CHAPTER VI

CONTINENTAL DRIFTAND PLATE TECTONICS

Foreward:

In the early 1960s, the emergence of the theory of plate tectonics revolutionized the earth sciences. Since then, the work of several scientists has clearly explained how our planet is shaped by the processes of plate tectonics. Today, everyone is convinced that geological processes are directly or indirectly influenced by plate tectonics.

The theory of plate tectonics is the unifying theory of the different disciplines of geology because it explains the origin of the forces which continuously shaped the surface of the earth.

This course is an introduction to the concept of plate tectonics. It traces the history of the development of this theory from its first proposal without forgetting the scientists who tirelessly worked to put it in its current form and for it to be accepted by everyone.

1- Introduction

In geology, a **plate** is a large, **rigid slab** of the **lithosphere** made up of solid rock. A tectonic plate is also defined as a piece of the Earth's lithosphere that rests on the **asthenosphere** (a relatively **ductile layer of the upper mantle**). The word **tectonics** comes from the Greek (teckton = to build). These two words (**plate and tectonics)** together give, Plate Tectonics which explains how the outermost layer of the earth is subdivided into a dozen or more plates, small and large moving continuously relative to each other on a warmer and less viscous **asthenosphere**.

The surface of a plate may be made up entirely of sea floor (as is the Nazca plate), or it may be made up of both continental and oceanic rock (as is the North American plate). Some of the smaller plates are entirely continental, but all the large plates contain some sea floor.

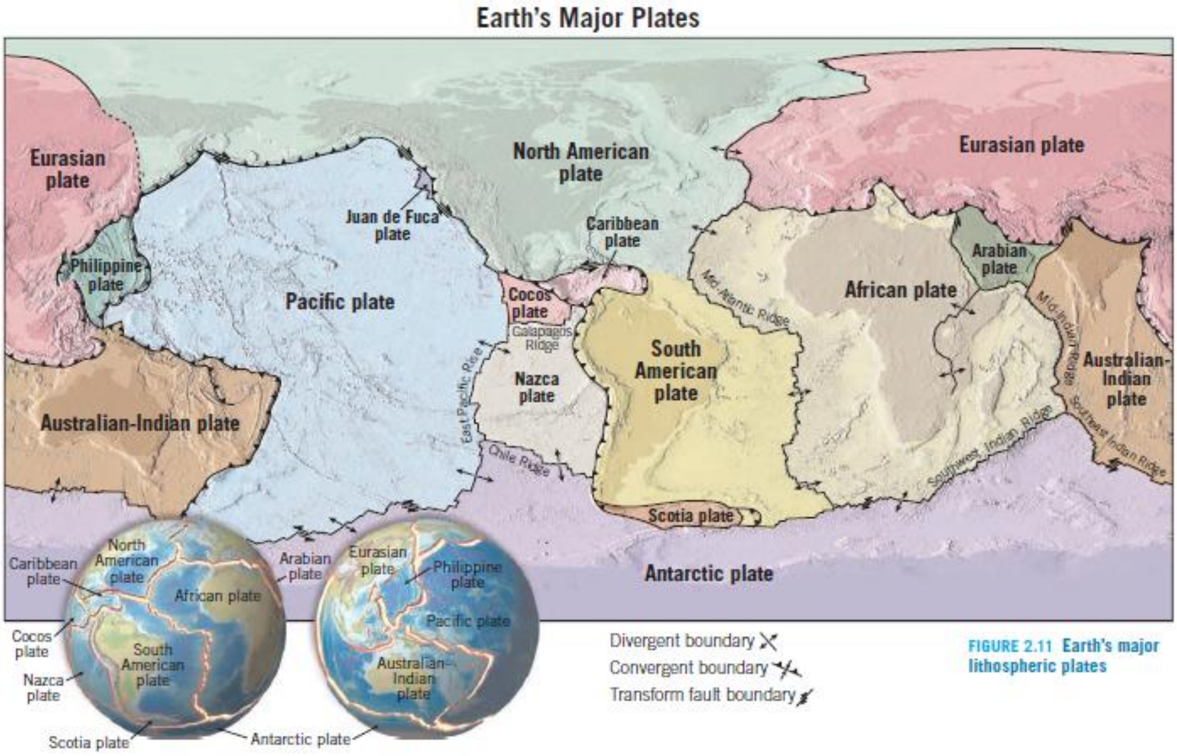
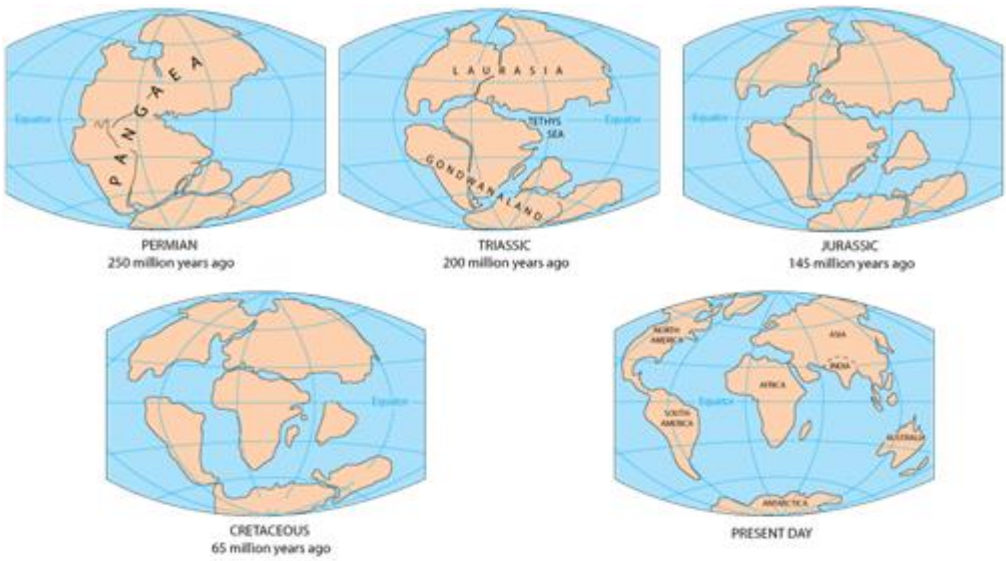


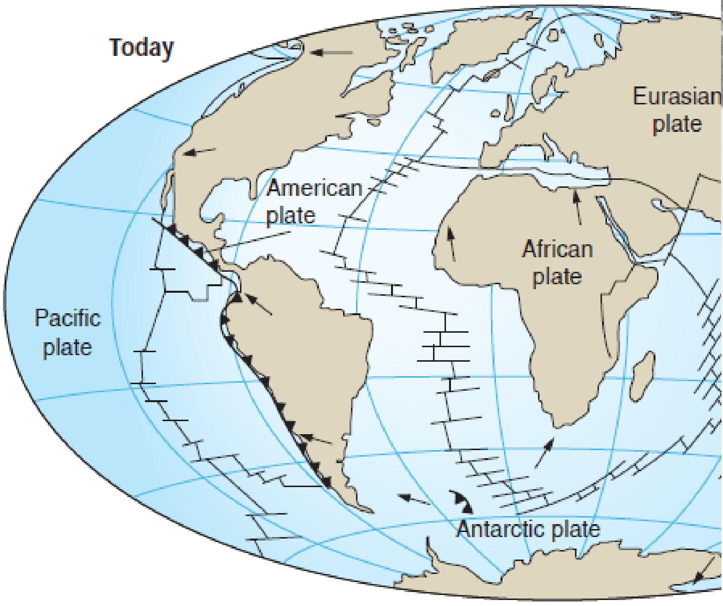
FIGURE 2.11 Earth's major lithospheric plates

2- Continental drift

The idea that continents were once joined together and have split and moved apart from one another has been around for more than 130 years (fig. 2). In fact, the current arrangement of the continents is the result of the fragmentation of the supercontinent known as **Pangaea** (giant continent).

In the early 1900s, Alfred Wegener, a German meteorologist, made a strong case for continental drift. He noted that South America, Africa, India, Antarctica, and Australia had almost identical late Paleozoic rocks and fossils.





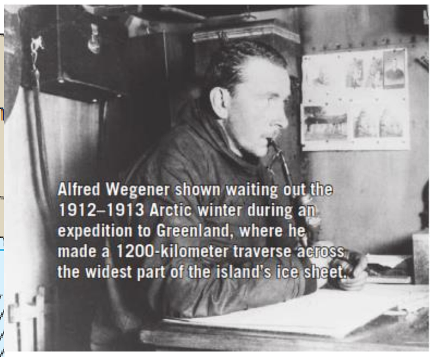


Figure 2 Pangaea breakup and continental drift. .

To back his theory, Wegner has advanced a set of arguments to strengthen his thesis. These arguments are:

2. 1- Arguments of continental drift:

2. 1.1- Topographic arguments:

The topographic arguments are reflected in the resemblance and almost perfect fit of the African and American coast lines (fig. 3).

