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Ministry of Higher Education and Scientific Research

8 May 45 University, Guelma

Faculty of Natural and Life Sciences and Earth and Universe Sciences

Department of Natural and Life Sciences

كلية علوم الطبيعة و الحياة و علوم الارض و الكون

قسم علوم الطبيعة و الحياة

Course brochure for the first year (L1)

Applied Geology Degree

MODULE

GEOLOGY 1

Presented by

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FUNDAMENTAL TEACHING UNIT I (FTUI)

(Credits: 10; Coefficients: 4)

Subject 1: Geology 1, Semester: 1

TEACHING OBJECTIVES:

The teaching of geology to a basic understanding of the major phenomena that govern the Earth and to demonstrate that it is an active planet characterized by dynamics that need to be understood.

COURSE STRUCTURE AND CONTENT

CHAPTER I Earth in the Universe

1.1- Introduction: Objects of Geology

1.2- Structure of the Universe and Birth of the Solar System

1.3- Earth and the Planets of the Solar System

CHAPTER II: Internal Geodynamics

2.1- Structure of the Earth and Concept of Geoid

2.2- Current Distribution of Land and Seas

2.3- Earth's Magnetic Field

2.4 -Continental Drift and Plate Tectonics

2.5 -Earthquakes

2.6- Volcanoes

CHAPTER III: Tectonics

3.1 Brittle Deformation: Faults

3.2 Ductile Tectonics: Folds

3.3 Thrust Faults and Nappe Structures

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CHAPTER 1

EARTH IN THE UNIVERSE

INTRODUCTION:

Earth sciences experienced tremendous growth during the latter half of the 20th century, with the formulation of theories that revolutionized our understanding of the origin of the planet and its dynamics. New technologies have opened up horizons, both in terms of observing the entire globe and in observing and analyzing the smallest components of matter. Throughout history, humans have been concerned with their relationship with the universe. We are subject to natural risks such as earthquakes, volcanic eruptions, tsunamis, meteorite impacts, landslides, etc. How far can we establish forecasts?

1. Geology and its objects?

1-1- <u>Definitions</u>

Geology from the ancient Greek γη- (gê-, "earth") and λογος (logos, "reasoned discourse"), is the science that studies the Earth in its various parts directly accessible to observation, striving to reconstruct their history through the study of their arrangement. It deals with other associated sciences of the composition, structure, history, and evolution of the internal and external layers of the Earth, and the processes that shape it.

Geology can be defined as a science of the earth that aims to study the various geological phenomena that tend to change over geological time. This study is approached from various perspectives (static, kinematic, and dynamic).

a) Static: This is descriptive geology which includes:

- Description of the constituent materials of the earth, which are minerals (mineralogy) and rocks (petrography);
- Their geometric distribution and arrangement (stratigraphy and structural geology);
- Extinct living beings (paleontology).

b) Kinematic:

Various geological phenomena do not remain the same over geological time. The general principle from this point of view is variation or evolution both in the domain of minerals (transition from one mineral to another), in rocks (transformation from a sedimentary rock to a crystalline rock), as well as in the domain of seas and continents (paleogeography), and in living organisms (biological evolution).

c) Dynamic:

The evolution and succession of geological phenomena such as the formation of mountain chains (orogenesis) and the formation of sedimentary rocks (erosion, transportation, and deposition) need to be understood in terms of the causes of geological events and the forces acting on them.

In summary, the purpose of geology is:

- To describe the constituents of the Earth and the materials composing it,
- To attempt to reconstruct the history of the Earth and its evolution up to the present period,
- To use the knowledge gained for the exploration of useful materials (ores, hydrocarbons, water, coal, etc.).

1.2-Disciplines of geology and related sciences:

a. Disciplines of geology

Comprises numerous scientific disciplines:

- **Stratigraphy,** which records and orders in time the succession of rock layers, using simple geometric principles, field observations, analysis of the fossil content of rocks, and radio chronological dating of rocks. Stratigraphy forms the foundation of geology.
- **Mineralogy,** which studies the constituent elements of rocks, including the form, nature, composition, and chemical and physical properties of minerals;
- **Petrography,** which describes rocks, studies their constitution, and classifies them;
- **Petrology,** which studies, beyond petrographic analysis, the mechanisms and conditions governing the formation (genesis) and transformation of rocks;
- **Structural geology**, which studies the deformations of rocks and the mechanisms governing the deformation of these rocks at all scales; on a large scale, it is referred to as tectonics;
- **Geodynamics,** which studies the morphological consequences of tectonic processes and erosion;

- **Geomorphology,** which studies the various forms of terrestrial relief, first in a descriptive manner and then in an explanatory manner, and highlights erosion forms; it is often considered to concern the geographer more than the geologist and is usually classified among the branches of physical geography;
- **Sedimentology**, which studies sedimentary rocks and formations; if the study focuses on the regular succession of different sedimentary layers or strata, it is called stratigraphy;
- **Paleontology,** which studies past organisms through the description and analysis of fossilized remains;
- **Micropaleontology,** which studies microscopic fossils contained in sediments;
- **Metallogeny,** which studies the mechanisms of formation of metal deposits and aims to define methodological tools and prospecting guides usable by mining explorers and prospectors;
- **Volcanology,** which analyzes and attempts to predict volcanic phenomena, studies the chemical and mineralogical composition and processes of emplacement of volcanic products;
- **Hydrogeology,** which studies the flow of groundwater, knowing that the nature of the subsurface traversed by the waters directly influences the quantity and quality of water emerging at the source or drawn from the borehole;
- **Glaciology,** which studies water in its solid form, ice, and its massive presence on the Earth's surface in the form of glaciers or ice caps.
- **Geotechnics,** which integrates civil engineering geology, geophysics, geomechanics (soil mechanics, rock mechanics, underground hydraulics) to adapt structures to their construction sites;

b. Relationship of geology with other sciences:

To better understand geological phenomena, especially the determination of rocks, the constitution of the globe, the exchanges between rocks, the fluids they contain (water, gas, oil, etc.), and water pollution issues, geology relies on other disciplines:

- **Physics**:

This is the application domain of the laws of physics such as gravity, the properties of the Earth's magnetic field, and the electrical and electromagnetic properties of rocks to provide us with information about the constitution of the subsurface, sometimes at significant depths concerning the globe.

- **Mathematics:**

Primarily statistics, or mathematical modeling to help, us understand geological phenomena.

- **Chemistry:**

Chemistry and geology are closely related to the point of the emergence of a discipline that studies the chemical phenomena of the Earth (geochemistry). This discipline is highly applied in mineralogy and petrography (the study of rocks) where chemical laws help explain the formation of the Earth.

- **Zoology, Botany, Biology:**

Knowledge of current living organisms, their forms, and biology is essential for the study of fossil forms and to highlight certain evolutionary phenomena.

- **Geography**:

The forms of a landscape are explained by geological causes. The analysis of these forms (geomorphology) is necessary for the geologist to recognize the structure of the globe.

2- Structure of the Universe and Birth of the Solar System

2.1-Structure of the Universe

We can only theorize about the birth of the universe, but we know for sure that it is continually expanding and that it is impossible to distinguish its boundaries, even with the most sophisticated instruments. It is populated by countless galaxies that continue to move away from each other at speeds of thousands or hundreds of thousands of kilometers per second, with their radial velocity increasing as they get farther away. In 1953, Gérard de Vaucouleurs surveyed space over distances of about 10 to 50 million light-years and noted that galaxies were clustering into clusters, confirming Abell's observations. Each cluster consisted of between a dozen and several thousand galaxies.

A- The Galaxy

The solar system is within a much larger structure: the Milky Way. The Milky Way is the galaxy in which we reside, which corresponds to a larger assembly consisting of several hundred billion stars and clouds of gas and dust (nebulae). The rotational motion animates them, often giving them a spiral shape, with broad arms extending around a dense, oval central bulge. The arms gather nebulae, within which stars form. It spans about 100,000 light-years (approximately 10^18 kilometers). Our solar system revolves around the center of the galaxy in 226 million years.

Fig.1: Artistic representation of our galaxy, **the Milky Way**

B- Galaxy Clusters

A galaxy cluster is a grouping of galaxies bound together by their gravitational force. Beyond the galaxy, galaxies also cluster to form galaxy clusters. Consequently, these are relatively stable structures because no member can escape from the cluster containing it. The known observable universe extends over about 45 billion light-years, approximately 4.3 x 10^23 kilometers.

C- Superclusters

Comprised of several tens of galaxy clusters, superclusters organize into filaments giving the universe a very peculiar aspect that can be compared to foam. The reason for the existence of this cosmic structure alternating between filaments and almost empty regions, almost devoid of matter, remains a mystery for astronomers. The dimensions of superclusters are colossal: from 100 to 320 million light-years! In conclusion, this hierarchical organization leads to the representation of the universe in its very large-scale structure as a network of irregular meshes, with matter concentrated on the peripheries of the meshes while their centers are empty. Currently, the age of the universe is estimated to be between 10 and 20 billion Earth years.

Summary:

Structures in the universe are numerous. Starting from simple stars, we arrive at colossal filaments.

- Planets orbit stars (~1 light-year), which is equivalent to 9.46 x 10^12 kilometers.
- Stars are contained within galaxies, each containing several tens of billions (~100,000 light-years).
- Galaxies cluster into clusters (~10 million light-years).
- Clusters gather into superclusters (~150 million light-years).
- Superclusters organize into filaments (~500 million light-years).

2.2-Birth of the Solar System

Several hypotheses have been proposed regarding the origin of the solar system. Recent interpretations, based on chemical studies of meteorites and the study of the physicochemical properties of celestial bodies, converge on the idea that the Sun and the planets originate from the same cloud composed of gas and dust that went through several stages:

1- About 5 billion years ago, such a cloud, found abundantly in galaxies tens of times larger than the current solar system, collapsed under its own gravity, flattening to form a disk with a diameter of about 200 astronomical units (AU = 150,000,000 km). Matter condensed within it, and atoms collided increasingly frequently.

2- The center of this disk compressed, and when its mass was sufficiently dense and hot, nuclear reactions began. Thus, a proto-star, the Sun, was born, becoming a real star around which the rest of the gas and dust revolves (10% of the initial mass).

3- Meanwhile, in the protoplanetary disk under gravitational influence and relatively cold, dust particles agglomerated (accretion) to form solid bodies: asteroids, then planetesimals, attracting more and more matter.

4- Through successive collisions, planetesimals formed an agglomerate of larger size; while the heat was so intense that these bodies melted: the resulting body is called a ***protoplanet.***

The evolution of the protoplanet occurs through the accretion of matter according to two hypotheses:

- **Homogeneous accretion** = aggregation of undifferentiated matter, then the heat trapped in the protoplanet and produced by collisions and the decay of radioactive elements will cause movements of the fluid matter. This fluid will undergo differentiation, with the accumulation of heavy elements towards the center of the future planet, while lighter elements will migrate to the surface.

- **Heterogeneous accretion**: differentiation occurs very early during the aggregation of solid bodies: iron cores differentiate first; they are attracted to the center by gravity while the lighter ones migrate to the outer zones.

  Thus, the terrestrial planets are born. In our Earth, we find a heavy core composed of iron and silicon, while silicates are found mainly in the mantle or crust. Subsequently, other light materials were added through intense meteorite bombardment.

  Meanwhile, solar wind drives dust and gases outward from the system, which condenses to form giant gas planets and their satellites.

3. Earth and Planets of the Solar System

Celestial objects in the solar system are as follows: Earth is one of the bodies of the solar system. The solar energy received by Earth determines the temperatures at its surface and the movements of its fluid envelopes. Permanent exchanges exist between these envelopes and cause them to evolve over geological time. Human activity is an important factor in this evolution

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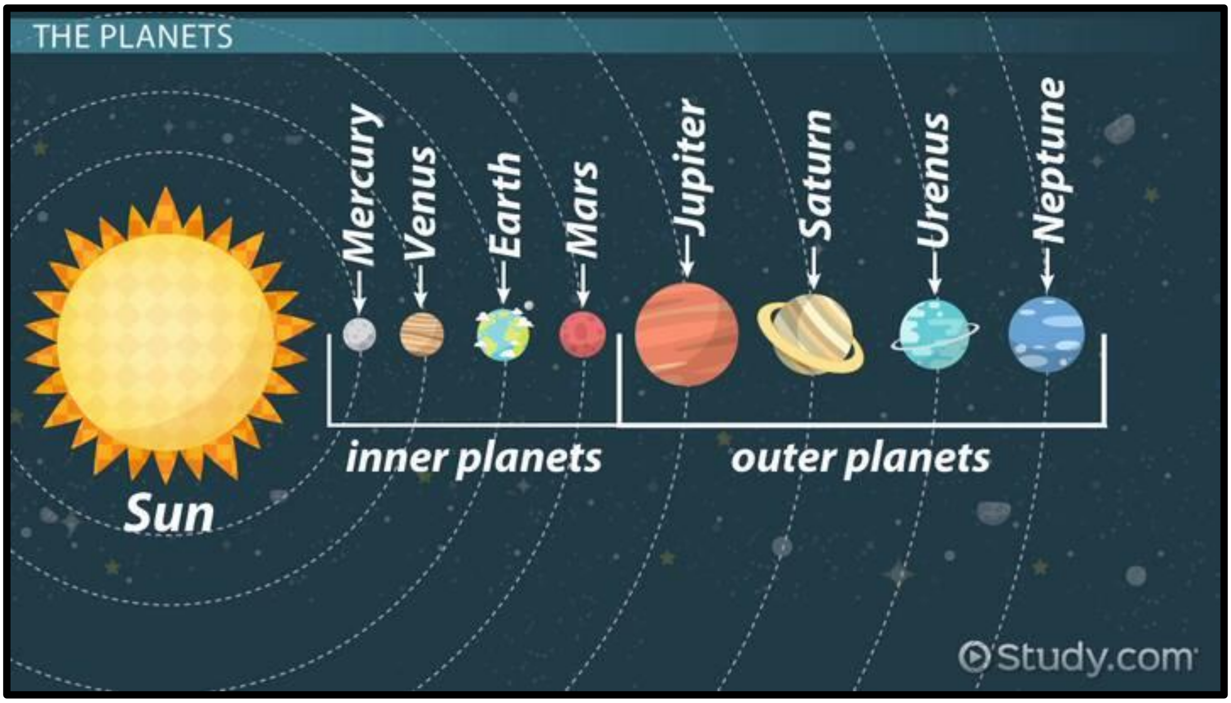


Fig.2: The Solar System

The different axes of rotation of the planets in the solar system bear witness to the bombardments and collisions that occurred in their youth.

The solar system consists of a star and various celestial bodies. The Sun is the star of the solar system.

- It emits energy that it diffuses in all directions.
- The other celestial bodies in the system orbit around it.
- It has a chemical composition similar to that of the primordial cloud: Hydrogen: 73.8%; Helium: 24.4%; and the rest: 1.8%.

Planets, accompanied by their satellites, describe elliptical orbits around the Sun.

The terrestrial planets are successively: **Mercury, Venus, Earth, and Mars.**

- Their surfaces, composed of silicate rocks, are solid.

- They are the planets closest to the Sun, called inner planets.
- They have the smallest diameters and high densities.
- Venus and Earth still have internal activity.
- Venus, Earth, and Mars have more or less dense gaseous atmospheres.
- Only Earth has water in liquid form.

The gas giant planets are successively: **Jupiter, Saturn, Uranus, and Neptune**.

- They are mainly composed of helium and hydrogen.
- They are distant planets from the Sun, called outer planets.
- They have the largest diameters and low densities.

Pluto is composed of silicates and solid water.

- It is the planet farthest from the Sun.
- It has the smallest diameter.

Asteroids and comets are smaller celestial bodies.

- Asteroids, rocky objects, are grouped mainly in a belt between the orbits of Mars and Jupiter.
- Comets, formed of ice and dust, describe orbits that intersect those of the planets.

The solar energy received by Earth is unequally distributed on its surface. The solar energy received at the surface of Earth varies with latitude for a given time of year.

- At the poles, the same surface receives less energy than at the equator. This is a consequence of the spherical shape of Earth and it affects climate distribution.

Tab.1: Approximate distance between the planets and the Sun as well as other statistical information about these planets

	Distance from sun (in AU)	"Radius (km)	Mass relative to Earth	Revolution (in days)	Rotation	moon satellites	the ecliptic	Inclination equator	orbital eccentricity	density (g/m3)
Sun	0	696	332.8		25-36	9				1.41
Mercury	0.39	2.962	0.05	87	58.7 J	0	7	0.3	0.21	5.43
Venus	0.72	6.051	0.89	224	243 J	0	3.39	3	0.01	5.25
Earth	1	6.378	1	365	24 H	1	0	23	0.02	5.52
Mars	1.5	6.392	1.07	686	24.6 H	2	1.85	25	0.09	3.95
Jupiter	5.2	71.492	318	4.332	9.8 H	16	1.31	3	0.05	1.33
Saturn	9.5	60.268	95	10.759	10.6 H	18	2.49	27	0.06	0.69
Uranus	19.2	25.559	15	30.685	17.2 H	15	0.77	98	0.05	1.29
Neptune	30.1	24.764	17	60.19	16.1 H	8	1.77	30	0.01	1.64

3.2- Earth

3.2.1 - Age of the Earth

Earth formed 4.6 billion years ago. Clouds of gas and dust condensed to form planetesimals. These then agglomerated to form young planets. Despite continuous bombardment from remaining planetesimals for a billion years, Earth began to cool. Volcanic eruptions over the next 100 million years released gases, forming the atmosphere. Finally, 100 million years of torrential rains formed the oceans, giving rise to primitive continents. The Earth has a long history: 4.55 billion years. To decipher the history of the planet, we need a reliable geological time scale. In the 19th century, such a calendar was established based on relative dating methods, mainly through the study of fossils. But it was not until the early 20th century, with the discovery of radioactivity by Marie and Pierre Curie, that an absolute time scale was provided, allowing us to establish the venerable age of our planet. This tool, radiometric dating, uses certain chemical elements that have the property of radioactive decay. By calculating the time it took for a certain portion of an element contained in a mineral to decay, we obtain the age of formation of that mineral.

3.2.2- Shape of the Earth

The study of the shape of the Earth and its gravity field constitutes geodesy. This science, essentially based on solving geometric problems, has greatly benefited from the arrival of artificial satellites. Measurements have shown a slight flattening of the Earth at both poles, resulting in an ellipsoidal shape.

• **Geodetic Hypothesis** (Geoid): This hypothesis consists of finding the shape of the solid by neglecting irregularities on the Earth's surface; that is, the shape of a globe with leveled reliefs: this is the geoid. Since the Earth's surface is about 7/10 oceans and seas, this surface is approximately that of the liquid element extended under the continents. It is a representation of the Earth's globe where all points are subject to the same gravitational force. The vertical is defined at these points by the local direction of gravity (by a plumb line).

These verticals are not all parallel due to the presence of reliefs that "attract" (or deviate) the vertical component of gravity. The line composed of horizontals, perpendicular to the vertical component of gravity: **this is the equipotential surface of gravity closest to the average ocean** surface, which is **the Geoid**. It is, in fact, the gravitational form of the Earth.

In clear terms, the geoid corresponds to the extension of the average sea level under the continental mass. This surface is very irregular because it is deformed by an unequal distribution of masses within and on the Earth's globe (ex: near a mountain range or a volcanic chain, the geoid will be deformed).

• **Ellipsoidal Hypothesis: Ellipsoid:**

Since calculations are impossible on the still imperfectly known geoid, geodesists adopt a mathematical surface that approximates an ellipsoid most closely. This surface is perfectly defined by its parameters: length of the minor axis, length of the major axis, and Earth's flattening. An example can be easily found in physics: by taking a steel circle and rotating it around an iron rod, you can see this circle flatten at the top and bottom.

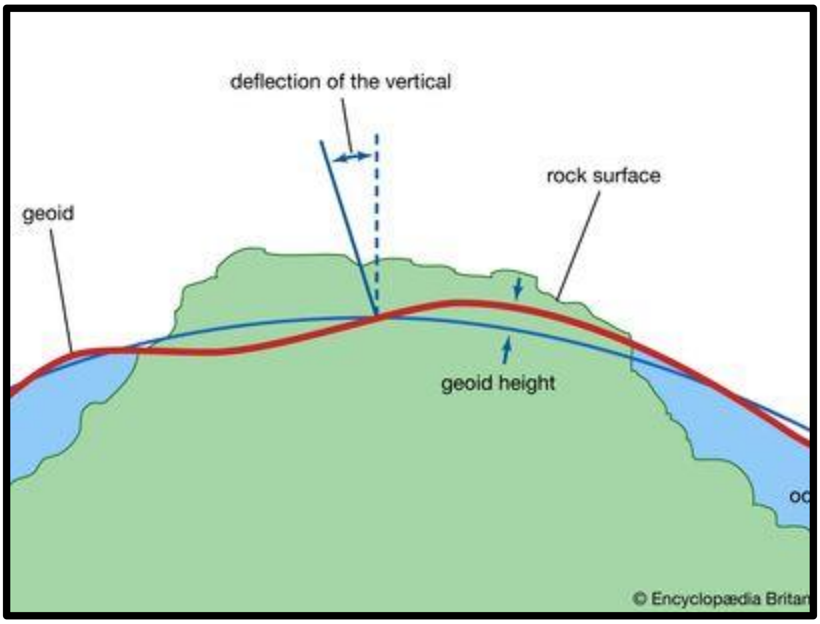


Fig.3: The geoid

The shape of the globe is a flattened ellipsoid at the poles. By ignoring surface irregularities of the globe, we can deduce a "simplified" and theoretical surface of the planet: the reference ellipsoid. This ellipsoid, adopted by the International Union of Geodesy and Geophysics (IUGG) in 1980, is defined by:

- Equatorial radius a = 6378.136 km;
- Polar radius b = 6356.752 km.
- Surface: 510 million km²
- Volume: 1083 billion km³
- Flattening f = (a-b)/a = 0.003 352 810 681 18 This reference shape allows for the definition of theoretical or normal gravity (g0) at any point on the Earth's surface at a latitude L (in degrees), which includes the effect of centrifugal force (International Gravity Formula, IUGG, 1980)

g0 (L) = 9.780327 (1+0.0053024 sin2 L-0.0000058 sin2 2L) m/s²

Furthermore, the force of gravity is higher at the poles, and the maximum axial centrifugal velocity is at the equator. Gravity varies with latitude; we see that the gravity acceleration is minimal at the equator (978 Gal) due to the shape of the ellipsoid (points farthest from the center). At the poles, it reaches 983 Gal.

3.2.3. Earth's Revolution

The revolution (or orbiting) of Earth around the Sun is the movement that Earth makes around its star, the Sun. The plane created by this revolution movement is called the plane of the ecliptic. One complete circuit takes 365 days, 6 hours and 9 minutes (approximately). This movement determines the duration of the inequality of day and night and partly the seasons known in different places on the Earth's surface.

