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FACULTE OF NATURAL AND LIFE SCIENCE, EARTH AND UNIVERSE SCIENCE
DEPARTEMENT OF ECOLOGY AND ENVIRONMENT
LFILIERE OF BIOLOGY
SPECIALIZATION OF ECOLOGY AND ENVIRONMENT

Geomorphology Course

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Course designed for
Third-year students in ecology and environment in life Science

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Geomorphology Course

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Summary

This module explores the fundamentals of geomorphology, highlighting the relationships between landform features and internal processes (tectonics, isostasy) as well as external processes (erosion, climate). It addresses the Earth's structure, the influence of lithology, tectonic deformations, and the formation of landforms. Erosion processes (areal, linear, aeolian, periglacial) and specific models (karstic, desert) are analyzed, with a focus on anthropogenic impacts. Finally, it examines morphological systems in various climatic contexts (humid, arid, desert) and emphasizes the ecological importance of these geomorphological dynamics.

Preface

This geomorphology module, designed for third-year undergraduate students, aims to introduce you to the study of Earth's landforms and the dynamic processes shaping them. By exploring internal forces (tectonics, volcanism) and external forces (erosion, sedimentation), it will help you understand the complex interactions that mold landscapes and influence environmental dynamics. This course also emphasizes the impact of these processes on ecosystems, human activities, and the management of natural hazards (landslides, floods, coastal erosion).The creation of this course material would not have been possible without the valuable contributions of experts whose knowledge and experiences greatly enrich this pedagogical resource. We wish to extend our deep gratitude to [insert names or institutions of experts] for their collaboration and scientific support in preparing this content. We hope this module serves as a solid foundation for your study of Earth sciences while sparking your curiosity and critical thinking about contemporary geomorphological challenges. We encourage you to fully engage with the course, ask questions, and deepen your understanding of Earth's dynamics.

Happy reading and learning!

The teaching team.

Table of Contents:

Introduction

Geomorphology (from the Greek gê = earth, morphê = form, logos = study) is a branch of physical geography that studies the form and structure of the Earth's surface as well as the processes that have shaped them over time. It plays a crucial role in land use planning, landscape design, as well as in the prevention of natural hazards and the exploration of natural resources.

The purpose of this study is to provide a descriptive and analytically explanatory account of the relief forms and a synthetic understanding of the constituents of each set. Two domains share the scientific field of geomorphology:

a) **Structural geomorphology** concerns the influence of structure (lithology, tectonics) on relief at different scales, from plate tectonics to elementary structural forms (surfaces, escarpments).
b) **Dynamic geomorphology** is the study that contributes to the formation and evolution of relief forms (erosion, weathering, transportation, and deposition) that modify formations (coastlines, hydrographic networks) based on current climate or legacies of past climates.Geomorphology is therefore a discipline that analyzes one component of the natural environment, in close relation to other disciplines of physical geography and earth sciences (geology) (Dylik , 1957).

Chapter I: Generalities

1. **Relief** is the set of irregularities observed on the Earth's surface, measured in relation to sea level. Generally, two types of relief are distinguished: continental relief and ocean relief.
   1.1. **Continental relief (or continental landforms)** occupies 29% of the Earth's surface.

It can be broken down into five different types (or morphologies): valleys (or depressions), plains, plateaus, hills, and mountain ranges. Continental relief depends on the nature of rocks, changes in their structure (folding, faults), and erosion (degradation by water, wind, or frost) (Coque, 1977 ;Viers, 2003).

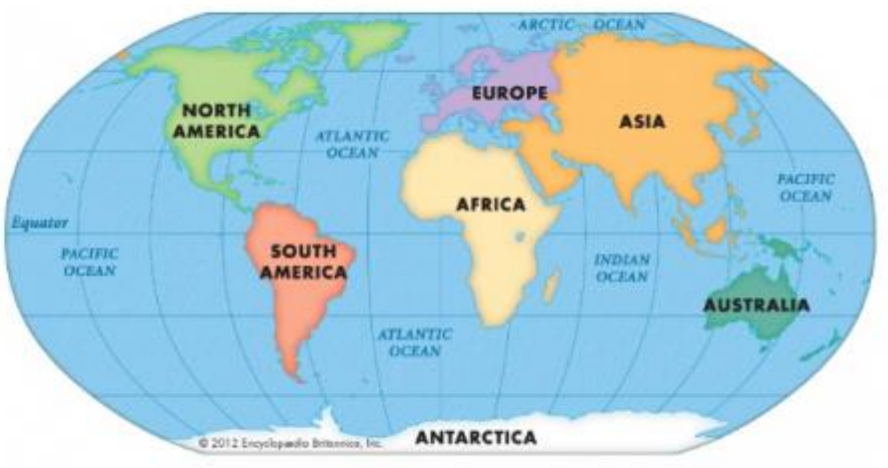


Figure 1: Distribution of Continents and Oceans

1.1.1. Different types of continental reliefs

a). A plain is an extensive, flat, or slightly undulating surface over which rivers flow without being entrenched. The elevations are low, and the slopes are slight (Jouty, et Odier, 2009).