Fig 3 adjustement remaquable des cotes Africaines et Americaines

2.1.2- The geologic arguments:

The geologic arguments are manifested by the similarity of formations and geological structures (fig. 4) on the coasts of America and Africa, Europe and Greenland which are currently largely separated by the ocean.

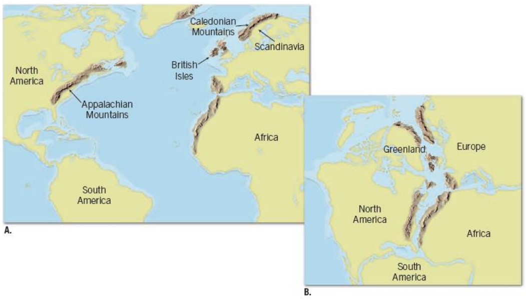


Fig 4 Ressemblance et continuité de certainnes formations géologiques sur les deux continents l'Afrique et L'Amérique

2.1.3- Paleontologic Arguments

The paleontologic arguments are spectacular because of the resemblance of fossils on the continents (America, Africa, Australia, India and Antarctica) (Fig. 5). For Wegner, the presence of identical fossil species along the coastal parts of Africa and South America was the most convincing evidence that the two continents were once joined together.

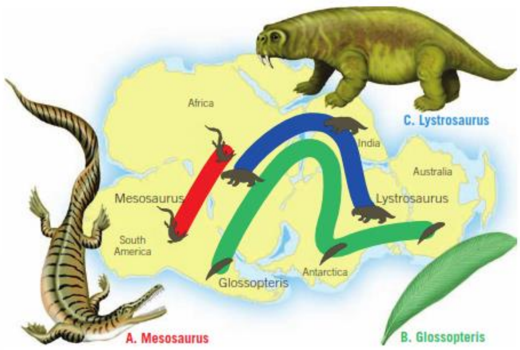


FIGURE 4 Fossil evidence supporting continental drift
Fossils of identical organisms have been discovered in rocks of similar age in Australia, Africa, South America, Antarctica, and India—continents that are currently widely separated by ocean barriers. Wegener accounted for these occurrences by placing these continents in their pre-drift locations.

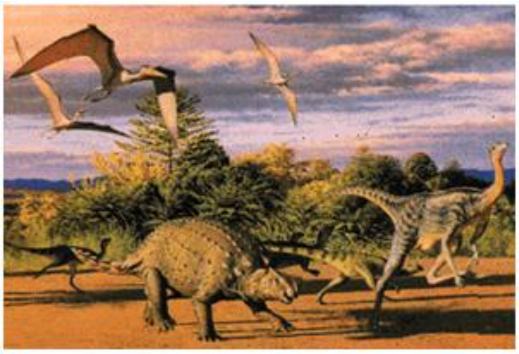


Fig.5, Les Dinosors polaires qui ont vecu en Australie quand cette dernière etait colée à l'antarctique

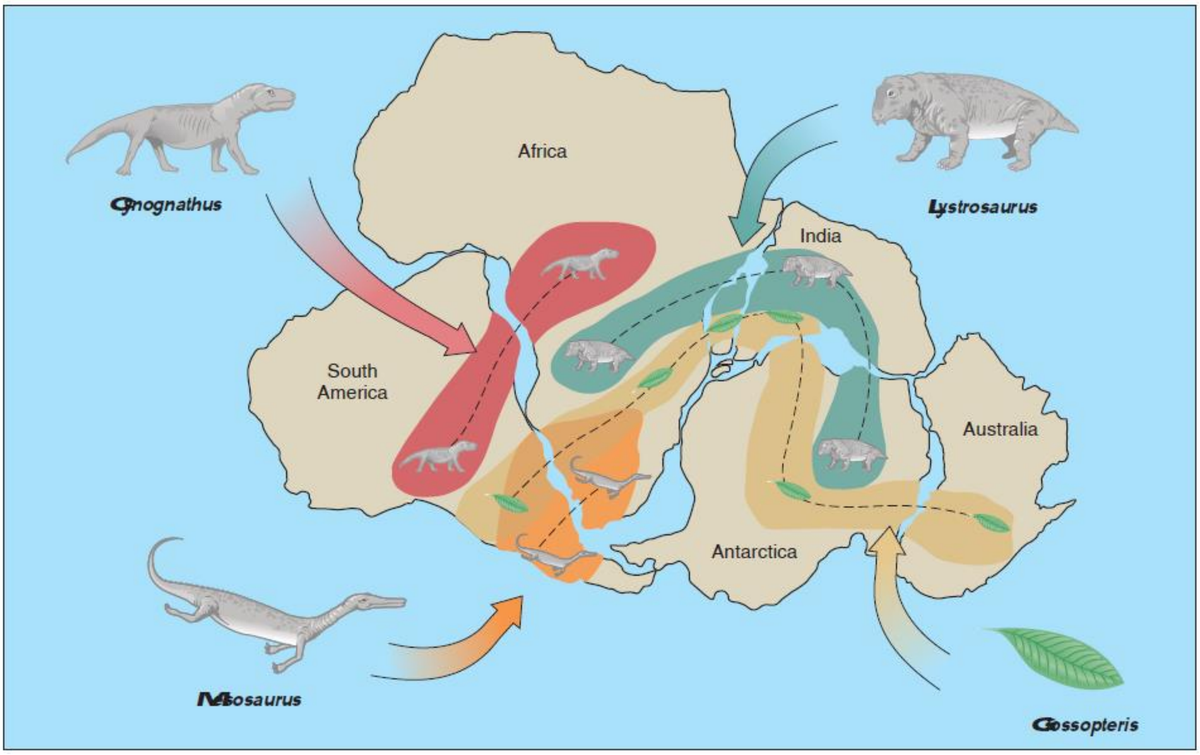


FIGURE 5

Distribution of plant and animal fossils that are found on the continents of South America, Africa, Antarctica, India, and Australia give evidence for the southern supercontinent of Gondwana. *Glossopteris* and other fernlike plants are found in Permian- and Pennsylvanian-age rocks on all five continents. *Cynognathus* and *Lystrosaurus* were sheep-sized land reptiles that lived during the Early Triassic Period. Fossils of the freshwater reptile *Mesosaurus* are found in Permian-age rocks on the southern tip of Africa and South America.

2.1.4- Climatic arguments:

For climatic arguments, the presence of glacial sediments (tills) in South America, South Africa and Australia (fig.6) testify that there was a time when these regions were polar regions. The presence of peat deposits in the Arctic is an indication that this region was once equatorial (fig.6).

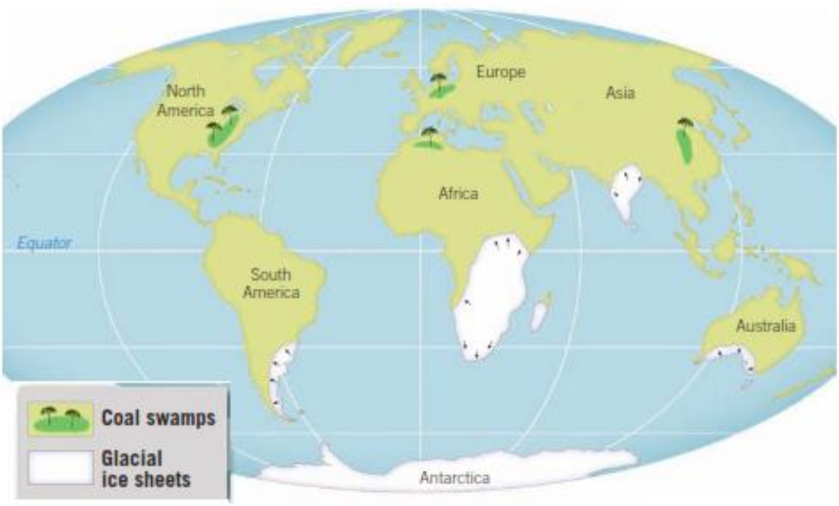


Fig. 6, distribution des sediments glaciales

The theory of continental drift would become the spark that ignited a new way of seeing the Earth. But at the time when Wegener presented his theory, the scientific community firmly believed that continents and oceans were permanent, immobile features on the Earth's surface. It is not surprising that his proposal was not well received, even though it appeared to be in agreement with the scientific information available at the time. A strong weakness of Wegener's theory lies in the fact that it could not satisfactorily answer the most fundamental question raised by his opponents:

What forces could be strong enough to move such large masses of solid rock along such great distances? Wegener suggested that the continents were simply sliding on the ocean floor, but Harold Jeffreys, a renowned English geophysicist, argued that it was physically impossible for such a large mass of solid rock to move on the ocean floor without breaking. The theory was rejected by the scientific community at the time. The force of the tides is also too insufficient to push the continents.