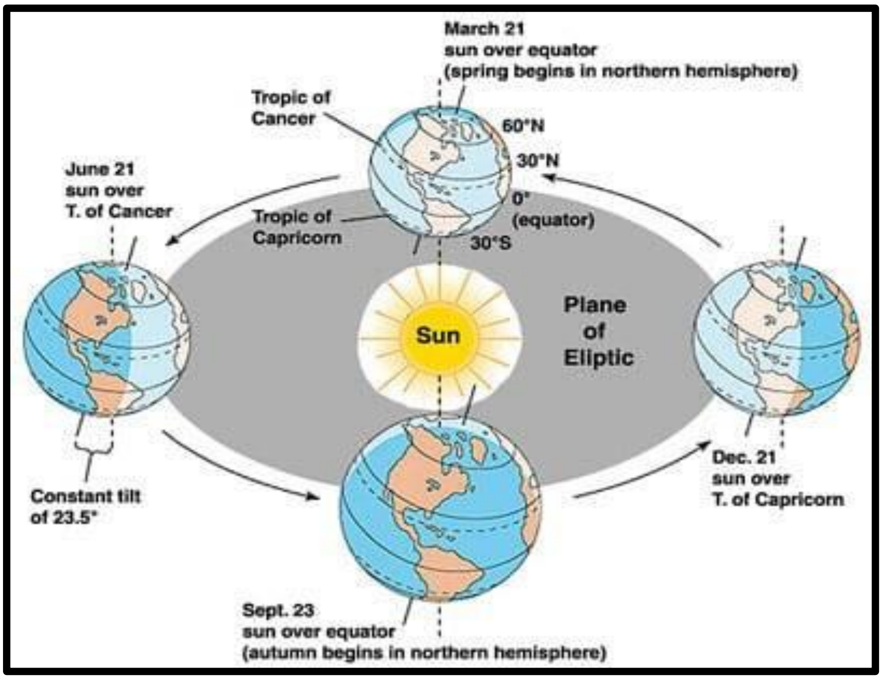


Fig.4: Earth's Revolution

The Earth rotates on itself around an axis of rotation that is always inclined by about 23.5° relative to the perpendicular to the plane of the ecliptic and remains parallel to itself regardless of the Earth's position relative to the Sun. This is what we call the Earth's obliquity. The distance from Earth to the Sun, which is 149 million km on average, varies throughout the year. Earth passes each semester, alternately, at **perihelion** (147 million km), meaning closer to the Sun, and at **aphelion** (152 million km), meaning farther from the Sun. The difference between these two distances is determined by **eccentricity**.

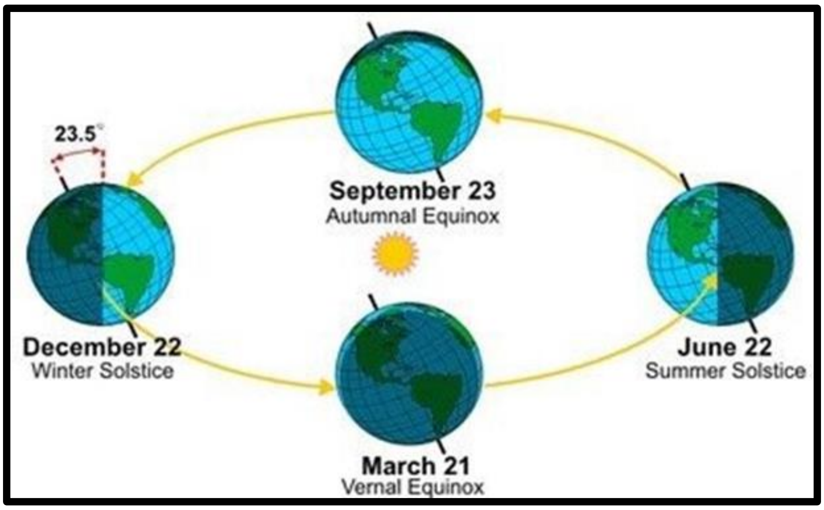


Fig.5: Earth's Positions

During a year, the Sun rises and sets, appears and disappears, at different points on the horizon, describing a course every 24 hours whose progressive evolution, in our latitudes, will determine the seasons.

4 positions of the Earth: **2** solstices (summer, winter) and **2** equinoxes

- **At the spring equinox**, the Sun rises in the east and sets in the west; day and night each last 12 hours and balance each other out.
- **At the summer solstice**, the Sun rises in the northeast and sets in the northwest; at noon, it appears at its highest point of the year. The day is the longest of the year and the night the shortest.
- **At the autumn equinox**, again the Sun rises in the east and sets in the west; day and night each last 12 hours and balance each other out.
- **At the winter solstice**, the Sun rises in the southeast and sets in the southwest; at noon, its height is the lowest of the year. The day is the shortest of the year and the night the longest.

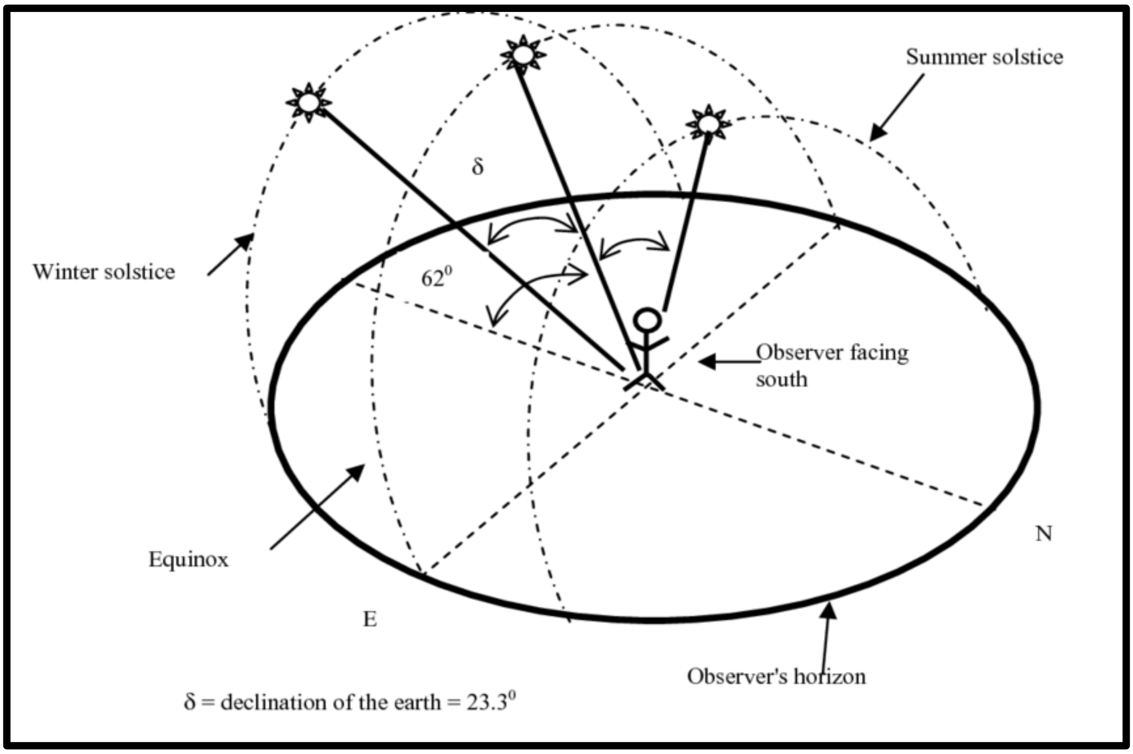


Fig. 6: Apparent motion of the sun

3.3- External envelopes of the earth

3.3.1- The Atmosphere

Measurements concerning the atmosphere were first made on the ground, then at the tops of mountains. Then came the scientific contribution of manned balloons (airships), followed by sounding balloons up to about 40 km and finally beyond, spacecraft.

3.3.1.1. Composition of the Atmosphere

The atmosphere is a gaseous envelope that surrounds the Earth. It is composed mainly of:

- nitrogen (N) 78%
- oxygen (O2) 21%
- Rare gases, argon: 1% (Ar), helium (He), ozone, and in the lower layers of water vapor and carbon dioxide.

3.3.1.2. Structure of the Atmosphere

The Earth is enveloped by three external fluid layers. **The atmosphere**, a gaseous layer between 0 and 1000 km, is maintained by gravity around the rotating Earth; its pressure and density decrease with altitude. Beyond 1000 km begins interstellar vacuum. In the **exosphere,** molecules are no longer held by gravity and escape through the **magnetosphere** into space.

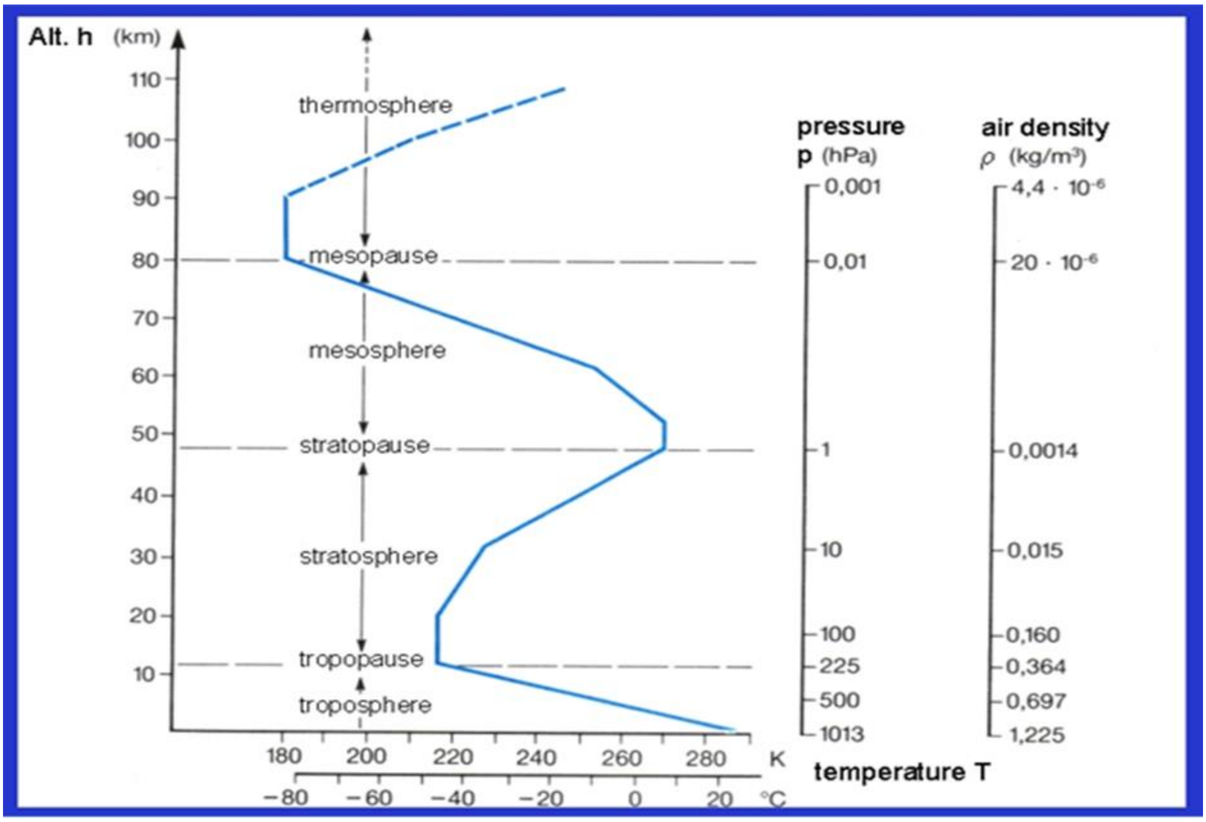


Fig. 7: Average Vertical Structure of the Atmosphere

The atmosphere is divided into several concentric layers separated by narrow transition zones. These layers are defined by their chemical composition and, consequently, their thermal structure which determines their dynamic properties.

- ***Troposphere*** (90% mass) is the seat of atmospheric phenomena and convection. The temperature decreases from 15 to -60°C.

- ***Stratosphere*** (12-50 km) has an ozone-enriched layer under the action of solar UV rays (20-35 km).

- ***Mesosphere*** has a very strong thermal decrease; presence of CO_2 which absorbs infrared, atmospheric pressure is very low.
- ***Thermosphere*** (>80 km above the mesopause) atoms are ionized, temperature increases due to absorption of solar radiation. Beyond 400 km exosphere
- ***Exosphere***: This is the highest layer of the atmosphere. It gradually dissipates into interplanetary space and the air becomes extremely rare. Radio waves are reflected there, and many artificial satellites orbit the Earth in this zone.
- Atmospheric Pressure: Pressure at sea level is 1 bar and decreases with altitude.
- Atmospheric Temperature: The variation in temperature with altitude is not constant. It has helped to identify a vertical structure of the atmosphere.

3.3.2 - The Hydrosphere

This is the liquid sphere which, if distributed uniformly on the globe, would be about 2,500m thick, of which 2,440m is for the oceans, 60m for ice (cryosphere), and only 1m for freshwater. Therefore, it is actually concentrated in the oceans.

The density of seawater = 1.025 and it is at the interface of the hydrosphere, the atmosphere, and the lithosphere that life originated and developed.

CHAPTER 2

INTERNAL GEODYNAMICS

Introduction

The internal dynamics of the Earth, or internal geodynamics, concerns the movements and processes that affect the Earth's interior. One of the most tangible manifestations of this dynamic is the movement of rigid plates (lithospheric plates) on the surface of the planet, plates that slide on plastic material (asthenosphere). This mechanics is described by the theory of plate tectonics, which explains major geological phenomena such as earthquakes, volcanoes, deformation of the Earth's crust, and the formation of large mountain chains.

II- Internal Structure of the Earth

The Earth is one of the nine planets in the solar system. Its internal constitution can be established through various methodologies:

II.1- Investigation Methods

- Through direct observations of its surface composition by observing visible surface structures. These observations are limited to very limited knowledge (a few thousand meters) of our globe compared to its 6,370 km radius.
- Through drilling, which reaches a few kilometers deep (5 to 10 km).
- Through geophysical methods (seismic-gravity-magnetism-heat flux) which, through physical measurements, indirectly interpret the deep structure of the globe.
- Through studies of meteorites-asteroids which, like Earth, belong to the solar system and are therefore likely to provide information about the deep composition of our Globe. Meteorite falls are frequent, but most fall in the middle of the oceans, which represent 2/3 of the Earth's surface. Most of them are small, with a diameter of less than 10 cm (107 to 109 tons per year); those larger than one kg are not rare (10,000 tons per year). The largest ones are exceptional; thus, the probability of a meteorite fall with a diameter of more than one km is of the order of 100 million years.

Interpreting data from direct observations, astronomical, geochemical, and seismological data leads to a schematic representation of the Earth's structure.

II.1.1- Characteristics of the Different Layers of terrestrial globe

Direct knowledge of the structure of the Earth concerns only the atmosphere, hydrosphere, and the upper part of the crust. It is possible to study only the first few kilometers of the Earth directly, with the deepest drilling not exceeding 12 km. To determine the internal structure of the Earth, geologists have therefore resorted to indirect methods, such as seismology (the study of earthquakes). The approach to wave propagation has had a decisive influence on understanding the structure of the Earth.

Three concentric layers are distinguished, each subdivided:

I1.1.1.1- The Core

The core, which represents about 16% of the volume of the Earth, consists of two parts:

- The inner core or seed, solid and at high temperature (5,000°C). It is essentially formed of a mass of pure iron containing about 4% nickel.
- The outer core, liquid (3,500 to 2,800°C), whose composition is similar to that of the inner core, enriched in sulfur and oxygen. Astrophysicists presume that the origin of Earth's magnetism is linked to the presence of this liquid zone within the globe. It is separated from the inner core by the Lehmann Discontinuity.

I1.1.1.2- The Mantle

The mantle is an envelope that represents 82% of the volume of the Earth and is composed mainly of silicates and oxides. The Gutenberg Discontinuity separates this layer from the core. This layer is characterized by great heterogeneity. In turn, the mantle is subdivided into two parts:

- The lower mantle or mesosphere is the thickest layer of the Earth. Its structure is dense and rigid due to high pressures.
- The upper mantle (2,800 to 1,700°C) consists of:
- A layer of viscous material or asthenosphere (iron and magnesium silicates associated with oxides) capable of deforming. It is in this zone that magmas are formed and convection currents (heat transfer) are formed. The depth of the asthenosphere ranges from 70 to 150 km below the Earth's surface to 700 km deep.

- A solid layer of the upper part of the upper mantle and the Earth's crust form the lithosphere.

I1.1.1.3- The Crust

The crust is separated from the mantle by the Mohorovicic Discontinuity (Moho) and is characterized by lower density (ρ = 2.8) and great heterogeneity. The depth of the Moho is very different depending on whether it is in an oceanic or continental domain. Under the oceans, it is located at a depth of 10-12 km, while it is, on average, 35 km under continents. The combination of the crust and the upper part of the upper mantle is called the lithosphere.

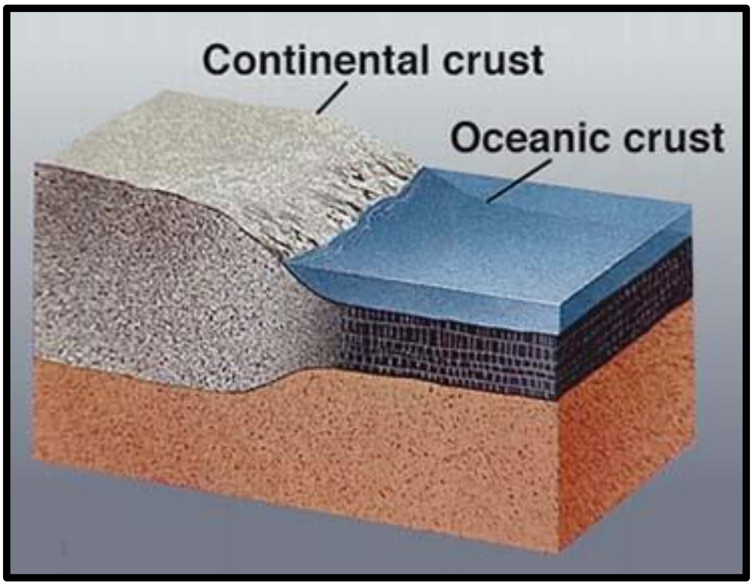


Fig.8: The Earth's Crust

II.1.1.3.1- Continental Crust

In stable continental areas, such as large shields and platforms, like those of Africa or Russia, which have not undergone deformations for several hundred million years, we distinguish:

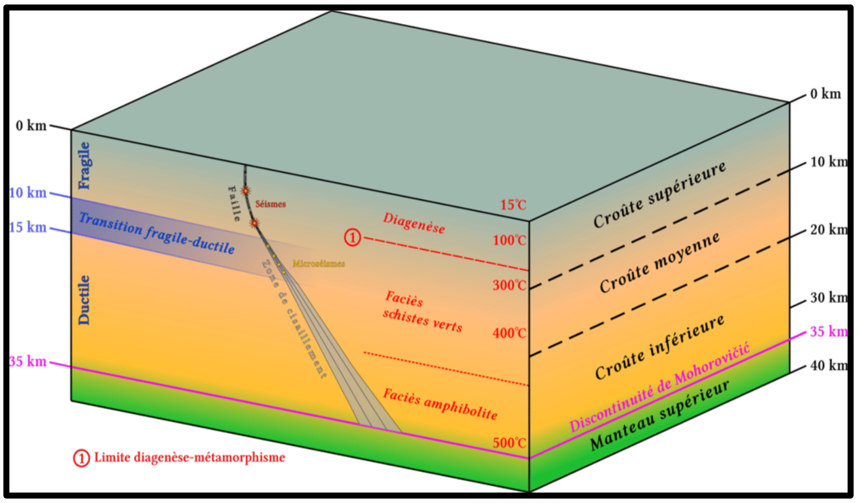


Fig.9: Schematic Block Diagram of Continental Crust Structure

- The upper crust (10 to 15 km), density (d) = 2.7, P-wave velocity (Vp) = 6 km/s (velocity of P seismic waves). This upper crust extensively outcrops in large shields and is sometimes visible throughout its thickness in both ancient and current mountain chains.

- The lower crust (10 to 15 km), density (d) = 2.8 to 2.9, P-wave velocity (Vp) = 7 km/s. The density of the medium (2.8 to 2.9) is that of basalt, hence the name basaltic layer. The lower crust is believed to consist of intrusions of basic to ultrabasic mantle material within a series of metamorphosed sedimentary origin, as mentioned, under eclogite to amphibolite facies.

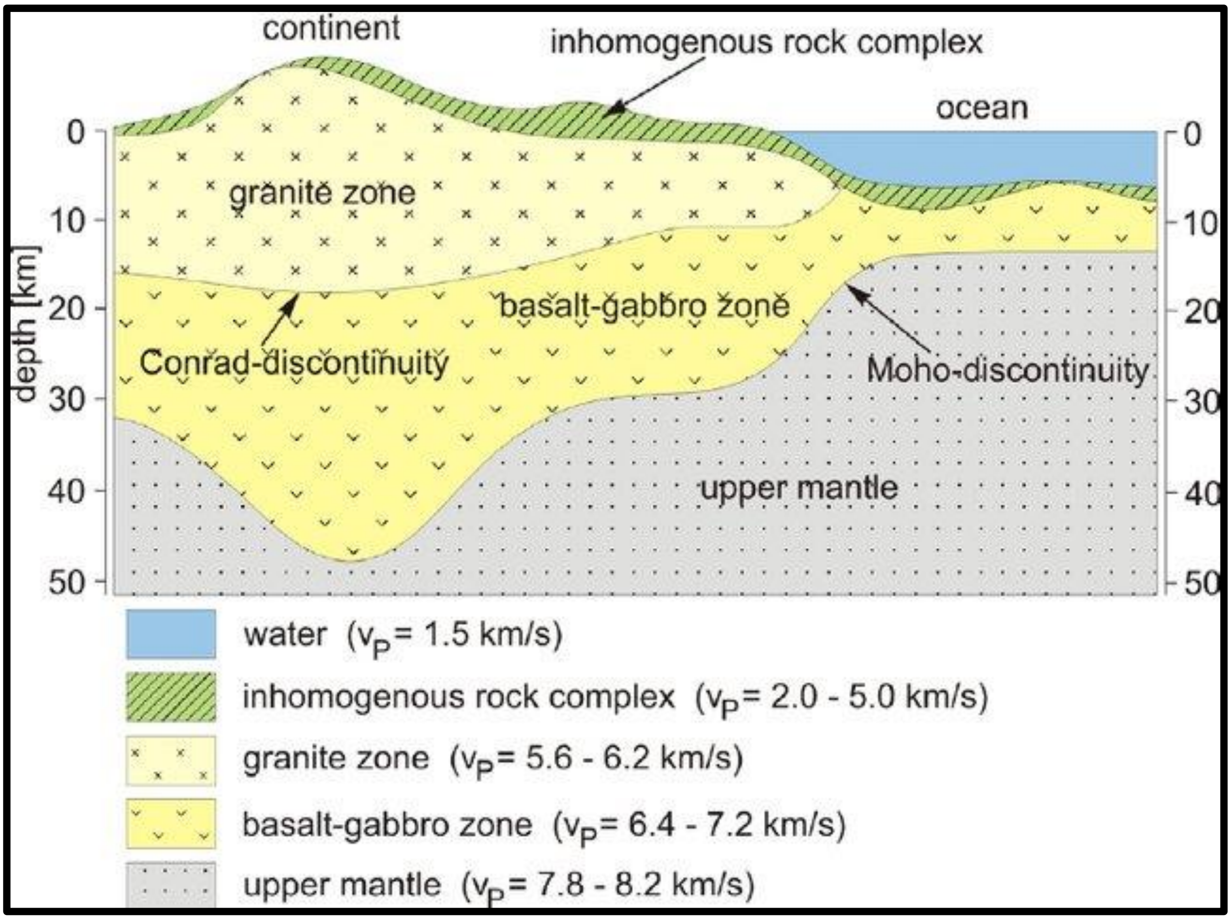


Fig.10: Continental Crust Structure

The continental rocks that outcrop at the surface of the ground are highly varied (sedimentary, metamorphic) and depend on the regions, but deep rocks are essentially composed of:

- Granite: a plutonic magmatic rock (formed by slow cooling of magma in depth), granular, composed of feldspar, quartz, micas. The major chemical elements are Si, Al, K, and it forms 40% of the continental crust.