Figure 2: A plain in misissibi

b). A plateau is also an extensive, flat, or slightly undulating surface; however, unlike a plain, rivers flow through it by entrenching themselves. Plains and plateaus differ not in altitude but in the entrenchment of rivers (Coque. 1977 ; Viers, 2003; Jouty, et Odier, 2009).

Figure 3: Several plateaus in Kenya

c). Mountains are elevated and extensive regions with significant variations in elevation, steep slopes, high ridges, and deep valleys. A mountain is characterized by its altitude, aeration (width and depth of valleys), the orientation of its ridges, and the arrangement of its hydrographic network (Coque. 1977; Jouty, et Odier, 2009).

Photos 1: Mont Babor Sétif, Algeria.

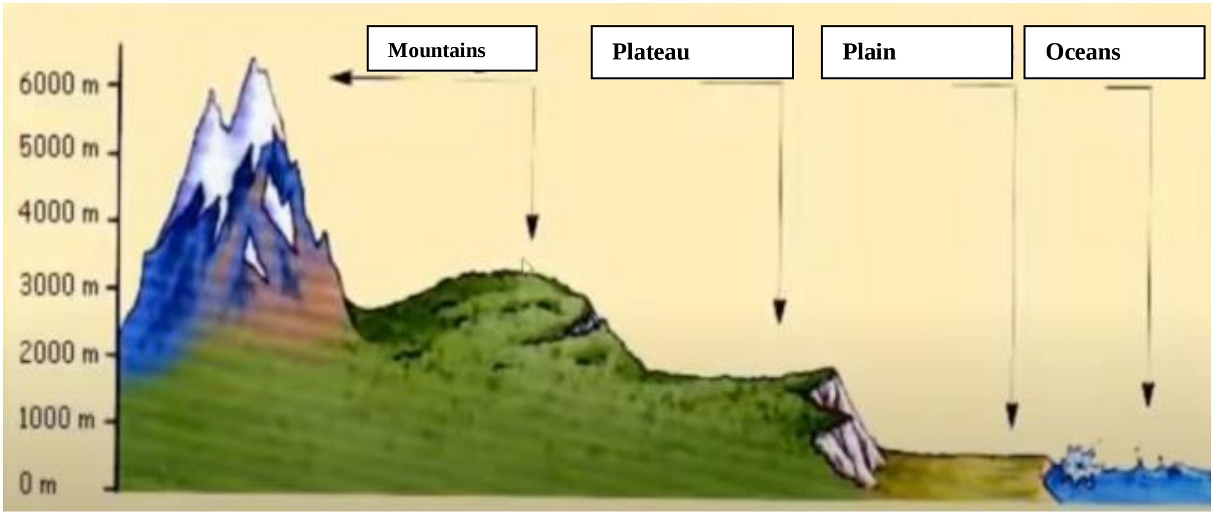


Figure 4: Recapitulation of a topographic profile of types of continental reliefs

1.2.Ocean Relief: (or submarine relief) represents 71% of the Earth's surface. Submarine relief is divided into three zones: continental shelves located just off the continents, ocean basins in the open sea, and deep oceanic trenches that form the abyssal zone (Coque. 1977 ;Viers, 2003; Jouty, Odier, 2009).