Despite being unable to argue the origin of the forces that generate these movements, Wegener devoted the rest of his life relentlessly pursuing additional evidence to defend his theory. He was frozen to death in 1930 during an expedition to Greenland. However, long time after his death, new evidence from ocean floor exploration and other studies revived interest in Wegener's theory, eventually leading to the development of the theory of plate tectonics.

3-Theory of plate tectonics

The theory of continental drift has been definitively rejected as eccentric, absurd and improbable. However, starting in the 1950s, new discoveries revived Wegener's theory. In particular, four major scientific developments have stimulated the formulation of the theory of plate tectonics: (1) the relatively recent age of the ocean floor; (2) confirmation of reversals of the Earth's magnetic field; (3) the emergence of the ocean floor spreading hypothesis; And (4) The concentration of seismic and volcanic activity along ocean trenches and underwater mountain ranges.

The lithosphere is divided into a dozen plates that are commonly called tectonic plates (fig. 1). These plates move relative to each other.

3.1 Paléomagnetism and the revival of continental drift

Much work in the 1940s and 1950s set the stage for the revival of the idea of continental drift and its later incorporation, along with seafloor spreading, into the new concept of plate tectonics. The new investigations were in two areas: (1) study of the sea floor and (2) geophysical research, especially in relation to rock magnetism.

Rock magnetism which showed the polar wandering (تغير موقع القطب المغنطيسي مع الزمن) played a great role in considering the continental drift theory.

3.2 - Ocean floor mapping

Bathymetric measurements revealed the existence of underwater mountain ranges comparable to those seen on the continent and that the ocean floor is not as flat as previously thought. These measurements have confirmed the existence of a mountain range in the center of the Atlantic Ocean and cross it from north to south; it is called the **mid-oceanic ridge**. Indeed, works have shown that the entire earth is surrounded by a mid-oceanic ridge called (**Global Oceanic Ridge System**) (fig. 7).

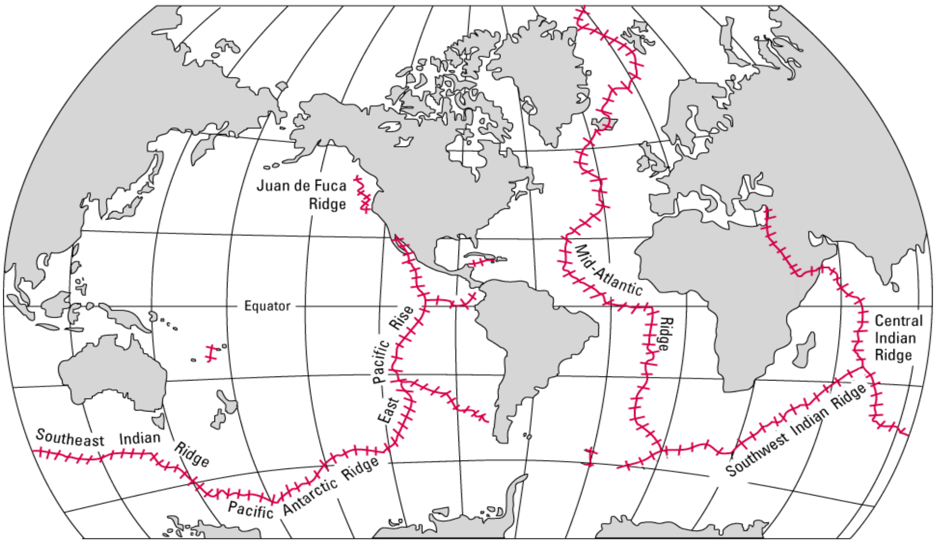


Figure 7. The Global oceanic mid-ocean ridge system

It was also discovered that the thickness of sediments on the ocean floor is much reduced compared to what it would have been if the oceans had been there since the beginning of time. This confirms that the age of the oceans is relatively young compared to the continents.

3 3- Reversals of the earth's magnetic field

The Earth's magnetic field is fossilized by ferromagnetic minerals during their formation. It was then discovered that the earth's magnetic field has a polarity that is sometimes normal (N-S) and sometimes inverse (S-N). On either side of the mid-oceanic ridges we encounter, symmetrically, rocks with a magnetic field of N-S polarity which alternate with others where the magnetic field is of S-N polarity. These alternations when mapped give a banded appearance (zebra like pattern) (Fig.8).

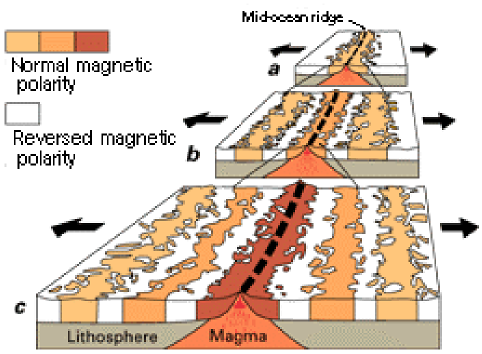


Figure 8. *Magnetic striping. Nouvelle croute océanique en formation continue le long de la ride midio-oceanique. La croute devienne plus ancienne en s'éloignant de la ride.* ***a.*** *the spreading ridge about 5 million years ago;* ***b.*** *about 2 to 3 million years ago; and* ***c.*** *present-day*

3.3.1 The Vine-Matthews Hypothesis

Two British geologists, Fred Vine and Drummond Matthews, made several important observations about these **magnetic anomalies**.

They recognized that the pattern of magnetic anomalies was symmetrical about the ridge crest. That is, the pattern of magnetic anomalies on one side of the mid-oceanic ridge was a mirror image of the pattern on the other side (figure 8, 8b).

Vine and Matthews noticed that the pattern of **magnetic *anomalies*** at sea matches

the pattern of **magnetic *reversals*** already known from studies of lava flows on the continents.

They suggested that there is continual opening of tensional cracks within the rift valley on the mid-oceanic ridge crest. Basaltic magma rising from below cools to form dikes.

When Earth's magnetic field has a ***normal polarity*** (the present orientation), cooling magmas are normally magnetized. When magnetic field has a ***reverse polarity,*** magmas are reversely magnetized**.**

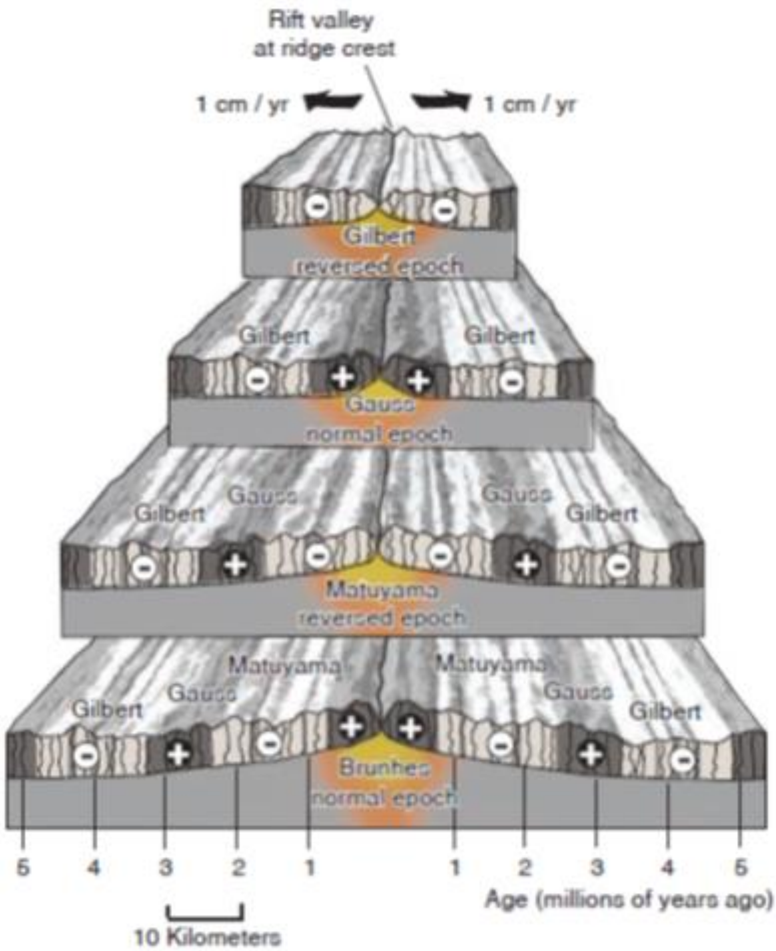


FIGURE 8b

The origin of magnetic anomalies. During a time of reversed magnetism (Gilbert reversed epoch), a series of basaltic dikes intrudes the ridge crest, becoming reversely magnetized.

3.3.2- Measuring the Rate of Plate Motion

Vine-Matthews hypothesis of magnetic anomaly has allowed to measure the **rate of seafloor motion** (which is the same as plate motion, since continents and the sea floor move together as plates).

