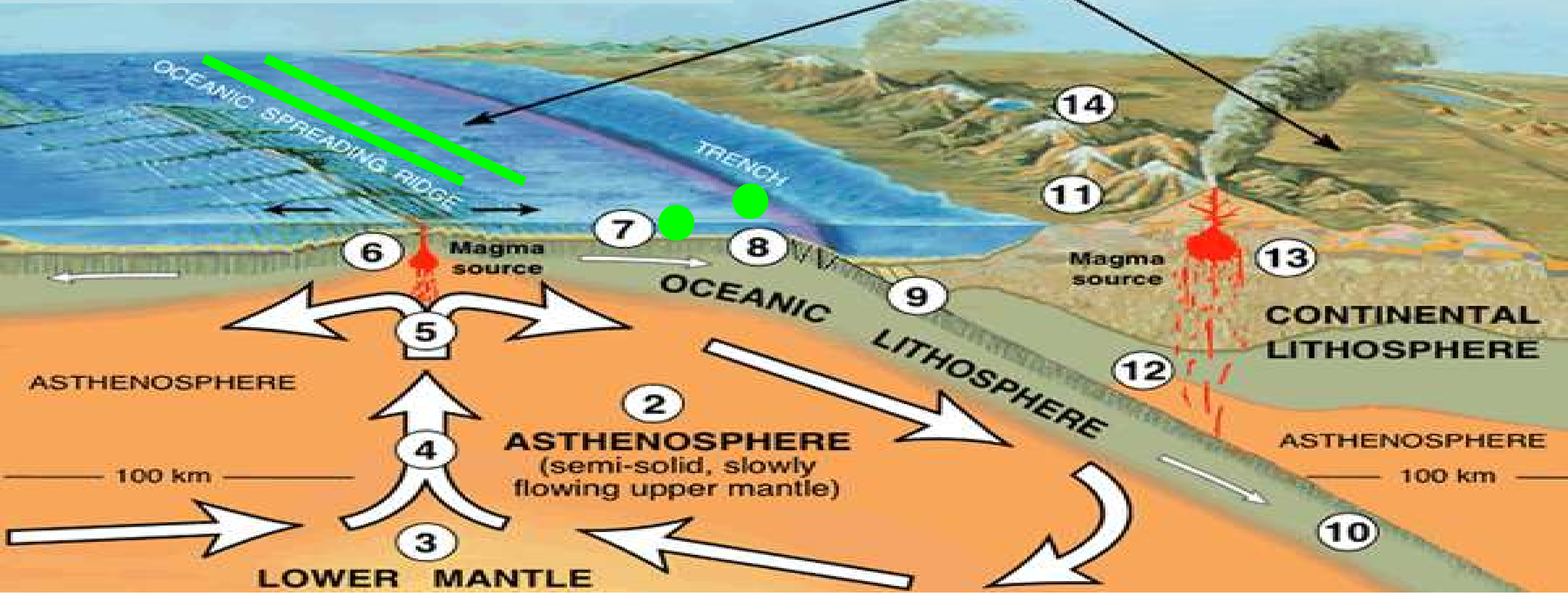
## What happens in Plate Tectonics??!!




**6. The space between these diverging plates is filled with molten rocks (magma) from below. Contact with seawater cools the magma, which quickly solidifies, forming new oceanic lithosphere. This continuous process, operating over millions of years, builds a chain of submarine volcanoes and rift valleys called a MID-OCEAN RIDGE or an OCEANIC SPREADING RIDGE.**



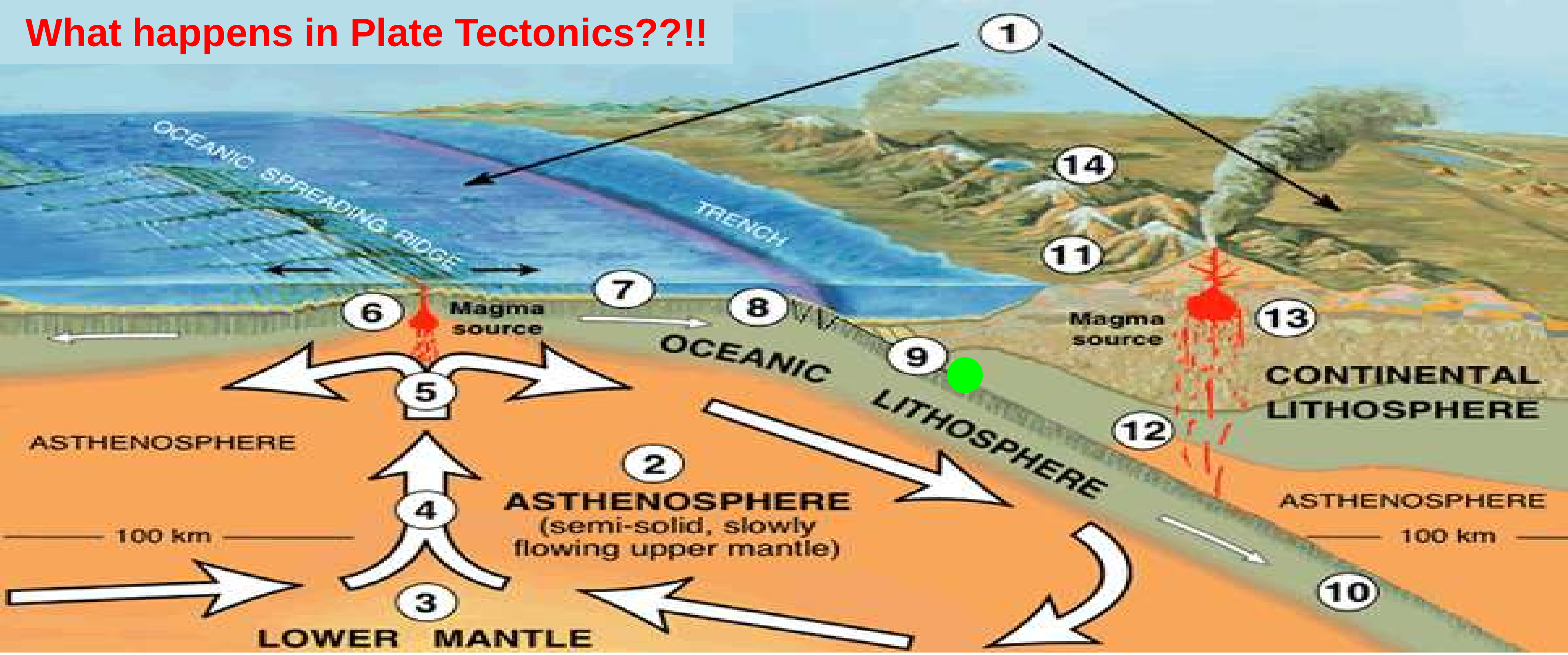
# What happens in Plate Tectonics??!!



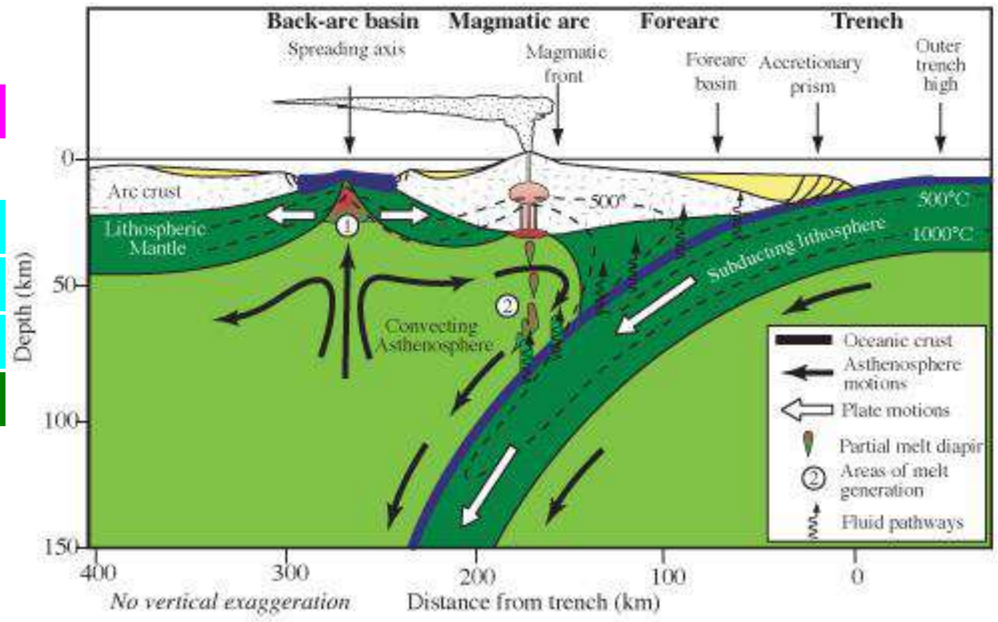

7. As new molten rock continues to be extruded at the mid-ocean ridge and added to the oceanic plate (6), the older (earlier formed) part of the plate moves away from the ridge.

8. As the oceanic plate moves farther and farther away from the active, hot spreading ridge, it gradually cools down. The colder the plate gets, the denser ("heavier") it becomes. Eventually, the edge of the plate that is farthest from the spreading ridges cools so much that it becomes denser than the asthenosphere beneath it.

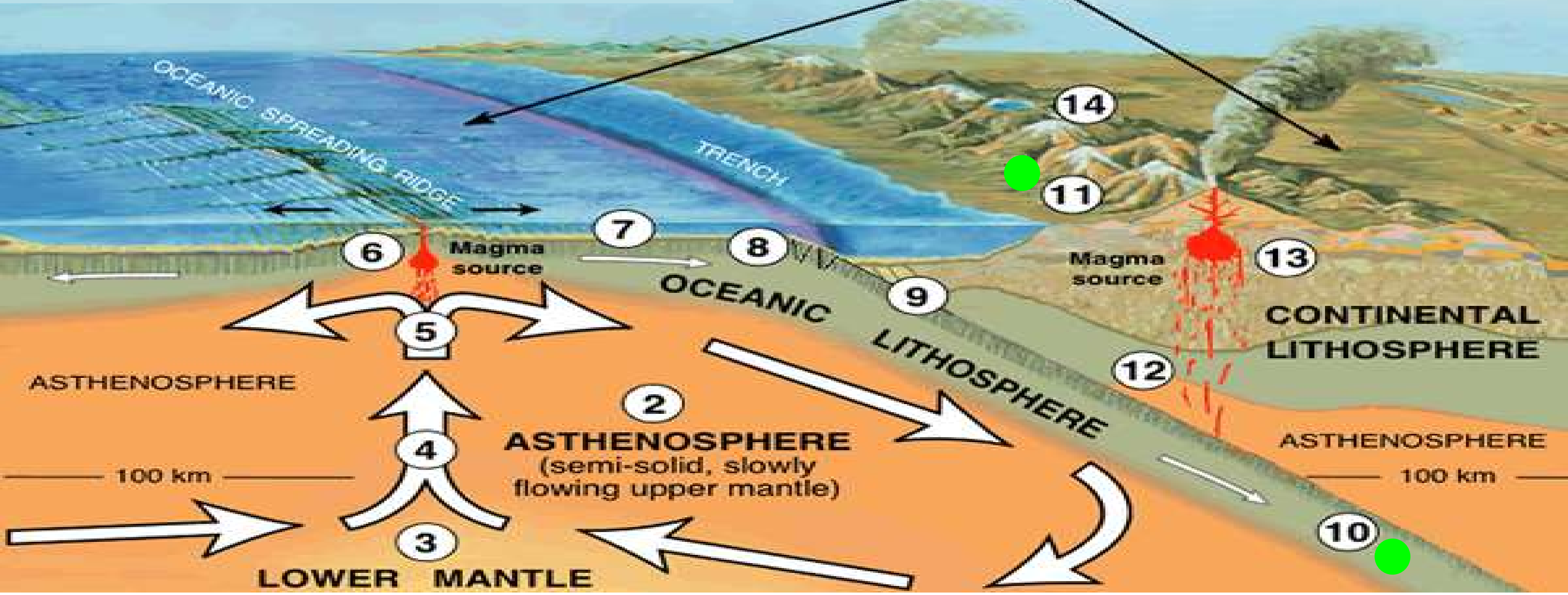
# What happens in Plate Tectonics??!!




**9. As it is known, denser materials sink, and that's exactly what happens to the oceanic plate—it starts to sink into the asthenosphere! Where one plate sinks beneath another a subduction zone forms.**

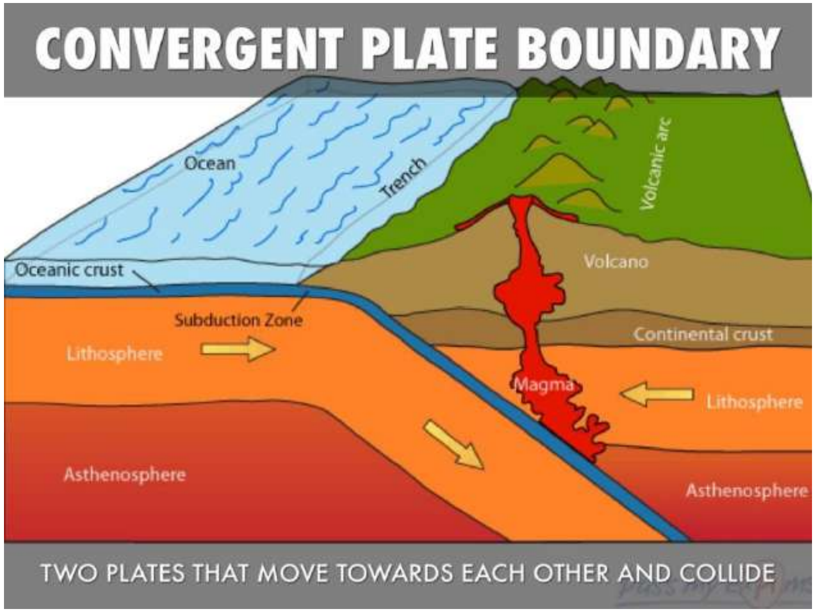


What happens in Plate Tectonics??!!

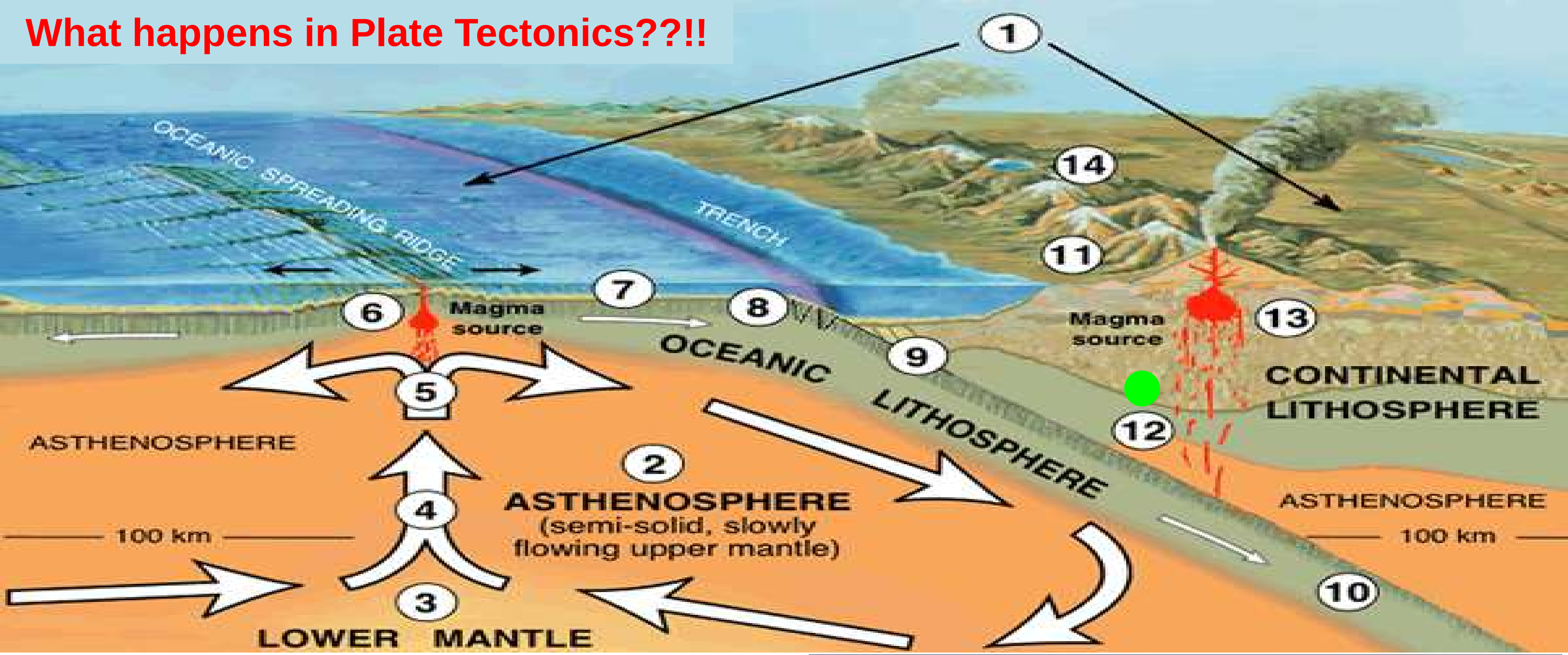



10. The sinking edge of the oceanic plate "pulls" the rest of the plate. The oceanic plate remains solid far beyond depths of 100 km beneath the Earth's surface.

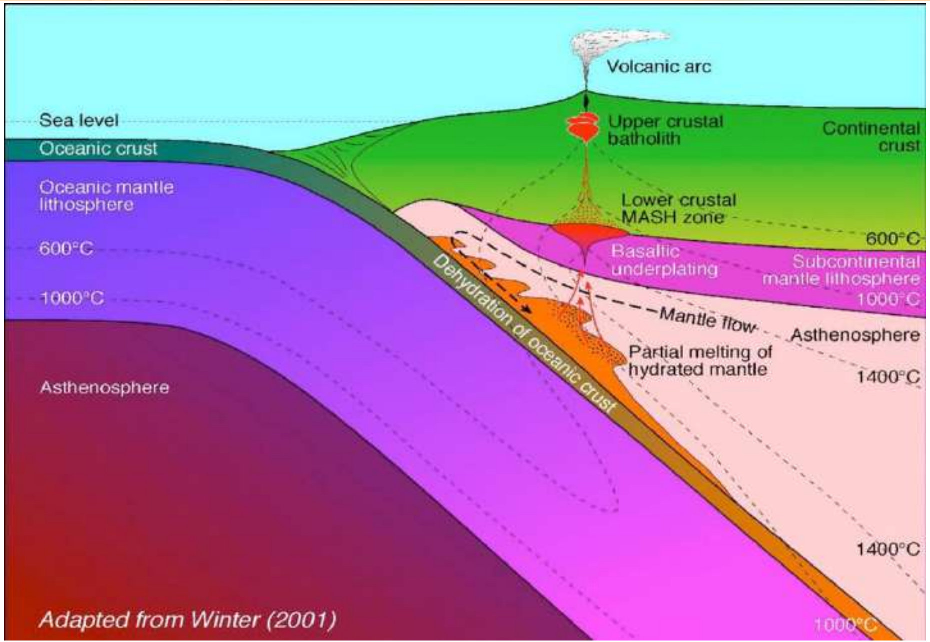
11. Subduction zones are one type of CONVERGENT PLATE BOUNDARY, where two plates are moving toward one another. Although the cool oceanic plate is sinking, the cool but less dense continental plate floats on top of the denser asthenosphere.