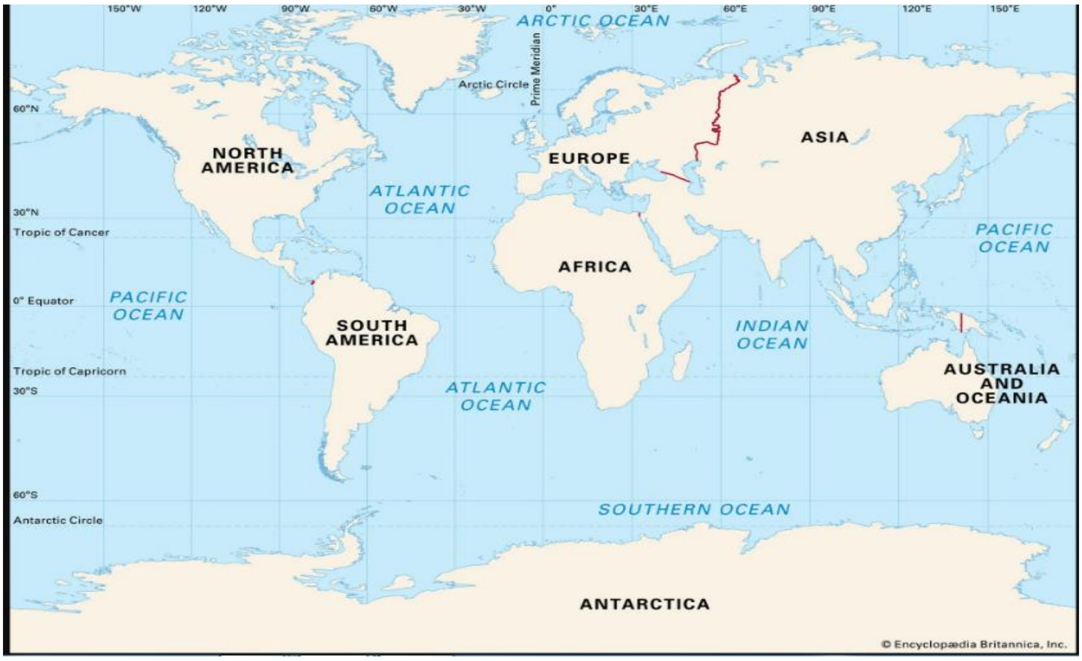


Figure 5: Distribution of Oceans (source: encyclopedia Britanica.inc)

1.2.1- Different Types of Submarine Reliefs

Submarine reliefs exhibit a variety of forms and are associated with different geological and geographical features. Here are some types of submarine reliefs:

a) **Continental Margin:**
- **Continental Shelf:** A shallow zone that extends from the shore to the outer edge called the outer limit of the continental shelf. It is an area rich in marine life.
- **Continental Slope:** The steep slope that marks the transition between the continental shelf and the continental rise.
- **Continental Rise:** A gentle slope descending from the continental slope towards the abyssal plains.

b) **Oceanic Basin:**
- **Abyssal Plain:** A vast expanse of flat seafloor often covered with sediments. Abyssal plains are found in ocean basins and are among the deepest regions of the oceans**.**

c) **Ocean Ridge:**

A geological formation characterized by a high ridge at the center where oceanic lithosphere is created through volcanic activity. It is the location where tectonic plates move apart, allowing magma to rise and form new oceanic crust.

Ocean ridges are often associated with phenomena such as tectonic plate divergence, the creation of new oceanic plates, and may be accompanied by transform faults (Viers, 2003).

2. **The relationship between geomorphology and ecology** is significant, as the relief play a crucial role in the distribution of living organisms. Geomorphology is a vital aspect of landscape ecology, as the forms and structures of the landscape have a determining impact on flora, fauna, and their functions within ecosystems. This is especially true for biological corridors and specific features such as islands, lakes, rivers, mountain passes, straits, and basins. These features naturally control the flow of genes, species, and populations. Continental masses also play a crucial role in climate change,

where the relief can alter temperature, wind patterns, and surface water temperature. These changes in climate, in turn, influence sedimentary deposits, flora, fauna, and the distribution of plants and their ecology, contributing to biodiversity modifications (Coque. 1977).

2.1. Geomorphological tools have significantly benefited from technological advancement, enabling a more detailed interpretation of landscapes and their evolution. In regions with challenging conditions such as mountains, extensive vegetation cover, or intense urbanization, field data collection becomes particularly difficult, necessitating the use of specific techniques and methods. Geomorphological mapping serves as a comprehensive summary of information regarding the geometry, arrangement, and forms of the landscape. It includes details about the nature and structure of surface formations, the processes involved (including their duration and formation rates), and the age of landscape features. Geodetic methods, such as GPS, are instrumental in cartographic localization and the measurement of specific points (Coque. 1977; Viers, 2003).

3. Elementary forms of relief

Valley: A more or less enclosed groove at the bottom through which a watercourse (thalweg) flows, including valley slopes (narrow space between two or more mountains).