- Gneiss: a metamorphic rock, is the main rock component of the continental crust (55%). It forms through the metamorphism of granite and is composed of the same minerals. The upper crust is called the granito-gneissic layer (or sialic). Sedimentary rocks make up 5%, with a thickness of 2 to 3 km at the surface. Except for sedimentary rocks, granite and gneiss constitute the main framework of the continents, with a thickness varying from 30 to 70 km and an average density of 2.7.

II.1.1.3.2- Oceanic Crust

It is characterized by the absence of a granito-gneissic layer; it corresponds to the part of the Earth's crust that forms the ocean floor. It lies above the Mohorovicic discontinuity (Moho). It is characterized by its thinness and an average density of 3, making it denser than continental crust, with a thickness of about 10 km. It is also called the Sima, opposite to Sial, because of the abundance of silica and magnesium.

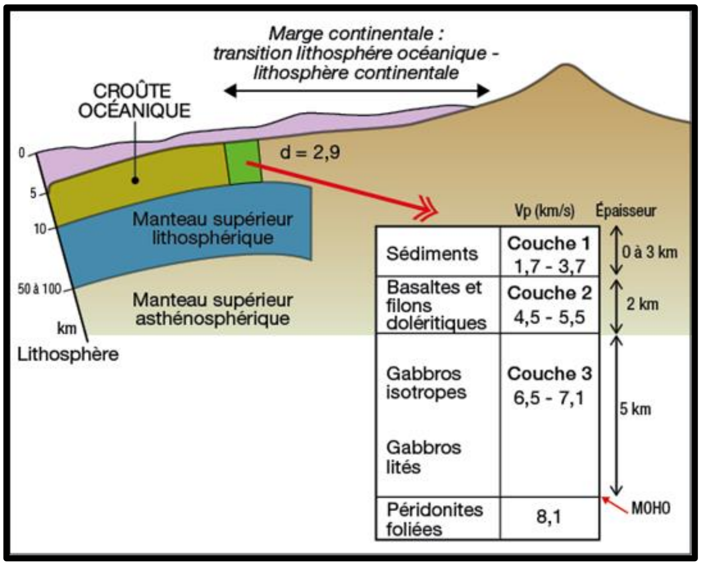


Fig.11: Lithosphere Structure

From top to bottom, under an average water depth of 4.5 km:

- A variable thickness of sediment, 200 to 300 m.
- The upper oceanic crust, with a thickness of about 2 km, density (d) = 2.5 to 2.7, P-wave velocity (Vp) = 5 km/s. It shows basaltic flows containing some consolidated sedimentary levels.
- The lower oceanic crust, with a thickness of 5 km, density (d) = 2.8 to 2.9, P-wave velocity (Vp) = 7 km/s. Its nature is debated; open oceanic faults have yielded basalts, metamorphosed gabbros, amphibolites, and serpentinized peridotites. There are also other magmatic layers. The whole can reach a variable thickness of 7 to 12 km.

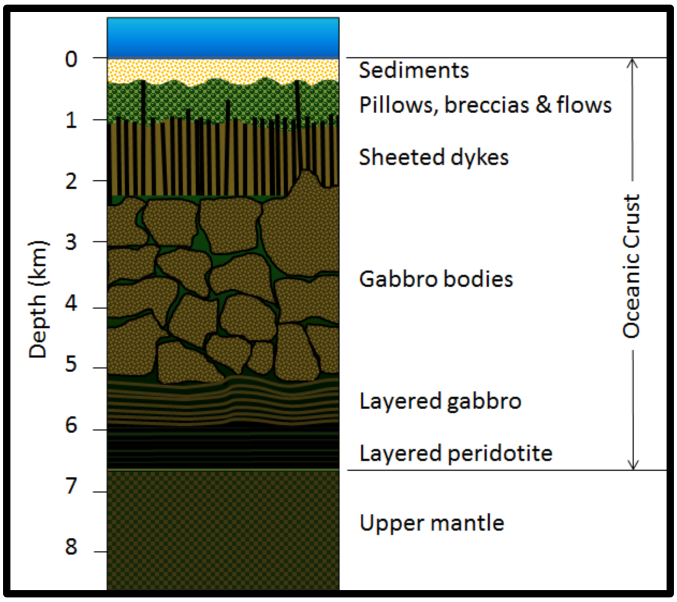


Fig.12: Oceanic Crust Structure

The interior of the Earth is composed of a number of superimposed layers, which are distinguished by their solid, liquid, or plastic state, as well as by their density. An "ultrasound" of the Earth's interior has been established from the behavior of seismic waves during earthquakes. Seismologists Mohorovicic and Gutenberg succeeded in determining the state and density of the layers by studying the behavior of these seismic waves.

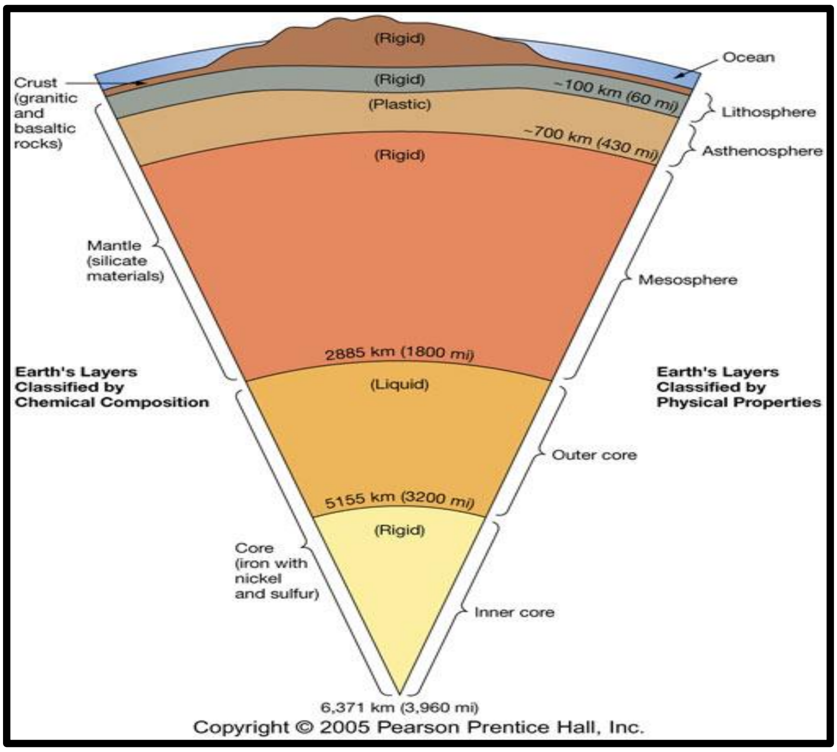


Fig.13: Internal Structure of the Earth

II.2. Characteristics of Seismic Waves

When a wave **reaches a discontinuity** (boundary separating two media of different physical properties: **state** and **density** of matter), the wave reflects or refracts. The propagation velocity of waves depends on the characteristics of the medium in which they propagate:

- Pressure

- Temperature

- Composition.

There are two main domains of wave propagation: **surface waves**, those that propagate on the surface of the globe, in the Earth's crust, and cause all the associated earthquake damage, and **body waves (volumes),** those that propagate inside the Earth and can be recorded at several points on the globe.

II.2.1. Body Seismic Waves

- **P waves** (primary waves, the fastest) are **compression-decompression** waves: as they pass, particles undergo successive compression and dilation, and the particle displacement occurs parallel to the direction of wave propagation. P waves are therefore **longitudinal** waves. They propagate in **both solid** and **liquid media.**

- **S waves** (secondary waves) are **transverse shear waves**: solid particles move perpendicular to the direction of wave propagation. S waves only propagate in **solids.**

II.2.2. Surface Seismic Waves

- **L** and **R** waves (**L**ove waves and **R**ayleigh waves), which arrive last, have a more complex behavior. They propagate like large waves causing not only sea waves (tsunamis) but also Earth's crustal waves. These waves can cause entire cities to collapse during major earthquakes.

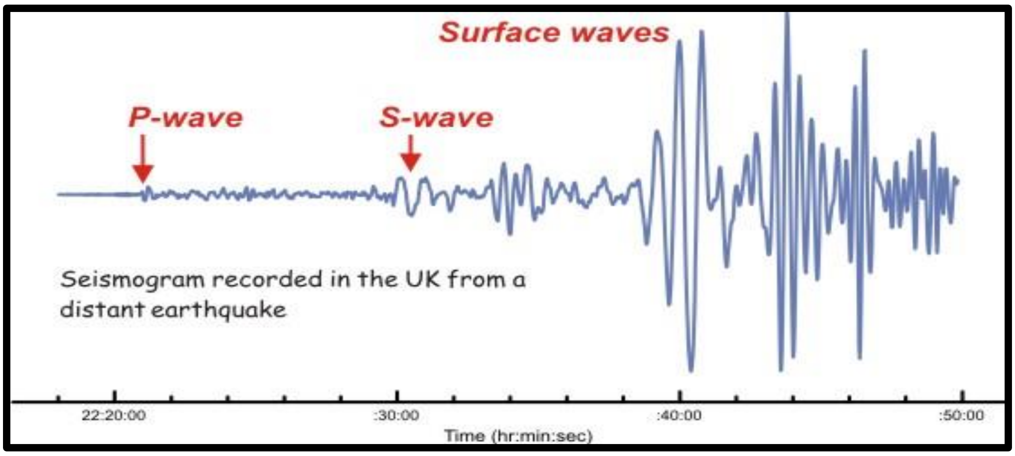


Fig.14: Seismogram with Types of Seismic Waves

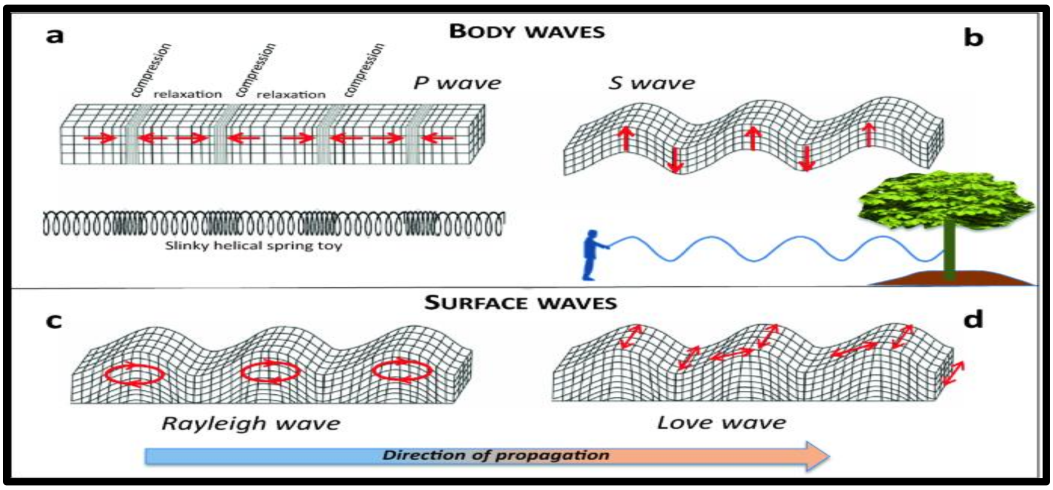


Fig.15: Surface Seismic Waves

All observation stations on the Earth's surface record the same type of curve. Therefore, it can be inferred that the globe is composed of concentric envelopes.

- At the lithosphere-asthenosphere boundary, there is a slight decrease in the propagation velocities of P and S waves corresponding to the transition from a solid material (lithosphere) to a plastic material (asthenosphere).
- The gradual increase in the velocities of P and S waves in the mantle indicates an increase in density of the material as one descends into this mantle.
- The sudden interruption of S wave propagation at the boundary between the mantle and the core indicates that the outer core is liquid.

- The abrupt decrease in the velocity of P waves at the mantle-core boundary is related to the change in state of matter (from solid to liquid), but the relative velocities continue to increase, indicating an increase in densities.
- The reappearance of the S wave indicates that the inner core is solid, along with an increase in P wave velocity.

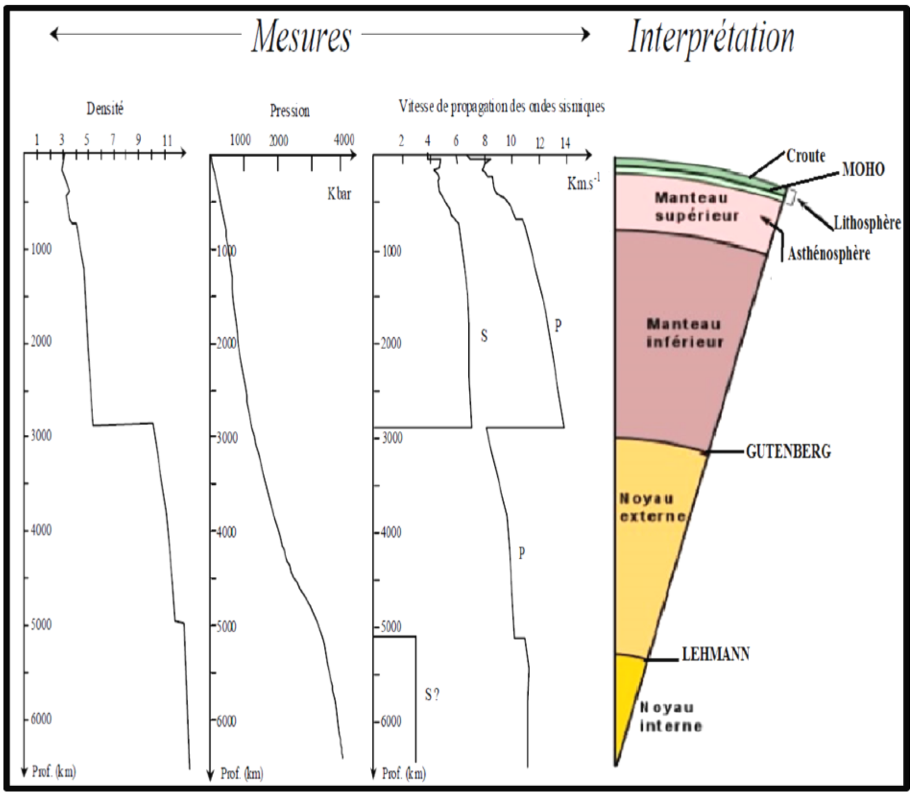


Fig.16: Observation Stations on the Earth's Surface

II.3. Earth's magnetic field

While knowledge about the shape and structure of the Earth is primarily due to gravimetry and seismology, magnetism is responsible for the discovery and measurement of movements within the Earth.

II.3.1 - Magnetism

Understanding terrestrial magnetism was a significant step in formulating the theory of plate tectonics. Two aspects of magnetism are notable: *paleomagnetism and terrestrial magnetic reversals*.

The discovery of bands of magnetic anomalies on the ocean floor parallel to mid-ocean ridges supported the theory of seafloor spreading.

- It took nearly two centuries, until the late 19th century, to develop the magnetometer, a device capable of measuring the intensity of the magnetic field, paving the way for quantitative exploration of the Earth's magnetic field.
- The Earth's magnetic field (EMF) corresponds to a magnetic dipole whose axis is close to the Earth's rotation axis (it makes an angle of 11 degrees with the Earth's axis). The negative pole is close to the geographic North Pole, and vice versa. Its position constantly changes, so the magnetic poles move about 10 kilometers per year.

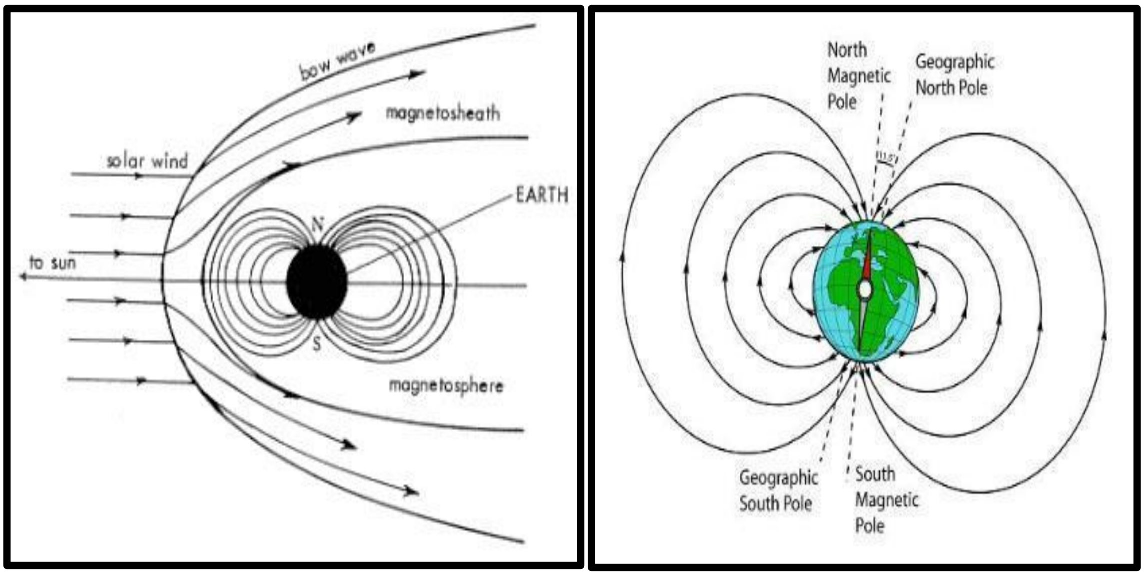


Fig.17: The Earth's Magnetic Field

The magnetosphere acts as a shield that deflects charged particles from the solar wind. Without this shield, solar wind particles and cosmic rays would produce a harmful radiation level that would endanger the existence of living species. Since the EMF decreases with altitude, it cannot come from the Sun or the exterior, but it can only come from the Earth's interior. The Earth behaves like a giant magnet, generated by the movements of the liquid metallic core in the deep layers of the Earth.

II.3.2. Parameters of the Magnetic Field

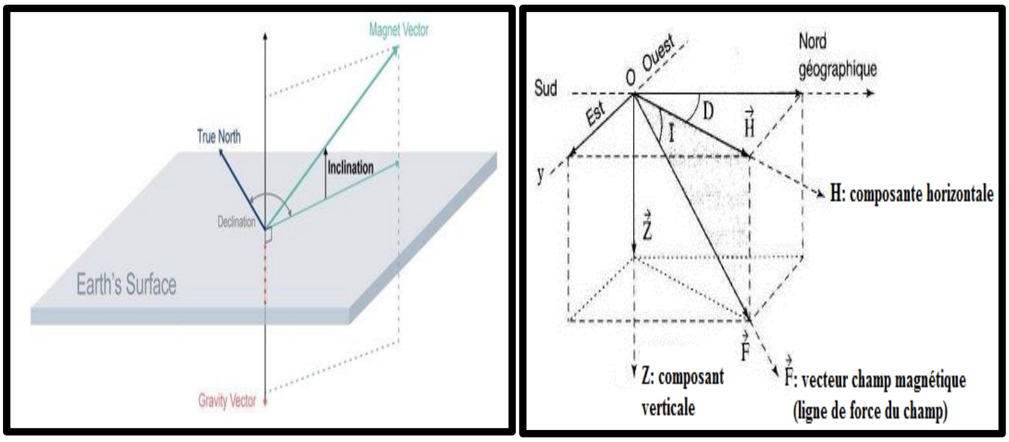


Fig.18: Parameters of the Magnetic Field

The EMF at any point on the globe is defined by three parameters:

- Its intensity (F) in nano Tesla, which varies depending on latitude (60,000 nT at the North Pole and 30,000 nT at the equator).
- Its inclination (I) in degrees, which is the angle between the horizontal component of the field and the field direction. I is positive if the field lines enter the Earth (Northern Hemisphere).
- Its declination (D) in degrees, which is the angle between the horizontal component of the field and geographic North. It varies from 0 to 360°: 0 to 180° means that D is west of geographic North, and 180 to 360° east.

II. 4-Continental Drift and Plate Tectonics

Introduction

The theory of continental drift was formulated by the German scientist Wegener in 1912. Wegener proposed that the continents, now separated, were once joined in the early eras as a single immense continent called Pangaea. This continent subsequently fragmented, and these fragments were displaced to occupy their current positions.

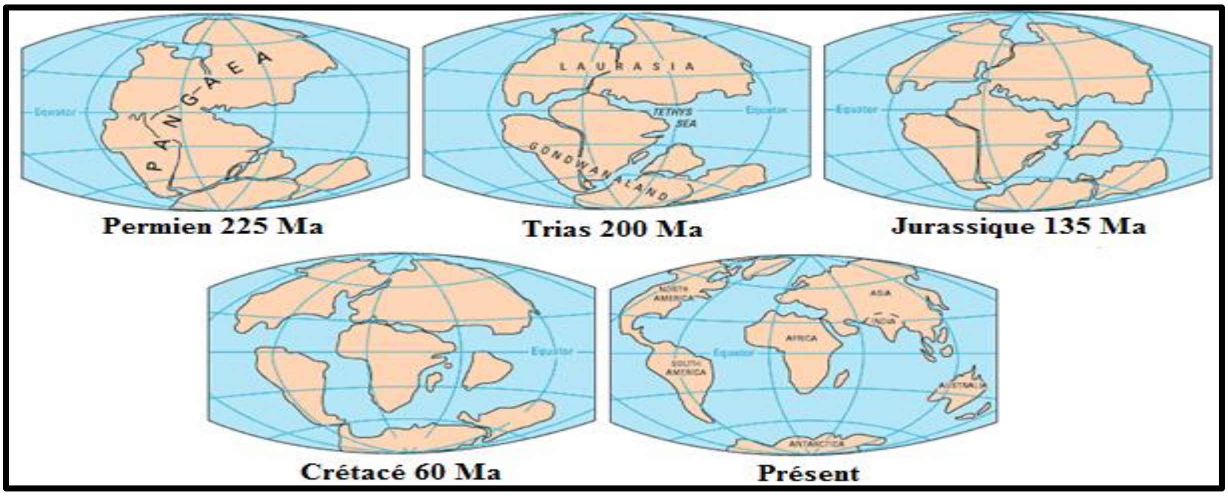


Fig.19: Pangaea

Plate tectonics, also known as continental drift, studies the evolution and deformation of the lithospheric plates constituting the Earth's surface. The outer shell of the Earth, or lithosphere, is formed of relatively rigid plates, about a hundred kilometers thick, floating on the relatively plastic asthenosphere. The lithosphere includes the continental or oceanic crust and the upper part of the mantle.