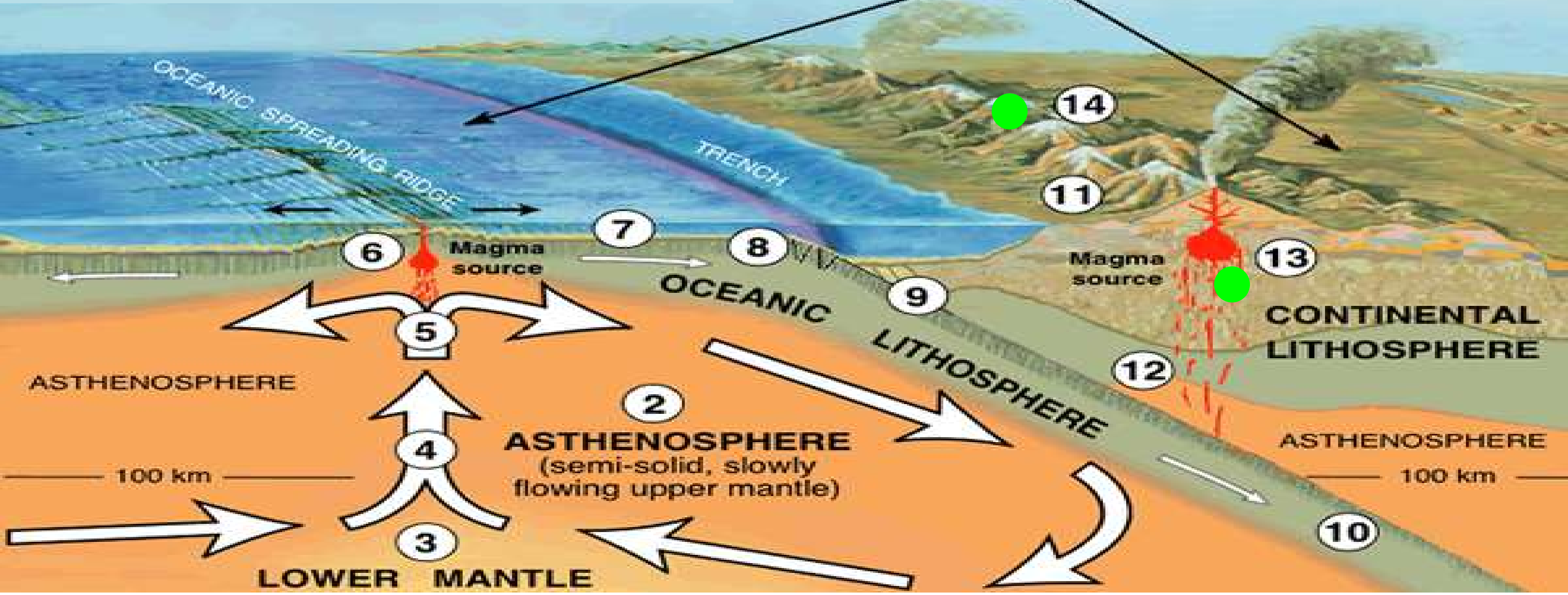
# What happens in Plate Tectonics??!!




12. When the subducting oceanic plate sinks deep below the Earth's surface, the great temperature and pressure at depth cause the fluids to "sweat" from the sinking plate. The fluids sweated out percolate upward, helping to locally melt the overlying solid mantle above the subducting plate to form pockets of liquid rock (magma).

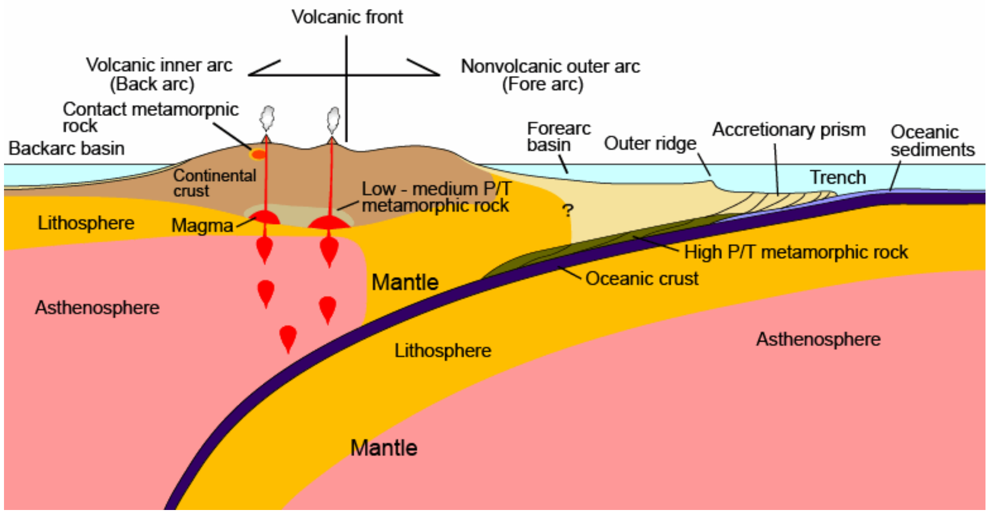


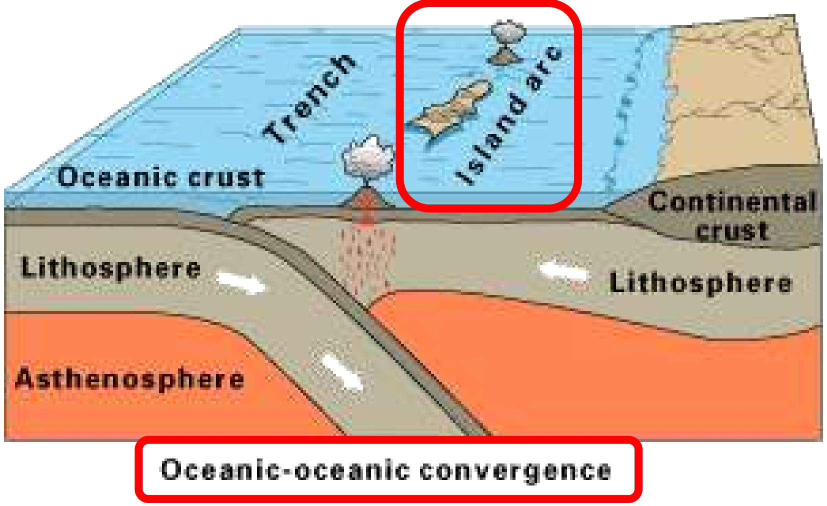
# What happens in Plate Tectonics??!!



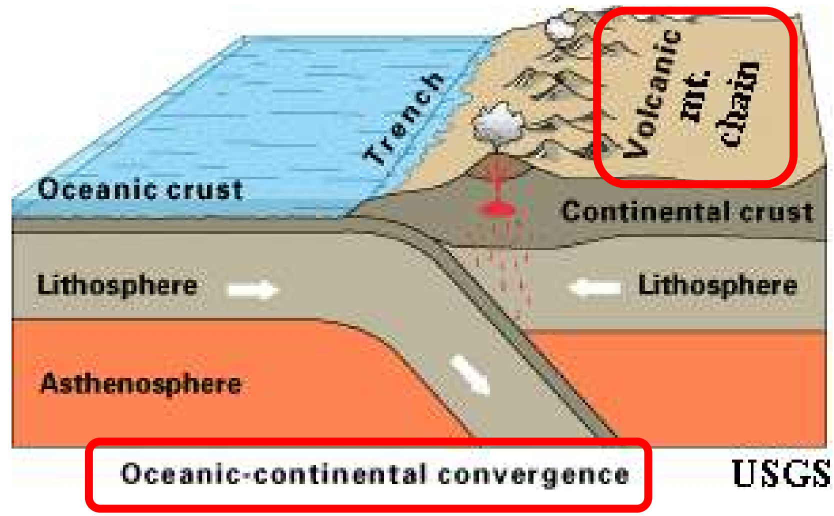

13. The generated magma is less dense than the surrounding rock, so it rises toward the surface. Most of the magma cools and solidifies as large bodies of plutonic (intrusive) rocks far below the Earth's surface.

14. Some of the molten rock may reach the Earth's surface to erupt as the pent-up gas pressure غاز مكبوت in the magma is suddenly released, forming volcanic (extrusive) rocks.

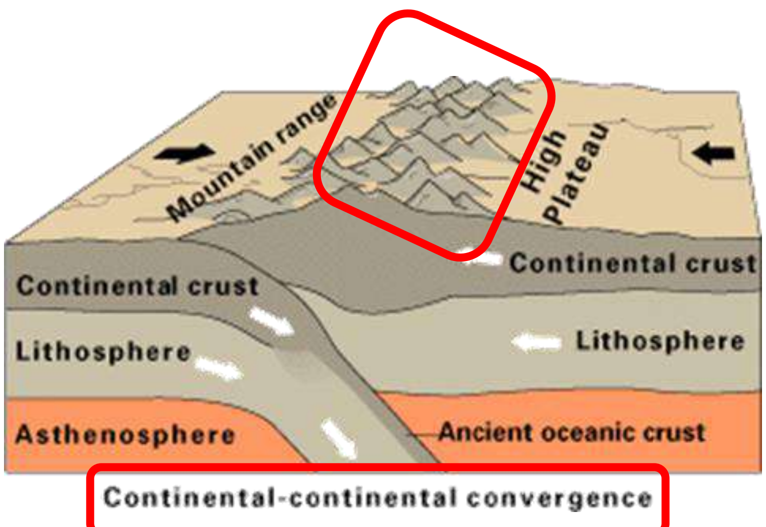





**Oceanic-Oceanic convergence leads to the formation of Island arc.**




**Oceanic-Continetal convergence leads to the formation of Volcanic arc chain.**

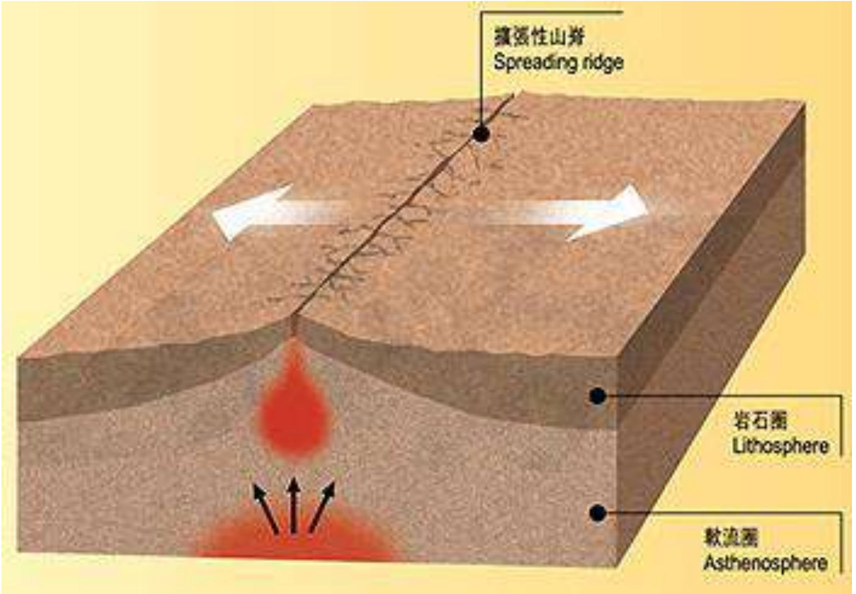



**Continental-Continental convergence leads to the formation of Mountain range.**

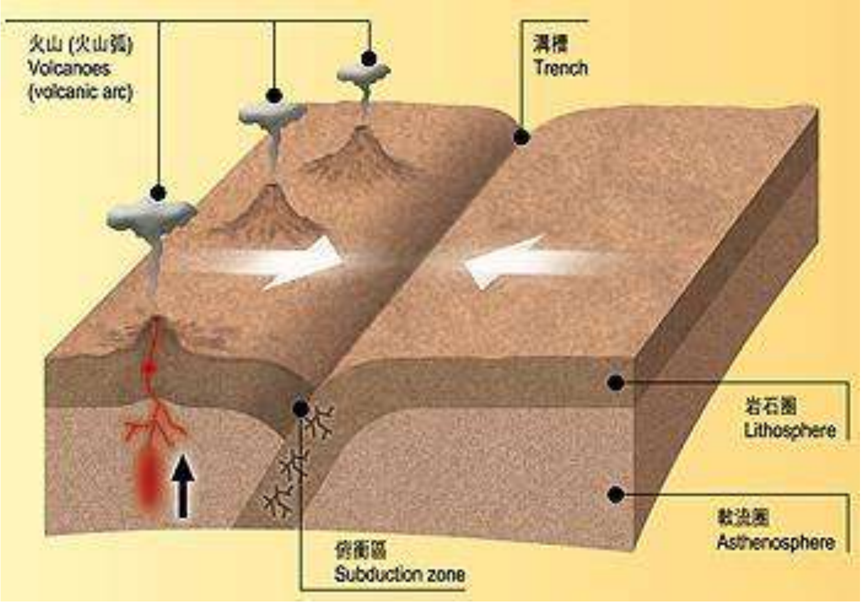
# III. Types of Plate Boundary

There are three types of plate boundary: **convergent**, **divergent**, and **transform plate boundaries**.

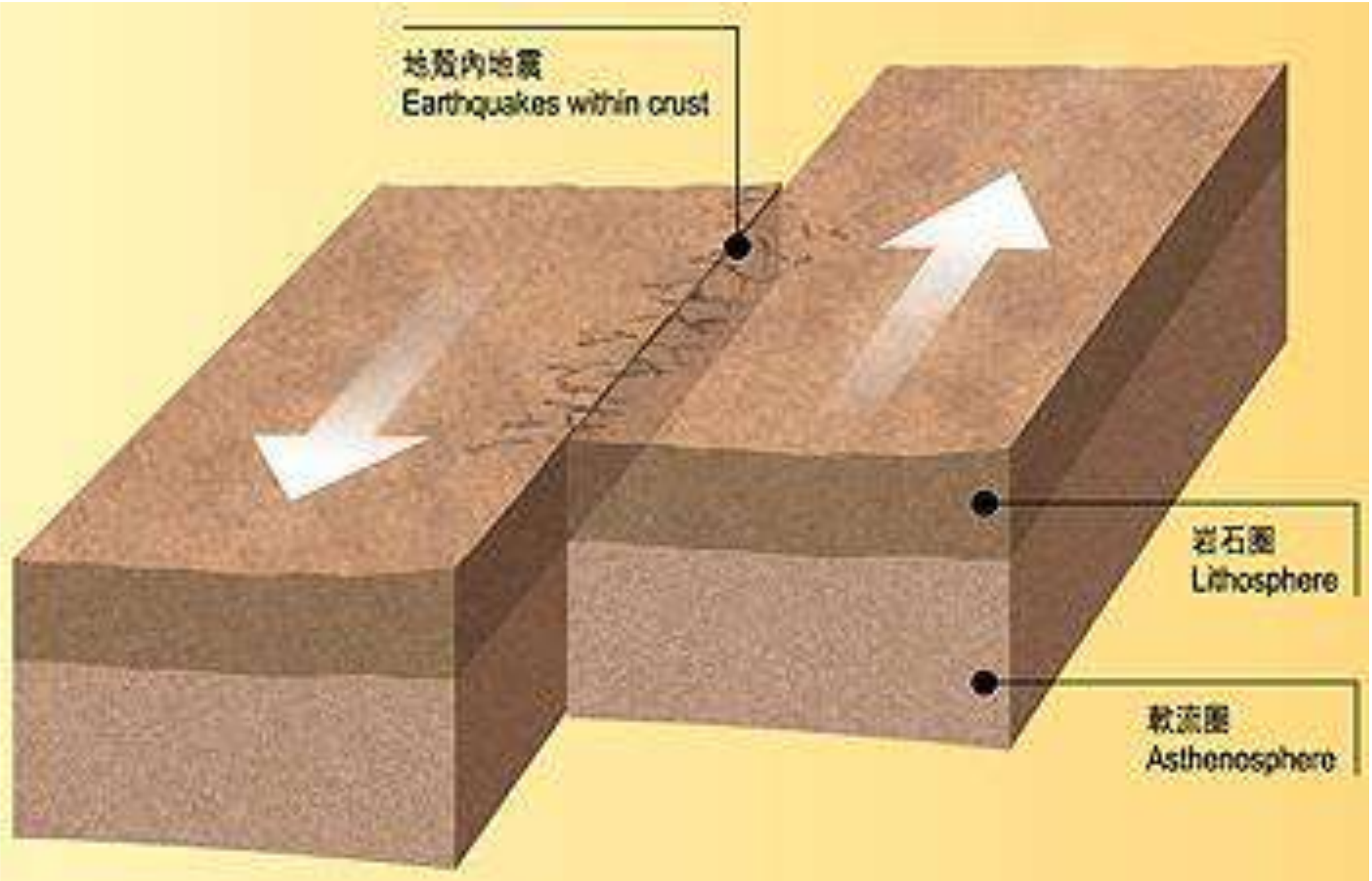
1. **Divergent plate boundaries occur where two lithospheric plates move away from each other, driven by magma rising from deep within the mantle. Volcanic activity at a divergent plate boundary creates new lithosphere along what is known as a spreading ridge.**




2. **Convergent plate boundaries occur where two lithospheric plates move towards each other, with one plate overriding the other. The overridden plate (sinking plate) is driven back into the mantle, and is subsequently destroyed along what is known as a subduction zone. During this process, earthquakes and volcanic activity are generated in the overriding plate.**

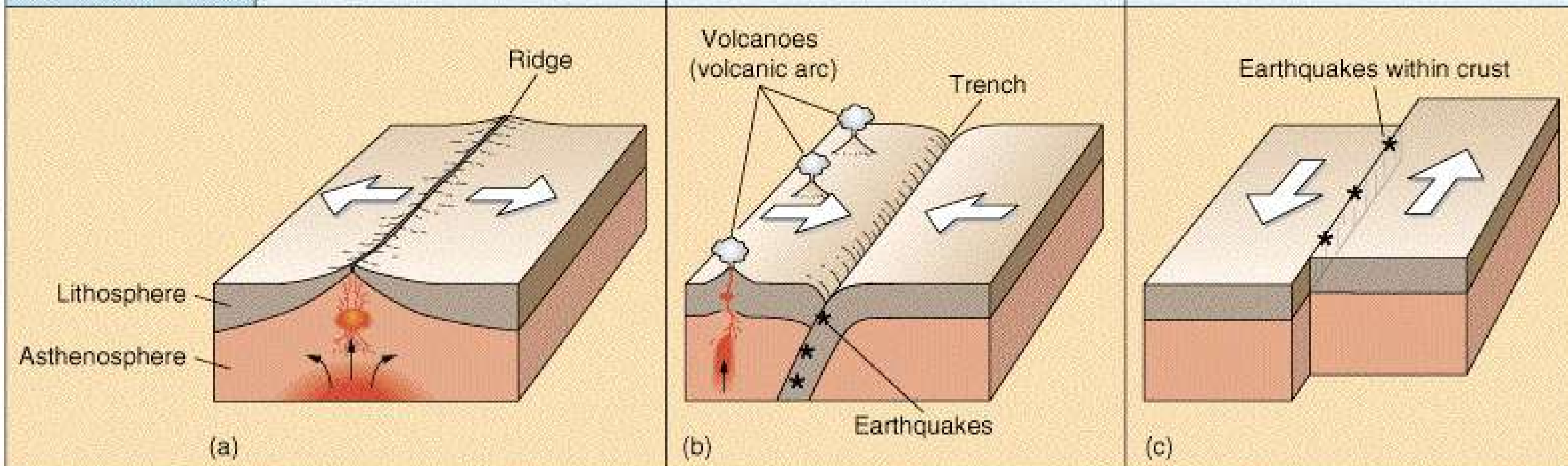


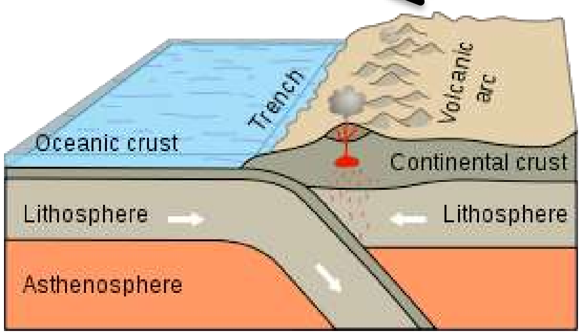
3. Transform plate boundaries occur where two lithospheric plates slide laterally past each other. Earthquakes are generated along this type of plate boundary. Importantly, lithosphere is preserved along transform boundaries, it is not created or destroyed as it is at divergent and convergent plate boundaries.