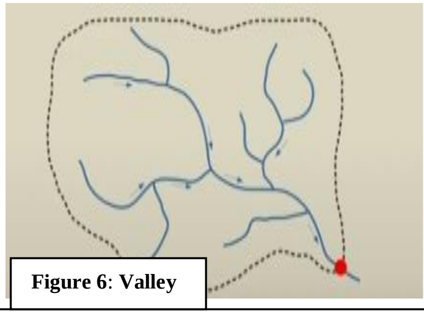


Figure 6: **Valley**

Talweg: Composed of Tal ("valley") and Weg ("path"). It is the line connecting the lowest points of a valley (e.g., a watercourse). This is where water flows and where streams and torrents flow.

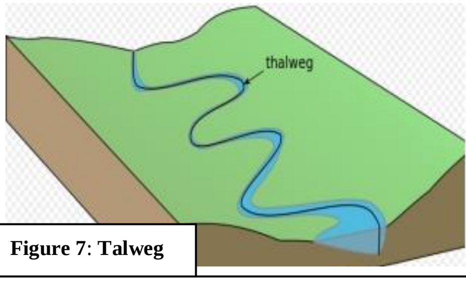


Figure 7: **Talweg**

Interfluve: The area located between two watercourses.

-Regions separating the valleys, mostly overland flow, no clear drainage pattern established, Nested hierarchy of drainage basins.

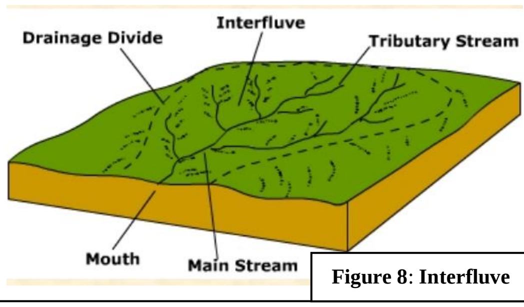


Figure 8: **Interfluve**

Slope: Inclined topographic surface located between high points and low points (talweg), which receives and collects rainwater and drains it towards a single point called an outlet.

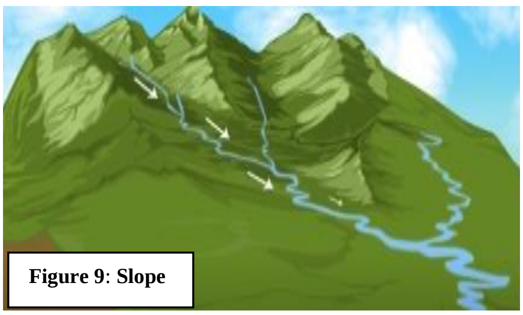
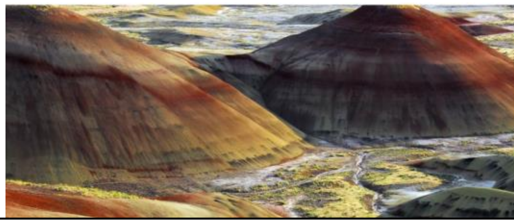


Figure 9: **Slope**

Hill: A rounded form with moderate elevation, with an altitude not exceeding 600 meters. When it is a small isolated hill, it is referred to as a hillock.



photos 2: Different rock strata are visible in the Painted Hills, in the U.S. state of Oregon (PHOTOGRAPH BY MICHEL HERSEN, MYSHOT)

Butte: A small isolated hill with a flat top and a more asymmetric slope (Viers, 2003).

Chapter 2: The Structure

2. Definition of Structure

Structures are an important indicator of sediment transport and deposition conditions. Some structures are characteristic of a particular environment (glacial, desert, etc.), but most are common to several deposition environments for the interpretation of paleoenvironments.

- **Pre-sedimentary structures** are observed on the upper surface of beds and are most often related to erosion processes. For example, traces of objects sliding on the bottom. Many of these structures provide indications of the direction and flow of currents.
- **Syn-sedimentary structures** form during the deposition of sediments and provide information about the speed, nature, and direction of transporting agents. A good example is cross-bedding.
- **Post-sedimentary structures** develop within the sediment after its deposition. This includes hydrostatic rearrangements, structures resulting from lateral movements of sediment masses, and processes related to the physico-chemical modification of sediments under surface pressure and temperature conditions.

Finally, it should be noted that certain sedimentary structures, in folded sequences, help determine the polarity of the layers (Viers, 2003).

1.2.General Structure of the Globe

The three major concentric units and discontinuities form a model of a layered structure with increasing density from the periphery to the center and differing chemical composition:

A). Earth's Crust: Primarily composed of silico-aluminous (SIAl) materials, the Earth's crust is the outermost layer. It includes two types: the thicker continental crust, mainly composed of granite, and the thinner oceanic crust, made up of basalt.