II.4.1. Lithospheric Plates:

The rigid outer shell of the Earth (Lithosphere) is subdivided into several vast domains whose internal deformation can be considered negligible. The lithosphere can be considered a mosaic of large rigid plates covering the entire globe. These lithospheric plates are subject to relative movements with respect to each other.

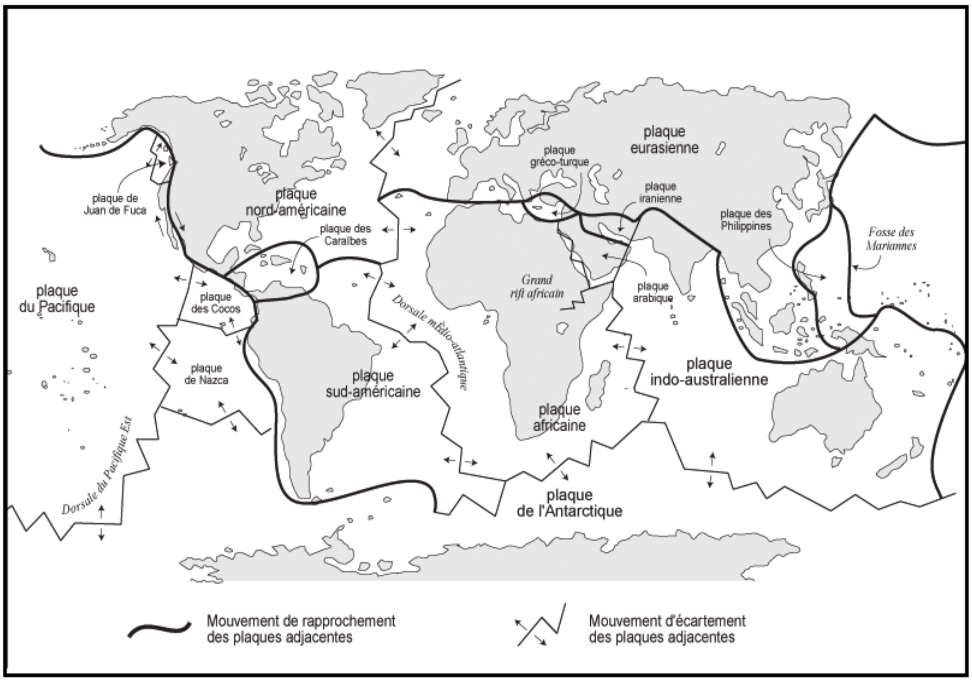


Fig.20: Major Lithospheric Plates

The Eurasian Plate; African Plate; North and South American Plates; Pacific Plate; Nazca Plate; Indo-Australian Plate; Antarctic Plate. Other microplates have been defined subsequently. Two plates consist entirely of oceanic lithosphere (Pacific Plate and Nazca Plate); the other plates are mixed, consisting of both oceanic and continental lithosphere.

II.4.1.1. Plate Boundaries

Lithospheric plates are separated from each other by narrow zones where most of the Earth's internal geodynamic activity is concentrated (volcanism, seismicity, deformations). Three types of plate boundaries are defined.

- **Divergent boundaries**, where plates move away from each other and new oceanic crust is produced.
- **Convergent boundaries**, where two plates collide, resulting from divergence.
- **Transform boundaries**, where two plates slide laterally against each other along faults.

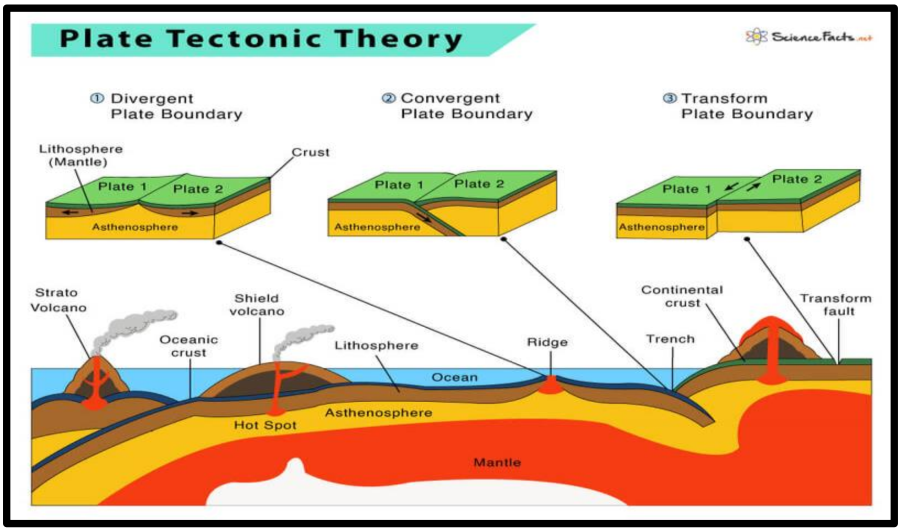


Fig.21: Plate Boundaries

II.4.1.1.1 Divergent Boundaries

We know there is a heat flow from the Earth's center to its exterior, caused by the radioactive decay of certain chemical elements, generating **convection cells** in the plastic mantle (asthenosphere). Due to this convection, heat is concentrated in an area where heated material expands, explaining the corresponding uplift at mid-ocean ridges. This heat concentration leads to partial melting of the mantle, producing magma. Convection in the rigid part of the Earth's envelope (lithosphere) creates tension forces that cause two plates to diverge, resulting in oceanic lithosphere on either side of the **ridge**. Between these two diverging plates, the influx of magma creates new oceanic crust.

- Mid-ocean ridges are the birthplace and growth site of oceanic crust. They are sites of intense basaltic volcanic activity, serving as "factories" for oceanic crust production.
- Rates of oceanic spreading vary from 2.2 cm/year (Atlantic Ocean) to 10 cm/year (Pacific Ocean).

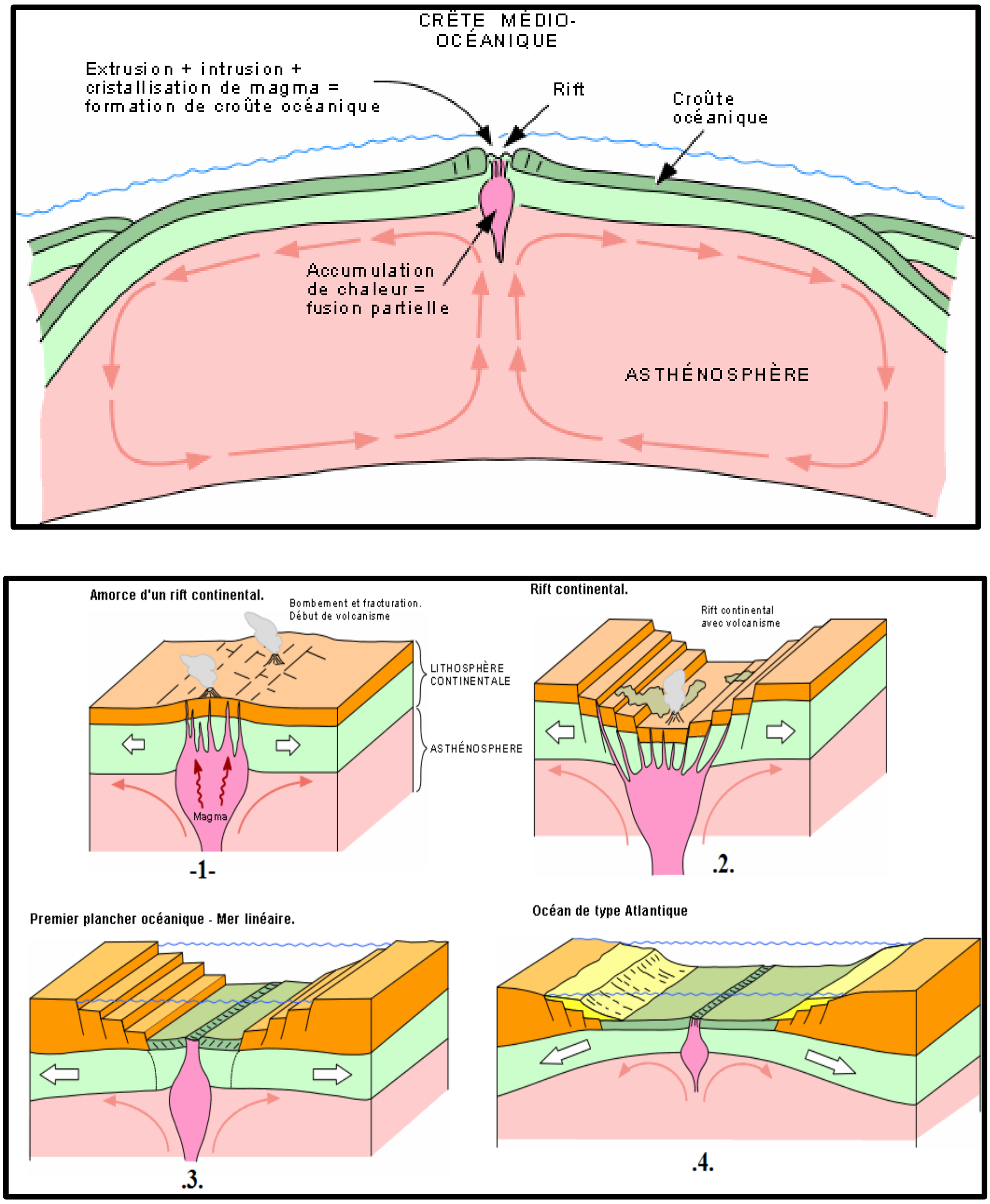


Fig.22: Stages of Oceanic Crust Formation

II.4.1.1.2. Convergent Boundaries

Given that the Earth's surface area has always remained constant, the continual creation of new plates at divergent boundaries implies that lithosphere must be destroyed elsewhere. This destruction occurs at convergent boundaries, which, as the name suggests, mark the contact between two lithospheric plates converging toward each other.

- Plate destruction occurs as one plate sinks beneath the other into the asthenosphere and by the assimilation of the subducted plate portion into the asthenosphere. Thus, the volume of the Earth remains unchanged.

- The process by which lithosphere descends into the asthenosphere is called **subduction** (from "sub" and the Latin "ducere," to draw). The margins along which plates are subducted are called **subduction zones**. They are marked by **deep trenches** in the ocean floor.

- The outcomes (earthquakes, volcanoes, mountain ranges, deformations) differ depending on the nature of the plates (oceanic or continental) colliding.

Convergent plate boundaries can be of three types:

II.4.1.1.2.1- First Type of Collision:

Results from the convergence between two oceanic plates. In this type of collision, one of the plates, usually the older and denser one sinks beneath the younger plate to form a subduction zone.

This case leads to the formation of an oceanic insular volcanic arc on the edge of the non-subducted plate. Example: the Mariana Trench in the Pacific Ocean.

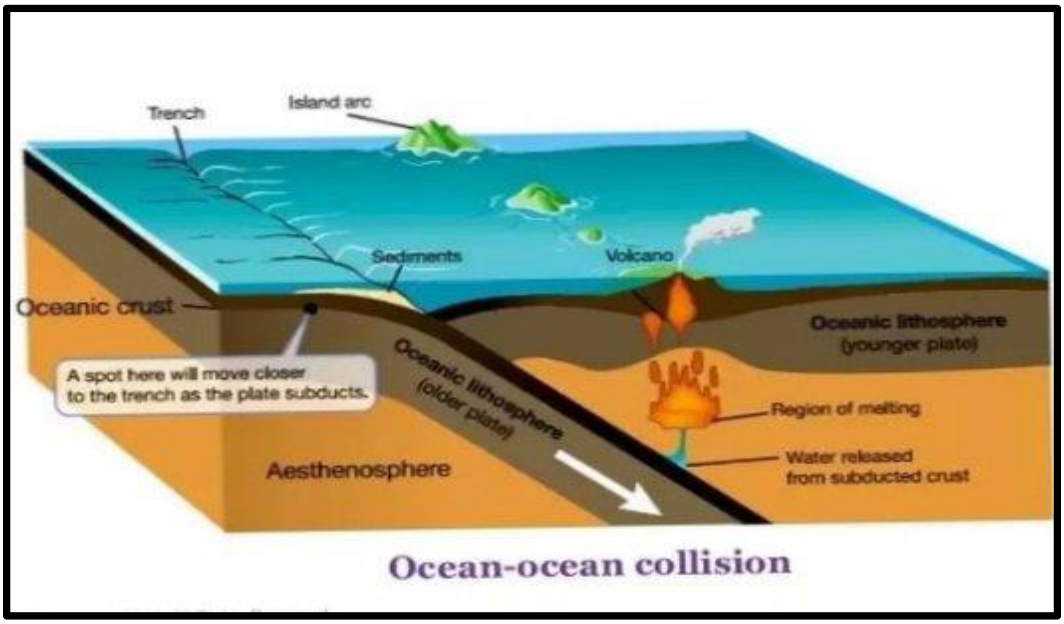


Fig.23: Convergence between two oceanic plates "Subduction"

II.4.1.1.2.2-Second Type of Collision:

Results from the convergence between an oceanic plate and a continental plate. In this type of

collision, the denser oceanic plate sinks beneath the continental plate.
This leads to the formation of a chain of volcanoes on the continents (continental volcanic arc). Example: the Peru-Chile Trench.

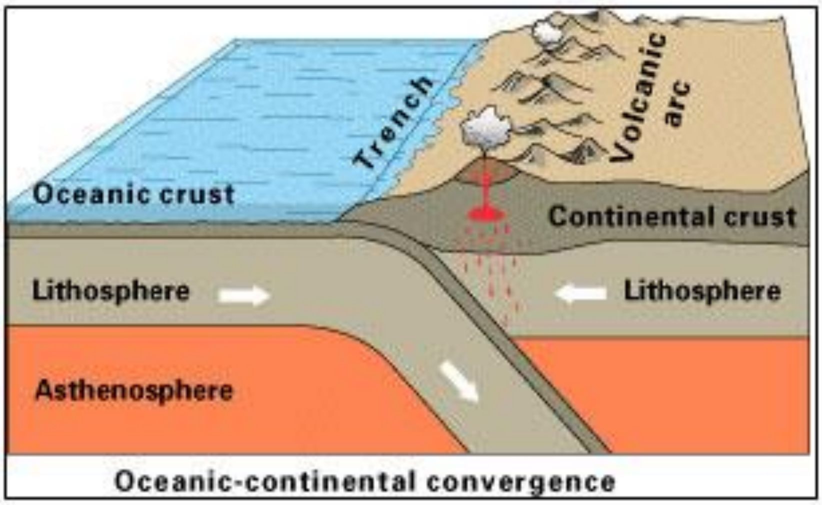


Fig.24: Ocean-Continent Convergence "Subduction"

II.4.1.1.2.3 -Third Type of Collision:
Involves the convergence of two continental plates. As the oceanic space closes gradually due to the approach of two continental plates, the continental crust cannot sink into the asthenosphere due to its lower density compared to that of the asthenosphere.
Sedimentary material from the ocean floor, more abundant near the continents, and that of the accretion prism concentrate increasingly. The prism grows with uplift, folding, and the formation of a mountain range.
The most famous example is the collision of India with the Asian continent, resulting in the formation of the Himalayas.

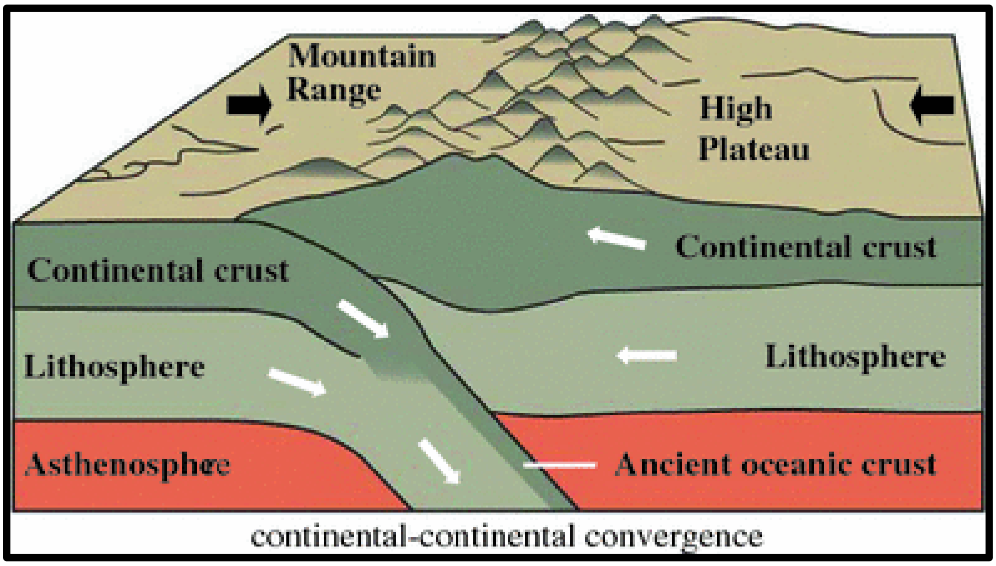


Fig.25: Convergence between two continental plates

When two plates collide, the mechanism gets stuck: the driving force (convection in the upper mantle) is not strong enough to sink one of the plates into the asthenosphere due to the lower density of the continental lithosphere compared to that of the asthenosphere. All the sedimentary material is compressed and uplifted to form a mountain range where rocks are folded and faulted.

II.4.1.1.3.. Transform Boundaries

- Transform boundaries correspond to regions where two plates slide past each other. The plates move laterally against each other.
- These sliding margins produce large fractures that affect the entire thickness of the lithosphere; they are more commonly referred to as **transform faults.**
- They are mostly found in the oceanic lithosphere and form when there is offset along the same mid-ocean ridge due to differences in spreading rates.
- Sometimes these faults relay between divergent and convergent boundaries (these faults transform the movement between divergence and convergence, hence their name transform faults).

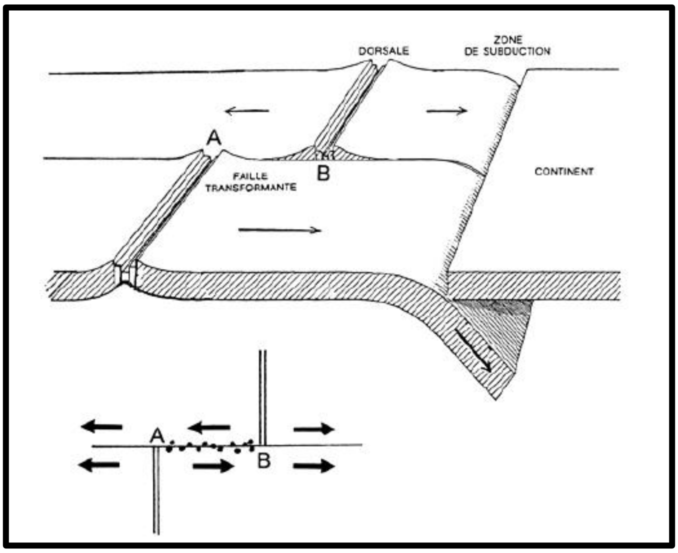


Fig.26: Transform Boundaries

The most well-known transform fault is the San Andreas Fault in California. It is actually a system of transform faults that accommodates the sliding of the Pacific Plate against the North American Plate.

Fig.27: The San Andreas Fault in California

II.5. Earthquakes

Earthquakes, or tremors, are a geological phenomenon characterized by a sudden shaking of the ground caused by a sudden relative movement of two tectonic plates (the Earth's crust).

II.5.1. Origin of Earthquakes

When a rigid material is subjected to shear stresses, it will first deform elastically, and then, when it reaches its elastic limit, it will rupture, releasing all the energy accumulated during the elastic deformation instantaneously.

This is what happens when the lithosphere is subjected to stresses. Under the influence of stresses caused most often by the movement of tectonic plates, the lithosphere accumulates energy. When the elastic limit is reached in certain places, one or more ruptures occur, resulting in faults. The energy suddenly released along these faults causes earthquakes.

In a given region, earthquakes will occur repeatedly along the same fault, since the fault constitutes a plane of weakness in the lithosphere. It should be noted that earthquakes only occur in **rigid material**. Therefore, earthquakes will always occur in the lithosphere, never in the plastic asthenosphere.

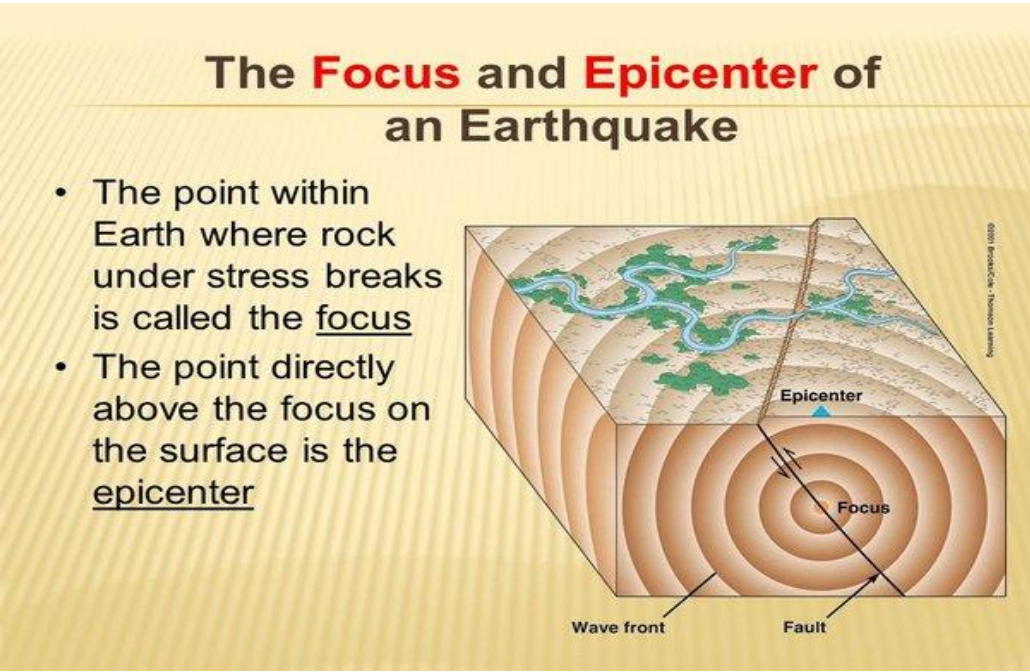


Fig.28: Focus and Epicenter of an Earthquake

When an earthquake is triggered, a front of seismic waves propagates through the Earth's crust.

The focus is the place on the fault plane where the earthquake actually occurs, while the epicenter refers to the point on the Earth's surface directly above the focus. This is usually where the intensity of the earthquake is strongest.

II.5.2. Measuring an Earthquake.

We have two scales to assess earthquakes: the Mercalli scale and the Richter scale. Today, we only use the Richter scale, but past earthquakes can only be evaluated according to the Mercalli scale.

- **The Mercalli** scale was developed in 1902 and modified in 1931. It indicates the intensity of an earthquake on a scale from I to XII. This intensity is determined by two factors: ***the extent of damage caused by an earthquake*** and ***the population's perception of the earthquake.***

1st degree:

Only recorded, by sensitive instruments.

2nd degree:

Very weak, few resting observers notice it.

3rd degree:

Weak, Felt by a small number of inhabitants.