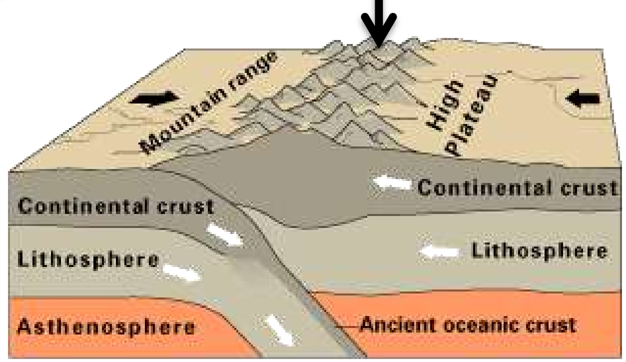


# EARTHQUAKE CHARACTERISTICS: PLATE BOUNDARY TYPES

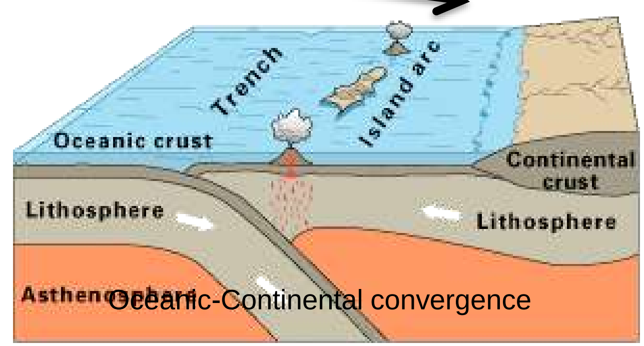
| Type of Margin | Divergent | Convergent | Transform |
|---|---|---|---|
| **Motion** | Spreading | Subduction | Lateral sliding |
| **Effect** | Constructive (oceanic lithosphere created) | Destructive (oceanic lithosphere destroyed) | Conservative (lithosphere neither created or destroyed) |
| **Topography** | Ridge/Rift | Trench | No major effect |
| **Volcanic activity?** | Yes | Yes | No |



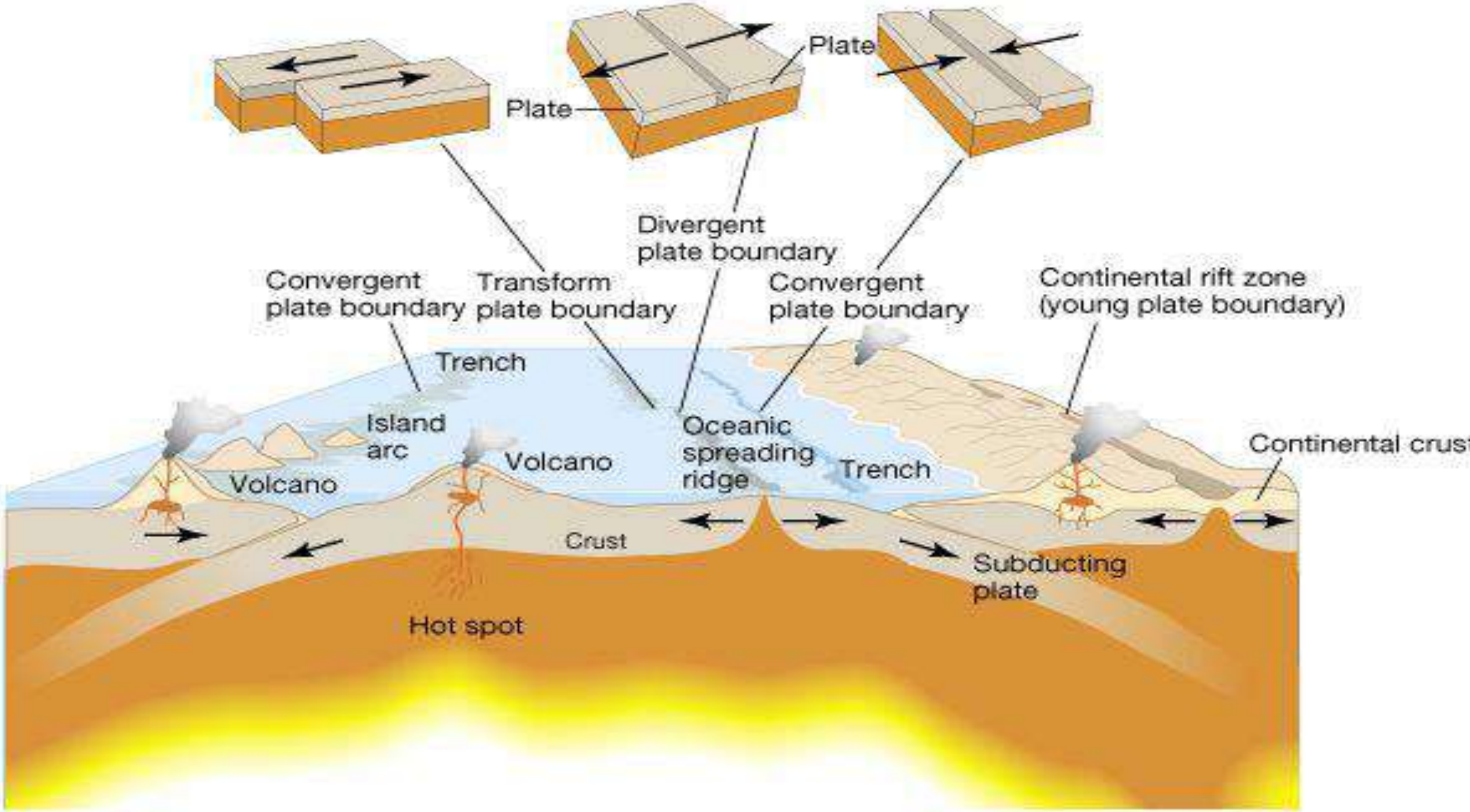



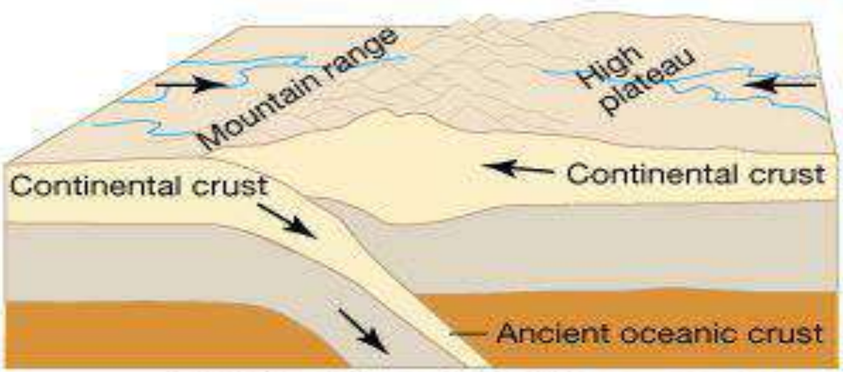




Continental-continental convergence

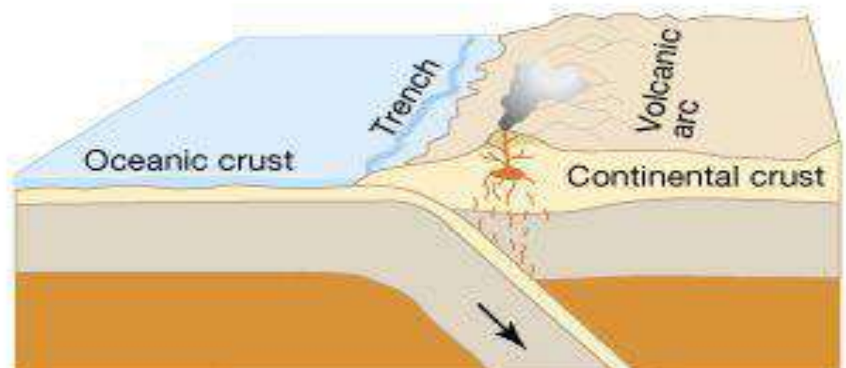



Oceanic-oceanic convergence

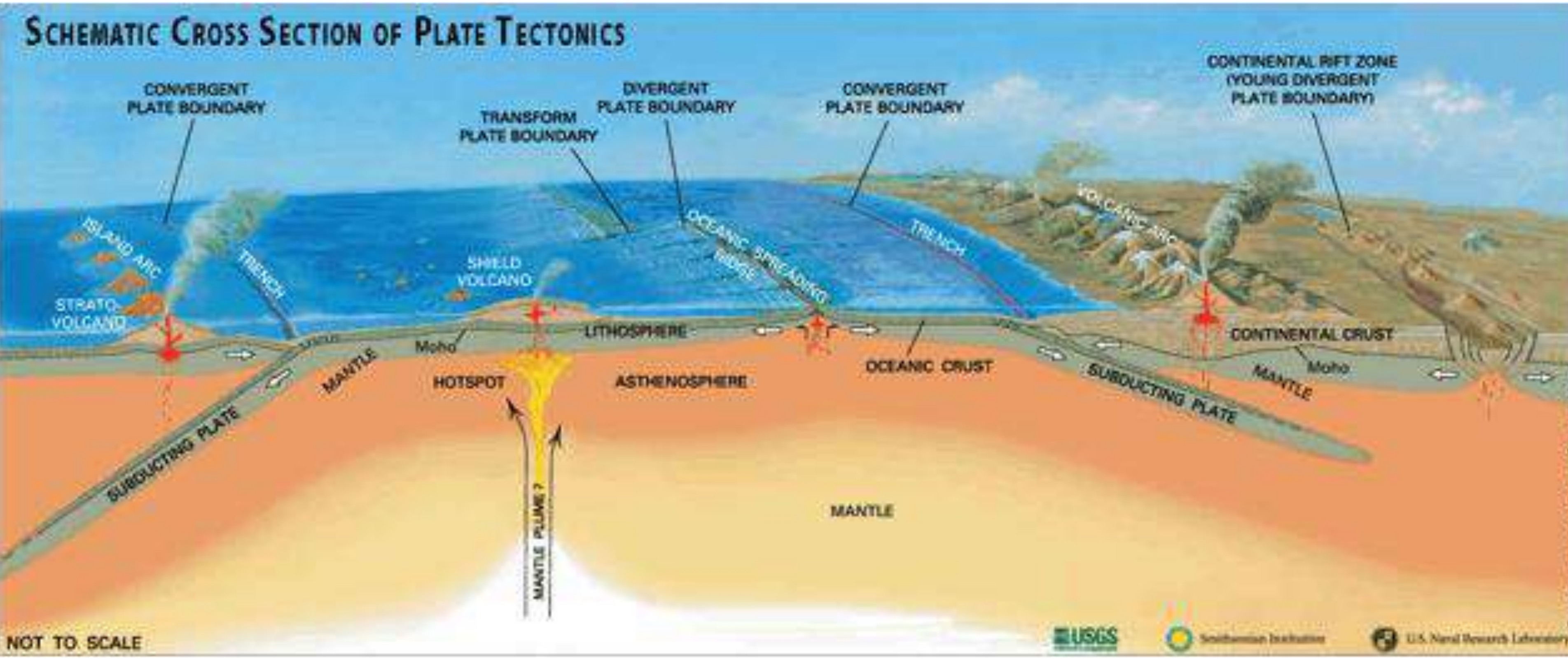



Continental-continental convergence

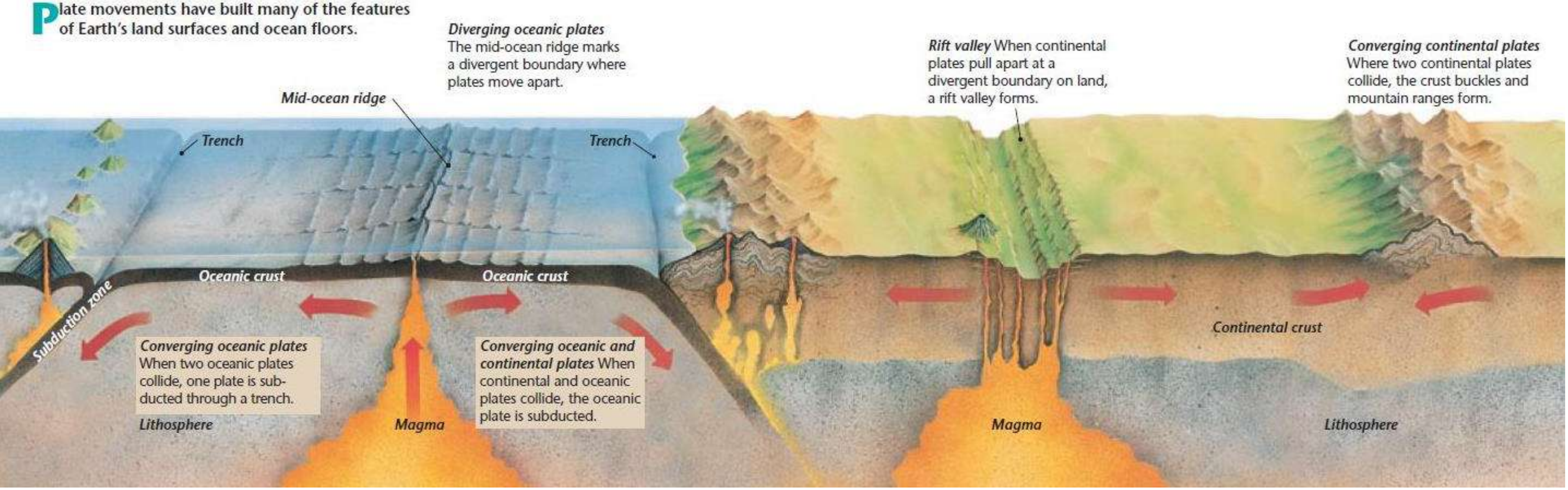


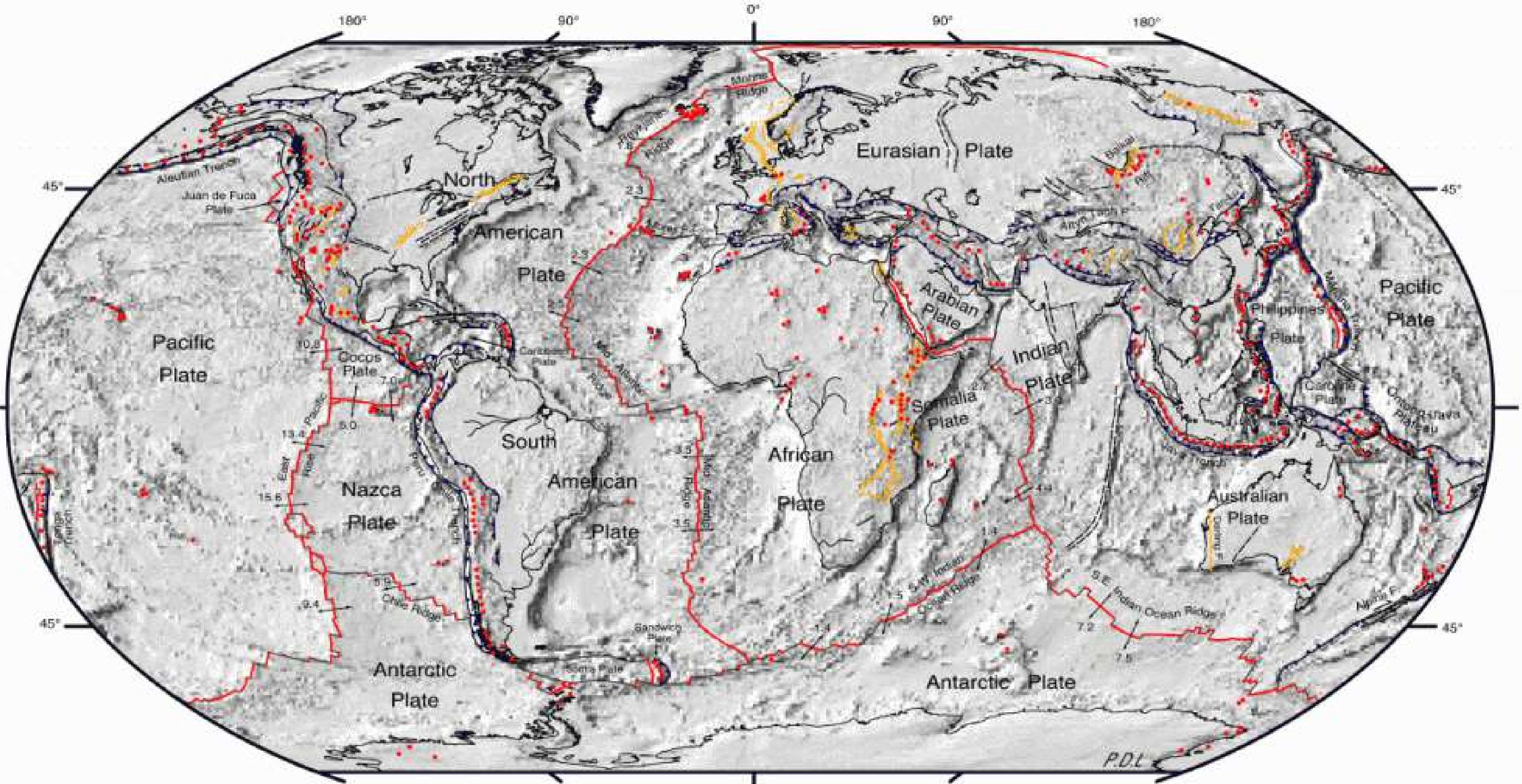

Oceanic-continental convergence


SCHEMATIC CROSS SECTION OF PLATE TECTONICS
CONVERGENT PLATE BOUNDARY
TRANSFORM PLATE BOUNDARY
DIVERGENT PLATE BOUNDARY
CONVERGENT PLATE BOUNDARY
CONTINENTAL RIFT ZONE (YOUNG DIVERGENT PLATE BOUNDARY)
ISLAND ARC
STRATO-VOLCANO
TRENCH
SHIELD VOLCANO
OCEANIC SPREADING RIDGE
TRENCH
VOLCANIC ARC
LITHOSPHERE
Moho
MANTLE
HOTSPOT
ASTHENOSPHERE
OCEANIC CRUST
CONTINENTAL CRUST
SUBDUCTING PLATE
MANTLE
Moho
SUBDUCTING PLATE
MANTLE PLUME ?
MANTLE
NOT TO SCALE
USGS
Smithsonian Institution
U.S. Naval Research Laboratory

# EXPLORING Plate Tectonics

**Plate movements have built many of the features of Earth's land surfaces and ocean floors.**






**DIGITAL TECTONIC ACTIVITY MAP OF THE EARTH**

Tectonism and Volcanism of the Last One Million Years

**DTAM**

NASA/Goddard Space Flight Center
Greenbelt, Maryland 20771

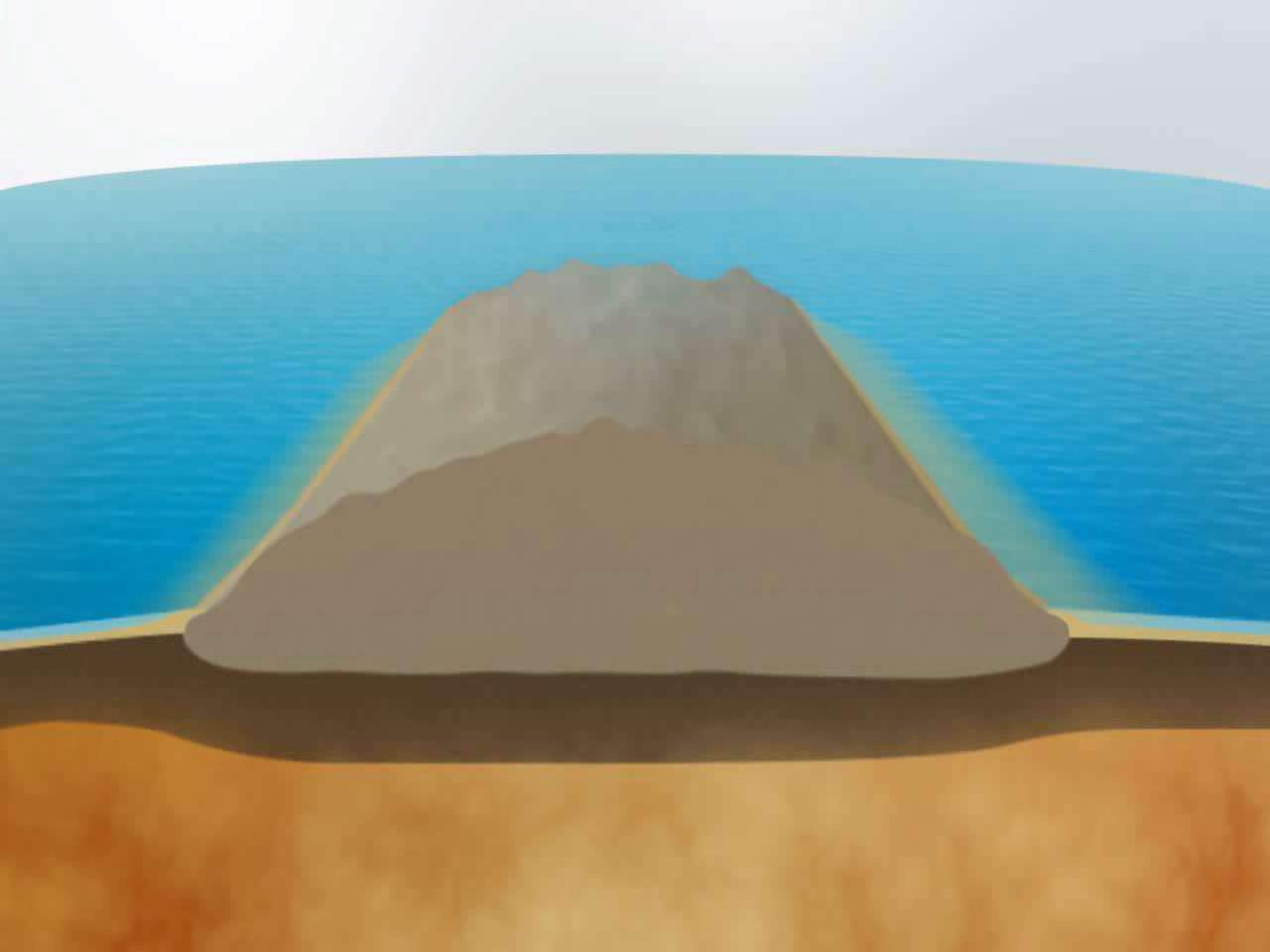
Robinson Projection
October 1998

LEGEND

- Actively-spreading ridges and transform faults
- Total spreading rate, cm/year, NUVEL-1 model (DeMets et al., Geophys. J. International, 101, 425, 1990)
- Major active fault or fault zone; dashed where nature, location, or activity uncertain
- Normal fault or rift; hachures on downthrown side
- Reverse fault (overthrust, subduction zones); generalized; barbs on upthrown side
- Volcanic centers active within the last one million years; generalized. Minor basaltic centers and seamounts omitted.