B). Mantle: Located beneath the crust, the mantle is primarily composed of ferro-magnesian silicates. It constitutes a significant portion of the Earth's volume and features convection currents that play a crucial role in geological processes.

C). Core: Situated at the center, the Earth's core is primarily composed of iron and nickel (NiFe). It consists of the outer core, partially liquid, and the inner core, solid. The core generates the Earth's magnetic field through movements in its outer core.

This layered structure with distinct compositions provides insights into the Earth's internal dynamics and the geological phenomena associated with it (Aubouin, et *al.*, 1968).

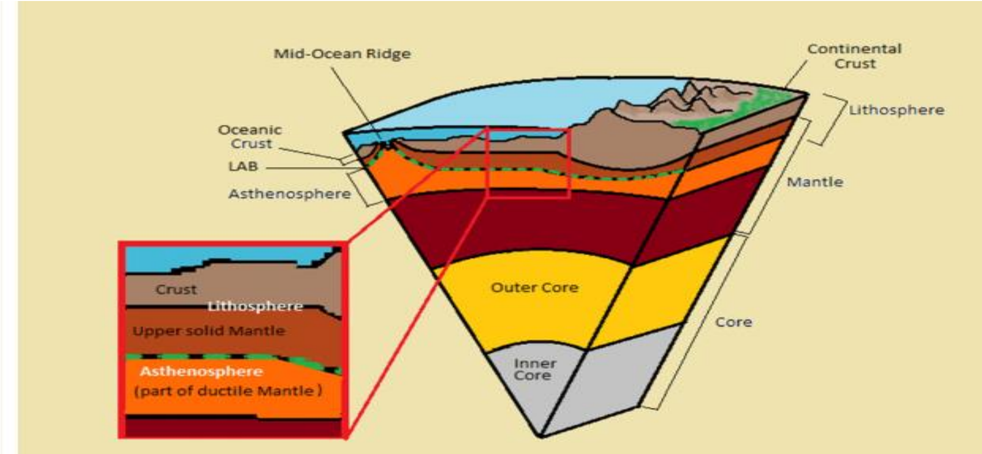


Figure 10 : Diagram showing layers of the Earth including lithosphere: photo credit: Nealeys at English Wikipedia, CC BYSA 3.0, via Wikimedia Commons.

1.2.1.Seismic Discontinuities and Layer Subdivision

Variations in the propagation speed of seismic waves have allowed the subdivision of major layers into sub-layers, revealing discontinuities where the speed undergoes abrupt changes:

1.2.1.1.**Mohorovičić Discontinuity (MOHO):** Marks the boundary between the solid Earth's crust and the solid upper mantle, characterized by a significant difference in chemical composition.

1.2.1.2.Gutenberg Discontinuity: Marks the boundary between the solid lower mantle and the fluid outer core, where seismic wave velocities change abruptly.

1.2.1.3. Lehmann Discontinuity: Marks the boundary between the fluid outer core and the solid inner core. At this discontinuity, seismic wave behavior undergoes a sharp transition.

These discontinuities provide valuable insights into the composition and characteristics of Earth's internal layers, contributing to our understanding of its structure and dynamics.

The structure of the Earth is composed of three main compartments: the core, the mantle, and the Earth's crust, each subdivided into sub-compartments. The core is divided into the inner and outer core, the mantle into the lower and upper mantle, and the Earth's crust into the continental and oceanic crust. The upper mantle includes the liquid asthenosphere and the solid part. By combining the Earth's crust with the rigid part of the upper mantle, we obtain the lithosphere, consisting of the oceanic and continental lithosphere (Aubouin *et al*., 1968).

The oceanic crust, thinner (5-15 km) and denser (density of 3.2), differs from the continental crust, which is thicker (30-35 km) and less dense (density between 2.7 and 3). In summary, the oceanic crust is thinner and denser than the continental crust.

The concept of tectonic plates reveals that the lithosphere is not a continuous piece but is divided into discontinuous lithospheric plates, creating a complex network of tectonic movements on the Earth's surface (Viers, 2003).

2.3. Stages of Relief Formation

Relief is the result of the combined action of factors (internal; endogenous, external; exogenous) and anthropogenic influences. Endogenous factors involve knowledge of geological structure. Constructive forces or orogenic forces (tectonic deformations) manifest as plate movements, earthquakes, volcanism, fractures, faults, and folding. Exogenous factors include gravity and climate, which influence and shape the relief. These factors involve water, ice, wind, and temperature variations, contributing to erosion (Viers, 2003).

2.4. Definition of Lithology

Lithology is the nature of the rocks forming an object, a set, or a geological layer. It refers to the lithology of a rock sample as well as that of a geological formation or an entire mountain massif. It is essential for understanding erosion.