4th degree:

Mediocre. Generally felt indoors, but by a small number of people outdoors. Slight oscillations of objects. Some sleepers awakened.

5th degree:

Fairly strong, perfectly felt outdoors oscillation as on board a ship.

6th degree:

Strong causes panic; heavy objects and furniture are moved.

7th degree:

Very strong serious damage can occur, waters are disturbed, and chimneys fall.

8th degree:

Ruinous objects are transported over significant distances.

9th degree:

Disastrous houses can collapse. Destruction of well-built buildings.

10th degree:

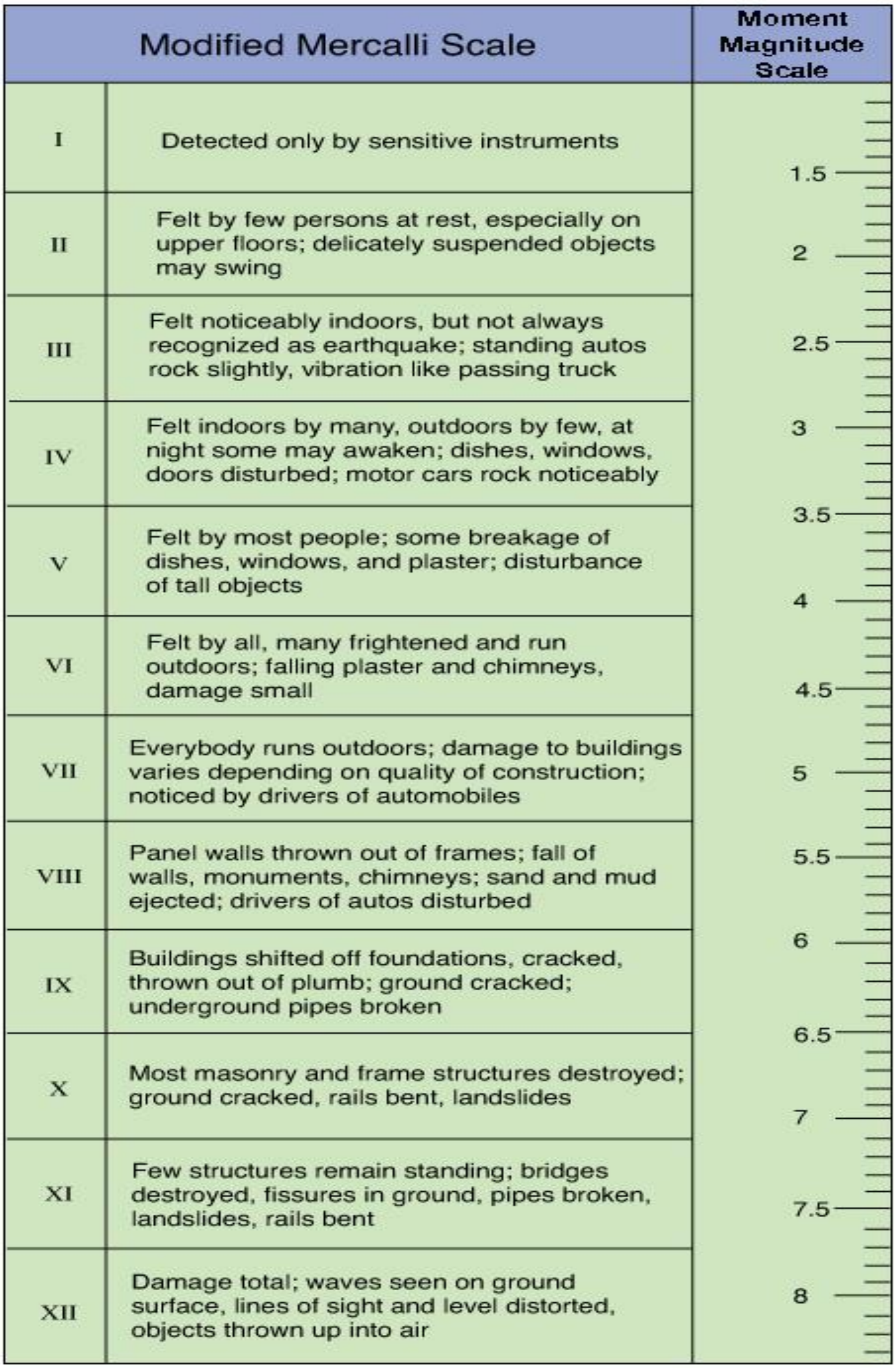
Very disastrous dikes collapse; water and gas pipes are cut off.

11th degree:

Catastrophic even the strongest bridges are destroyed.

12th degree:

Cataclysm nothing remains of human works. Geography is altered.



Modified Mercalli Scale		Moment Magnitude Scale
I	Detected only by sensitive instruments	1.5
II	Felt by few persons at rest, especially on upper floors; delicately suspended objects may swing	2
III	Felt noticeably indoors, but not always recognized as earthquake; standing autos rock slightly, vibration like passing truck	2.5
IV	Felt indoors by many, outdoors by few, at night some may awaken; dishes, windows, doors disturbed; motor cars rock noticeably	3
V	Felt by most people; some breakage of dishes, windows, and plaster; disturbance of tall objects	3.5 4
VI	Felt by all, many frightened and run outdoors; falling plaster and chimneys, damage small	4.5
VII	Everybody runs outdoors; damage to buildings varies depending on quality of construction; noticed by drivers of automobiles	5
VIII	Panel walls thrown out of frames; fall of walls, monuments, chimneys; sand and mud ejected; drivers of autos disturbed	5.5
IX	Buildings shifted off foundations, cracked, thrown out of plumb; ground cracked; underground pipes broken	6
X	Most masonry and frame structures destroyed; ground cracked, rails bent, landslides	6.5 7
XI	Few structures remain standing; bridges destroyed, fissures in ground, pipes broken, landslides, rails bent	7.5
XII	Damage total; waves seen on ground surface, lines of sight and level distorted, objects thrown up into air	8

Fig.29: The Mercalli Scales

- **Richter scale**: The Richter scale was established in 1935. This scale provides us with the magnitude of an earthquake, calculated from the amount of energy released at the focus. It is measured on an open logarithmic scale; to date, the strongest earthquake reached 9.5 on the Richter scale (Chile). The magnitude is calculated from the measurement of the ground movement amplitude determined from the recording obtained on a seismograph 100 kilometers from the epicenter.

The magnitude M is related to the energy developed by a formula of the type:

$$aM = \log (E / E0)$$

With:

a = 1.5, E0 = 2.5.10^11

For M = 0 E = 2.2.10^5 ergs and for magnitude 8.9 (Chile) E = 5.6.10^11 ergs

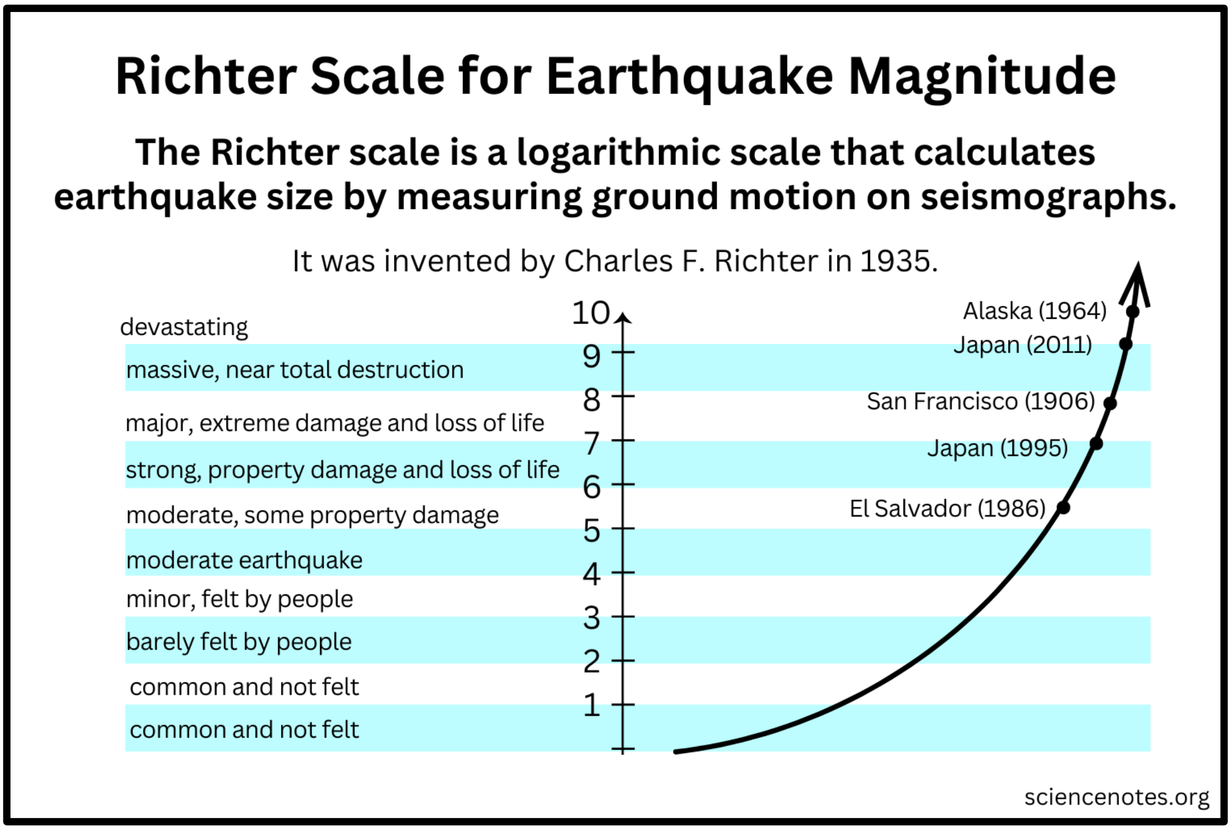


Fig.30: The Richer Scales

II.5.3. Locating an Earthquake on the Earth's Surface

Less than an hour after an earthquake, its epicenter is announced. How do we manage to locate an earthquake so quickly and accurately?

P waves propagate faster than S waves; it is this property that allows earthquake localization. Seismic waves are recorded at various locations around the globe by a device called a **seismograph**, and the recording obtained is called a **seismogram**.

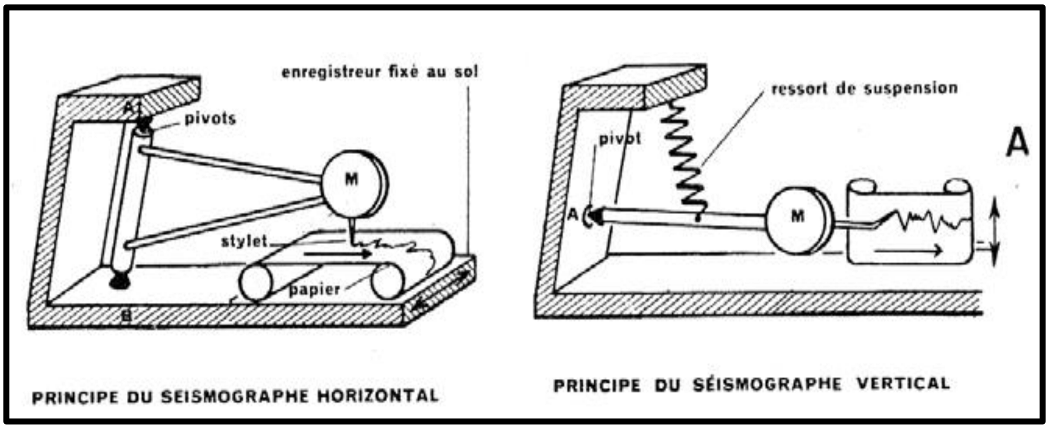


Fig.31: Seismograph and Seismogram.

In a given location, since P waves arrive first, there will be a time lag in the seismic record between the onsets of recording of the two types of waves. The propagation velocities of the two types of waves in the Earth's crust have been established, and therefore, calibrated curves are available, such as this one.

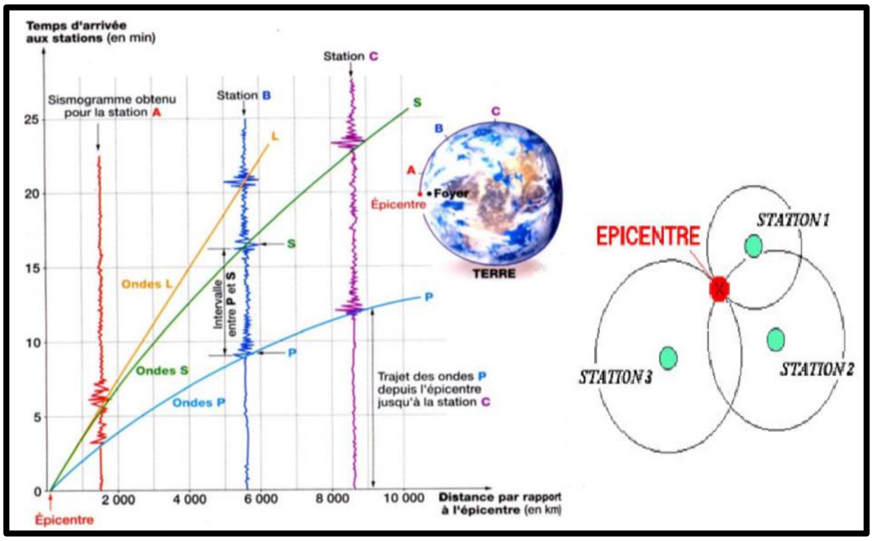


Fig.32: Locating an Earthquake on the Surface

In this example, consider recordings of an earthquake at three points: thus, the earthquake is located at the point of intersection of the three circles. In practice, more than three points are used.

II.5.4. Distribution of Earthquakes

Earthquakes do not have a random distribution on the Earth's surface. This ordered distribution supports the theory of plate tectonics, particularly concerning the existence of subduction zones.

Earthquakes are mainly found at the boundaries of lithospheric plates. Furthermore, three classes of earthquakes are distinguished based on the depth at which they occur:

- **Shallow earthquakes** occur at shallow depths, typically within the first few tens of kilometers, and are found both at divergent and convergent boundaries.

- **Intermediate earthquakes** occur between a few tens and a few hundred kilometers deep and are concentrated only near convergent boundaries.

- **Deep earthquakes** occur at depths of up to 700 km, typically at the base of the asthenosphere in practice, and are exclusively found near convergent boundaries.

The northern coast of Algeria is traversed by a convergent continental lithospheric plate boundary: the Eurasian plate to the north overrides the African plate to the south. It is within this thrust fault that earthquakes in the region occur.

II.5.5. Tectonic Accidents

The most interesting facts for geologists are the vertical movements of terrains (subsidence, uplift) which result in fractures with elevation differences, called faults. Vertical displacements are also observed.

II.5.6. Tsunamis and Tidal Waves

Tsunamis (a name derived from Japanese) generate a particularly destructive phenomenon following a movement of the seafloor generated by an earthquake, volcanic eruption, or landslide. The uplift of the seafloor creates a swelling of the mass of water. This swelling gives rise to a wave which, on the ocean surface, can reach unprecedented heights (up to 30m) and rushes at regular intervals onto the coast, destroying ports, carrying away houses, etc.

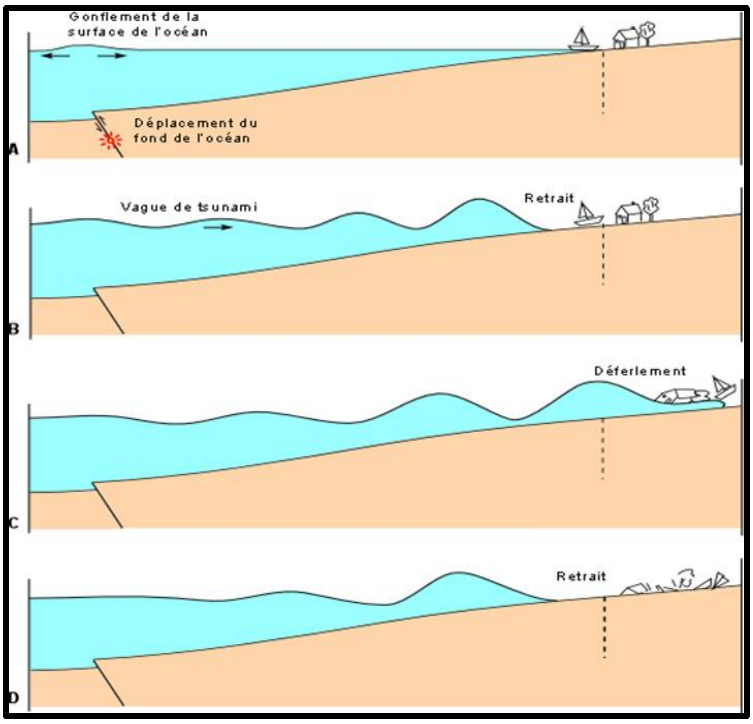


Fig.33: Tsunami and Tidal Wave

II.6. Volcanoes

Definition: Volcano comes from Vulcanus, Vulcan, the Roman god of fire. When heat melts rock inside the Earth, it produces a burning liquid called magma. The **magma** rises, erupts at the surface as lava, and gives birth to a volcano.

Volcanoes are openings in the solid crust of the Earth from which smoke, ash, stones, and finally lava emerge at the surface of the earth or underwater (ocean). These openings have the shape of a funnel and are called **craters.**

II.6.1. Volcano Structure:

A volcano consists of:

- **a.** ***A magma chamber***: supplied by magma from the mantle and serving as a reservoir and place of magma differentiation. When it empties after an eruption, the volcano may collapse and give rise to a caldera. Magma chambers are located between ten and fifty kilometers deep in the lithosphere.

- **b.** ***A main vent***: which is the preferred transit route for magma from the magma chamber to the surface.

- **c.** ***A summit crater*:** where the main vent opens.

- **d.** ***One or more secondary vents***: originating from the magma chamber or the main vent and generally opening on the flanks of the volcano, sometimes at its base. They can give rise to small secondary cones.

- **e.** ***Lateral fissures***: which are longitudinal fractures in the flank of the volcano caused by its swelling or deflation. They can allow the emission of lava in the form of a fissure eruption.

The first effect of an earthquake is to violently break the solid crust of the globe. First, the terrain rises over a more or less considerable extent. A tall cone forms, and soon, the explosion occurring, there is an opening in the shape of a funnel through which ash, smoke, stones, and lava emerge.

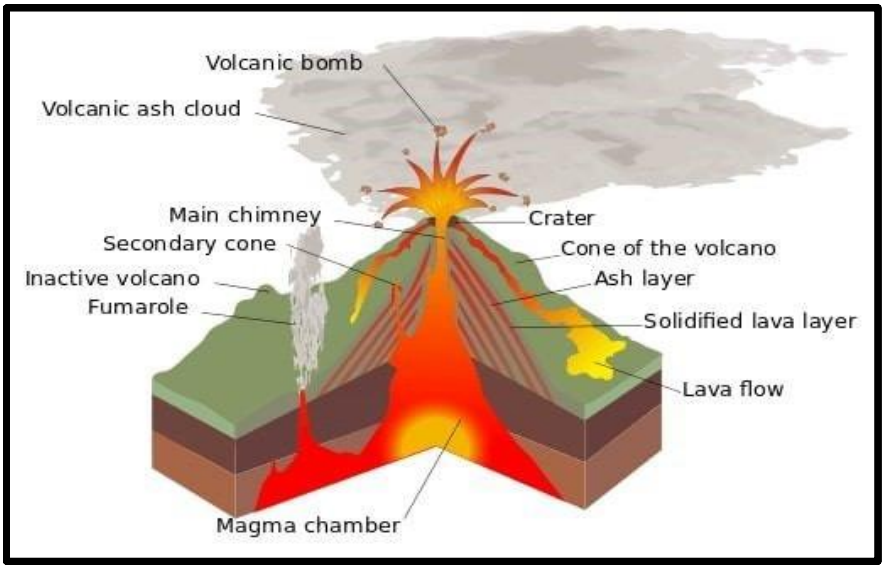


Fig.34: Volcano Cross-section

II.6.2. Materials Emitted by a Volcano

The materials emitted by a volcano can be gaseous, fluid, or solid.

Smoke:

The huge columns of smoke seen coming out of the crater are mainly composed of water vapor. But as this vapor is often charged with carbonic acid, a violent poison, it is dangerous to approach.

Ashes:

These ashes of extraordinary fineness are carried into the atmosphere and form fairly thick clouds. Sometimes these ash clouds are carried over long distances.

Lava:

Lava is a mass of melted rocks, more or less fluid, ranging from 800 to 1,200°C. Lava plays a crucial role in volcanic phenomena. The term "lava" is used for all melted materials that emerge in the form of streams. Lava is therefore rocky or metallic materials brought to a state of fusion by the high temperature of the globe. But volcanoes do not continually emit lava. Other volcanoes are too high for lava to exit through the crater. The slow cooling of lava is also remarkable: heat is retained inside for years.

Gases:

The gases expelled during volcanic eruptions are often water vapor, sulfur dioxide, carbon dioxide, ammonia, etc., into the atmosphere. Some of the gases emitted by volcanoes can be deadly in case of high concentrations.

II.6.3. Distribution of Volcanoes

Like earthquakes, volcanoes are not randomly distributed on the surface of the planet. Several are located at plate boundaries (mid-ocean ridges and subduction zones), but also within plates (intraplate volcanism, such as hotspot volcanism).

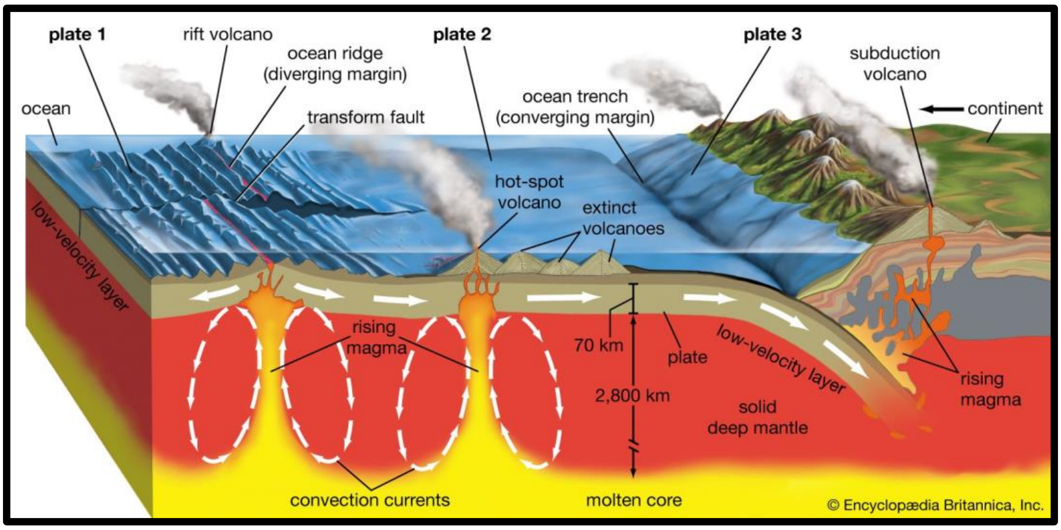


Fig.35: Distribution of Volcanoes

II.6.3.1. Mid-Ocean Ridge Volcanism:

There are underwater volcanoes all along the mid-ocean ridges, particularly in the central rift, where new oceanic lithosphere is formed. The composition of the lava from these volcanoes indicates that we are very close to the zone where partial melting of the mantle occurs. If there were no tension in this ridge area, there would be no fractures that allow the magma produced by partial melting to seep into the lithosphere and form volcanoes.