G221.001

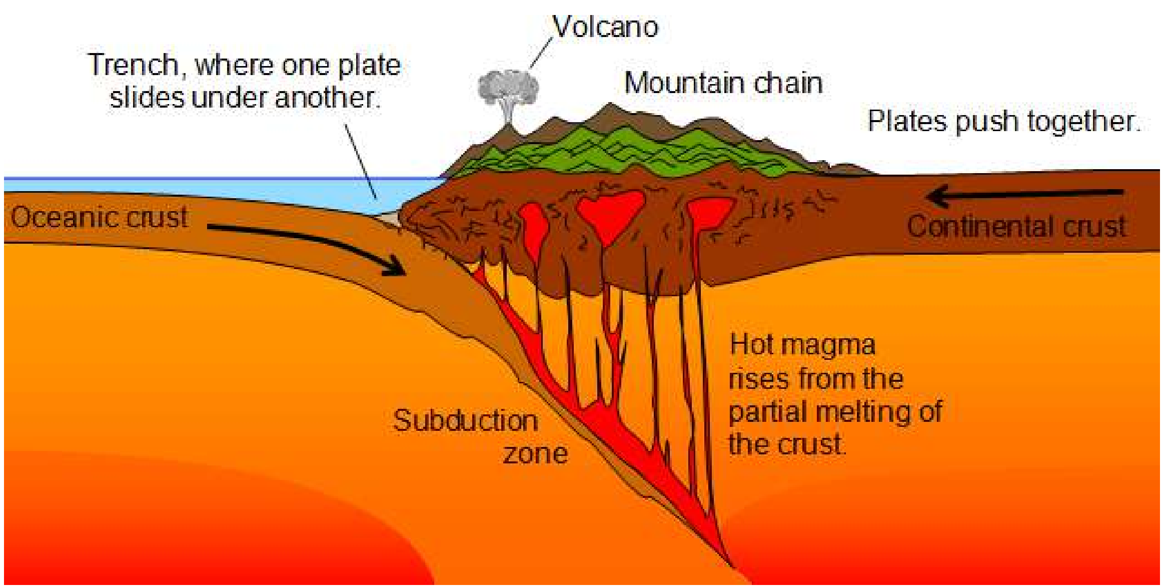
[redacted]

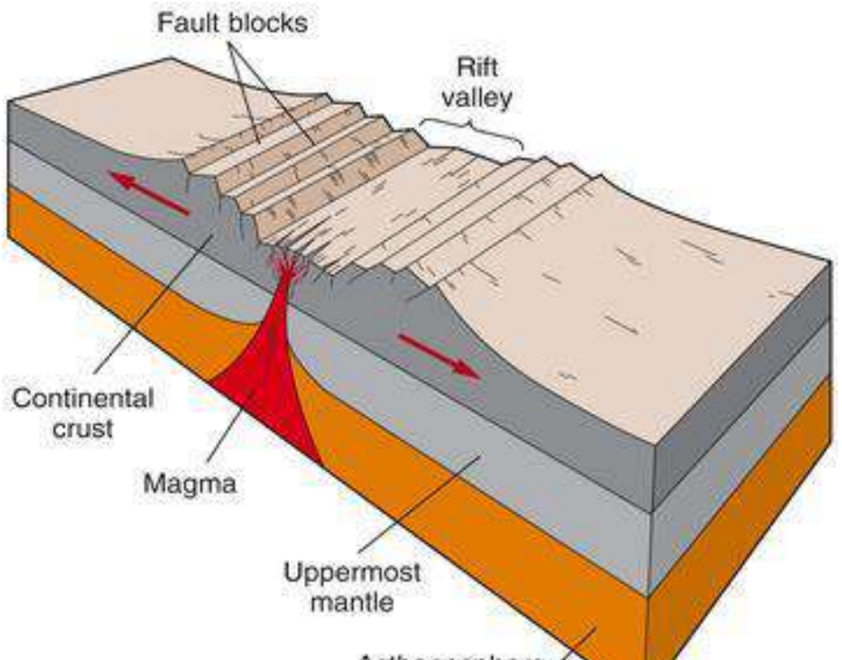


# IV. Plate Tectonics vs. Geological Processes

**Plate tectonics is the fundamental mechanism that drives geological processes in the geosphere. Plate tectonic theory is based on an understanding of the Earth's internal structure, the different types of tectonic plates and plate boundaries, and the driving forces of plate movements.**

**The occurrence of earthquakes and volcanoes, the distribution of different rock types, and the Rock Cycle, as well as the processes of mountain building, continental rifting and seafloor spreading, can be concisely explained by plate tectonic processes.**



(a)

# V. Magma

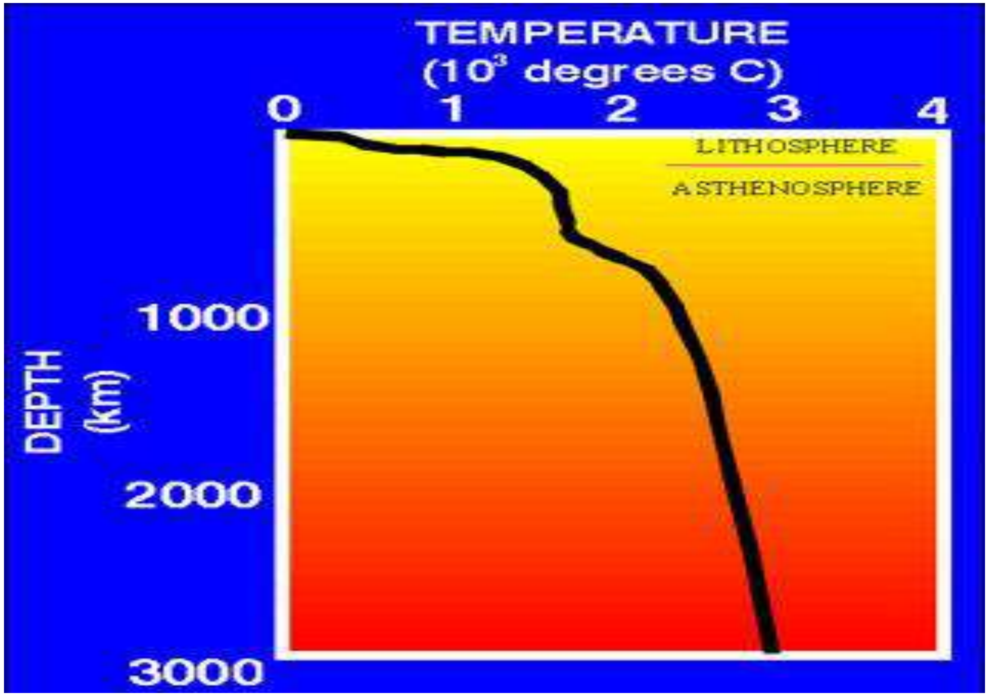
Magma is hot molten rock within the earth. It can well-up from deep to extrude from fractures as lava flows and/or pyroclastic ejecta.

The source for magma is not the earth's liquid outer core, a common misconception; instead, magma is generated at the relatively shallow depths of 100 to 300 km, through the partial melting of the earth's crust and mantle.

Magma is most often formed by decompression-melting of asthenosphere associated with divergent plate boundaries or mantle plumes, or by partial-melting of water-rich crust and/or asthenospheric material in association with subduction at convergent plate boundaries.

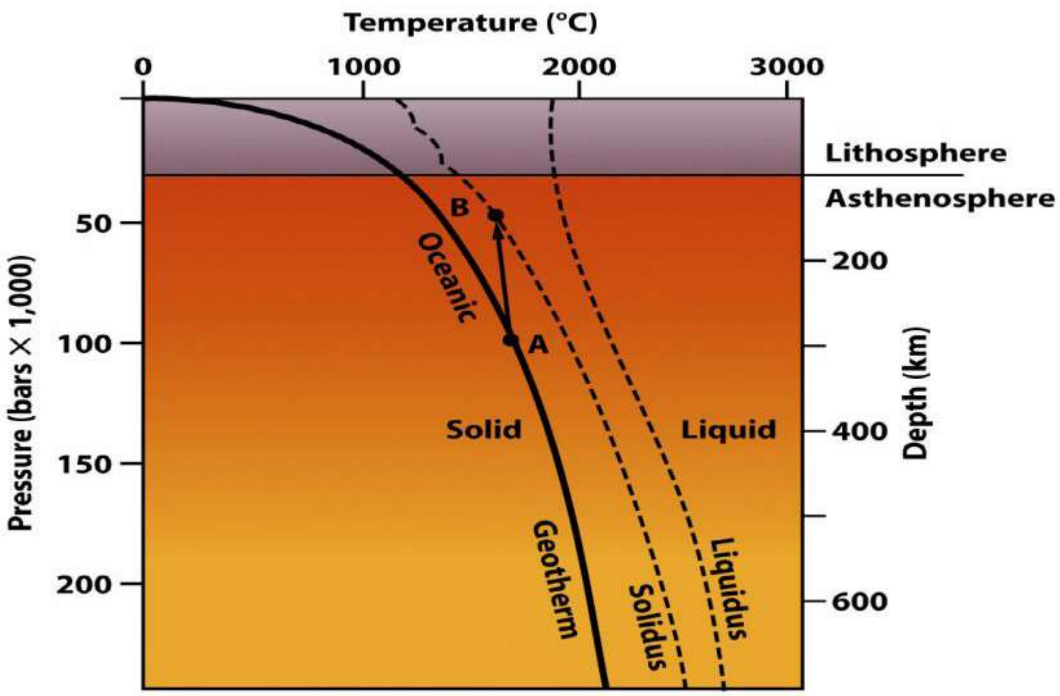
[redacted]

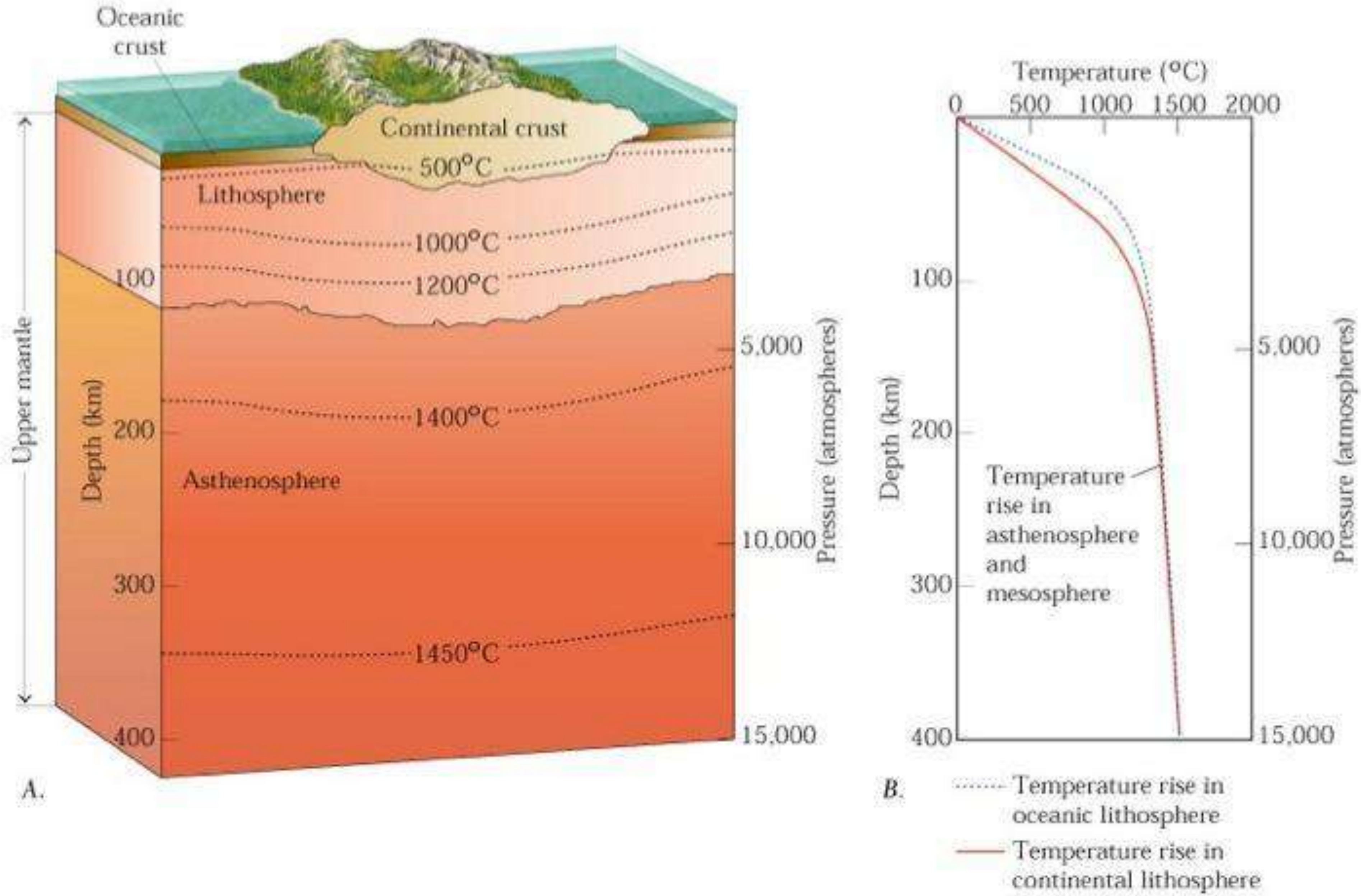
The ingredients necessary for the production of magma involve the interplay between heat, pressure, intra-granular fluids (present as gases within very hot rock or magma) and the composition of the material subject to melting.




1- Heating obviously brings solids closer to their melting points, the more heat, the more likely a solid will melt.

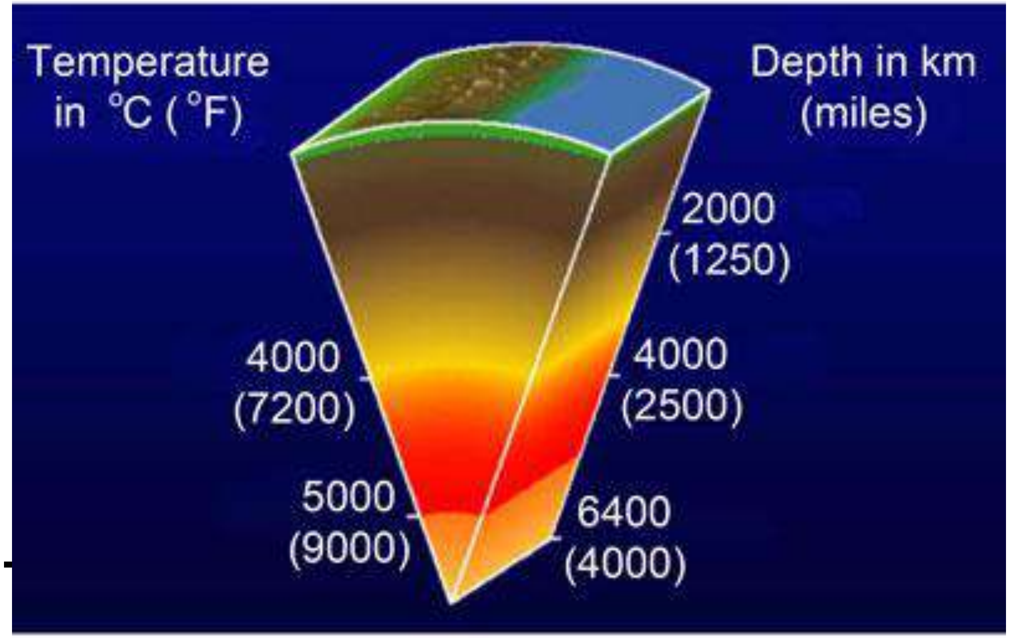
2- In general, higher pressures prevent melting because the constituent atoms of minerals in rocks are squeezed together and remain solids under high pressure. Consequently, lowering pressure on hot rock induces melting (as occurs in divergent plate boundaries).