Geological lithology is a description of its visible physical characteristics that appear on the surface, either in hand or with an electron microscope. It also takes into account color, texture, grain size, or composition. It can either be a detailed description of these characteristics or a summary of the raw physical character of a rock.

An accurate analysis of the relief begins with its description, which aims to characterize the main aspects of the relief and its location (Viers, 2003).

2.4.1. Influence of lithology

An accurate analysis of the relief begins with its description, aiming to characterize the main aspects of the relief and locate it. The degradation of rocks produces numerous blocks and particles that can be transported either in dissolved form in water circulation or in solid form by gravity; this is the state of equilibrium-disequilibrium (Cailleux, 1977).

1.4.1.1. The lithological types are: Deformation intersected by a vein (Layer of magmatic or sedimentary rock intersecting old rocks, the host rock, corresponding to the filling of a fracture or fissure.

-Flexible (folds) and brittle (faults) deformations affecting a sedimentary series (Tricart, Cailleux, 1963; Cailleux 1977; Viers, 2003).

1.4.2. The different types of tectonic deformations in mountain chains:

1.4.2.1.Continuous or ductile soft deformation (folds): A fold is a continuous, ductile deformation of initially flat geological layers in the form of undulations with more or less large curvature radii, following tectonic stress

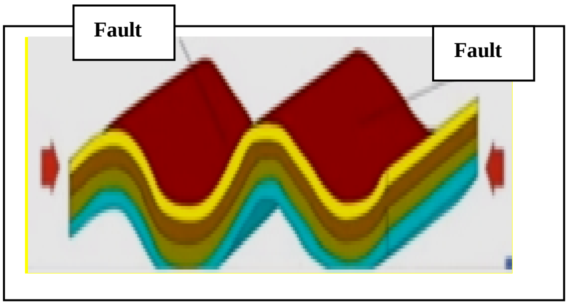


Figure 11: A fold

1.4.2.1.1.The undulation can be:

a.1)- In convexity: anticline fold, a convex fold with its center occupied by the oldest geological layers (Tricart, Cailleux, 1963)

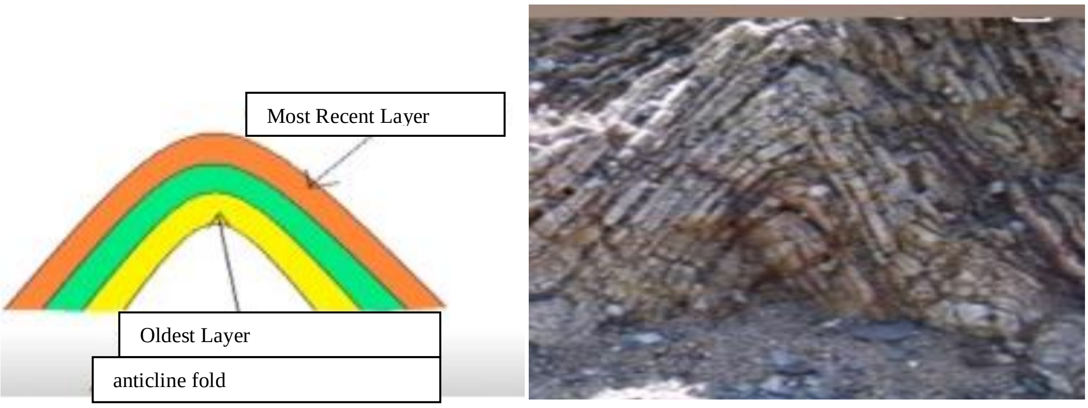


Figure 12: Anticline at Calico Ghost Town Location: San Bernardino County, California, United States. Photo Copyright © Garry Hayes

a.2)- In concavity: syncline fold is a fold with its concavity turned upwards. Under normal conditions, with the youngest layers being the uppermost, after erosion, the most recent geological strata are found in the core of the syncline (Cailleux 1977; Viers, 2003).

Figure 13: Synclinal folds in bedrock, near Saint-Godard-de- Lejeune, canada (north America and Pacific plate Metamorphosed.

1.4.2.1.2. Fold elements: The hinge is an area of maximum curvature, and the limbs connect two successive hinges. **Limb of the fold:** it is the surface that connects two successive hinges. **Axial plane** (or axial surface): an imaginary surface that connects the hinges of the layers of the fold. **Fold axis:** the bisector line between the axial plane and the topographic surface (Cailleux, 1977 ; Viers, 2003).