II.6.3.2. Subduction Zone Volcanism:

Volcanism related to the subduction of one tectonic plate beneath another forms chains of volcanoes. However, depending on whether it involves a collision between two oceanic plates or between an oceanic plate and a continental plate, the nature of the volcanism differs.

- In the case of convergence between two oceanic plates, a chain of volcanoes arises above the ocean surface to form an island arc.
- In the case of convergence between an oceanic plate and a continental plate, the volcanoes are located on the margin of the continental plate and form a continental arc.

II.6.3.3. Hotspot Volcanism:

Hotspot volcanism is intraplate volcanism found primarily, but not exclusively, on oceanic plates. Chains of hotspot volcanoes support the theory of seafloor spreading. For reasons that are still not fully understood, there are localized concentrations of heat in certain points of the mantle, leading to partial melting of the material. This is known as a hotspot.

II.6.4. Types of Volcanic Activities:

There are two types of volcanic eruptions:

- **Explosive eruptions**, characterized by more or less significant explosions, the formation of a dome in the volcano's crater, pyroclastic flows descending the volcano's slopes, and clouds of ash dispersing over long distances. These eruptions occur when **the magma is viscous**.
- **Effusive eruptions**, characterized by flows of fluid lava that emerge from fissures and descend the volcano's slopes. These eruptions occur when **the magma is fluid.**

There are four main types of volcanic activities, generally categorized from the first to the fourth type:

- The temperature and fluidity of the lava decrease.
- The nature of the emitted rocks becomes more acidic.
- The explosions become more violent.
- The proportion of solid materials ejected increasingly outweighs the proportion of liquid materials.

Hawaiian Type

Effusive volcano crater formation very fluid lava. There is abundant emission of basaltic lava, which flows rapidly over significant distances. There are few gases or projections. When the lava comes into contact with seawater, it quickly solidifies into "pillow lavas." This result in the formation of immense flattened structures (shield volcanoes) with gentle slopes (5 to 6°) but considerable dimensions.

Strombolian Type

Explosive/effusive volcano, presence of a crater, fluid lava. This results in the formation of a stratovolcano, with layers of lava and ejecta, resulting from discontinuous eruptions, such as volcanic scoria that sometimes takes the form of volcanic bombs.

Vulcanian Type

Explosive volcano, presence of a crater (frequent and violent explosions ≈ atomic mushroom) viscous lava. The eruptions are very abrupt and discontinuous. There are few or no lava flows. The crater may be blocked by solidified lava. There is often projection of finely pulverized volcanic ash, which, when consolidated, forms volcanic tuff or cinerite. Generally, the volcanic cones are of reduced size.

Pelean Type

Explosive volcano, no crater, very viscous lava leading to dome formation, pyroclastic flows (avalanches of solid or pasty materials). (Mount Pelée, Martinique) is considered the most dangerous. Indeed, gases, subject to very high pressures, accumulate at depth. When the gas pressure reaches a certain level, the entire summit of the cone can explode. A "pyroclastic flow" then rushes down the slopes at very high speed. After the eruption, a vertical needle of dome rock appears at the top of the dismantled cone.

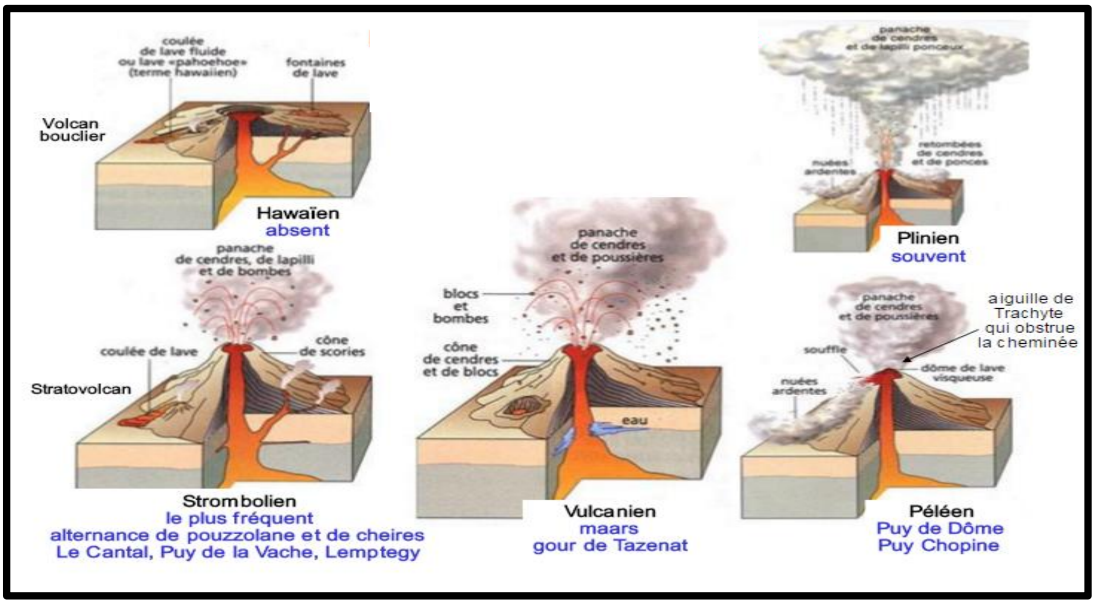


Fig.36: Types of Volcanoes

CHAPTER 3

TECTONICS

III-Definition of Tectonics:

Tectonics, from the Greek word τέκτων or tektōn meaning "builder," "carpenter," is the discipline of Earth sciences that deals with the deformations of the Earth's crust. Tectonics can be defined as follows:

- It encompasses all deformations that have affected geological formations subsequent to their formation (faults, folds, foliation, thrusting, shearing, etc.).

The study of tectonics involves distinguishing, within the current architecture of terrains in a given region, what is related to the original properties and relationships of rocks and what is due to their subsequent deformation, which is the focus of the study, also known as "structural geology."

Tectonics corresponds to the phenomena responsible for the deformation of rocks after their formation. These phenomena involve significant physical forces such as compression and extension. Rocks are constantly subjected to forces or stresses. These stresses can vary considerably depending on whether the rocks are subject to compression, extension, vertical movements, or are at rest within an undeformed plate.

Stress is a force applied to a certain unit of volume. Solids have a force to resist this stress. When the stress exceeds the material's resistance, the object is deformed, resulting in a change in shape and/or volume.

Examples:

1. An 8mm rope withstands a load of 400kg (r = 4.10-3m, F = 4.102 kg)
2. A 14mm rope withstands a load of 1200kg (r = 7.10-3m, F = 12.102kg)

The load ratio is equal to: (1200 / 400) = 3. The breaking load, or the maximum force F, is proportional to the section S of the rope.

For case 1): F(*) = 9.8 m.s-2 x 4.102 kg ≈ 4.103 N S(**) = π.(4.10-3 m)2 ≈ 5.10-5 m2

For case 2): F = 9.8 m.s-2 x 12.102 kg ≈ 12.103 N S = π.(7.10-3 m)2 ≈ 15.10-5 m2

The stress: F/S = 4.103 N / 5.10-5 m2 = 4/5108 N/m2 case 1 = 0.8 N/m2 case 1 F/S = 12.103 N/15.10-5 m2 = (12/15).108 N/m2 case 2 = 0.8 N/m2 case 2 These are stress units N/m2 = Pa.

There are several types of stresses:

- Compression: in this case, the forces are convergent, causing objects to bend.
- Tension: the forces diverge and have the effect of stretching materials.
- Shear: the stresses exceed the resistance forces of the materials.

The first two are called volume deformations, while the latter are shape deformations. Volcanism and earthquakes are the two main manifestations of tectonics on a human scale. Rock deformation is a longer-term consequence of these manifestations. When subjected to stresses, the Earth's crust deforms. Stress can simply be defined as a force applied to a certain unit of volume. Every solid has its own force to resist stress. When stress exceeds the material's resistance, the object is deformed, resulting in a change in shape and/or volume. There are three main types of deformations affecting the Earth's crust: elastic, plastic, and brittle. The following diagram illustrates the general relationship between stress and deformation.

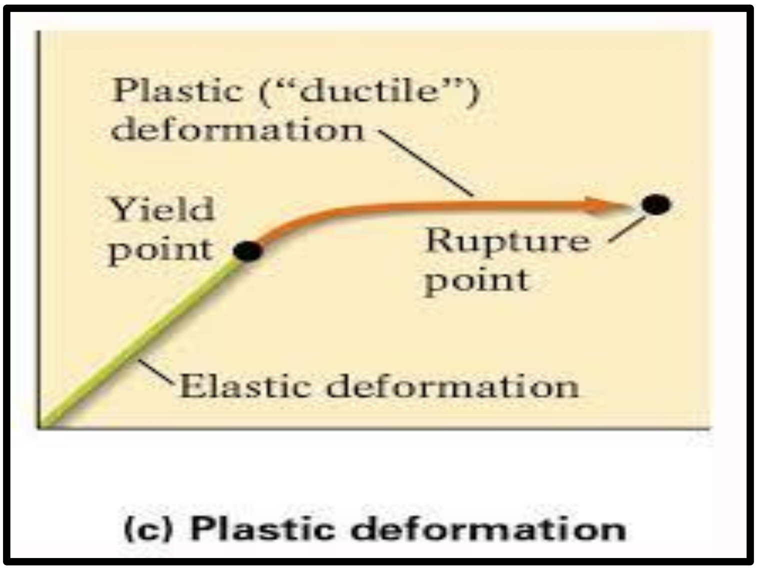


Fig.37: Types of Deformation

The first response of a material to stress is:

Elastic Deformation:

- When stress is released, the material returns to its original shape and volume. The energy stored by the material during deformation dissipates when the stress is released.
- At a certain point during elastic deformation, the stress-strain relationship becomes nonlinear, indicating the material has reached its elastic limit. If the stress exceeds this limit, the material undergoes permanent deformation, resulting **in plastic deformation**.
- With further stress increase, the material reaches its breaking point, and it fractures, resulting in **brittle deformation.**

Important Parameters: Three critical parameters must be considered when applying stress-strain concepts to crustal materials**: temperature, pressure, and time.**

- **Temperature and pressure** increase with depth in the Earth's crust and modify material behavior. Generally, there are two deformation fields: brittle deformation (fragile) and plastic deformation (ductile), with increasing temperature and pressure as one descends into the Earth's crust.

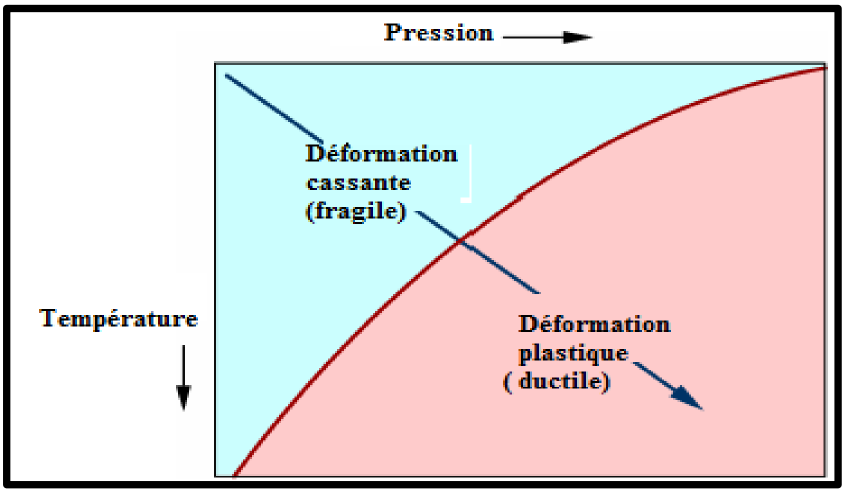


Fig.38: Relationship between strain, temperature, and pressure

- Time is also a significant factor in deformation.
- Rock composition is another essential factor. Some rocks are inherently brittle (limestone), while others are more ductile (clay).

Cassette Tectonics:

- Brittle Tectonics "FAULTS"
- Ductile Tectonics "FOLDS"

III.1. Brittle Deformation: Faults

A fault is a macroscopic fracture in the Earth's crust, accompanied by a relative displacement of the separated parts. The displacement can be vertical (normal fault), inclined (oblique fault), or horizontal (strike-slip fault). Minor displacements are sometimes called joints or microfaults if there is no relative movement. On the ground, a fault's existence can be recognized by:

- The abrupt contact of two very different terrains.
- In marls or marl-limestones, they are often poorly visible, but they may be identified by irregular crushing zones. In limestones and sandstones, it is generally easy to identify a fault by the presence of a clear, shiny surface caused by polishing due to friction, accompanied by parallel grooves (striae) indicating the direction of movement. Sometimes, friction breccias may be present on this surface. On geological maps, faults are represented by a dark black line independently of the geological contour lines that delimit the stages**.**

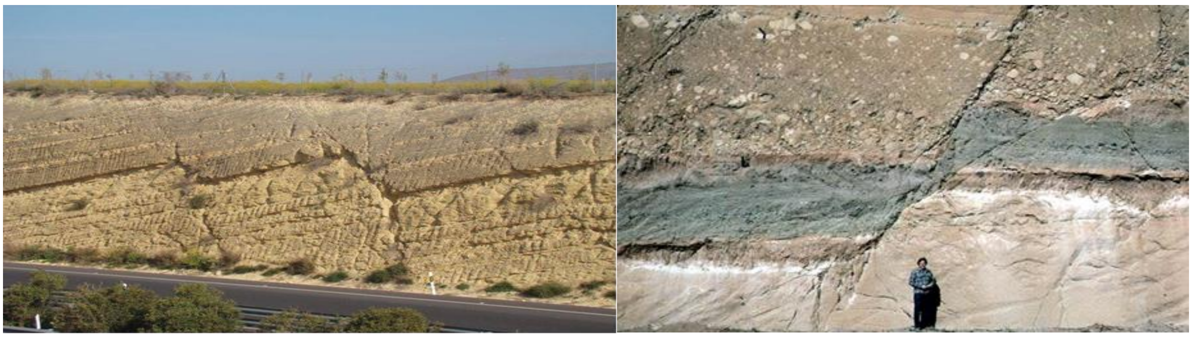


Fig.39: Faulted rocks

III.1.1- Geometry of a Fault:

1. **Fault Plane (Mirror of Fault):** It is defined by the surface on which the two blocks resulting from the terrain rupture slide, defining two separated compartments. It is a surface generated by the break on which usually the striae are seen, which materialize the direction of movement.

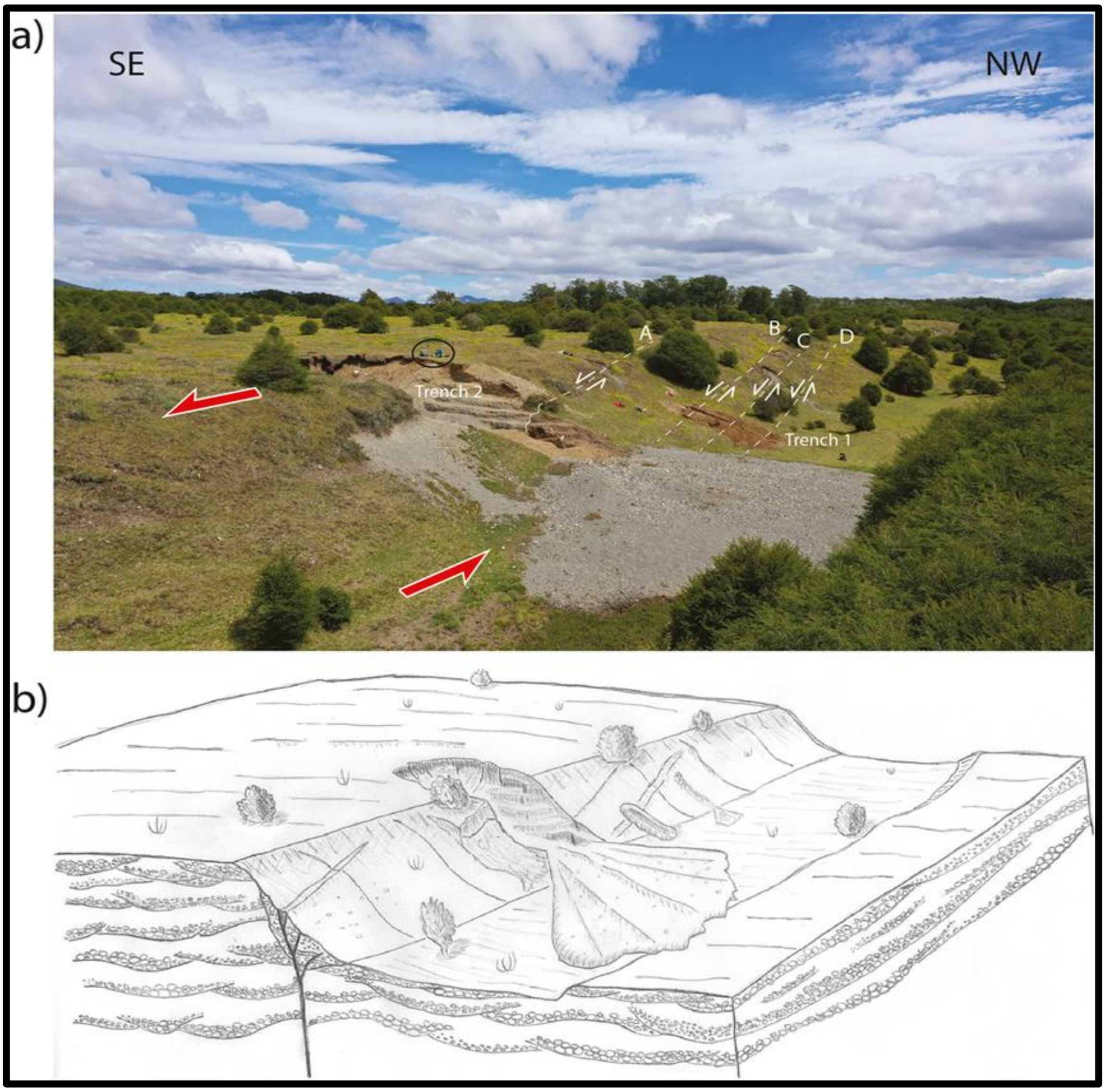


Fig.40: The look of the fault

2. **The Offset:**

- It is the amplitude of the displacement. The offset can be divided into two types:
    - Longitudinal or Direction Offset: measured horizontally.

- Dip Offset (AD): measured on the fault mirror along the line of the major slopes. It decomposes into:
  - Vertical Offset (AE): giving the difference in altitude between the two blocks.
  - Transverse Offset (ED): also called horizontal offset.

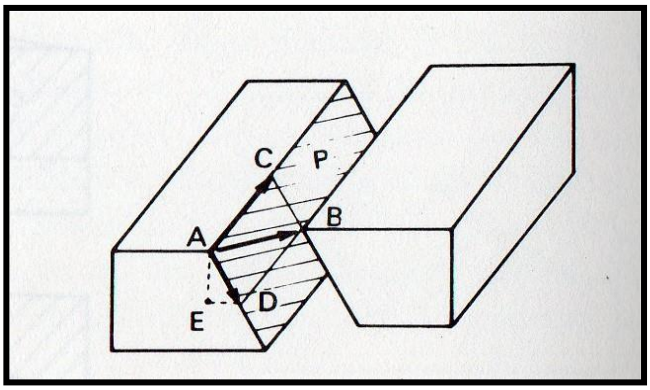
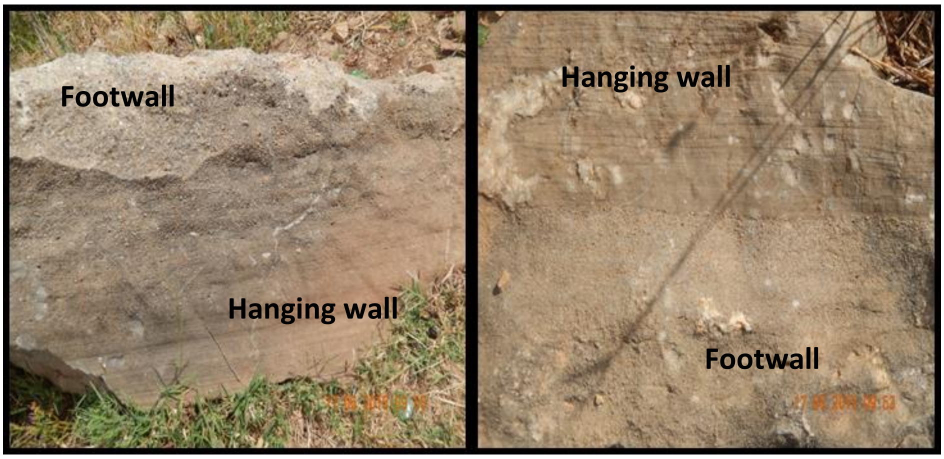


Fig.41: Block diagram showing the different offsets

Fault hanging wall: Compartment located above the fault plane.

Fault footwall: Compartment located below the fault plane.

Fault mirror: Polished fault surface, covered with striations that are roughly parallel.



III.1.2. Different types of faults

Depending on the type of relative movement, three types of faults are defined: normal, reverse, strike-slip (figure below):

III.1.2.1- Normal or extensional fault:

When the fault plane is inclined towards the down-dropped compartment.

In fact, if we were to drill, we would observe that certain layers have disappeared (here, the layer represented by dashed lines).

This is a fault associated with tectonic extensional contexts.

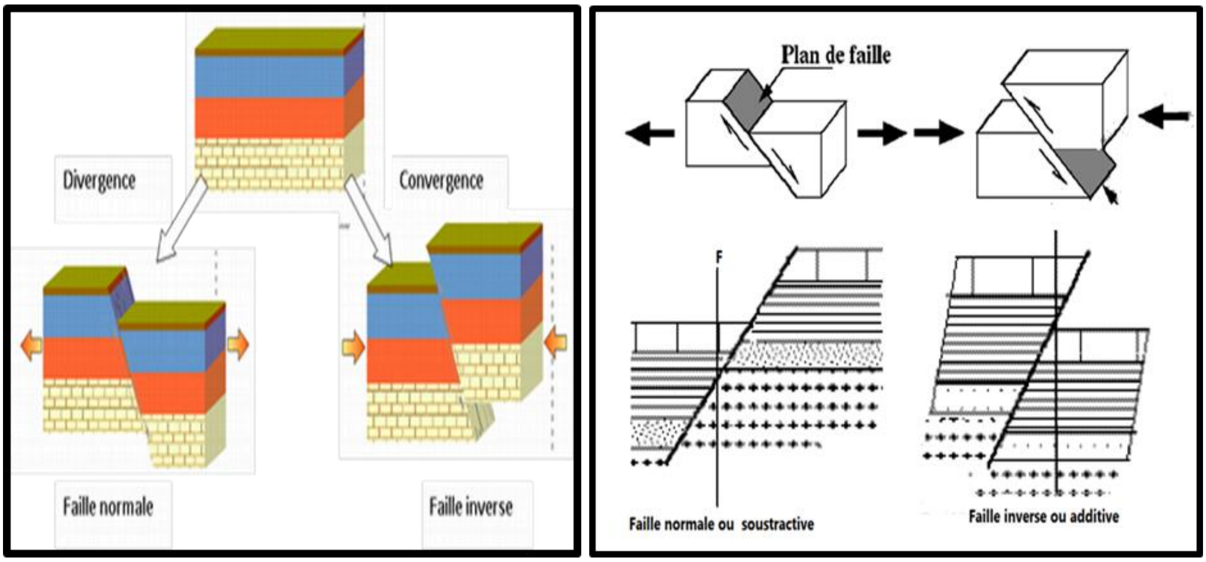


Fig.42: Normal faults and reverse faults

III.1.2.2- Reverse or Thrust (Compressive) Fault:

- The hanging wall is relatively uplifted compared to the footwall.
- The fault plane overhangs the downthrown block.
- It is a fault associated with compressive tectonic regimes**.**
- It is called "thrust" because during drilling, one can intersect the same layer twice.