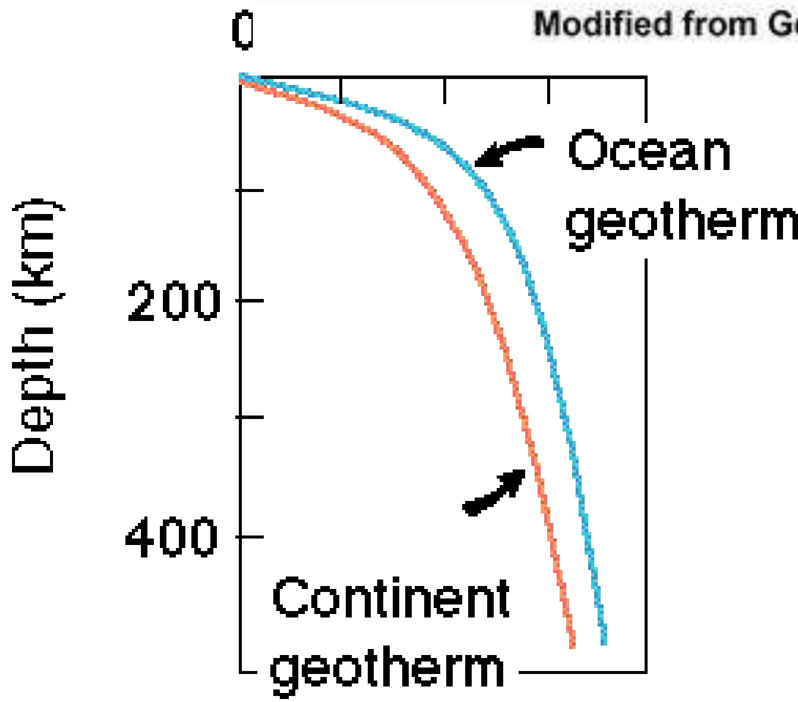


Oceanic crust
Continental crust
500°C
Lithosphere
1000°C
1200°C
1400°C
1450°C
Asthenosphere
Upper mantle
Depth (km)
100
200
300
400
Pressure (atmospheres)
5,000
10,000
15,000
A.
Temperature (°C)
0
500
1000
1500
2000
Depth (km)
100
200
300
400
Pressure (atmospheres)
5,000
10,000
15,000
Temperature rise in asthenosphere and mesosphere
B.
Temperature rise in oceanic lithosphere
Temperature rise in continental lithosphere

# TEMPERATURES IN THE EARTH

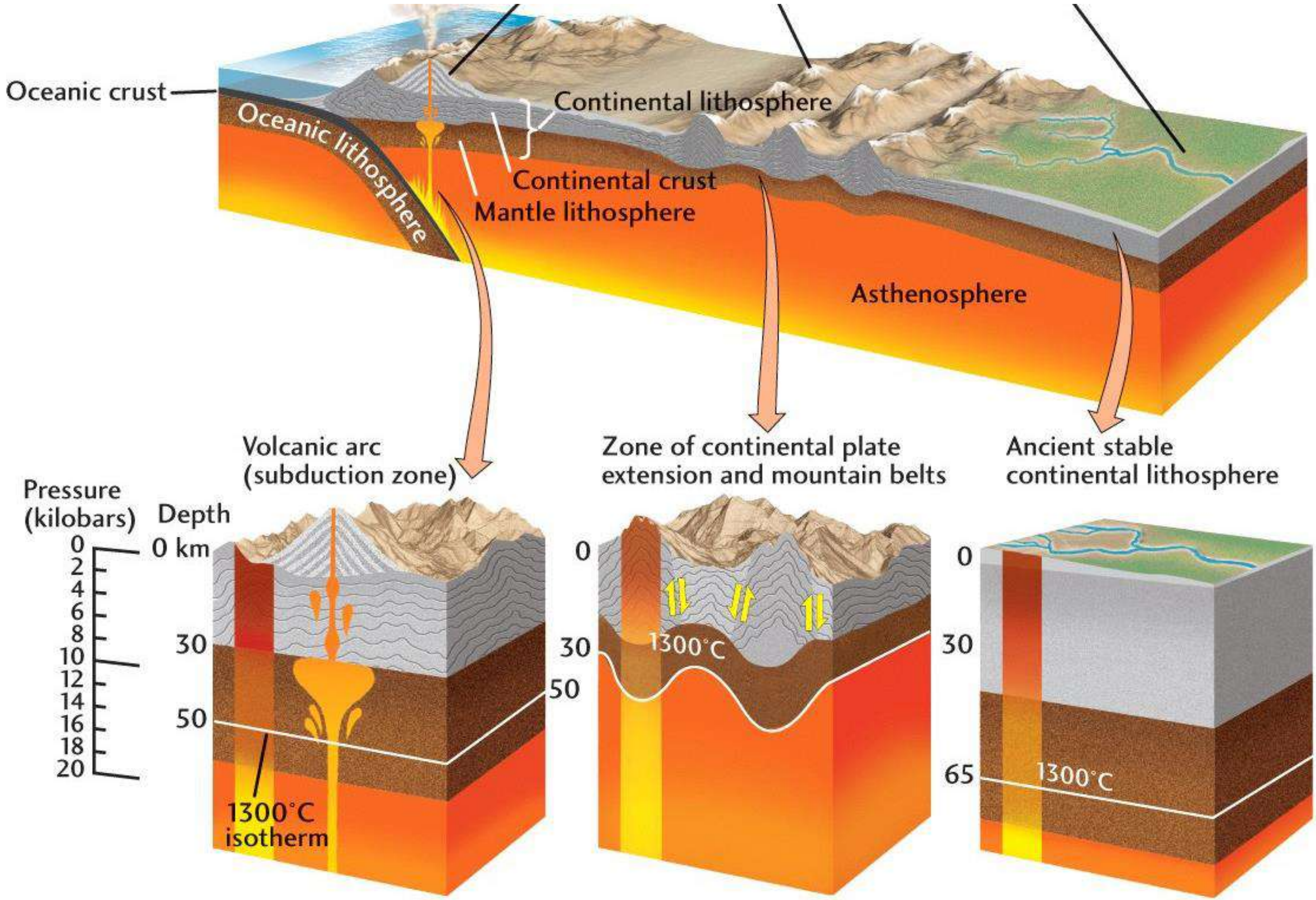



Modified from Geothermal Education Office

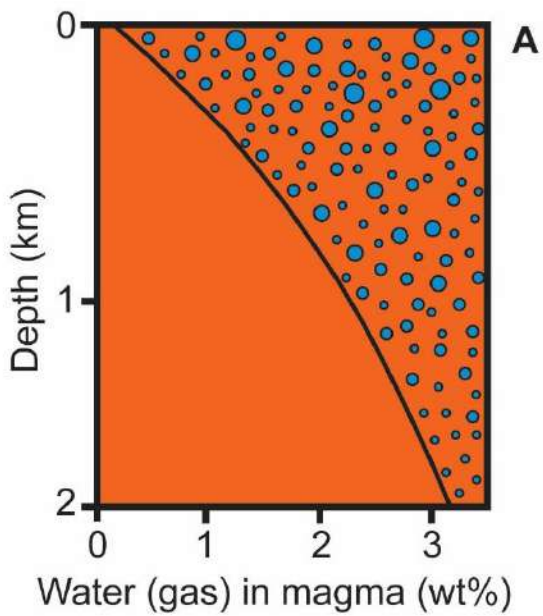


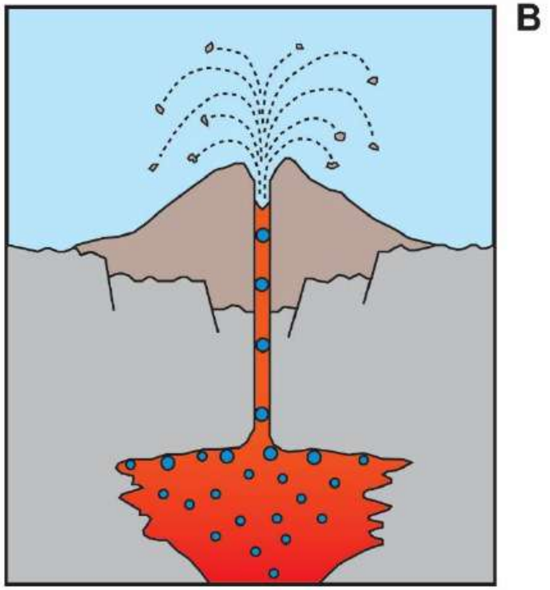

= temp. rise beneath the oceans

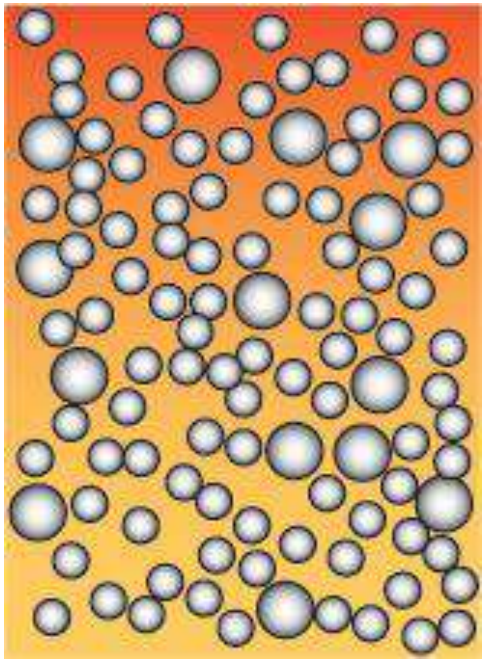
= temp. rise beneath the continents


Oceanic crust
Oceanic lithosphere
Continental lithosphere
Continental crust
Mantle lithosphere
Asthenosphere
Volcanic arc
(subduction zone)
Zone of continental plate
extension and mountain belts
Ancient stable
continental lithosphere
Pressure
(kilobars)
Depth
0 km
0
2
4
6
8
10
12
14
16
18
20
30
50
1300°C
isotherm
0
30
50
1300°C
0
30
65
1300°C

**3- Intra-granular fluids (gases within very hot rock or magma) lower the melting point of solids, so the presence of fluids (gases), generally water, allows solid rock to melt at a lower temperature (or heat content) than it otherwise would.**

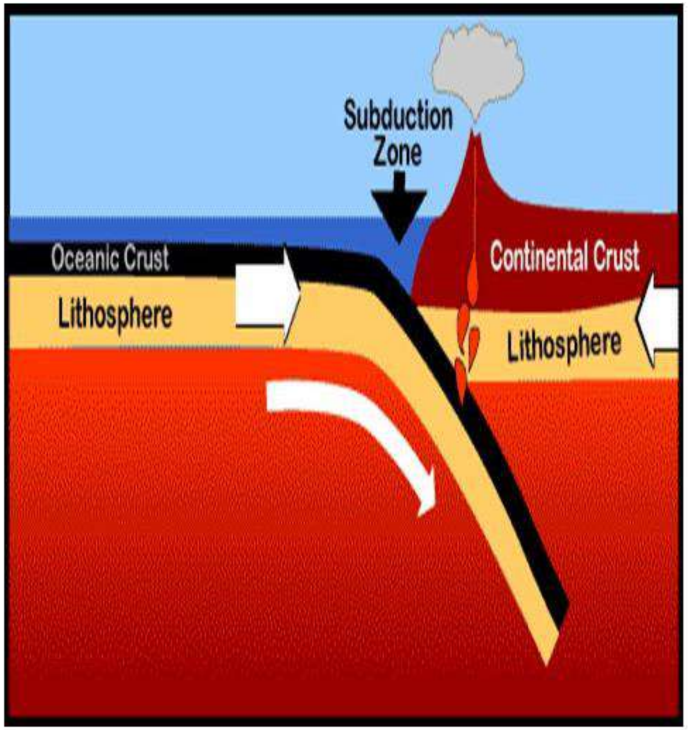


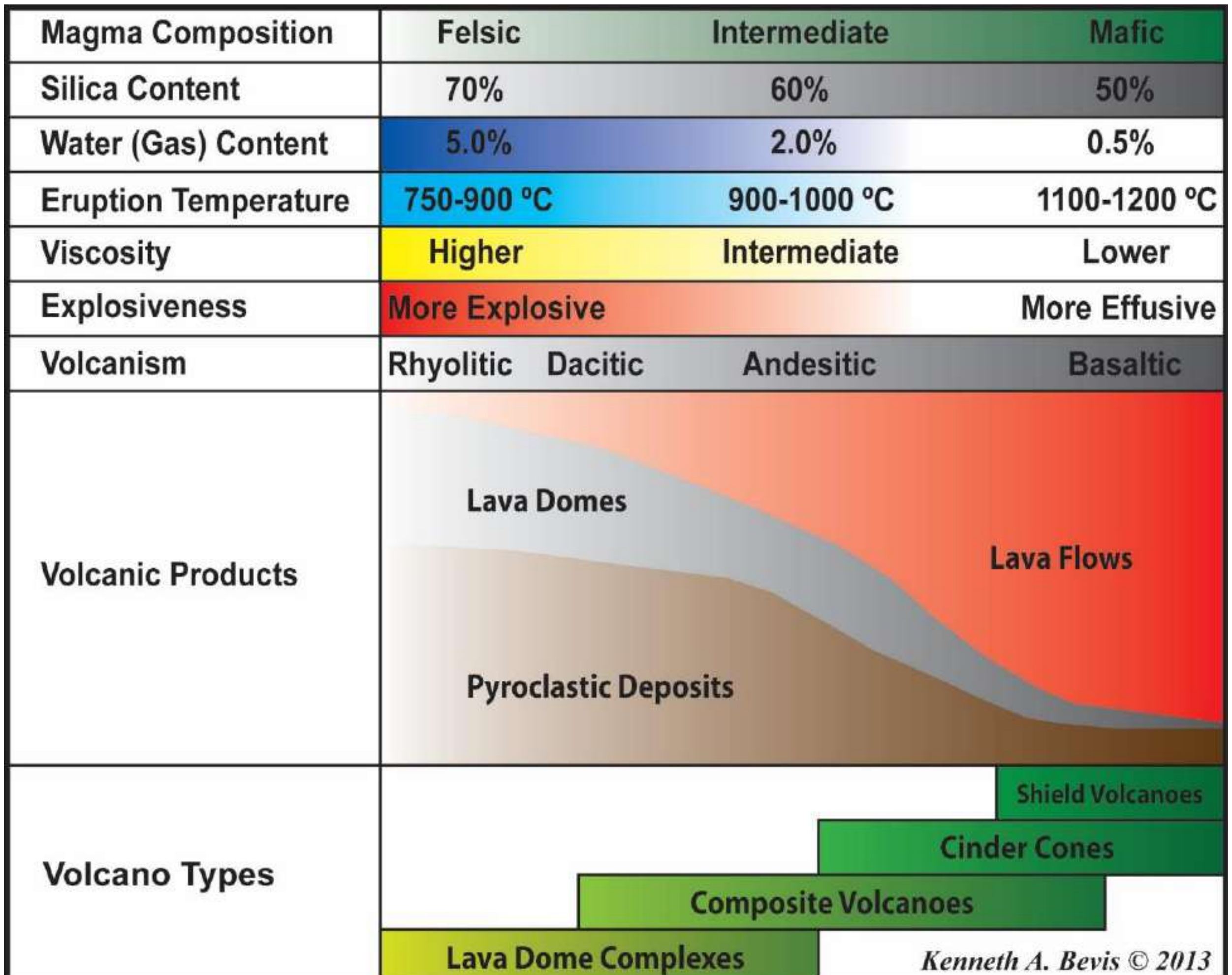



**Bubbles are common in magmas erupted at the Earth's surface**

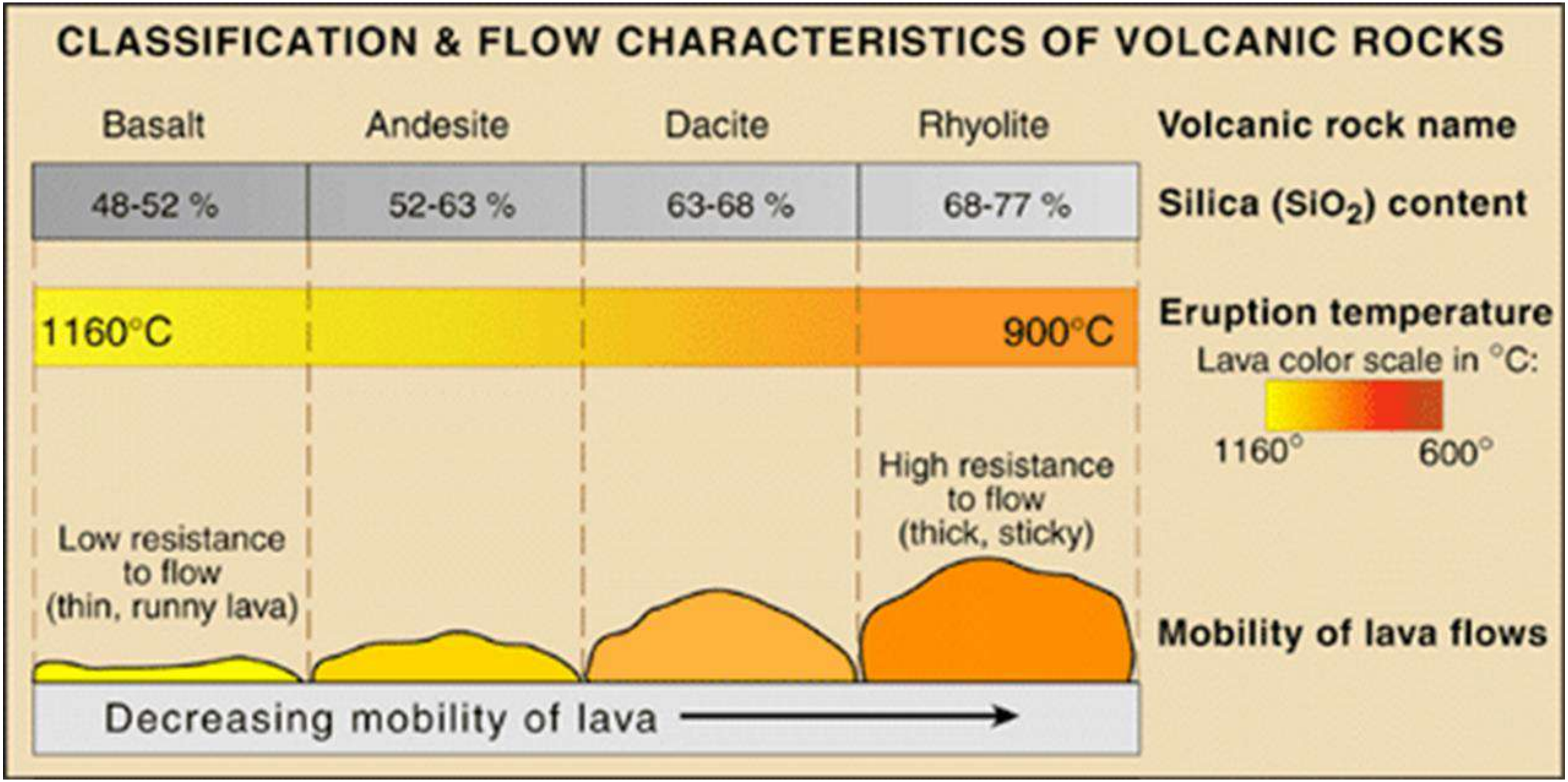
- Magma at some convergent plate boundaries contains water vapor
- The trapped water vapor in the magma can cause explosive eruptions.



**4- Finally, there are two general trends to explore in relation to rock composition: rock that contains a relative abundance of silica ($SiO_2$) and aluminum ($Al_2O_3$) will melt at a lower temperature (heat content); while a rock containing a relative abundance of ferromagnesian (Fe, Mg, and Ca) ions will melt at higher temperatures (heat content).**




**Factors that control the composition and viscosity of a magma; which in turn play a determining role in the style of volcanic eruption, eruptive products, and the nature of the volcano formed.**

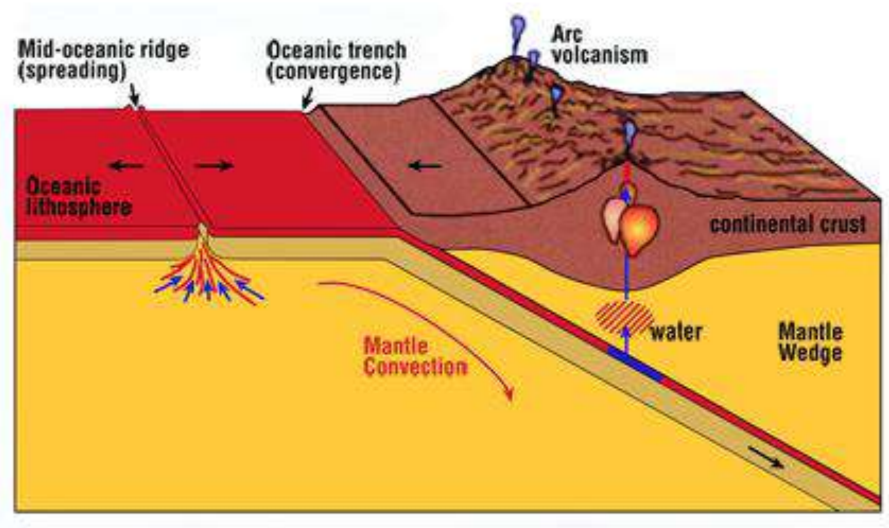

CLASSIFICATION & FLOW CHARACTERISTICS OF VOLCANIC ROCKS
Basalt
Andesite
Dacite
Rhyolite
Volcanic rock name
48-52 %
52-63 %
63-68 %
68-77 %
Silica ($SiO_2$) content
1160°C
900°C
Eruption temperature
Lava color scale in °C:
1160°
600°
High resistance to flow (thick, sticky)
Low resistance to flow (thin, runny lava)
Mobility of lava flows
Decreasing mobility of lava

| Summary Table | | | | | |
|---|---|---|---|---|---|
| Magma Type | Solidified Rock | Chemical Composition | Temperature | Viscosity | Gas Content |
| Basaltic | Basalt | 45-55 $SiO_2$ %, high in Fe, Mg, Ca, low in K, Na | 1000 - 1200 $^oC$ | 10 - $10^3$ PaS | Low |
| Andesitic | Andesite | 55-65 $SiO_2$ %, intermediate in Fe, Mg, Ca, Na, K | 800 - 1000 $^oC$ | $10^3$ - $10^5$ PaS | Intermediate |
| Rhyolitic | Rhyolite | 65-75 $SiO_2$ %, low in Fe, Mg, Ca, high in K, Na. | 650 - 800 $^oC$ | $10^5$ - $10^9$ PaS | High |

The majority of magma erupted at the Earth's surface is produced by melting of mantle rock at depths of less than 50 km. Some magmas are produced by melting of crustal rocks at shallower levels (less than 30 km). The Earth's interior is very hot, but it is solid because of the high pressures.

The melting occurs when mantle rock rises toward the surface, such as at mid-ocean ridges, and undergoes de-pressurization melting.