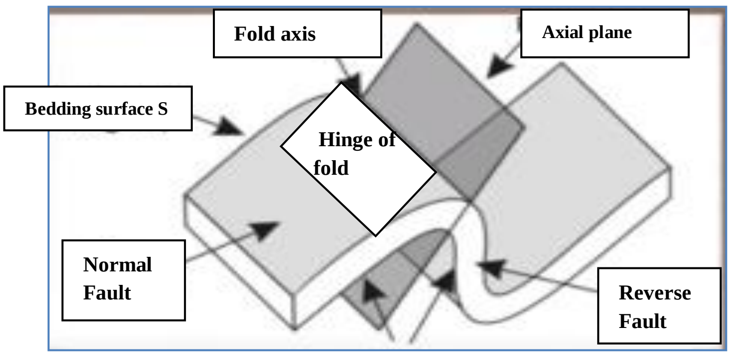


Figure 14: **Fold elements**

1.4.2..3.The different types of fold

- **Straight fold:** characterized by two limbs that are symmetrical with respect to its vertical axial plane. Equal-intensity compressive forces result in a straight fold (Cailleux 1977 ;Viers, 2003).

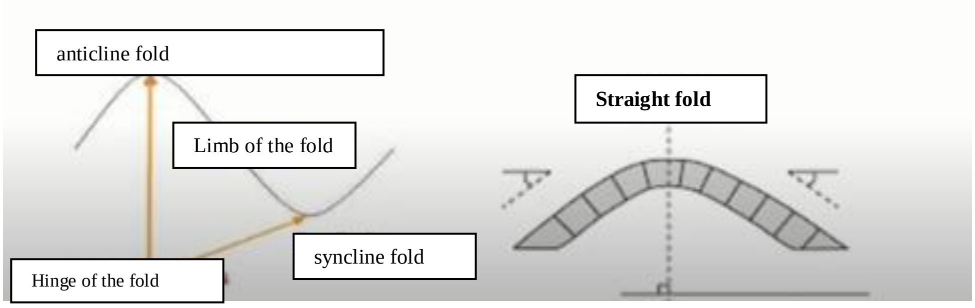


Figure 15: **Straight fold**

- **Overturned fold:** characterized by an oblique axial plane, and the two limbs have different inclinations (Cailleux, 1977).

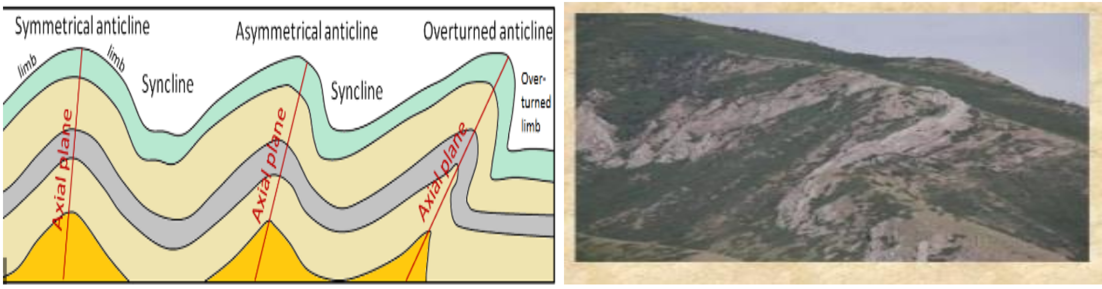


Figure 16: overturned flod in limestone, Wasatch Mountains, Utah, USA (sedimentary strata ; North American plate with Pacific plate).

- **Recumbent fold:** characterized by two limbs symmetrical with respect to its horizontal axial plane (Cailleux,1977 ; Viers, 2003).

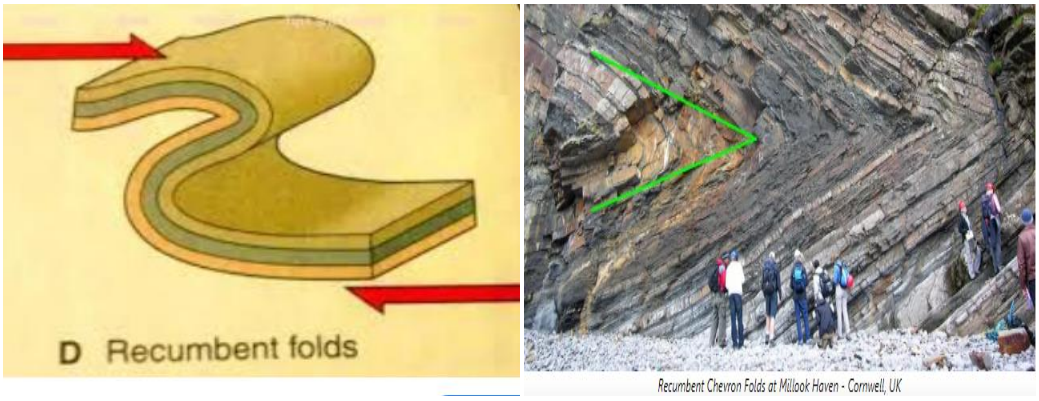


Figure 17: Recumbent fold (P.A. Bourque)