III.1.2.3- Strike-Slip Fault:

- A strike-slip fault involves horizontal movement of the wall relative to the footwall along a direction parallel to the fault.
- It is a vertical fault with horizontal offset.
- It can be associated with all tectonic contexts (extensional and compressive).
- It is said to be dextral if the movement is to the right and sinistral if the movement is to the left.

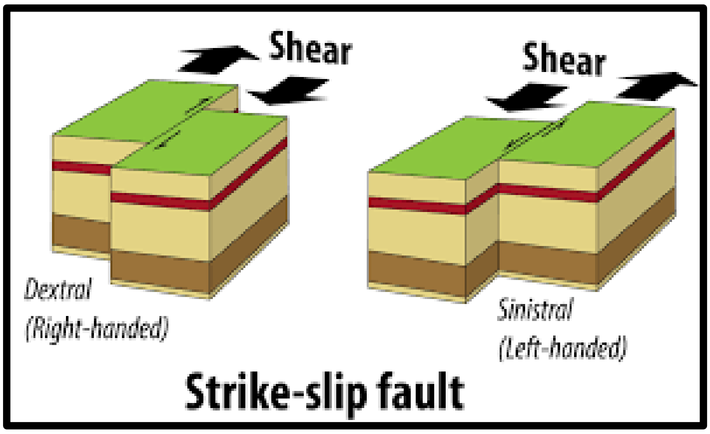


Fig.43: Strike-slip fault

An example of a famous strike-slip fault is the San Andreas Fault in California.

Fig.44: The San Andreas Fault

III.1.3-- Fault Grouping

III.1.3.1- Graben structure or collapse trench:

A tectonic structure formed by normal faults of the same direction, delimiting compartments increasingly lowered towards the middle of the structure.

III.1.3.2- Horst Structure:

A tectonic structure formed by normal faults of the same direction, delineating compartments increasingly lowered as they move away from the middle of the structure.

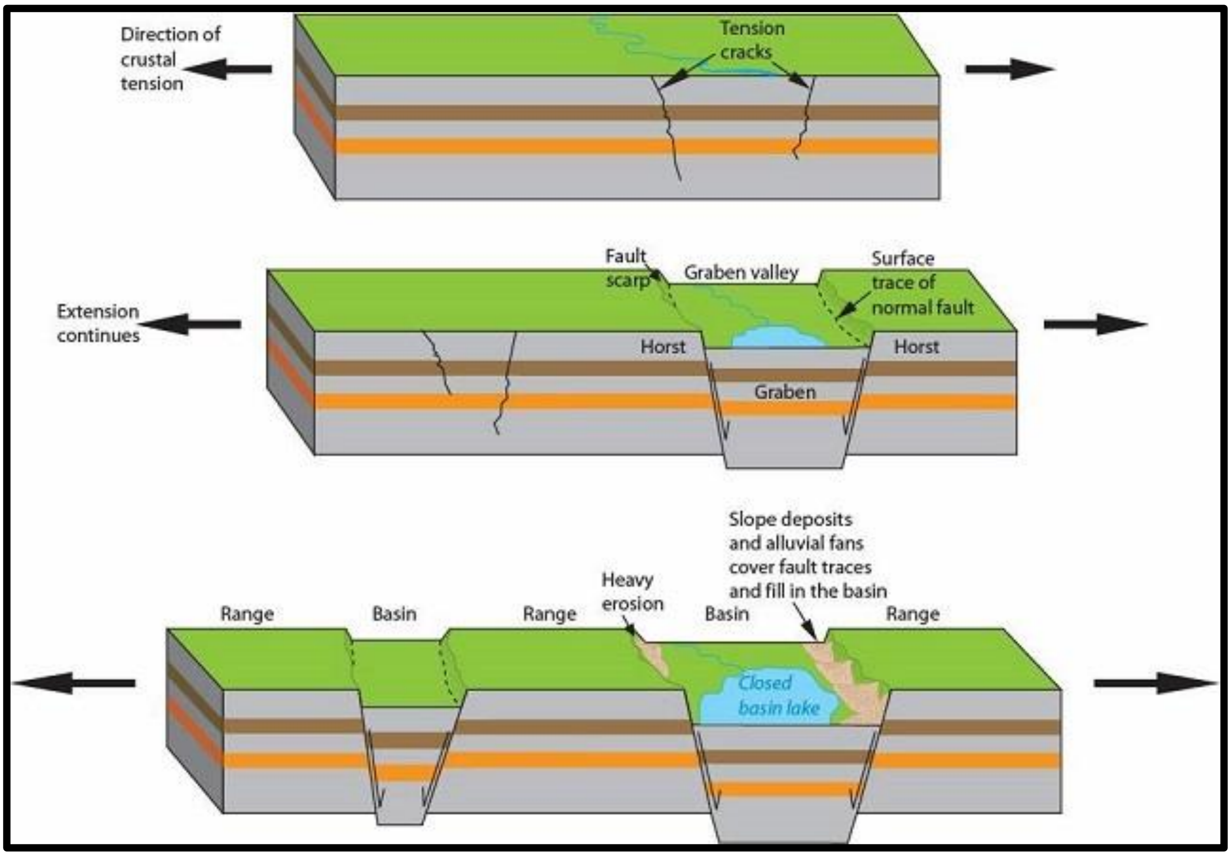


Fig.45: Graben and horst faults

III.2. Ductile Tectonics: Folds

Under the influence of tectonic stresses, sedimentary layers can deform in a more or less plastic manner. Their dips then become variable and directed in various directions; this is called folding.

Folds are undulations that affect the layers of sedimentary terrain, after they were originally horizontal (flat). Often, these undulations are not accompanied by fractures, indicating ductile deformation.

An elementary fold consists of a part convex towards the sky, called an anticline, and a concave part called a syncline, or synform and antiform when the age of the terrains is not known. If the core of a fold is occupied by ancient terrains surrounded on either side in a certain way, it is an anticline; if the center of a fold is occupied by the most recent terrains, we are dealing with a syncline.

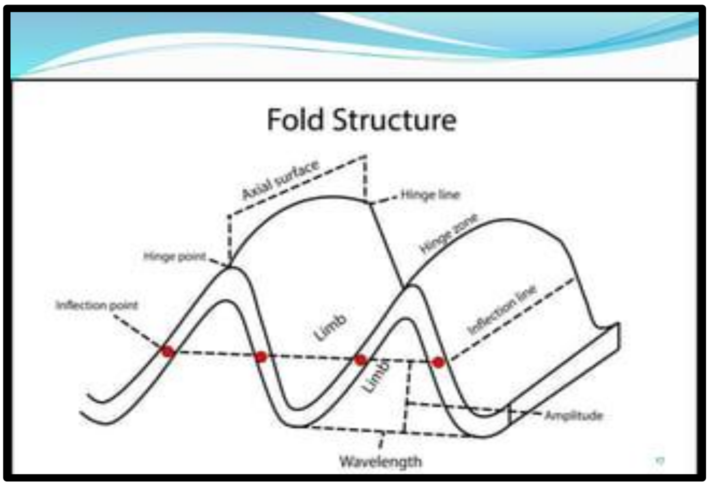
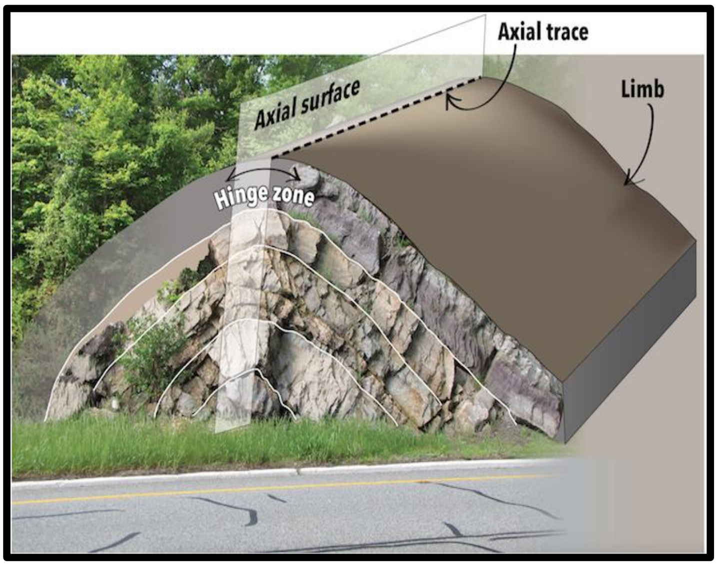


Fig. 46: Elements of a Fold



III.2.1 Elements of a Fold

A fold is defined by various elements:

Crest and trough lines:

The curves that connect the highest points of the reference surface of a fold are called crest lines, and the lines from the lowest points define trough lines.

Hinge:

It is the point of maximum curvature of a fold from which the curvature reverses. In a straight fold, the crest line and the hinge are coincident.

Inflexion point:

These are the points on either side of a fold where the curvature changes sign.

Fold axis:

These are the points of maximum curvature (lines connecting the hinge points).

Axial plane

It is the surface that contains the axes of the folded surfaces in an anticline or syncline.

Flanks of a fold:

These are the parts located on either side of the axial plane, consisting of the layers that connect two successive hinges.

In a fold, we define the normal flank, which limits the layers in normal superposition, and a reverse flank, limiting the overturned layers.

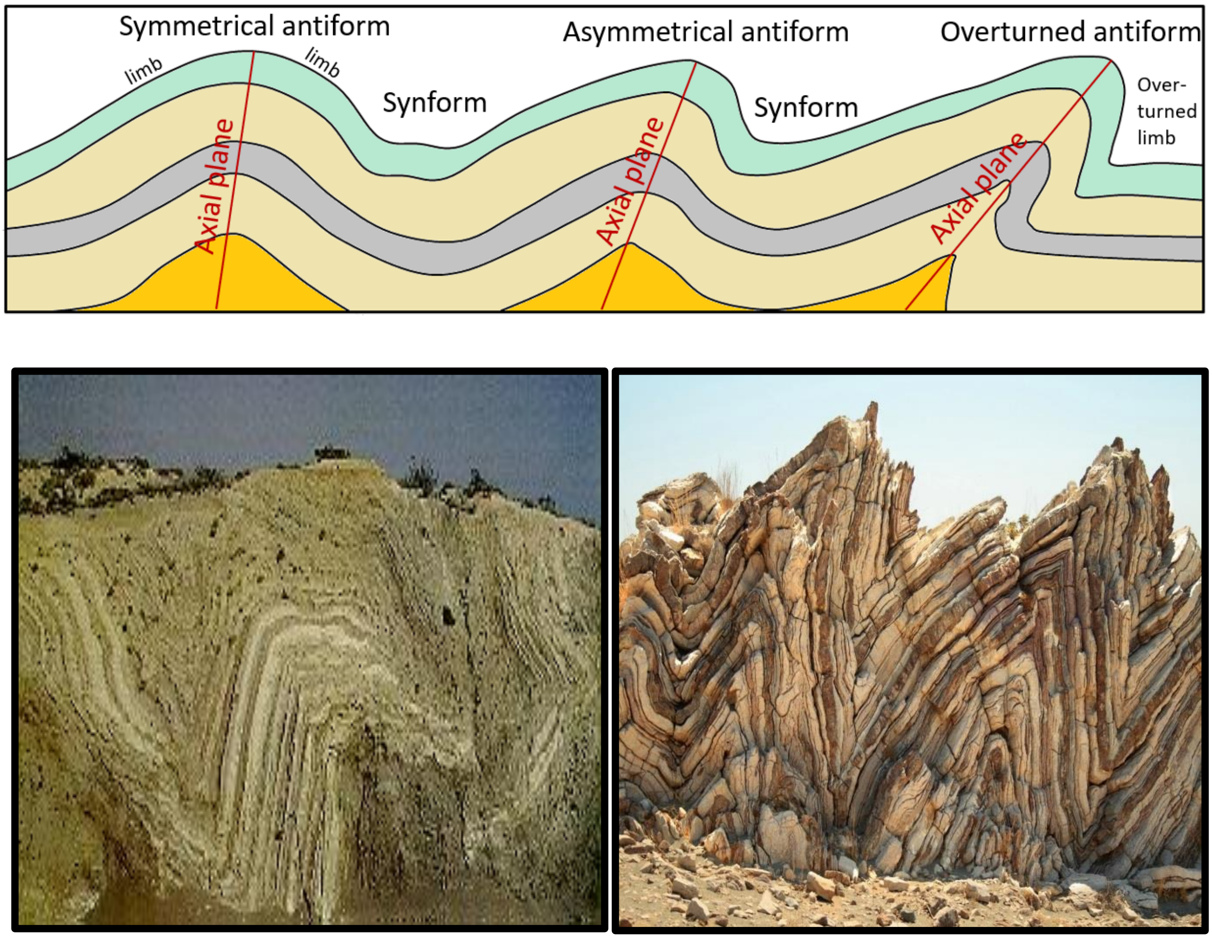


Fig. 47: Elementary Fold Forms

III.2.2 Classification of Folds

Folds can be classified based on two criteria:

- Geometric
- Genetic

III.2.2.1 - Geometric Classification: Folds are defined based on two main geometric elements:

III.2.2.1.1 - Based on the position of the axial plane:

Straight fold or symmetrical fold: the axial surface of the fold corresponds to a vertical plane, both flanks have the same dip, and the hinge and crest are coincident. If the flanks become vertical, the fold is called a vertical fold or box fold.

- ***Asymmetrical Folds*:**

In this type of fold, the limbs have different dips, the axial planes are inclined, and the crest point where the dip becomes zero is distinct from the hinge. As the axial plane inclines, we distinguish:

a- **Overturned Fold:** Both limbs have opposite dips.
b- **Kink Fold:** One of the limbs is vertical.
c- **Recumbent Fold**: Both limbs have dips of the same sense. (The inverse limb exceeds 45°).
d- **Overturned Fold:** It's a fold with limbs having the same dip sense, but the inverse limb has a dip angle less than 45°. An overturned fold with the inverse limb's dip equal to the normal limb's dip is called isoclinal.
e- **Lying Fold:** When the limbs and axial plane become horizontal, we have a lying fold.

III.2.2.1.2- Based on Layer Stretching:

a- **Stretched Fold:** Layers are stretched without breaking.
b- **Laminated Fold:** If the layers of a fold are stretched to the maximum, resulting in partial rupture of some layers, the fold is called laminated.
c- **Faulted Fold:** When layer stretching leads to rupture without flank displacement, the result is a faulted fold.
d- **Thrust Fold:** When the rupture intensifies, one of the limbs moves relative to the other along a surface called an overlap surface. The frontal part corresponds to the anticlinal hinge, and the rear part corresponds to the synclinal hinge. The extent of overlap is the distance separating the front and root of a displaced layer.

- **An isopachous** fold: a fold where the thicknesses of sedimentary layers are constant regardless of the local layer orientation.

- **An anisopachous** fold: a fold where the thickness of the layers varies.

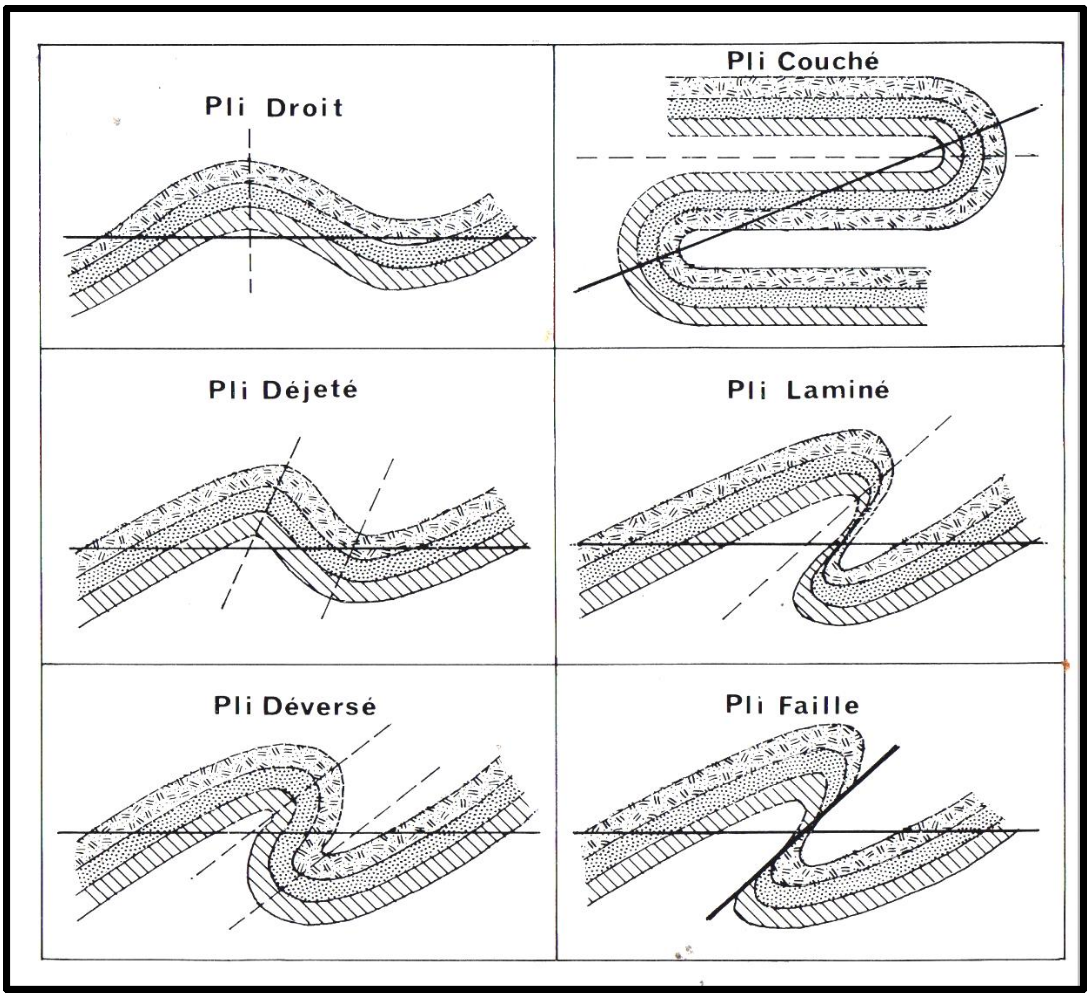


Fig. 48: Classification of Folds

III.2.2.2 - Genetic Classification:

We can define:

III.2.2.2.1 - Concentric or isopachous or parallel folds:

The layers retain their thickness and radii of curvature.

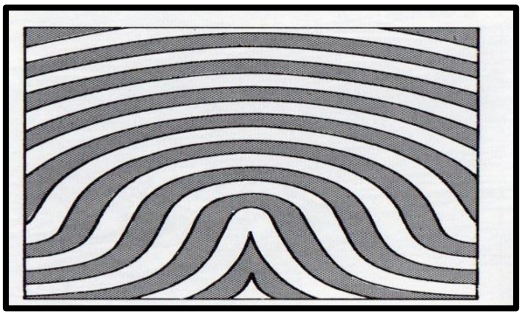


Fig. 49: Concentric Folds

III.2.2.2.2- Similar Folds:

These are folds where the folded layers are identical to each other; they are derived from one another by simple parallel translation along the axial plane. The thickness of the layers is not conserved.

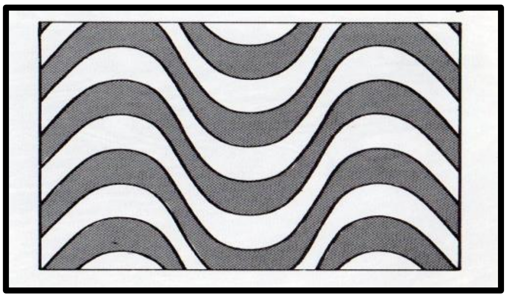


Fig. 50: Similar Folds

III.2.2.2.3- Cylindrical Folds:

The folded surface remains parallel to the fold axis up to a certain distance.

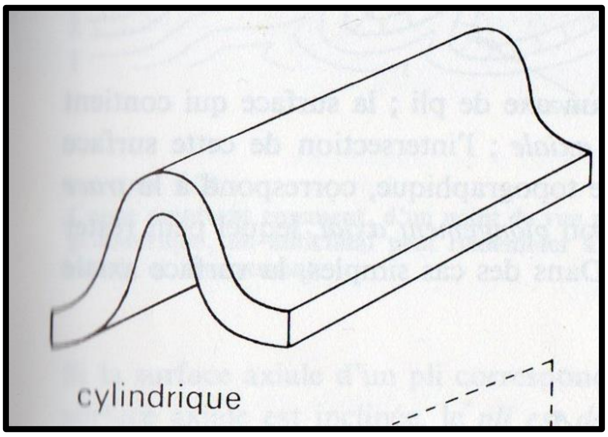


Fig. 51: Cylindrical Folds

III.2.2.2.4- Disharmonies:

In concentric folds, it is a differential folding from one layer to another, facilitated by sliding along the bedding planes

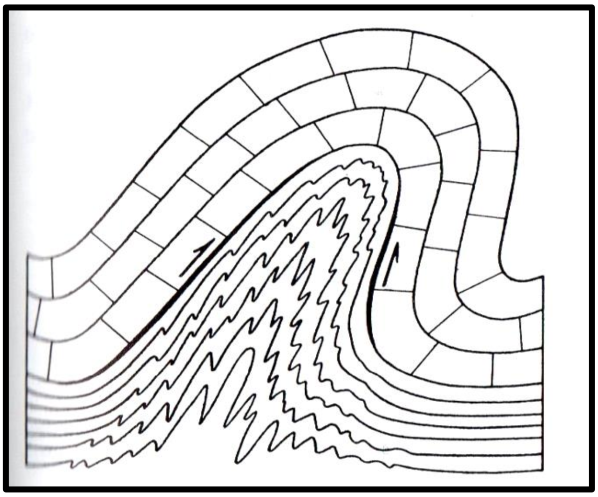


Fig.52: Disharmonies

III.3- Overthrusts and Nappe Tectonics

II.3.1 Overthrusts:

Overthrusts are tectonic features whereby the abnormal superposition of geological units occurs. The dip of these features is generally moderate (45°) to steep. The continuity of the upper unit, called the overlying unit, is preserved; the leading edge is always visible, with the overlap not exceeding a few kilometers.