For instance, a piece of the sea floor representing the reversal that occurred 4.5 million years ago may be found 45 kilometers away from the rift valley of the **ridge crest**. The piece of sea floor, then, has traveled 45 kilometers since it was formed. Dividing the distance the sea floor has moved by its age gives 1 centimeter per year. Such measured rates generally range from 1 to 24 centimeters per year.

3.3.3-Predicting Seafloor Age

The other important point of the Vine-Matthews hypothesis is that it **predicts the age of the sea floor**. Dating by this technique has been verified by geologists and it is widely used now a days for dating sediments. Moreover, this dating technique has shown that the rocks of the ocean are relatively younger than the continental rocks.

3 4- Sea floor spreading

In 1961, scientists hypothesized that the ocean floor is torn in two along the mid-ocean ridge. Magma easily rises through this tear to create new ocean crust. The creation of crust on either side of the mid-ocean ridge causes what is called seafloor spreading (Fig.10). This expansion is supported by several arguments:

• At or near the mid-ocean ridge, the rocks are very young, and they become progressively older away from the ridge;

• The youngest rocks, near the ridge, still have a current (normal) polarity;

• The bands of rocks parallel to the ridge alternate in magnetic polarity (normal then reversed, then normal and so on). This suggests that Earth's magnetic field has reversed several times. Additionally, oceanic crust is now considered a natural "tape record" of the history of Earth's magnetic field reversals.

A direct consequence of the expansion of the ocean floor is that the size of the earth continually increases. Is this the case? Most geologists believe that the Earth has changed little since its formation 4.6 billion years ago.

The answer always comes from the ocean floor, Hess showed that the oceanic lithosphere plunges deep into the earth at the levels of oceanic trenches. So, he concluded that the lithosphere originates at the level of the ridges (mid-oceanic ridges) and is consumed at the level of the oceanic trenches to be recycled and comes out a second time in the form of magma to build a new crust. This idea explained why the Earth is constant in volume and does not increase.

3. 5- Location and concentration of earthquakes

During the 20th century, improvements in seismic instrumentation and the increased use of seismographs around the world allowed scientists to learn that earthquakes tend to be concentrated in certain areas, notably along ocean trenches and mid-oceanic ridges and do not have a random distribution. Later seismologists found that the centers of earthquakes are located on a plane plunging from 40 to 60° called Benioff planes (fig. 9). This plane is the roof of the subducted lithospheric plate.

But what was the significance of the connection between earthquakes, trenches and ocean ridges? Recognition of such a connection helped confirm the seafloor spreading hypothesis by indicating areas where Hess predicted the formation of oceanic crust (along ridges) and areas where oceanic lithosphere dips into the mantel and get resorbed (under the trenches).

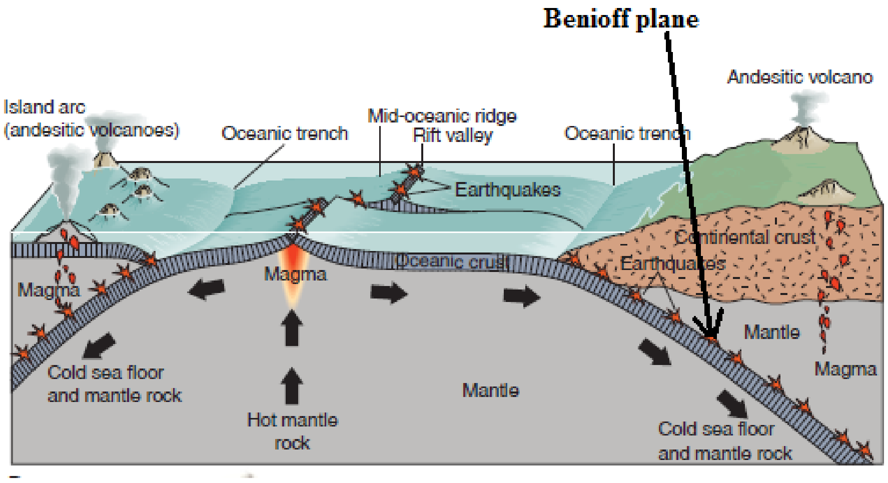


Figure 9. Benioff plane along which earthquakes are generated

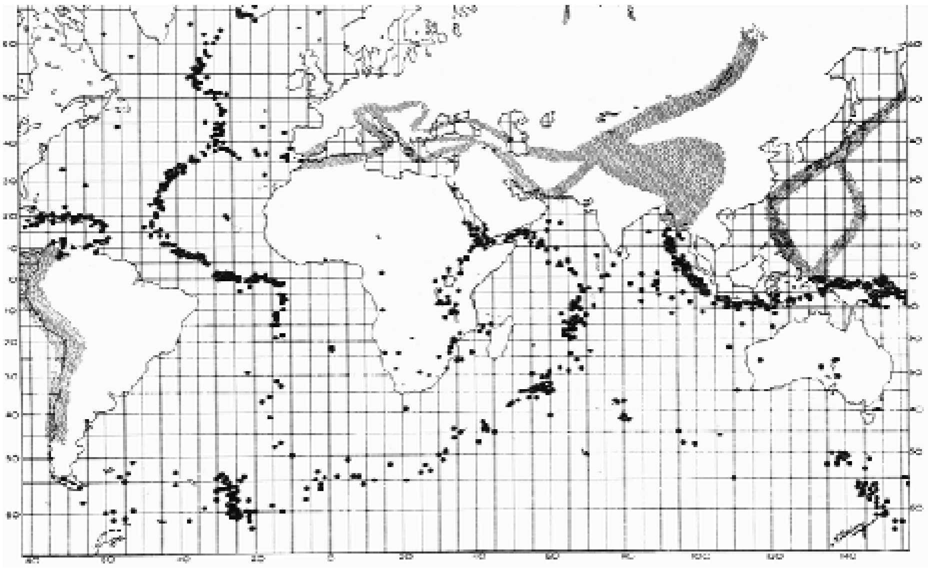


fig11. concentration des séismes le long des contactes entre les plaques lithosphériques

Once the arguments mentioned above were brought together the scientific community has unanimously accepted, in 1968, the **theory of plate tectonics** as being the unifying theory which explains the majority of past and recent geological phenomena. .

4- Plate boundaries

Scientists now have a fairly good understanding of how plates move and how these movements induce seismic and volcanic activity. There are four types of plate boundaries: Divergent boundaries, Convergent boundaries, Transform boundaries, Plate boundary zones (Fig. 10).

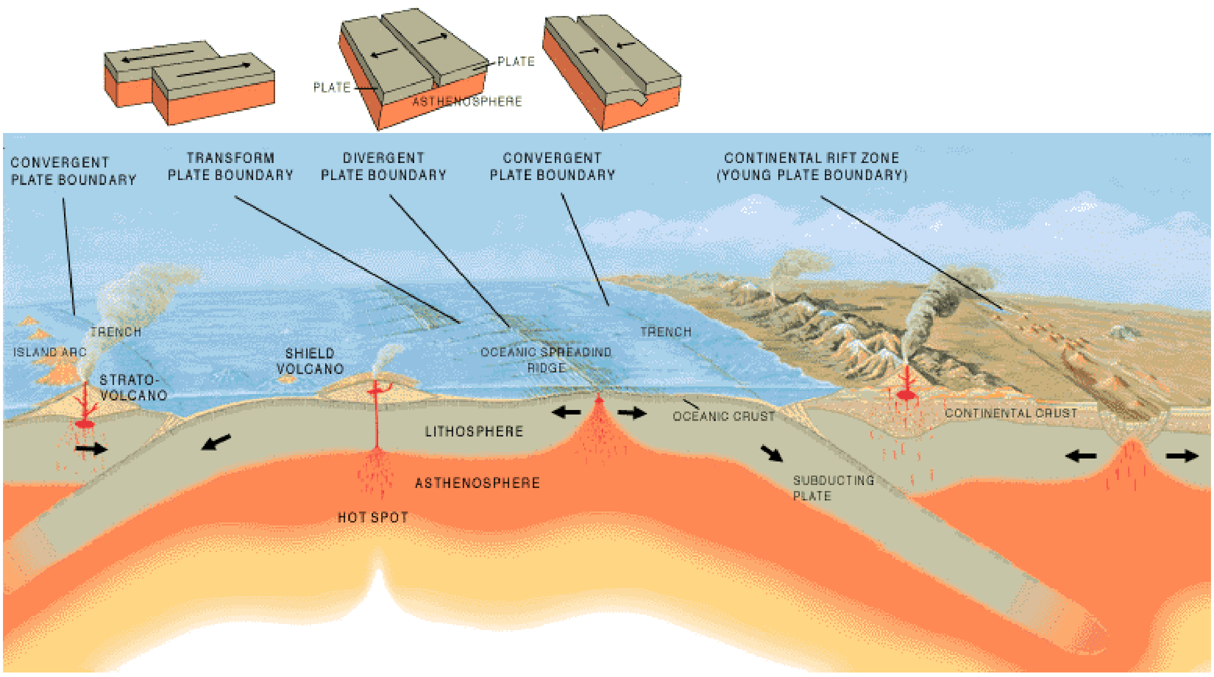
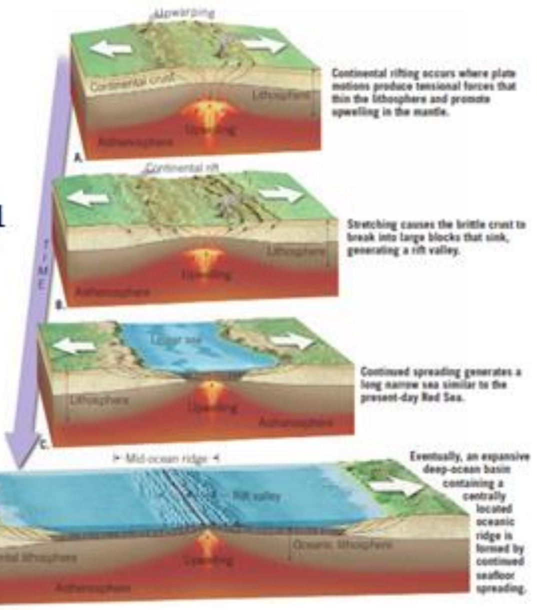