Magma can also be generated by melting due to the lowering of the mantle melting temperature because water and other volatile components have been introduced into the mantle. This occurs chiefly in subduction zones where oceanic lithosphere is descending back into the mantle. The oceanic lithosphere carries with it water in sediments and altered rocks.



**The melting of continental crust generates felsic magma enriched in silica and aluminum, while melting of mantle rock (asthenosphere) and oceanic crust forms ferromagnesian-rich, mafic magma. The earth's crust naturally contains a higher water content (because of its proximity to the hydrosphere) than the mantle, accounting for higher water (and thus gas) content in felsic to intermediate magmas. The relatively high content of silica and water in continental crust also correlates with the lower melting temperatures of felsic to intermediate magmas. Mantle material melts at greater depth and higher temperatures and pressures, not requiring as much "assistance" from silica and water in the melting process.**

| Type of Volcanic Rock | Melting Temperature | Silica Content ($SiO_2$) | Magma Characteristics |
|---|---|---|---|
| RHYOLITE | 1400°F (low) | 68-77% (high) | High gas, explosive, thick, sticky |
| DACITE | | 63-68% | |
| ANDESITE | | 52-63% | |
| BASALT | 2200°F (high) | 48-52% (low) | Low gas, less explosive, thin, runny |

Chemical Analyses of Magmas

| Oxide % | Basalt | Andesite | Dacite | Rhyolite |
|---|---|---|---|---|
| $SiO_2$ | 50.10wt.% | 59.20 | 67.20 | 75.20 |
| $TiO_2$ | 1.00 | 0.70 | 0.50 | 0.20 |
| $Al_2O_3$ | 17.10 | 17.10 | 16.20 | 13.50 |
| $Fe_2O_3$ | 3.40 | 2.90 | 2.00 | 1.00 |
| FeO | 7.00 | 4.20 | 1.80 | 1.10 |
| MgO | 7.10 | 3.70 | 1.50 | 0.50 |
| CaO | 10.60 | 7.10 | 3.80 | 1.60 |
| $Na_2O$ | 2.50 | 3.20 | 4.30 | 4.20 |
| $K_2O$ | 0.80 | 1.30 | 2.10 | 2.70 |
| $P_2O_5$ | 0.20 | 0.20 | 0.20 | 0.10 |

continuum of compositions

## Magma composition

The composition of magma (and extruded lava) depends on three main factors:

1) the degree of partial melting of the crust or mantle;
2) the degree of magma mixing;
3) magmatic differentiation by fractional crystallization.

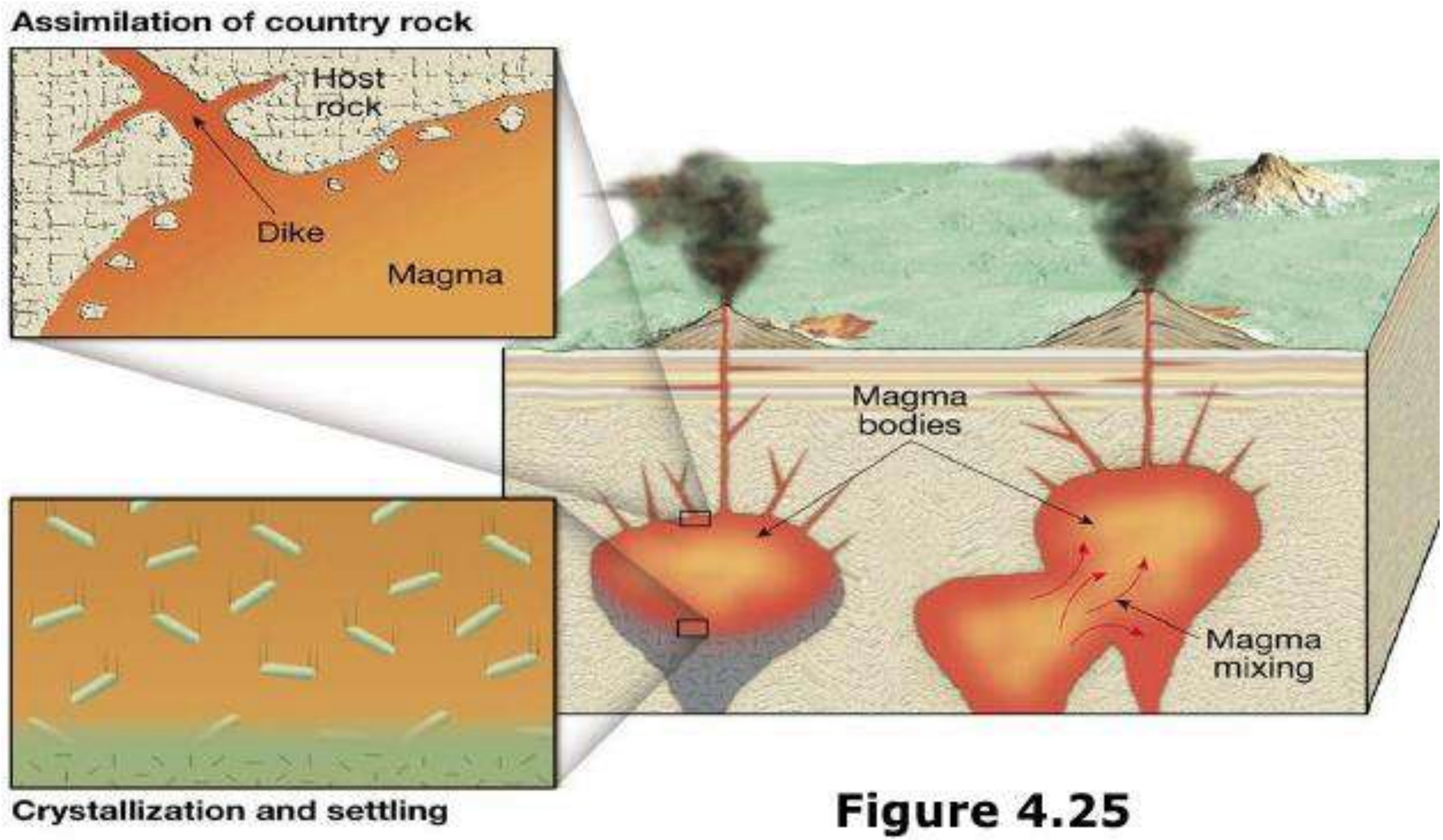
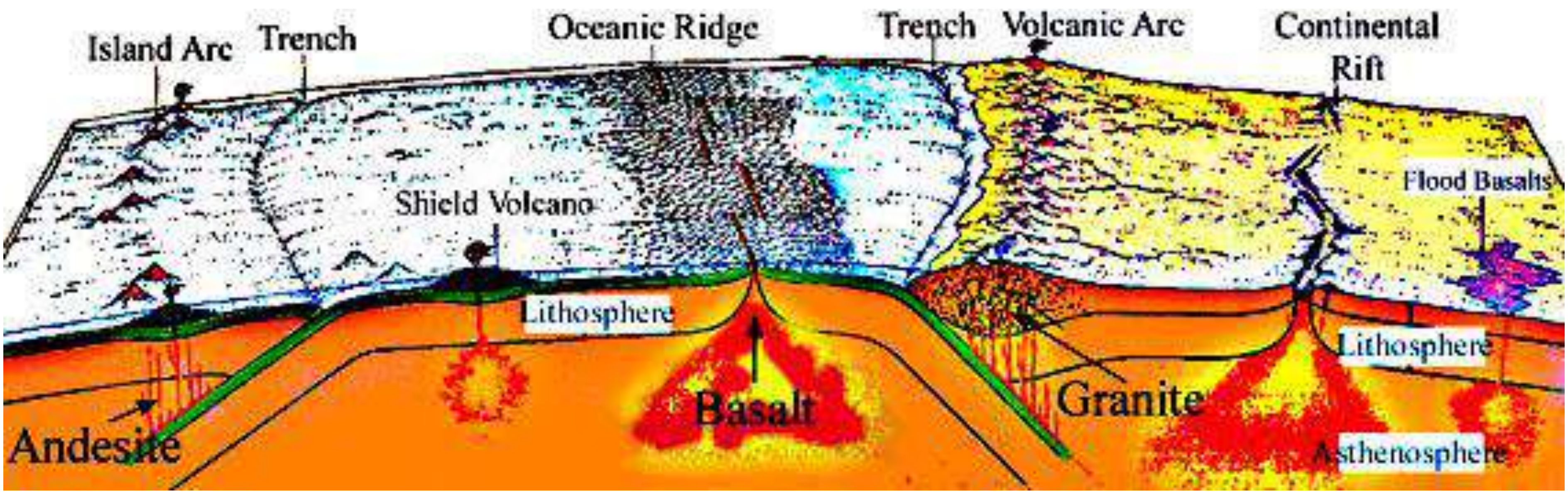



Figure 4.25

Several types of basaltic lavas result from partial melting of mantle and oceanic crust at subduction zones and mantle plumes.

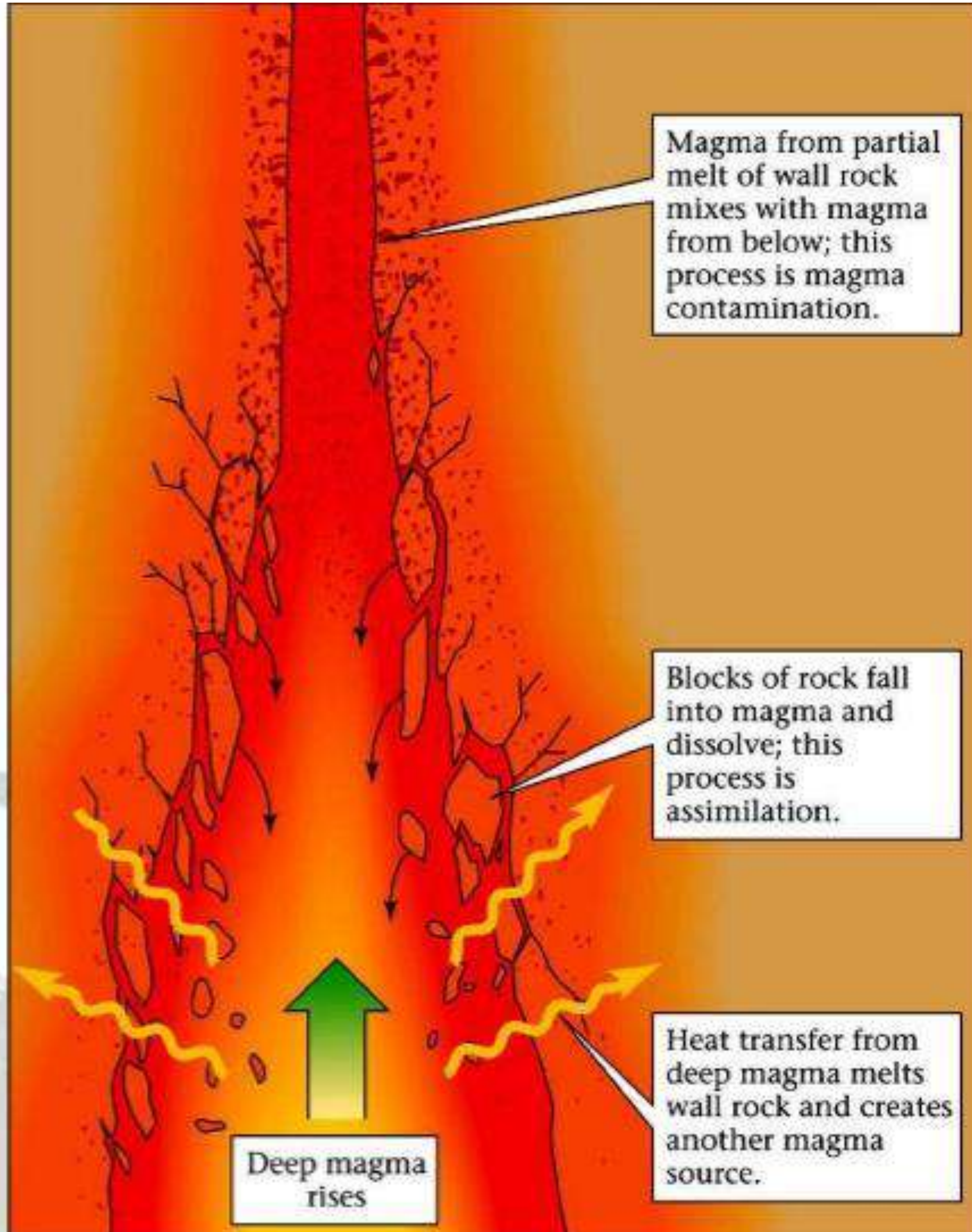
Emplacement of basaltic magma chambers within continental crust often raises the temperature of the surrounding silica- and water-rich country rock enough to cause the country rock significant melting. The country rock becomes assimilated into the basaltic magma to greater or lesser degree, contaminating it with felsic material.

If substantial mixing of the magmas occurs, usually requiring significant plate movement and/or magmatic convection, intermediate magma is born (ranging from andesitic to dacitic or rhyodacitic).

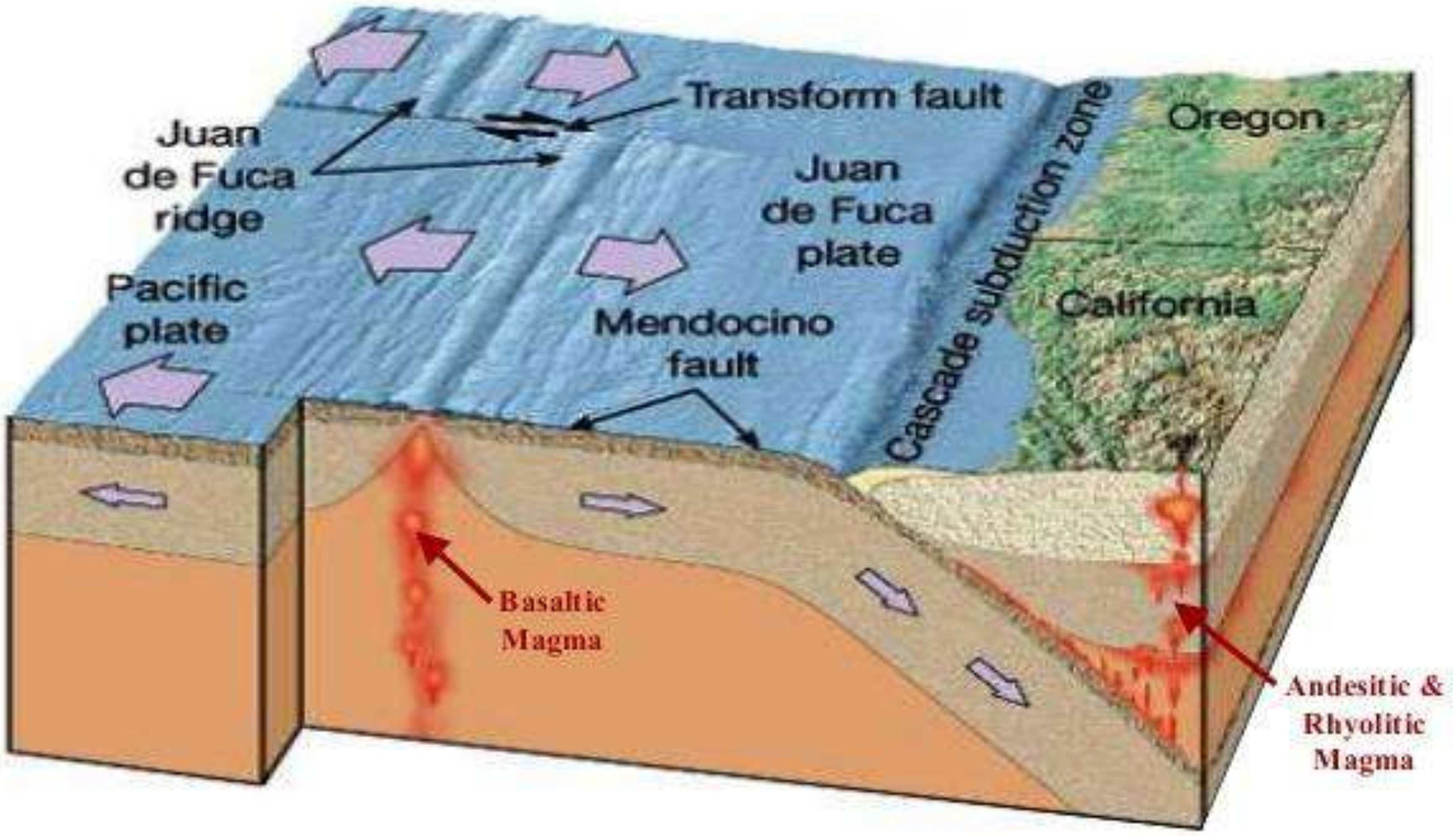


# Assimilation

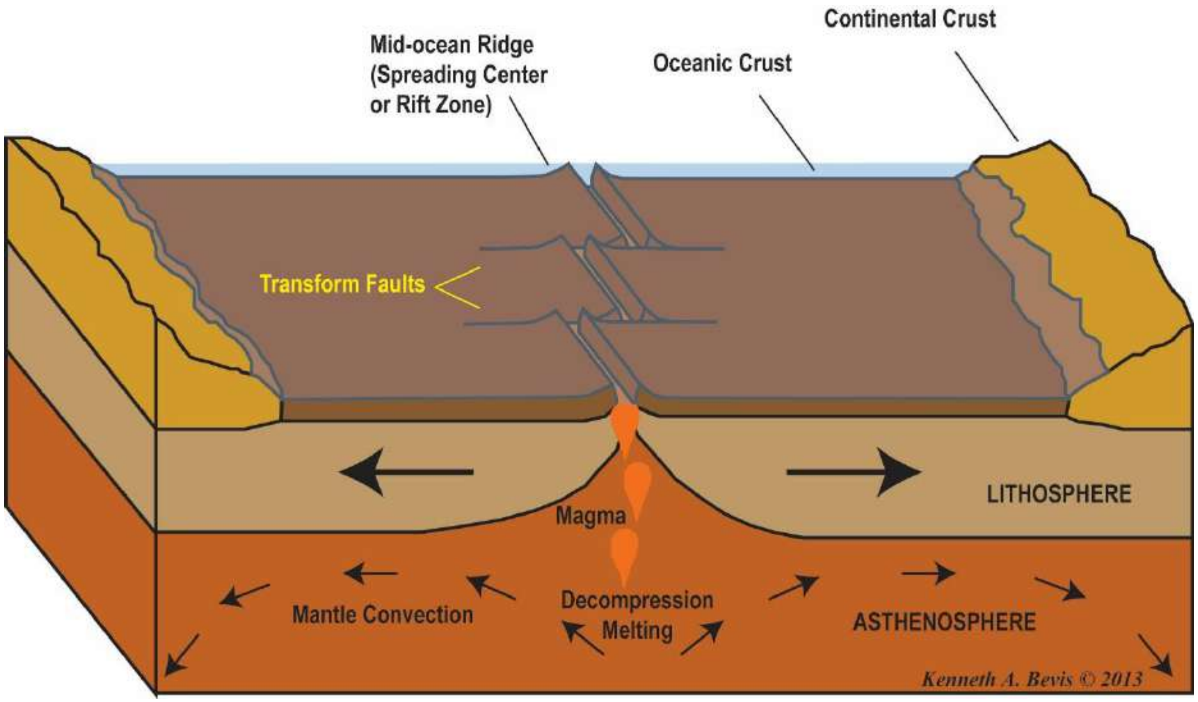
- As magma sits in its chamber, it may incorporate minerals from the surrounding wall rock
  - Called ***assimilation***
- Occurs when wall rocks fall into the magma and melt ***(stoping)*** or when the magma partially melts minerals from the wall rock
- Degree of assimilation depends on composition of wall rock, temp of magma, amount of $H_20$ present, amount fractures in and strength of the wall rock, and residence time