- They are flat reverse faults, with significant displacement (often reaching tens of kilometers).
- These compressive faults result in crustal thickening and shortening.
- It involves the vertical stacking of two sets of terrains with a non-normal succession. In the case of sedimentary rocks, this means a sequence that does not conform to the laws of stratigraphy, such as when the upper series is composed of older rocks than the lower series. For crystalline rocks, diagnosing this is more challenging since defining the normal succession of these types of rocks is more delicate and often depends on hypotheses about their origin. This stacking corresponds to the concepts of "abnormal contact" and "overlap."
- When the abnormal contact separating the two units is sub-horizontal, and the overlap reaches kilometer-scale values, the term "thrust" is used (the autochthonous and allochthonous units belong to different paleogeographic domains).

- In continental collision, the overriding plate can advance several hundred kilometers over the overridden plate, pushing crustal fragments: these are thrust sheets (a thrust sheet is a set of geological layers that, during an orogeny, detached from the bedrock and moved over long distances. These are referred to as allochthonous terrains in contrast to autochthonous terrains)

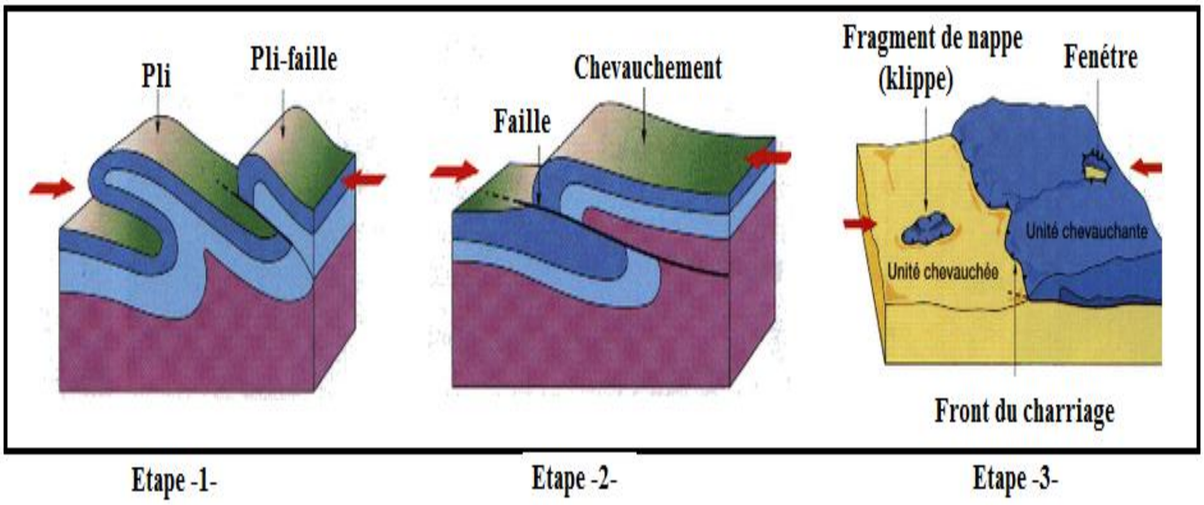


Fig.53: Stages of Overthrusts and Thrust Sheets

Overthrusts can separate sheets, potentially uprooted from their source, and then bring a transported, allochthonous terrain into contact with an autochthonous one.

- The most advanced part forms the leading edge of the sheet (it corresponds to the direction of relative movement of the sheet. It's the furthest point reached by the sheet, also known as the erosion front). The rest constitutes its body.

- Erosion, by clearing the frontal part, can leave a klippe (a piece of the sheet isolated from the rest by erosion is called a klippe. The term "island" has also been used in French, dating back to a time when the nature of thrust sheets was not understood, and it was thought that these thrust fragments came from islands surrounded by shallow seas).

- In front of the sheet, erosion can also clear or dig out a portion of the sheet and open a window into it (an eroded area of the sheet that allows viewing of the underlying autochthonous terrains)

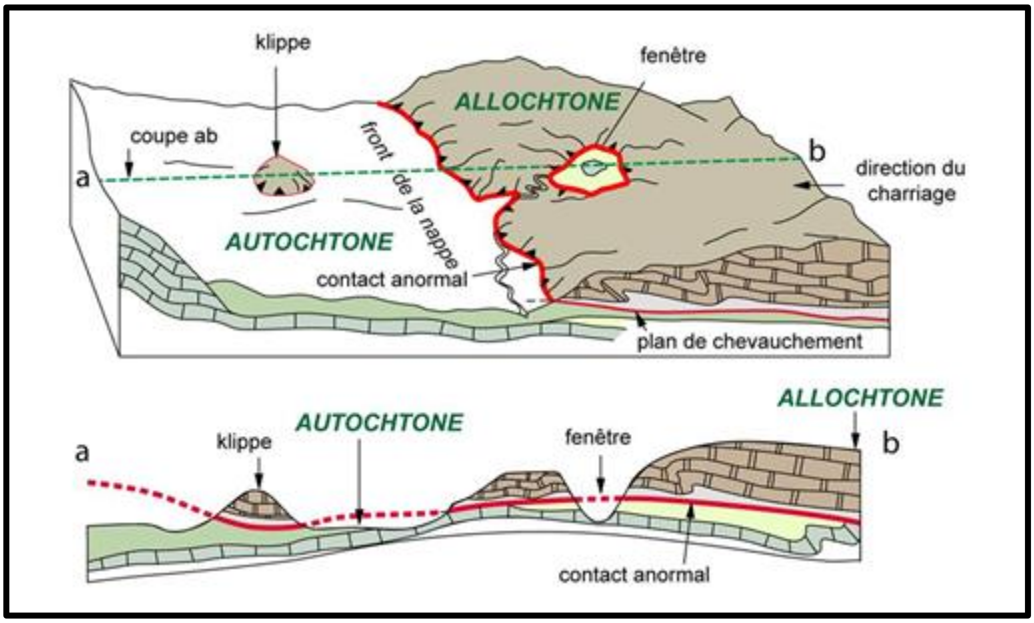


Fig.54: Thrust Sheets

III.3.2- Types of Thrust Sheets

Overthrusts can separate sheets, potentially uprooted from their source, and then bring a transported, allochthonous terrain into contact with an autochthonous one.

- The most advanced part forms the leading edge of the sheet (it corresponds to the direction of relative movement of the sheet. It's the furthest point reached by the sheet, also known as the erosion front). The rest constitutes its body.
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- In front of the sheet, erosion can also clear or dig out a portion of the sheet and open a window into it (an eroded area of the sheet that allows viewing of the underlying autochthonous terrains)

III.3.3 Formation of Mountain Chains

he question that has long puzzled geologists is the formation of large mountain ranges, such as the Alps, the Himalayas, or the Appalachians.

1. Sedimentary rocks are abundant in mountain ranges and contain fossils of marine organisms, implying that the sediments from which they are derived were deposited in a marine environment; furthermore, their composition indicates that much of these sediments were deposited in an oceanic basin.

First conclusion: Before ending up in a mountain range, all sedimentary material was located in an ocean.

2. There are also metamorphic rocks in mountain ranges, which are former sedimentary or igneous rocks transformed by very high temperatures and pressures. It's important to note that the location in the Earth's crust where both very high temperatures and pressures exist is deep underground, at least a few kilometers below the surface.

Second conclusion: Metamorphic rocks result from the transformation of sedimentary and igneous rocks in the mountain range, deep within the Earth's crust.

3. Another significant attribute of mountain ranges is that they often contain fragments of oceanic crust (basalts) wedged into faults.

Third conclusion: Not only were the sediments that form the mountain range deposited in a marine basin, but also on the basaltic oceanic crust.

4. Geologists studying the geometry of deformation in mountain ranges have long known that lateral compressive forces are needed to produce such geometry. They needed to find a mechanism responsible for these compressions. They also needed to find a mechanism responsible for the uplift of all the material deposited in an oceanic basin that makes up the range.

III.4. Continental Margins

he continental margin is the underwater area located at the edge of continents where the majority of sediments eroded from the continent are transported. It consists of the continental shelf, the continental slope, and the continental rise. This zone is situated beneath the sea along the edge of a continent and transitions to the ocean floor. There are two main types of continental margins: passive margins, which are stable, where the transition between the granitic continental crust and the basaltic oceanic crust occurs within the same lithospheric plate; and active or unstable margins, where the oceanic crust subducts beneath the continental crust at a subduction zone.

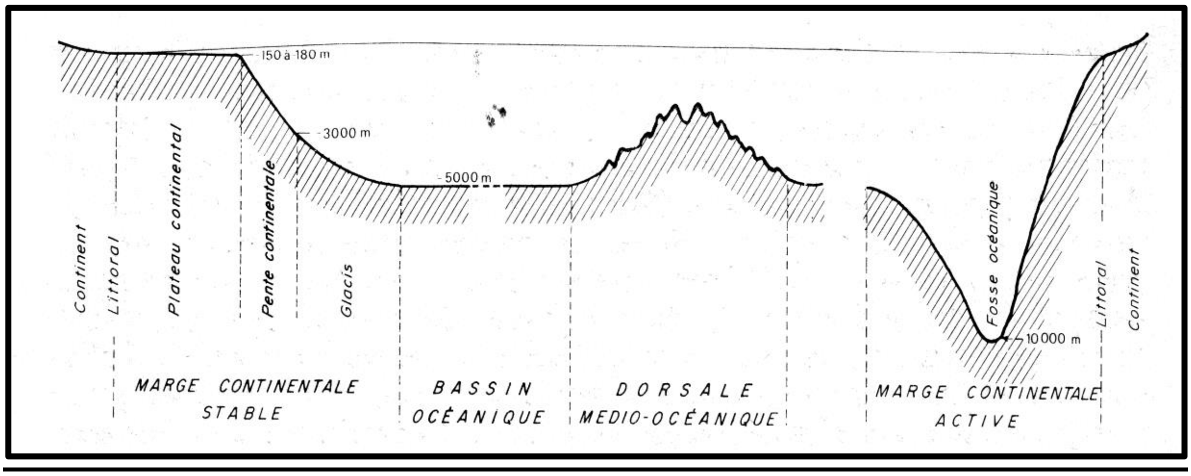


Fig.55: Continental Margins

III.4.1- Passive or Stable Margins:

This is the transition zone between a continental mass and the oceanic crust that forms within the same lithospheric plate, characterized by the absence of volcanic or seismic activity, where the crust thins. It is caused by tensional stresses perpendicular to the rift axis.

At a certain phase of rifting, it leads to the rupture of the lithosphere and oceanic accretion. The final result is the creation of two conjugate, passive continental margins structured by normal faults, and are the site of significant sedimentation.

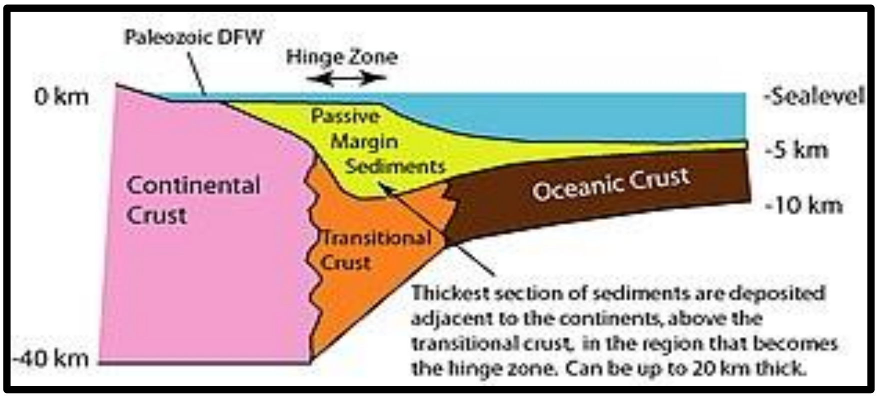


Fig. 56: The Passive Margin

III.4.2 - Active Margins:

An active margin corresponds to the boundary between oceanic crust and continental crust where subduction occurs. At this point, oceanic lithosphere dives beneath another oceanic or continental lithosphere and disappears into the mantle.

These margins are located vertically above a subduction zone and thus exhibit seismic and volcanic activity expressed by a volcanic arc. The boundary between two converging plates is marked by a deep trench that borders the margin on the oceanic side. This is where the greatest depths are reached (11 km in the Mariana Trench). Often, the bottom of the trench is flat due to partial filling by loose sediments. The slope on the oceanic side is gently inclined (from 2 to 50 degrees) and corresponds to the back of the subducting plate bulging before plunging into the asthenosphere. The other slope, belonging to the margin, generally has a steeper inclination (from 10 to 20 degrees).

According to their geographical location, active margins can be classified into two categories:

- Some form the edge of a large continent, such as South America on the Pacific Ocean side; these are cordillera-type active margins.

Others form island arcs, such as Japan, Indonesia, the Caribbean, or the Aleutian Islands; in this case, the curvature of the island arc indicates the polarity of the margin: the trench and the boundary with the subducting plate are on the convex side, while on the concave side, there extends a basin, often wide and deep, called a back-arc basin or marginal basin. In fact, the morphology of active margins directly depends on the geodynamic phenomena associated with subduction, particularly tectonic accretion and volcanism.

The following diagrams illustrate the major stages of mountain chain formation:

A- Let's start with what is called a passive continental margin, such as the current Atlantic margin, where a sediment prism accumulates on the continental shelf and margin from erosion of the continent.

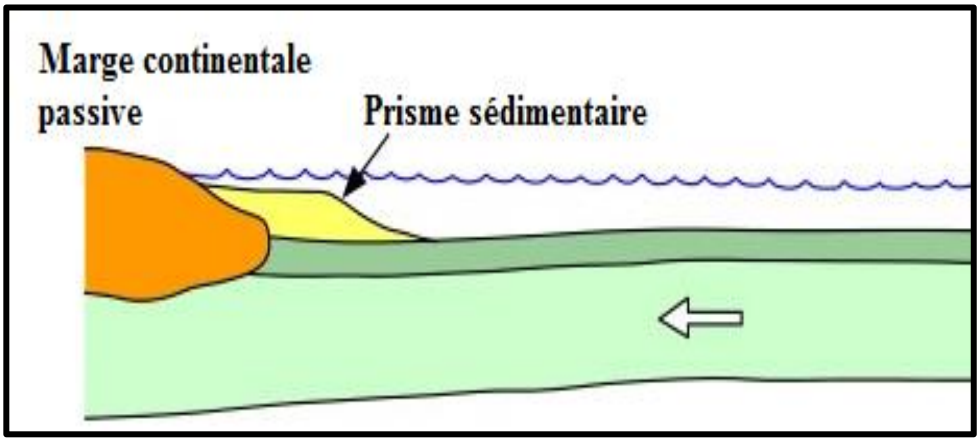


Fig.57:

B- As the lithosphere moves further away from the divergence zone, it becomes denser because it cools down progressively. There comes a point where, under the push of the conveyor belt and the increase in density, this lithosphere fractures, and one of the edges sinks beneath the other, creating a subduction zone.

- The movement transforms into a collision system between two plates (diagram below), a continental plate and an oceanic plate.
- We transitioned from a passive margin situation to an active continental margin situation. Off the coast, an island volcanic arc forms (Figure below).

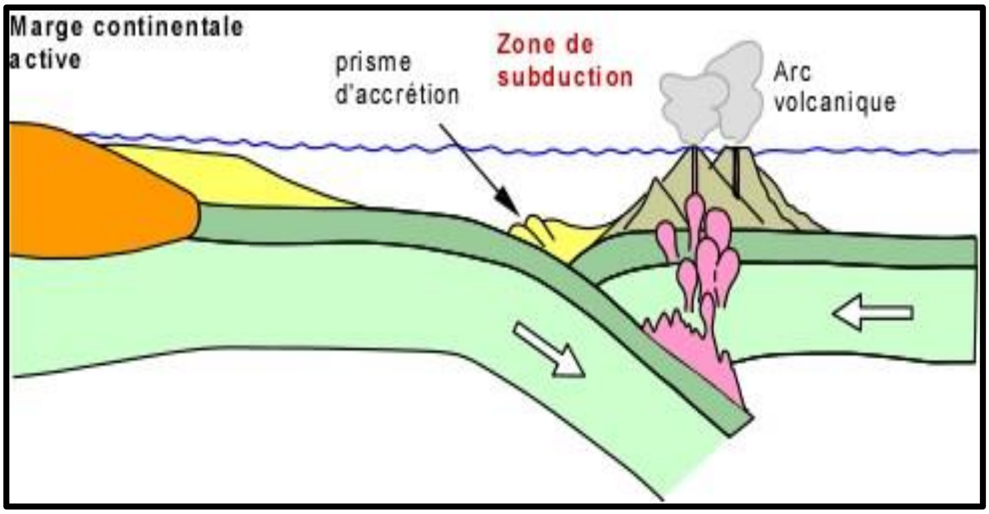


Fig.58

The progressive overlap of the oceanic plate onto what remains of the oceanic plate on the continental side concentrates material found on the ocean floor to form an accretionary prism that grows as the closure between the volcanic arc and the continent progresses.

C- The subduction zone transforms into an obduction zone: the collision between the volcanic arc and the continent creates significant overlap of all material from the accretionary prism onto the continental margin. Igneous activity ceases, and large masses of igneous rocks (in red) may remain trapped in the lithosphere.

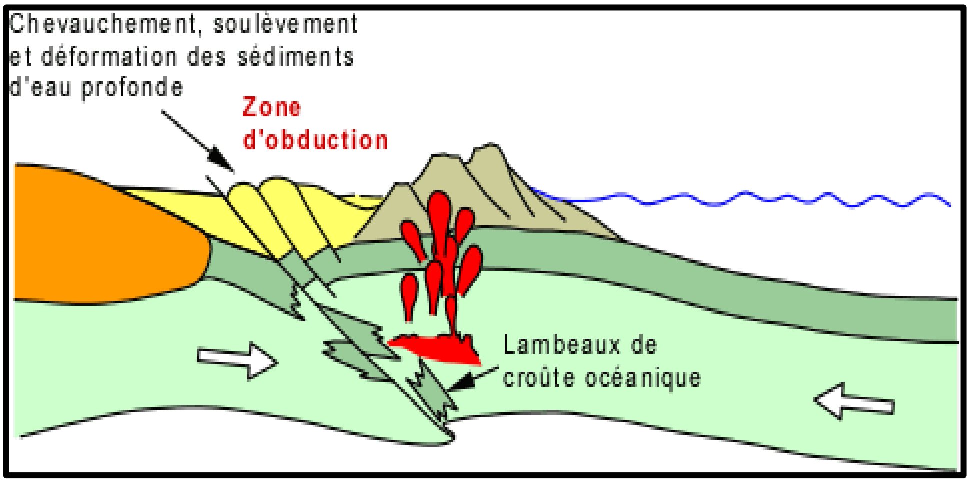
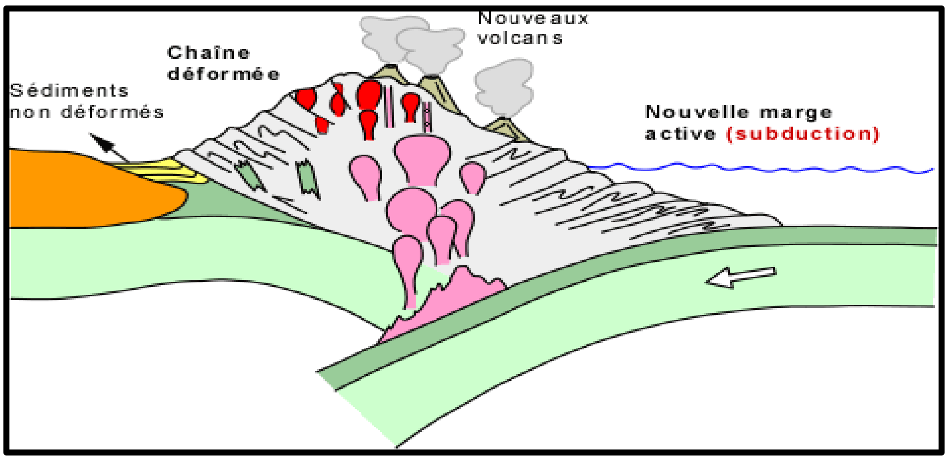


Fig.59

D- Eventually, the continued movement concentrates even more material and forms a deformed chain termed an immature mountain chain, indicating that the dynamics are not yet complete. The margin of this immature chain may transform into a new active zone (subduction), allowing the collision to continue and establishing continental arc volcanism on the new chain (figure below).



Un excellent exemple de cette dernière situation est la Cordillère des Andes, résultant de la collision entre la plaque océanique de Nazca et la partie continentale de la plaque sud-américaine.

Cependant, la véritable chaîne de montagnes mature est celle formée par la collision entre deux plaques continentales (figures ci-dessous). Dans cette configuration, à mesure que l'étau formé par l'approche des deux plaques se resserre, un prisme d'accrétion se construit progressivement. Ce prisme d'accrétion croît à mesure que le matériel se concentre dans un espace de plus en plus restreint, élevant ainsi la chaîne de montagnes progressivement.

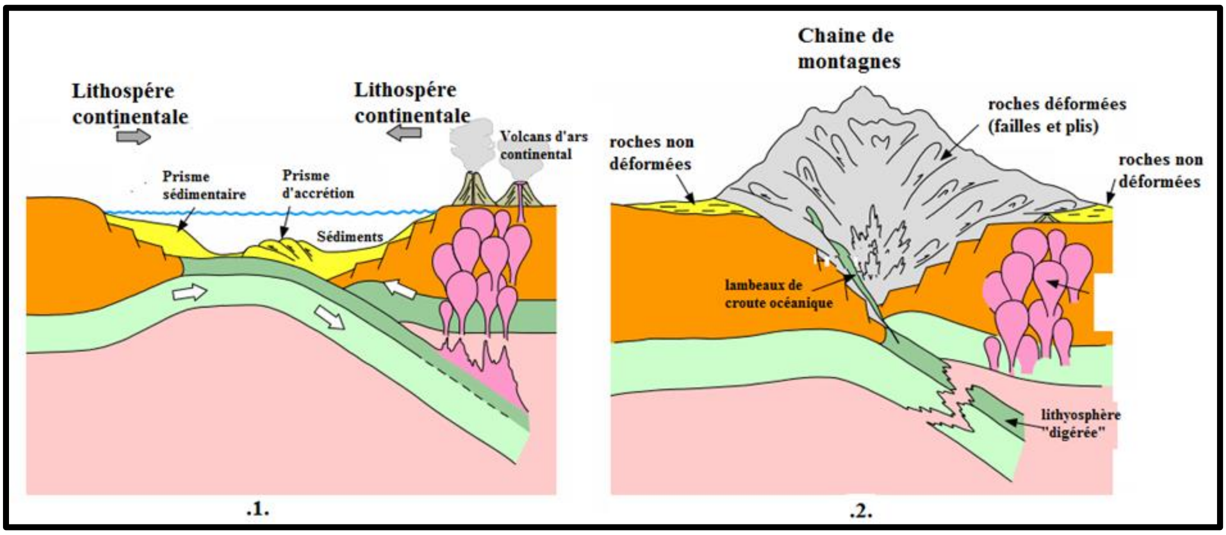


Fig. 61:

With the collision of the two plates and the cessation of movement, the mountain range has reached its maximum height and acquired its characteristics.

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