Figure 10; Les différents types de frontières de plaques

4.1- Divergent plate boundaries

Divergent plate boundaries, where plates move away from each other, can occur in the middle of the ocean or in the middle of a continent. The result of divergent plate boundaries is to create, or open, new ocean basins and this is the reason why we call it **constructive plate boundary**. This dynamic process has occurred throughout the geologic past.

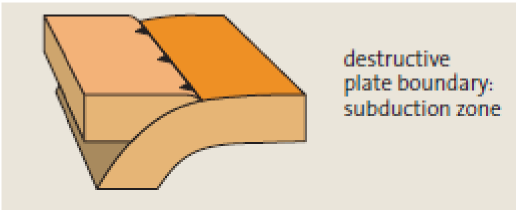
Figure 11



4 2- Convergent plate boundaries

C**onvergent plate boundaries**, Where two plates move towards each other, the denser plate is bent and pulled beneath the less dense plate, eventually plunging downward at an angle into the depths of the sub- lithospheric mantle. Such areas are called **subduction zones**.

The character of the boundary depends partly on the type of plates that converge. A oceanic plate can move toward another oceanic plate, in which case one plate dives (**subducts**) under the other. If an oceanic plate converges with a continental plate, the dense oceanic plate **subducts** under the continental plate. If the two approaching **plates** are both **continental**, the continents collide and crumple, but neither is **subducted**.



djust into a series
:tion.

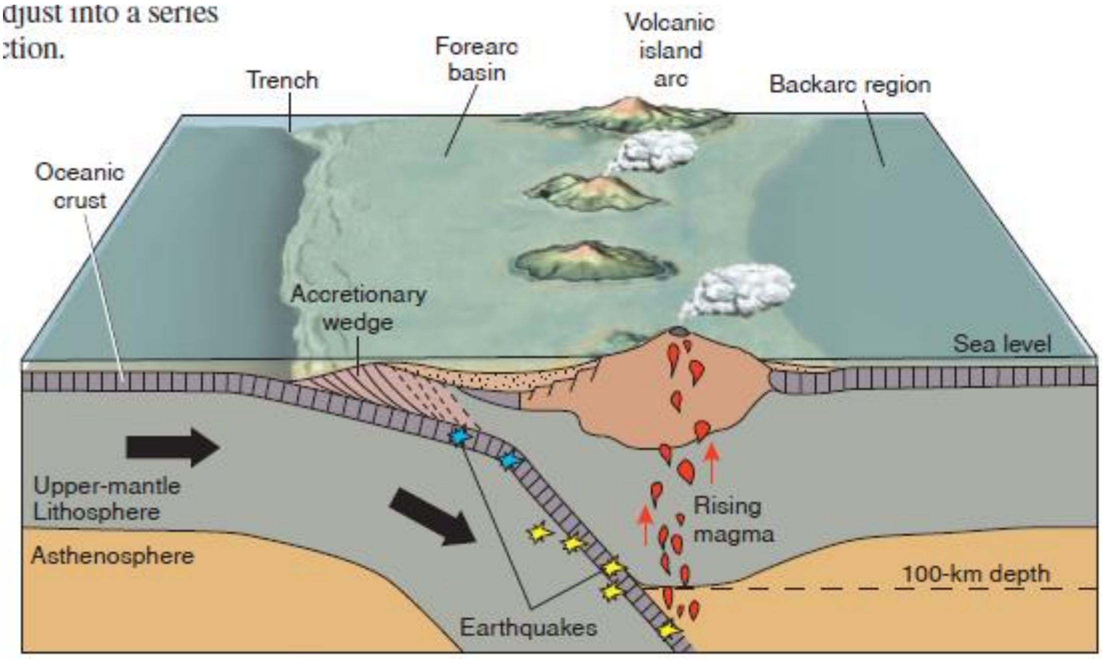


FIGURE 4.25

Ocean-ocean convergence forms a trench, a volcanic island arc, and a Benioff zone of earthquakes.

4.2.1- Ocean-Ocean Convergence

Where two **oceanic plates** converge, one plate **subducts** under the other (the Pacific plate sliding under the western Aleutian Islands is an example). The **subducting plate** bends downward, forming the outer wall of an **oceanic trench**, which usually forms a broad curve convex to the subducting plate (figures 4.25).

As one plate **subducts** under another, a **Benioff zone** of shallow, intermediate, and deep-focus earthquakes is created within the upper portion of the down-going lithosphere (fig. 7.23).

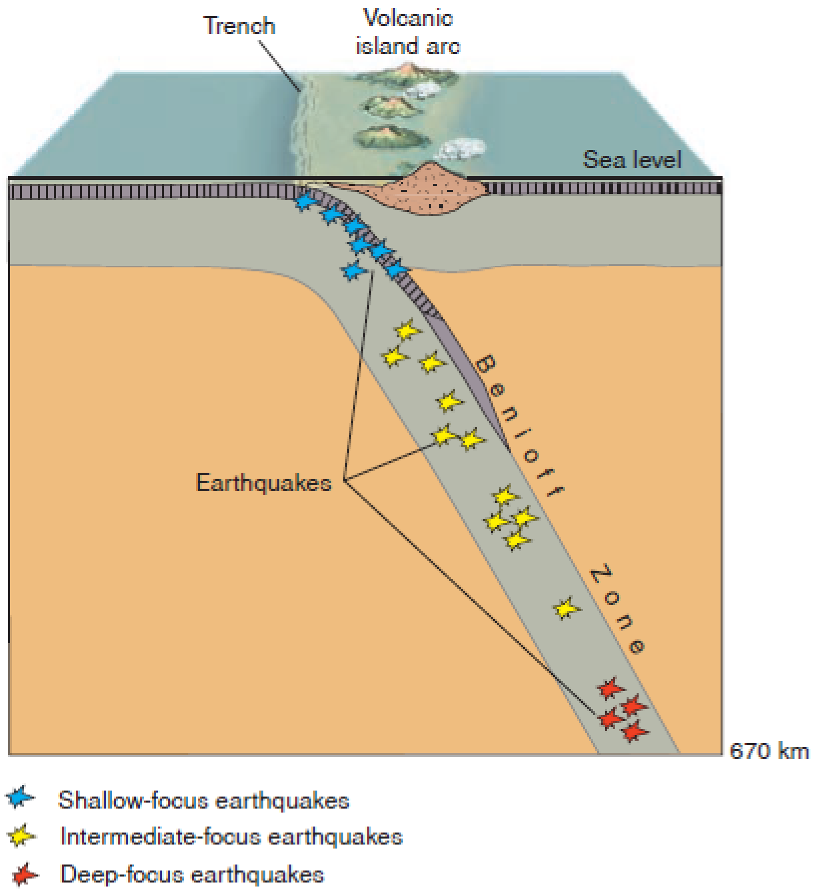


FIGURE 7.23

A Benioff zone of earthquakes begins at an oceanic trench and dips under a continent (such as South America) or a volcanic island arc. Upper part of Benioff zone may extend to a depth of 670 kilometers.

4.2.2- Oceanic Plate-Continental Plate Convergence

In this type of convergence, the denser **oceanic plate** (usually the older) sinks beneath the **continental plate** (fig. 14). The place where the oceanic plate sinks beneath the continental plate is called a **subduction zone**.