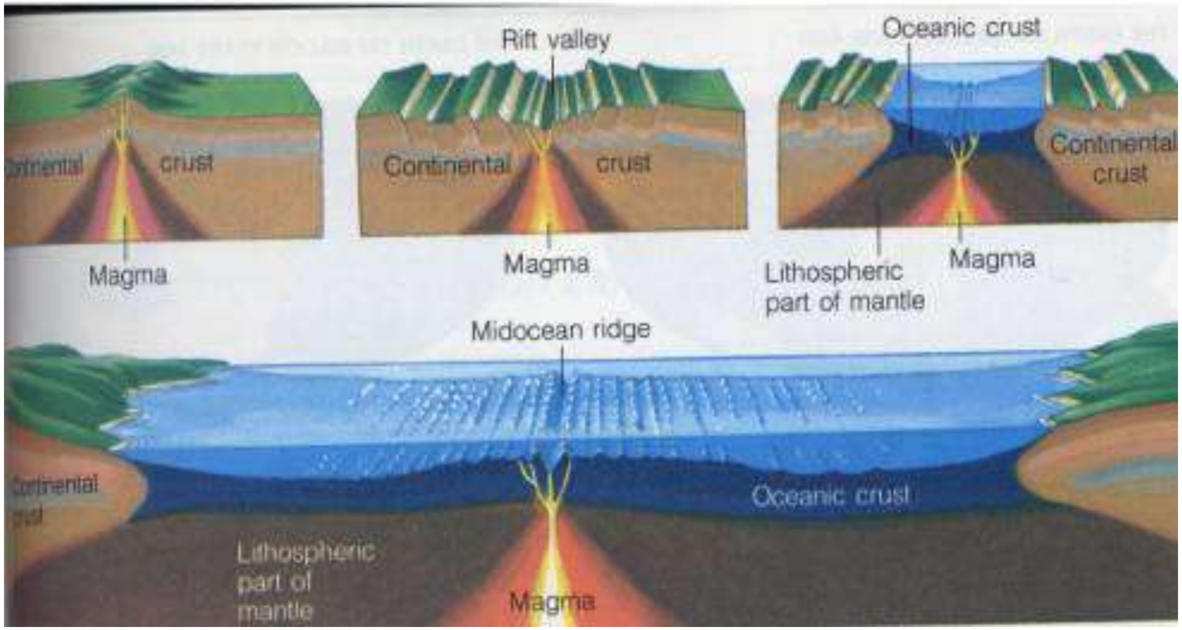


# *Magma Composition (tectonic setting)*

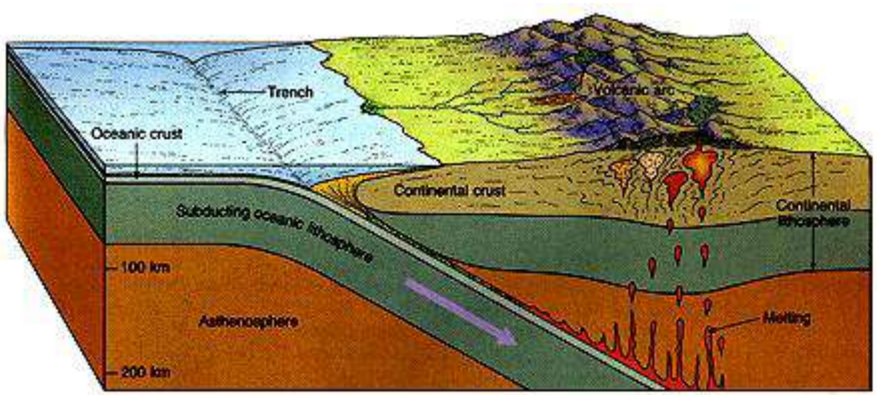


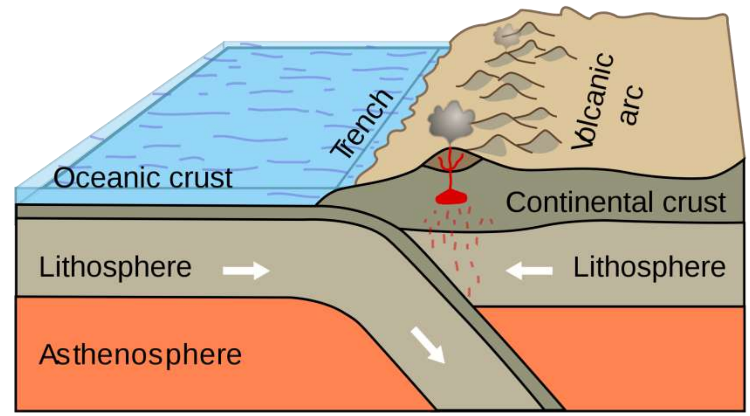
**Mafic magmas** are generated by decompression-melting of highly mafic asthenosphere and assimilation-melting of mafic oceanic lithosphere and crust in association with **divergent plate boundaries** and some mantle plumes. The magma source is naturally low in water content, however, these magmas have a much easier time of it; greater heat and less silica allows it to readily reach the surface as volcanic eruptions (despite its lack of gases). Mafic magmas have lower viscosities because of their greater heat content and lack of silica (they have a greater abundance of iron and magnesium ions).

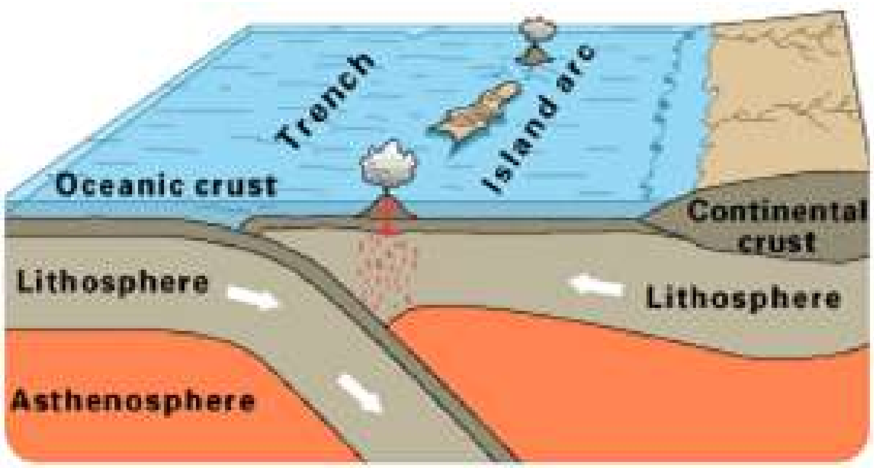


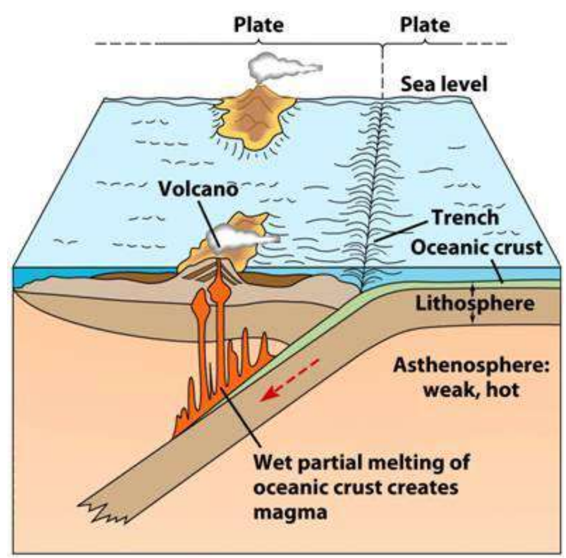
**Felsic magmas have higher viscosities because of their lower heat content and enrichment with respect to silica. Felsic magmas are generated by the partial melting of the more siliceous upper portion of water-saturated oceanic crust (more siliceous because of the thick sedimentary cover it carries) where it is subducted at convergent plate boundaries and by assimilation-melting of siliceous, water-rich, continental crust into the magma derived from partial melting of mafic oceanic crust and asthenosphere as it rises toward the surface.**



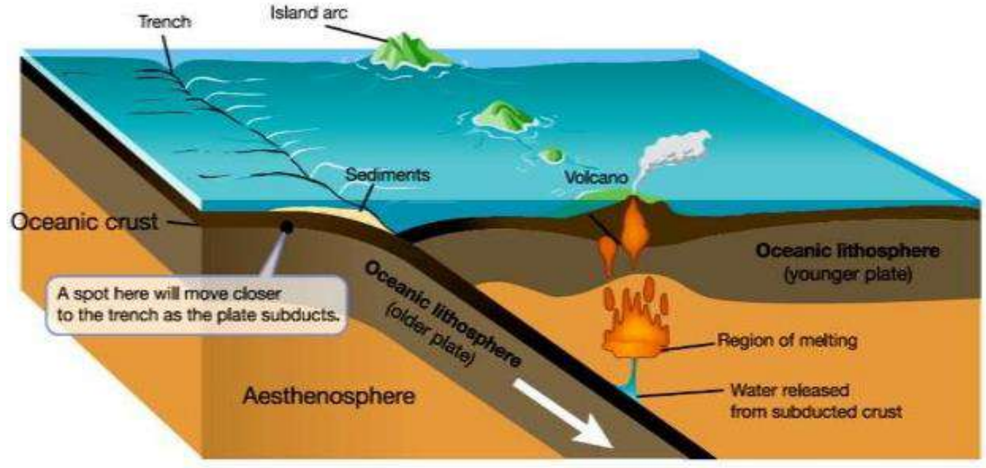




Oceanic-oceanic convergence

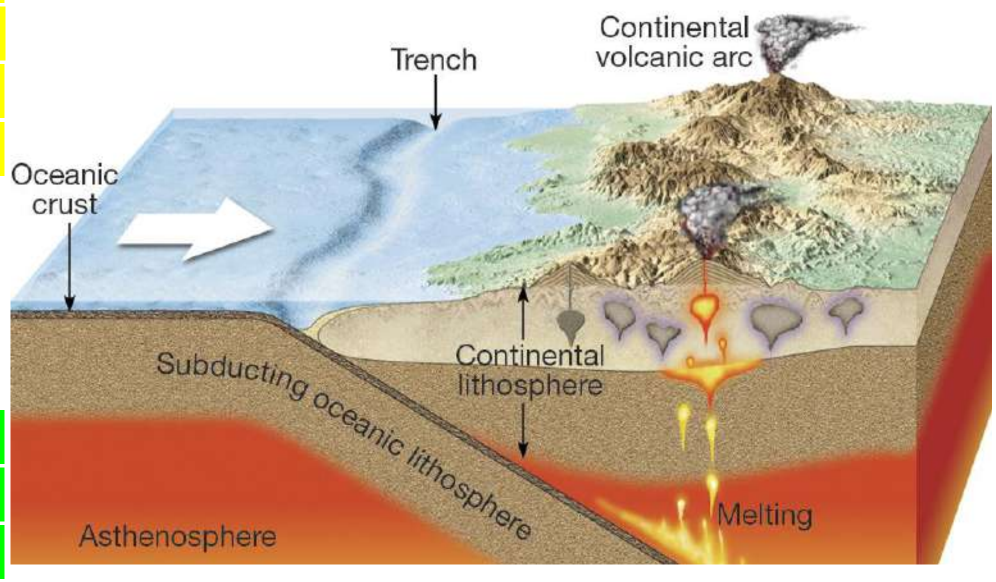


## Intermediate magma:

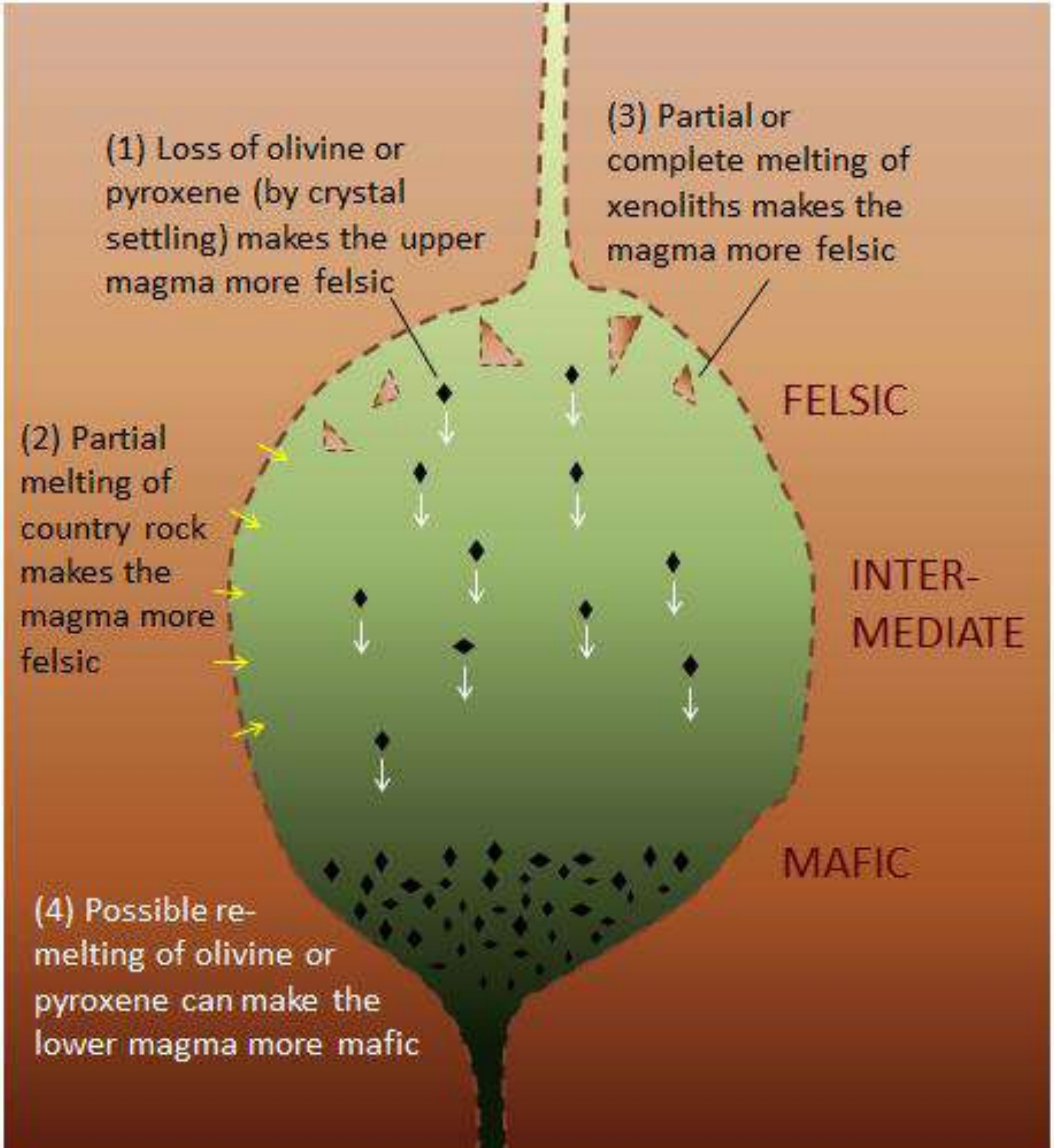
During oceanic-oceanic plate collisions, a basic magma rises through the overlying oceanic plate and is little changed by assimilation-melting (the original mafic magma simply assimilates more mafic material on its way upward); volcanic eruptions on the sea floor form island chains called island arcs. Volcanism is initially mafic in composition, but as time progresses and the volcanic arc ages and is subject to erosion (producing sediment that accumulates in the subduction zone), newer magmas become increasingly silicic and become intermediate. During oceanic-continental collisions, the generally mafic magma rises through felsic continental lithosphere to build a volcanic arc on the continental margin. Assimilation-melting of the overlying felsic continental plate produces intermediate magma.