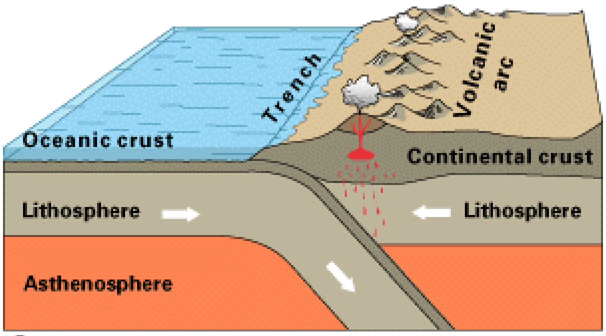


fig 14 **Oceanic-continental convergence**

4.2.3- Continent-Continent Convergence

A third type of collision involves the convergence of two **continental plates**. All the sedimentary material is compressed and uplifted to form a mountain range where the rocks are folded and faulted. As an example of this type of collision we have the Himalayan mountain range (fig. 15).

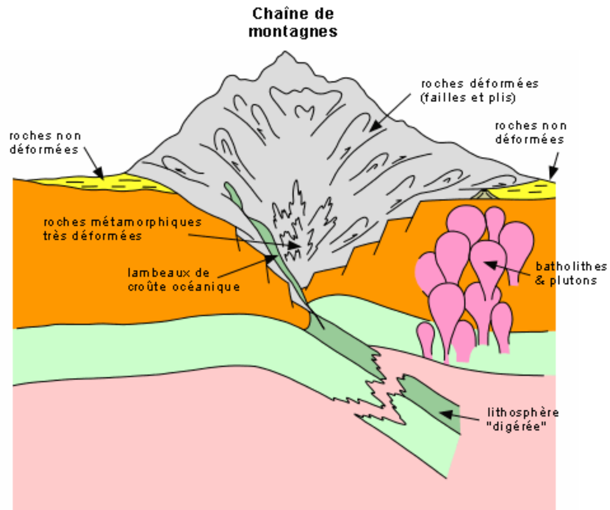
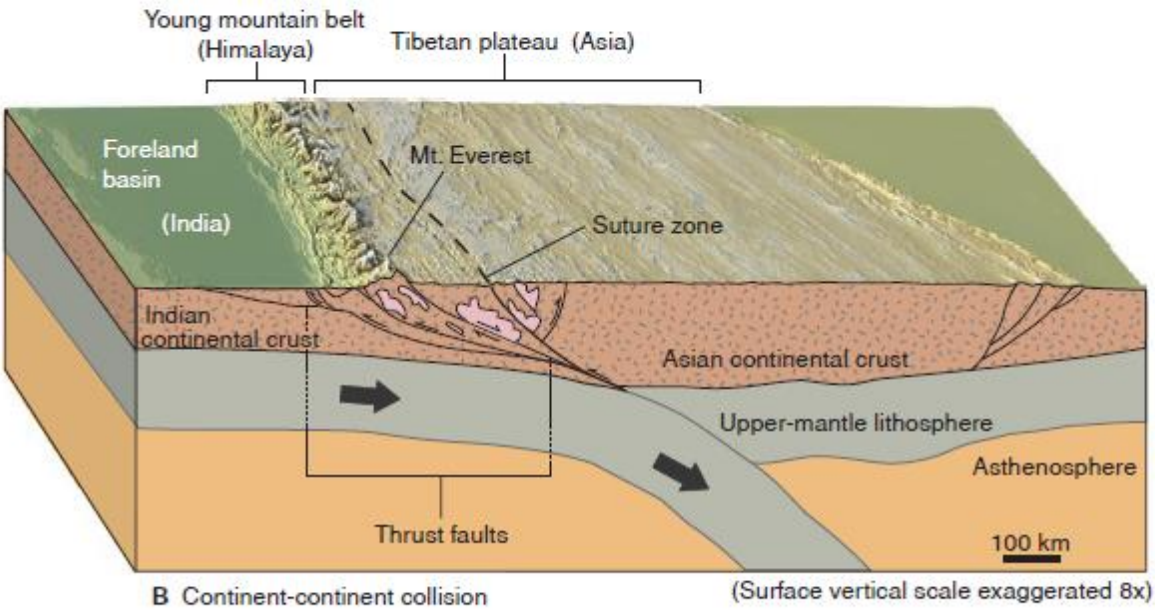


Figure 15, Collision entre deux plaques continentales



B Continent-continent collision

4.2.5 – Transform boundaries

Transform boundaries correspond to large fractures that affect the entire thickness of the lithosphere. Along these boundaries the plates slide past each other, the famous San Andreas fault in California is a good example (fig.16 and 17).

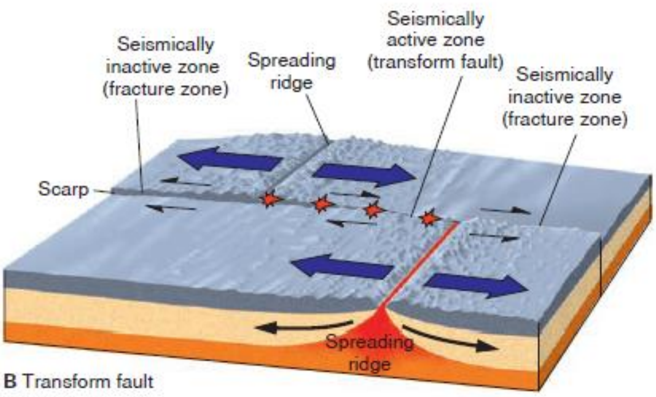


Figure 16. Frontière transformante matérialisée par la faille de Saint Andreas, au USA

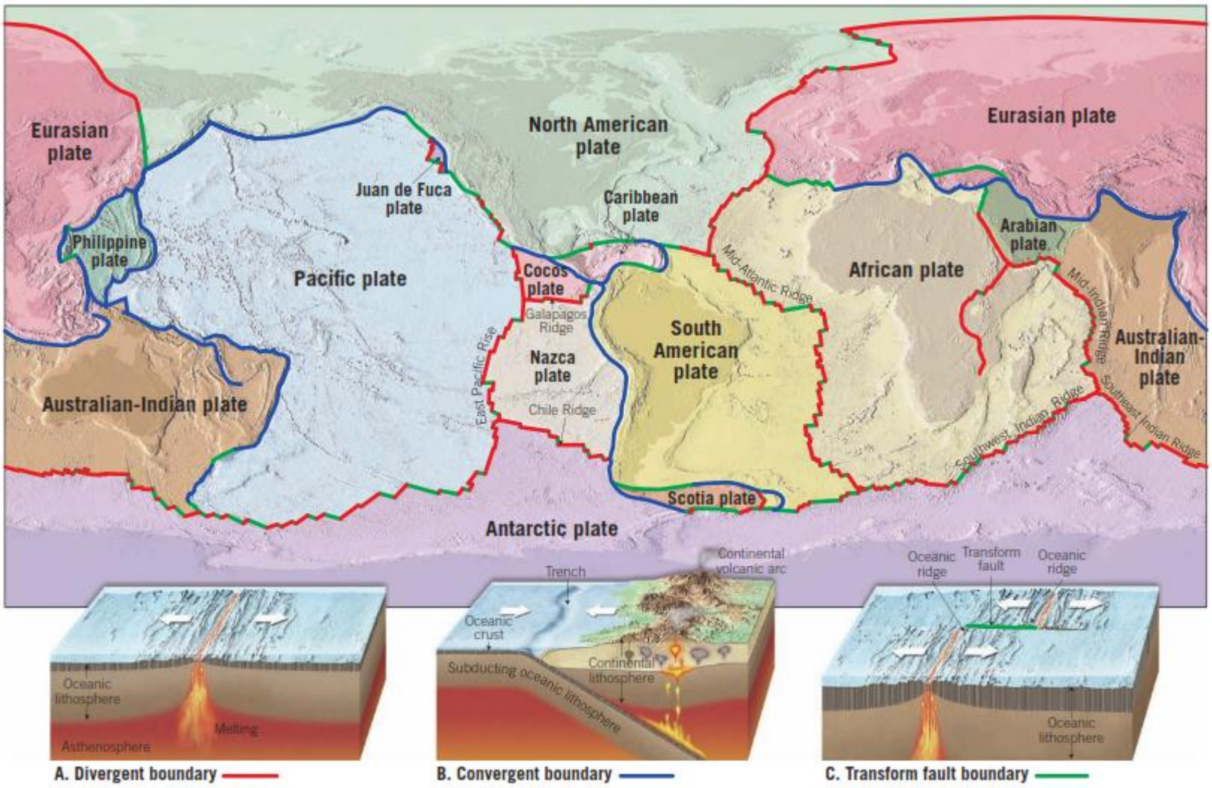


Figure 17. Schéma montrant les plaques tectoniques et les types de frontières

5- What causes plate motions?