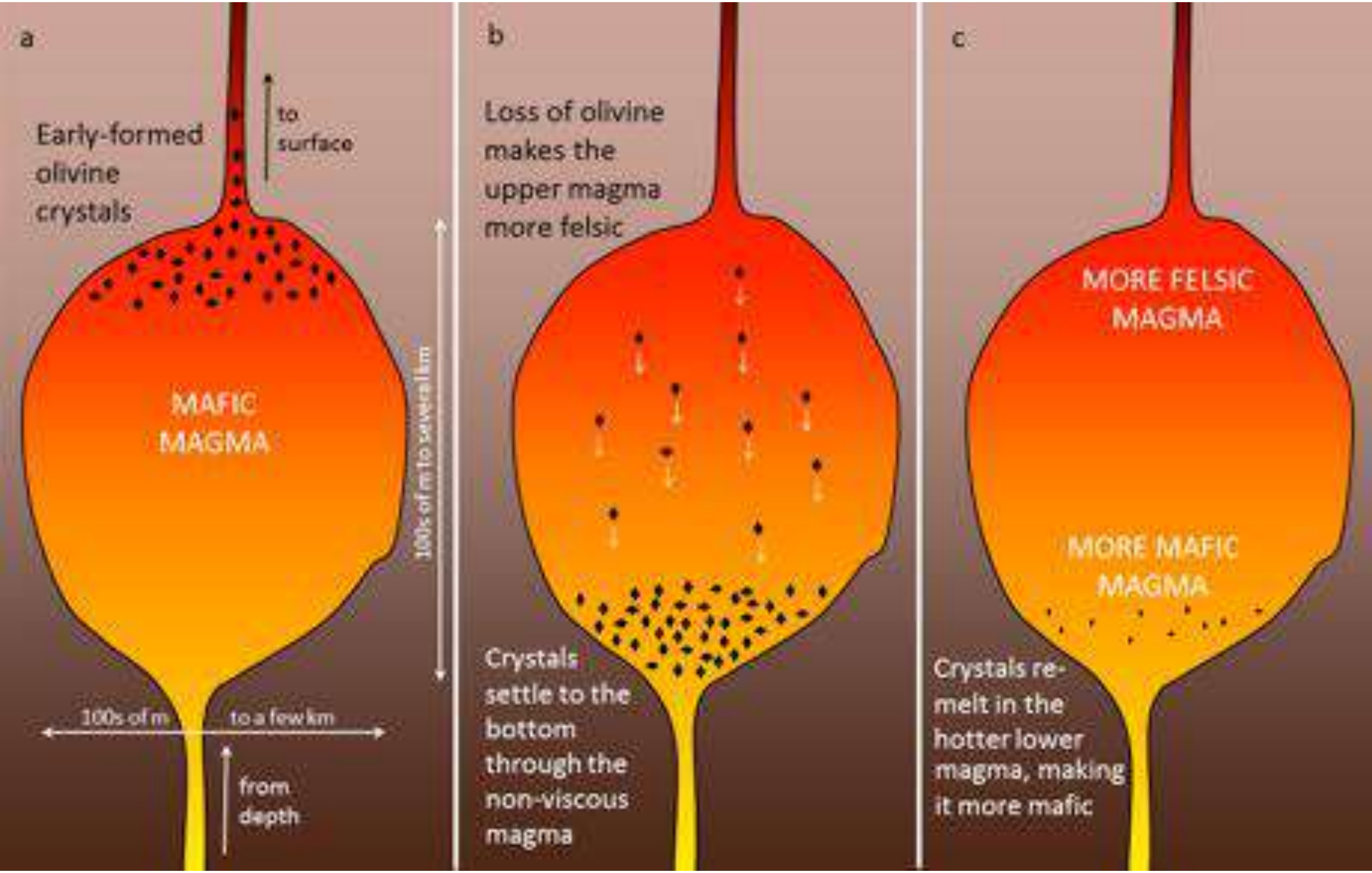


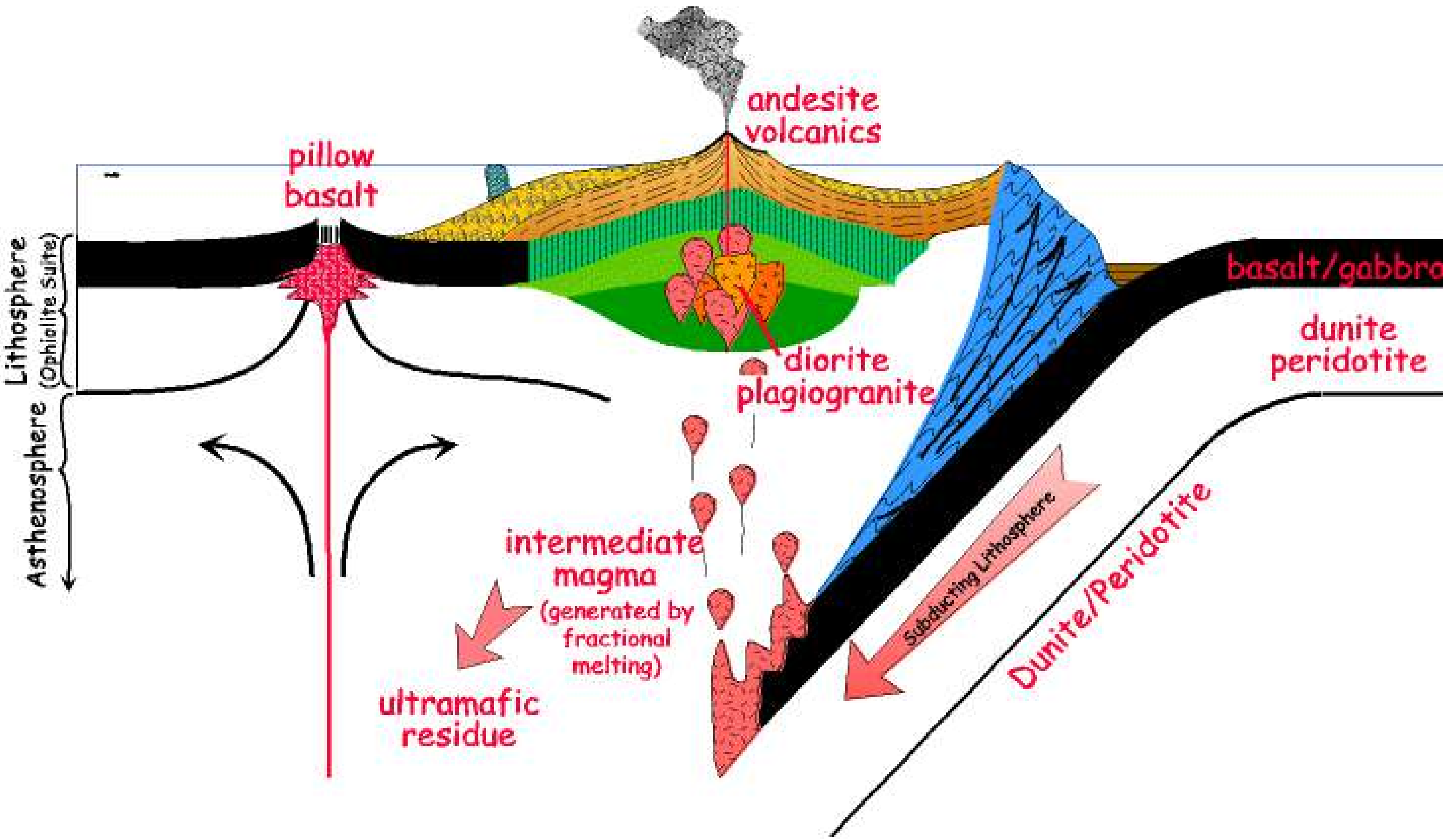

Ocean-ocean collision

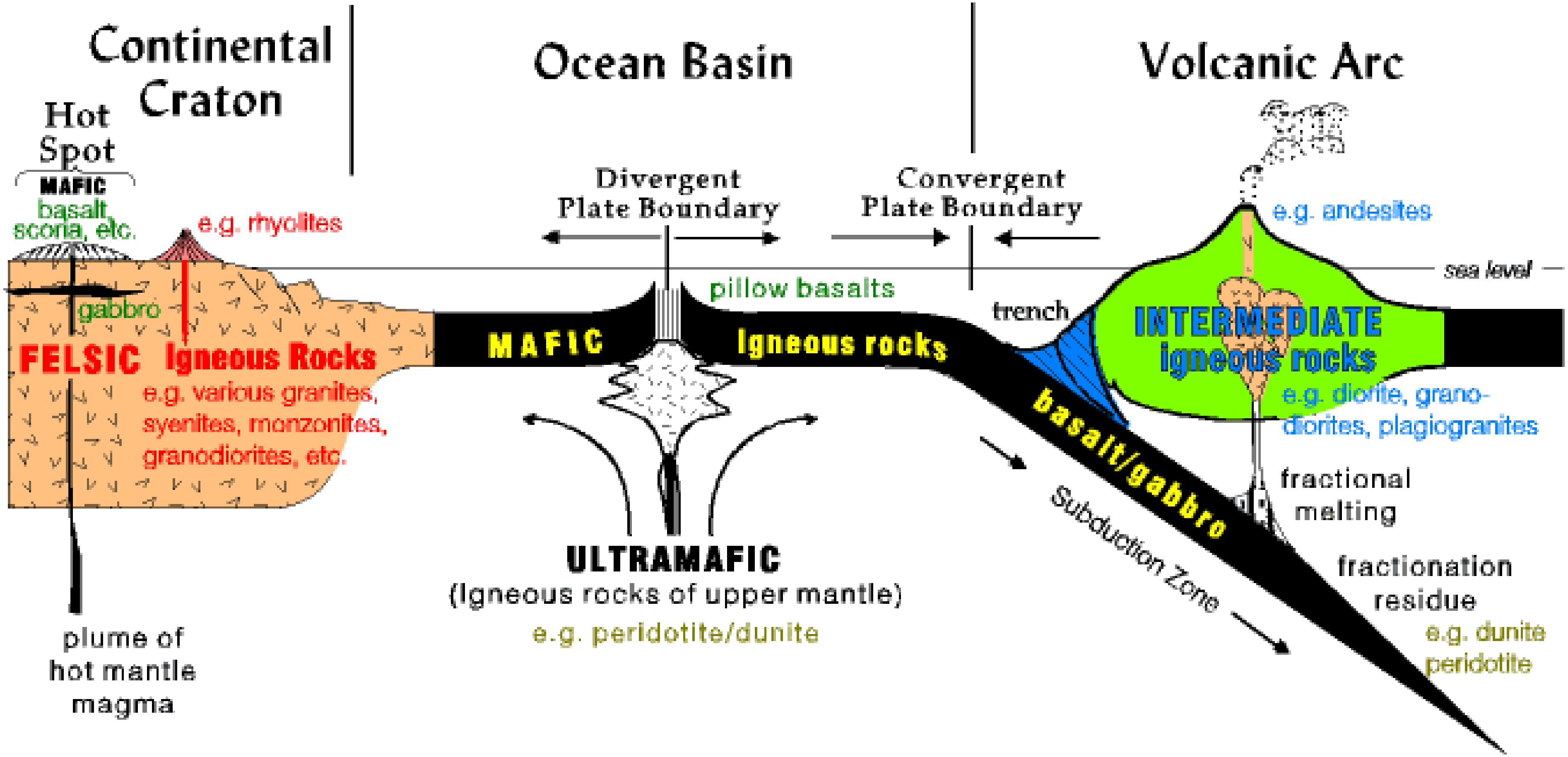



oceanic-continental collisions

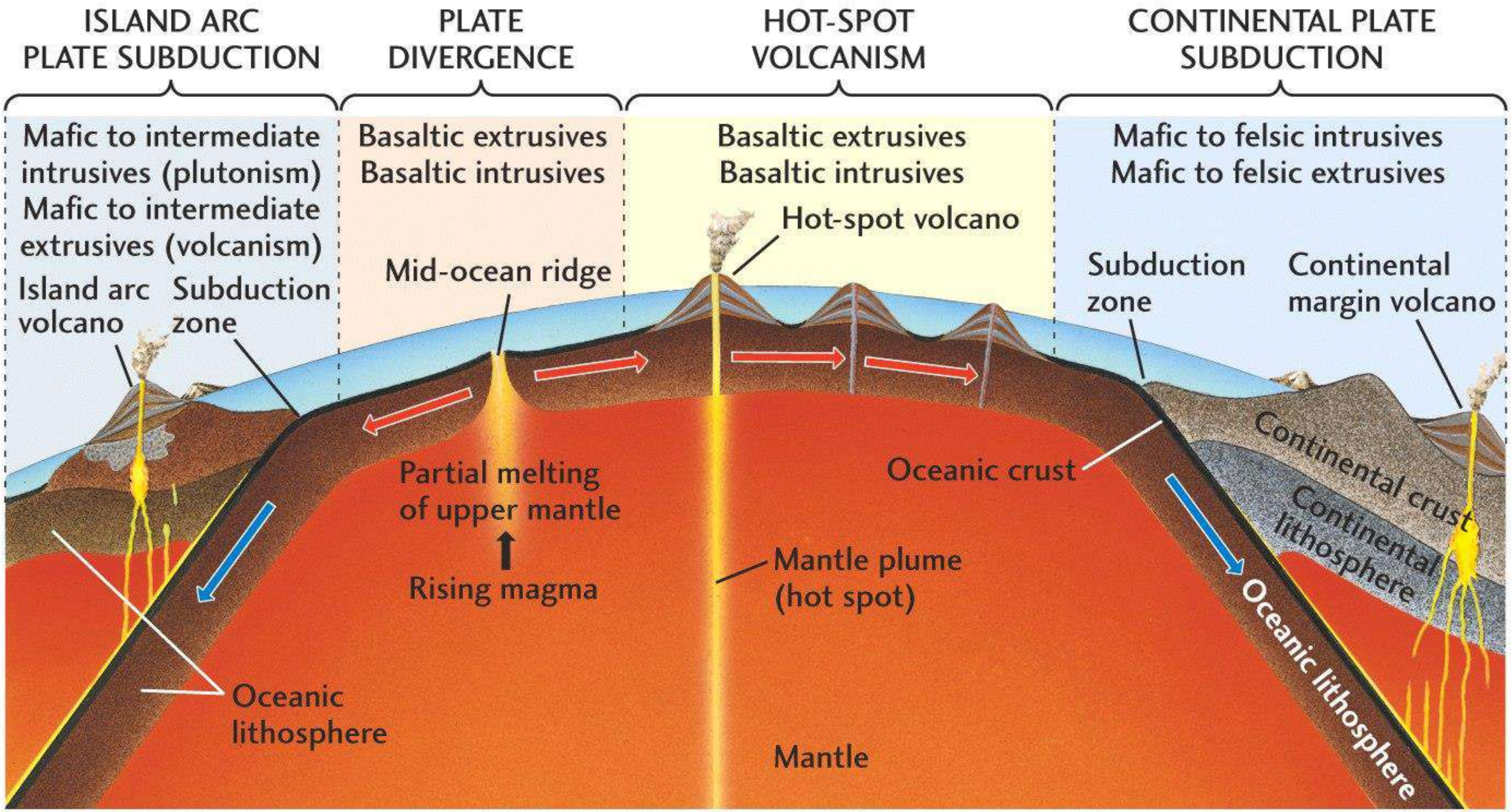

(1) Loss of olivine or pyroxene (by crystal settling) makes the upper magma more felsic
(3) Partial or complete melting of xenoliths makes the magma more felsic
FELSIC
(2) Partial melting of country rock makes the magma more felsic
INTER-MEDIATE
MAFIC
(4) Possible re-melting of olivine or pyroxene can make the lower magma more mafic

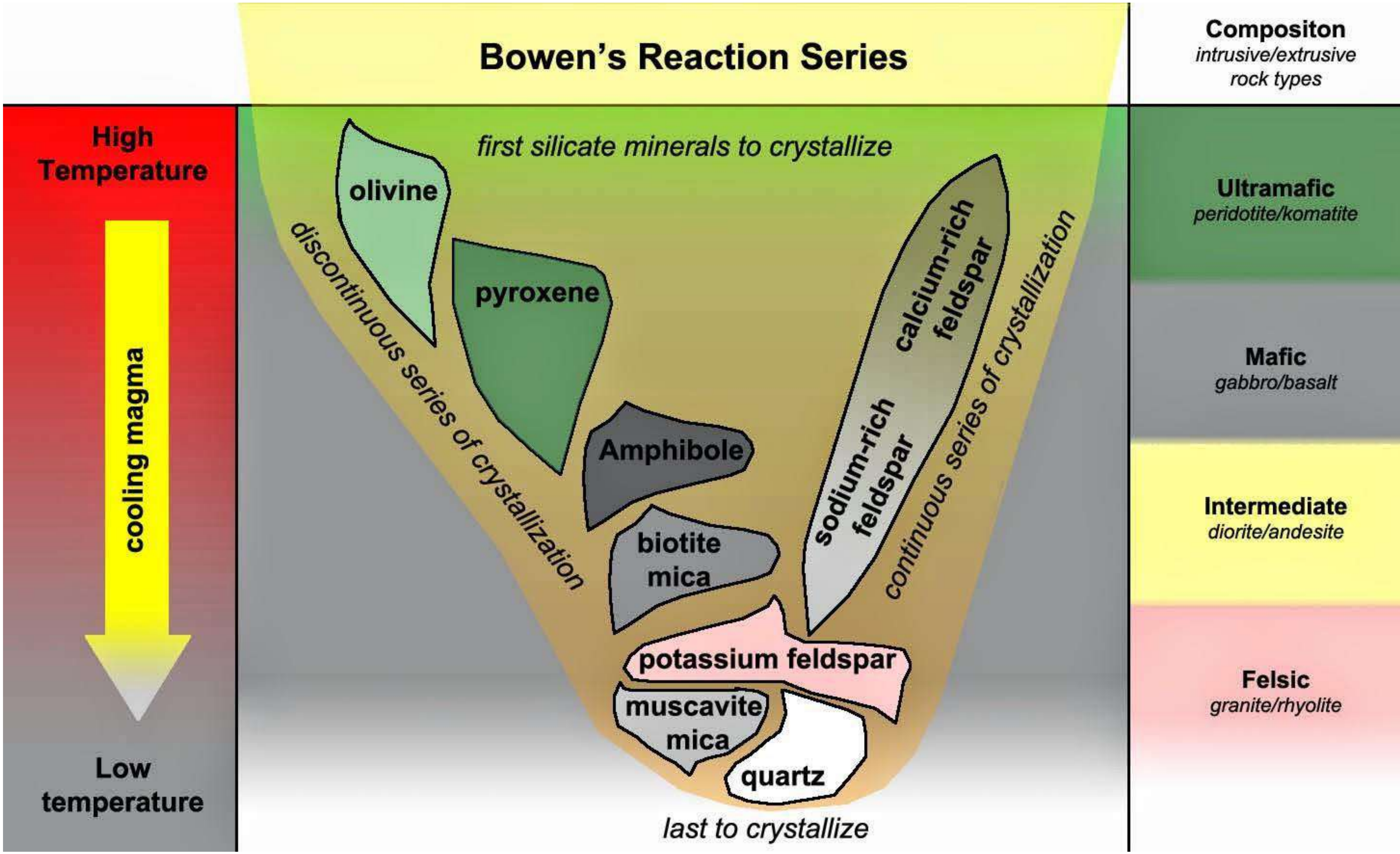

a
Early-formed olivine crystals
to surface
MAFIC MAGMA
100s of m to several km
100s of m
to a few km
from depth
b
Loss of olivine makes the upper magma more felsic
Crystals settle to the bottom through the non-viscous magma
c
MORE FELSIC MAGMA
MORE MAFIC MAGMA
Crystals re-melt in the hotter lower magma, making it more mafic

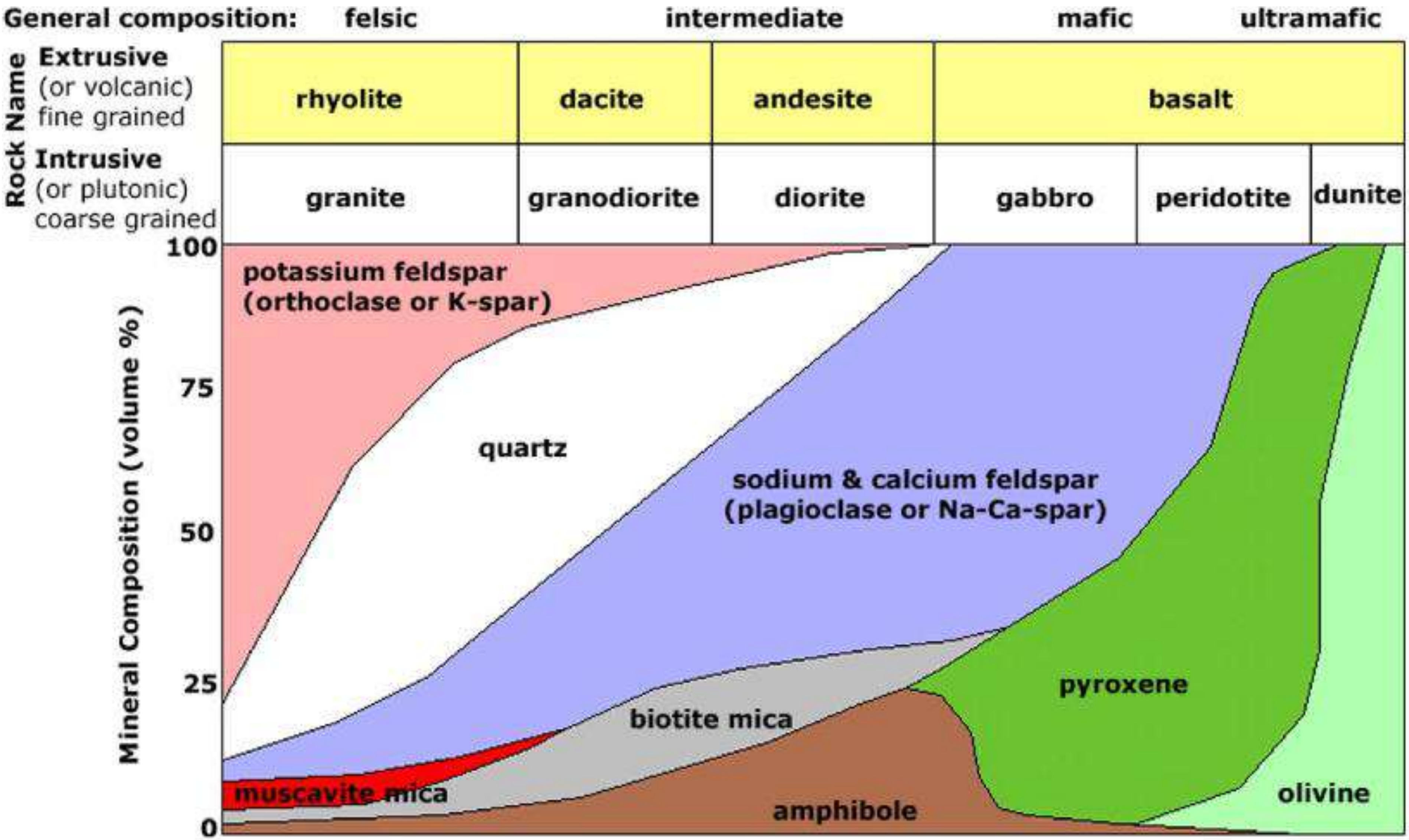

andesite volcanics
pillow basalt
Lithosphere (Ophiolite Suite)
basalt/gabbro
dunite peridotite
diorite plagiogranite
Asthenosphere
intermediate magma
(generated by fractional melting)
ultramafic residue
Subducting Lithosphere
Dunite/Peridotite



Continental Craton
Ocean Basin
Volcanic Arc
Hot Spot
MAFIC
basalt, scoria, etc.
e.g. rhyolites
Divergent Plate Boundary
Convergent Plate Boundary
e.g. andesites
sea level
pillow basalts
trench
gabbro
FELSIC Igneous Rocks
MAFIC Igneous rocks
INTERMEDIATE igneous rocks
e.g. various granites, syenites, monzonites, granodiorites, etc.
basalt/gabbro
e.g. diorite, grano-diorites, plagiogranites
fractional melting
Subduction Zone
fractionation residue
ULTRAMAFIC
(Igneous rocks of upper mantle)
e.g. peridotite/dunite
e.g. dunite peridotite
plume of hot mantle magma


ISLAND ARC PLATE SUBDUCTION
PLATE DIVERGENCE
HOT-SPOT VOLCANISM
CONTINENTAL PLATE SUBDUCTION
Mafic to intermediate intrusives (plutonism)
Mafic to intermediate extrusives (volcanism)
Basaltic extrusives
Basaltic intrusives
Basaltic extrusives
Basaltic intrusives
Mafic to felsic intrusives
Mafic to felsic extrusives
Hot-spot volcano
Mid-ocean ridge
Island arc volcano
Subduction zone
Subduction zone
Continental margin volcano
Partial melting of upper mantle
Rising magma
Oceanic crust
Continental crust
Continental lithosphere
Mantle plume (hot spot)
Oceanic lithosphere
Oceanic lithosphere
Mantle


Bowen's Reaction Series
Compositon
intrusive/extrusive
rock types
High
Temperature
cooling magma
Low
temperature
first silicate minerals to crystallize
olivine
pyroxene
Amphibole
biotite
mica
potassium feldspar
muscavite
mica
quartz
calcium-rich
feldspar
sodium-rich
feldspar
discontinuous series of crystallization
continuous series of crystallization
last to crystallize
Ultramafic
peridotite/komatite
Mafic
gabbro/basalt
Intermediate
diorite/andesite
Felsic
granite/rhyolite




A general classification of igneous rocks.

# End of Lecture