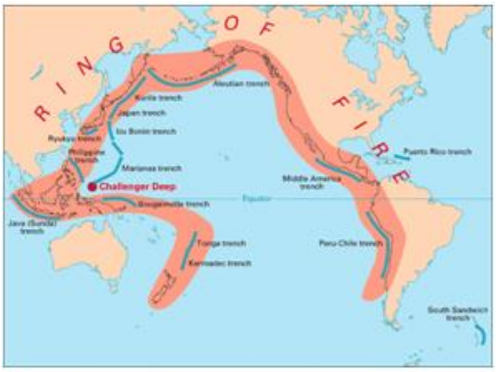
According to Harry Hess, the force causing the plates to move is the slow movement of the warm softened mantle beneath the rigid plates. Holmes (1930) suggests that the circular motion of the mantle drives the continents in the same way as a conveyor belt. Below the lithospheric plates, at a certain depth, the mantle is partially melted and can flow. Under the rigid plates the materials move in a circular manner much like a pot of thick soup when heated to a boil. The heated soup rises to the surface, spreads and begins to cool, then falls to the bottom of the pot where it is warmed and rises a second time. This cycle repeats over and over to generate what scientists call a convection cell or convective flow (fig.18).

6- The effects of plate tectonics

Since the dawn of time, plate movements along with other geological processes have created nature's most magnificent landscapes. The Himalayas, the Swiss Alps and the Andes are spectacular examples. Plate movements have caused terrible disasters, such as the 7.7 magnitude earthquake that struck China's Hebei province in 1976 and killed up to 800,000 people. Plate tectonics is then at the origin of:

6 1- Natural Hazard

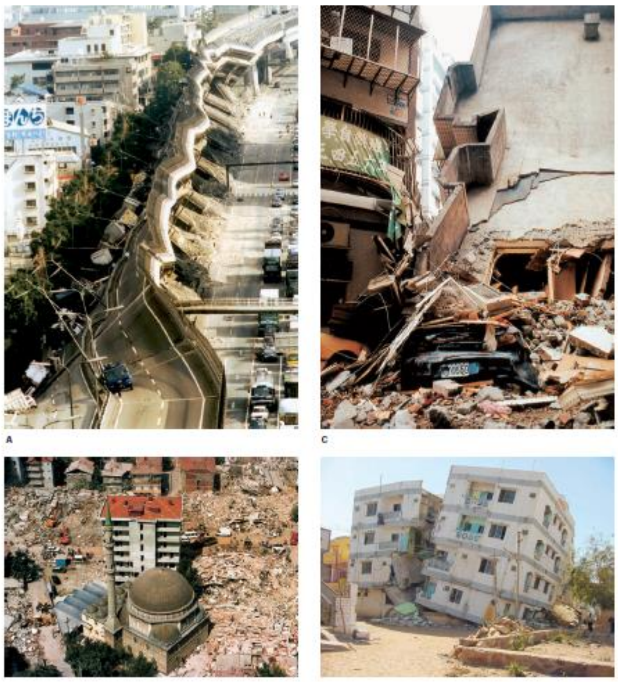
Earthquakes and volcanic eruptions occur along plate boundaries. One such area is the Ring of Fire, where the Pacific Plate meets many surrounding plates. The Ring of Fire is the most seismically and volcanically active zone in the world (fig. opposite). The earthquakes in northern Algeria are due to the convergence of the African and European plates.



La ceinture du feu due a la subduction de la plaque pacifique sous plusieurs autres plaques provoquant des seismes et du volcanisme

6 2- Earthquakes

Earthquakes are a direct consequence of plate movements. The most catastrophic earthquakes strike along convergent boundaries such as along the Ring of Fire.



6. 3- Volcanic eruptions

As with earthquakes, volcanic activity is linked to tectonic processes. Most active volcanoes under the sea are located near convergent plate boundaries where subduction occurs, particularly around the Pacific basin. Three-quarters of volcanic eruptions on Earth take place under the ocean, most often along mid-ocean ridges.

Figure 20. La ville d'Armero, en Colombie, dévastée par les coulées de boue déclenchées par l'éruption de Nevado del Ruiz en

6. 4- Tsunamis

Tsunamis are giant waves caused by large underwater earthquakes. In 2004, a tsunami caused by an earthquake in the Indian Ocean caused enormous damage in several countries, including Thailand (fig. 21). The epicenter is

Figure 21. Une zone dévastée de l'Ile de Saumatra

located on the border of the Eurasian and Indo-Australian tectonic plates, its magnitude was 9.1

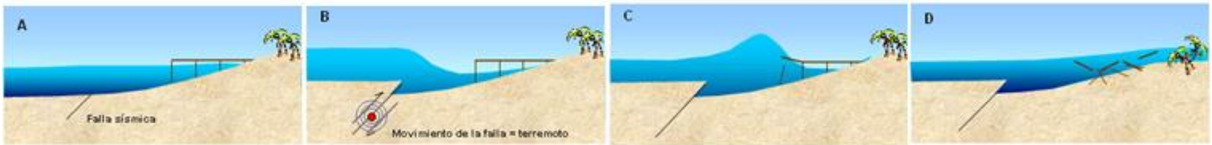


Figure showing how a tsunami is formed

7- Natural resources

Many of the world's natural resources, energy, minerals and fertile soil are concentrated near past or present plate boundaries. The use of these readily available resources has supported human civilizations, now and in the past.

7 1- Fertile soils

The most fertile soils on the planet are the result of the degradation of volcanic rocks.

7 2- Ore deposits

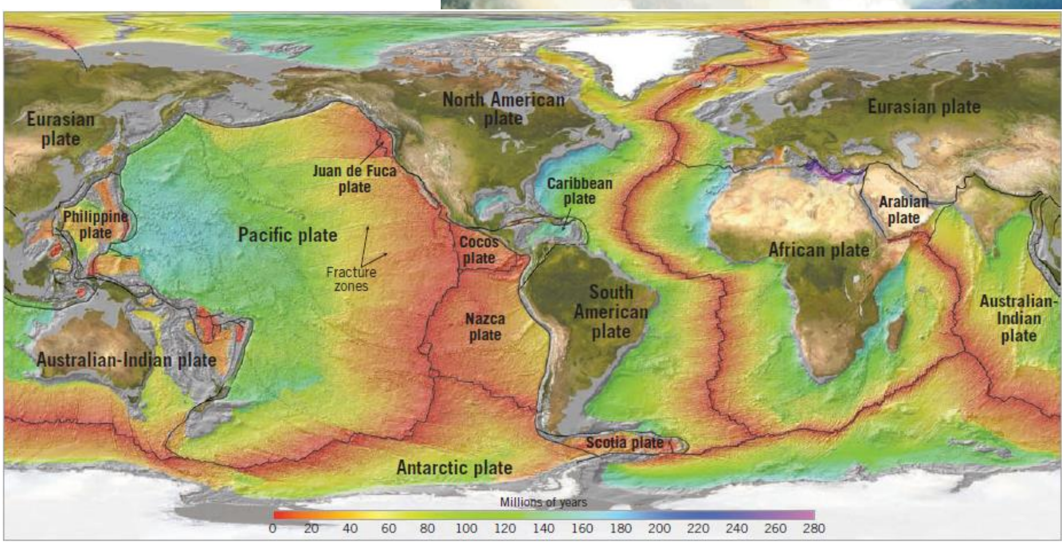
Most of the world's mined metallic minerals, such as copper, gold, silver, lead, and zinc, are associated with magmas found deep in the roots of extinct volcanoes located above subduction zones.

7 3- fossil fuels

Oil and natural gas are the product of deep burial and decomposition of organic matter accumulated in geological basins at the edges of mountain ranges formed by tectonic processes. Heat and pressure at depth transform decomposed organic matter into liquid gas and oil.

4 4- Geothermal energy

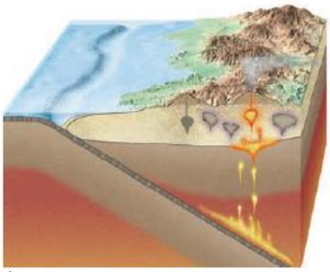
Steam from high-temperature geothermal fluids can be used to turn turbines and generate electricity, while lower-temperature



fluids provide hot water for heating homes, greenhouses, industrial installations and thermal stations (fig. 22). For example, the geothermal energy heats more than 70 percent of homes in Iceland, and the Geysers (geothermal field in Northern California) produces enough electricity to meet San Francisco's energy demand.

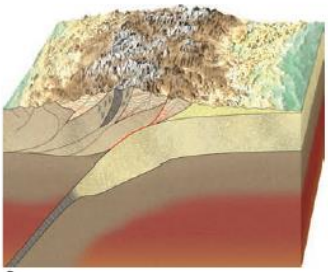
GIVE IT SOME THOUGHT

1. After referring to the section in Chapter 1 titled "The Nature of Scientific Inquiry," answer the following:
   a. What observation led Alfred Wegener to develop his continental drift hypothesis?
   b. Why was the continental drift hypothesis rejected by the majority of the scientific community?
   c. Do you think Wegener followed the basic principles of scientific inquiry? Support your answer.
2. Referring to the accompanying diagrams that illustrate the three types of convergent plate boundaries, complete the following:



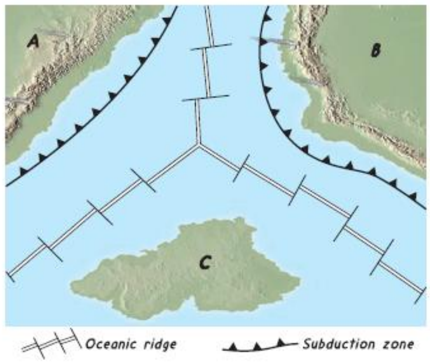
A.

B.

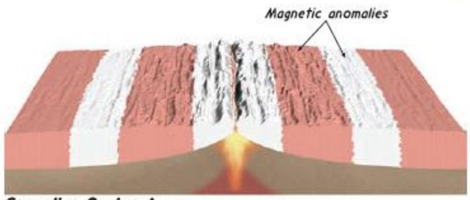


C.

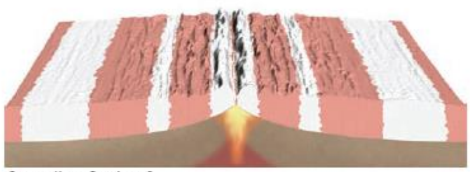
   a. Identify each type of convergent boundary.
   b. Volcanic island arcs develop on what type of crust?
   c. Why are volcanoes largely absent where two continental blocks collide?
   d. Describe two ways that oceanic–oceanic convergent boundaries are different from oceanic–continental boundaries? How are they similar?
3. Some predict that California will sink into the ocean. Is this idea consistent with the theory of plate tectonics? Explain.
4. Refer to the accompanying hypothetical plate map to answer the following questions:



   a. How many portions of plates are shown?
   b. Are continents A, B, and C moving toward or away from each other? How did you determine your answer?
   c. Explain why active volcanoes are more likely to be found on continents A and B than on continent C.
   d. Provide at least one scenario in which volcanic activity might be triggered on continent C.
5. Volcanoes, such as the Hawaiian chain, that form over mantle plumes are some of the largest shield volcanoes on Earth. However, several shield volcanoes on Mars are gigantic compared to those on Earth. What does this difference tell us about the role of plate motion in shaping the Martian surface?
6. Imagine that you are studying seafloor spreading along two different oceanic ridges. Using data from a magnetometer, you produced the two accompanying maps. From these maps, what can you determine about the relative rates of seafloor spreading along these two ridges? Explain.



Spreading Center A



Spreading Center B

7. Australian marsupials (kangaroos, koala bears, etc.) have direct fossil links to marsupial opossums found in the Americas. Yet the modern marsupials in Australia are markedly different from their American relatives. How does the breakup of Pangaea help to explain these differences?

8. Density is a key component in the behavior of Earth materials and is especially important in understanding key aspects of plate tectonics. Describe three different ways that density and/or density differences play a role in plate tectonics.

9. Refer to the accompanying map and the city combinations given below to complete the following:

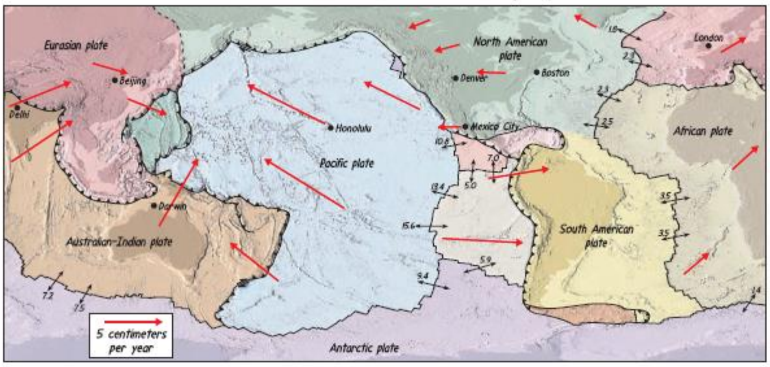
(Boston, Denver), (London, Boston), (Honolulu, Beijing)

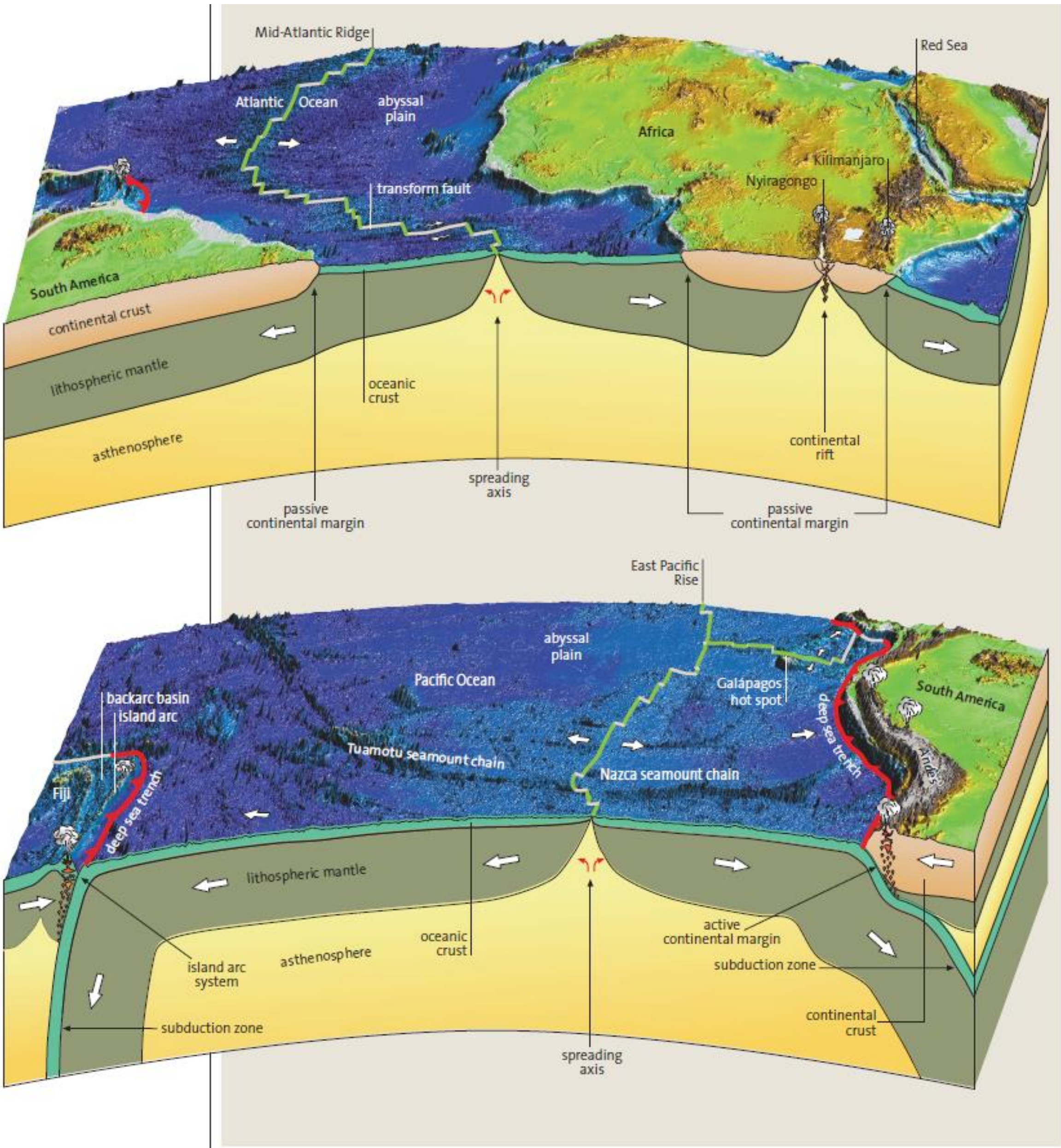
a. List the cities (in pairs) that are moving apart as a result of plate motion.

b. List the cities (in pairs) that are moving closer as a result of plate motion.

c. List the cities (in pairs) that are presently not moving relative to each other.

Plate motion measured in centimeters per year





▲ Fig. 1.3 Block diagrams of the outer shells of the Earth in the Atlantic and the Pacific region. Shown are the three types of plate boundaries, passive and active continental margins, island arcs, volcanic chains fed by hot-spot volcanism, and a graben system (strong vertical exaggeration). The plates consist of crust and lithospheric mantle. Relief data are from etopo30 (land surface) and gtopo2 data by Smith and Sandwell (1997), and etopo1 data by Amante and Eakins (2009).

Figure 10.