We will talk about **structural relief** when the arrangement of the subsurface rocks plays a predominant role in the topographic forms (these are the relief forms controlled by the subsurface structure), and modeled relief when the reliefs are explained by erosive actions (wind, water, freeze/thaw, glaciers, etc.). Thus, the vertical and tangential movements that affect the Earth's crust (via tectonic forces) result in the following structures:

1.4.2.1.4. Aclinal (tabular) and monoclinal (Cuesta)

Sedimentary layers are inclined in a constant direction. The dip is low (1 to 10°).

-Variations in the dip are observed as follows:

1-Flexure: a positive variation in the dip (or an increase in its value).

2-Structural shelf, a negative variation in the dip (or a decrease in the dip).

3-Regular dip - Cuesta

4-Anticlinal undulations (dome structures).

5-Synclinal undulations (basin structures, sedimentary basin).

The Cuesta form: It is a structural form (monocline structure) carved into a concordant sedimentary succession, consisting of a unit of loose rock between two units of resistant rocks and affected by a low dip (Birot , 1940; Tricart, Cailleux,1964).

-The cuesta is an asymmetric landform consisting of (**the front**): a concave-profile slope with a steep incline and (**the back**) a gently inclined plateau in the opposite direction. **A butte** is an elevated area that resists surrounding erosion due to its more resistant rock composition. A **depression** refers to a geographical area lower than the surrounding regions, which may include valleys, basins, or other forms of depressed terrain (Birot , 1940; Tricart, Cailleux,1964).

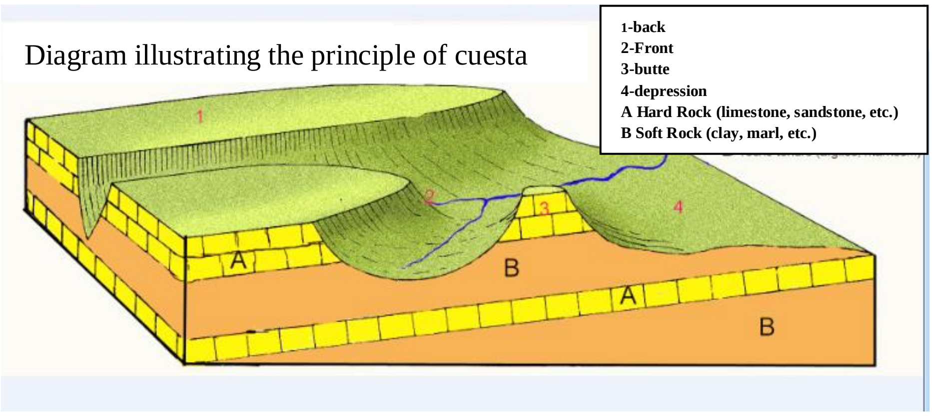


Figure 18 : Diagram illustrating the principle of cuesta . the Characteristics of the Balconies of the Sarthe. Source: Landscape Atlas of the Pays de la Loire.

1.5. The evolution of Jurassic forms in north africa:

This topic typically addresses the development and diversification of life forms, geological structures, or ecosystems during the Jurassic period (about 201 to 145 million years ago) in the North African region. It may include: (Aubouin *et al.,* 1968).

Paleogeography:

-The shifting landmasses and sea levels during the Jurassic that shaped North Africa's landscape.

-The presence of shallow marine environments, lagoons, and terrestrial areas, fostering diverse habitats.

Faunal and Floral Evolution:

-Marine species like ammonites, bivalves, and early marine reptiles thriving in shallow seas.

-Emergence or dominance of certain terrestrial dinosaurs and early mammals in the region.

-Evolution of vegetation like cycads, conifers, and ferns adapting to Jurassic climates.

Sedimentary and Fossil Records:

-Fossils embedded in Jurassic sedimentary rocks (limestones, marls) found across North Africa.

-Traces of transitional species or significant evolutionary adaptations captured in the rock record.

Tectonic Influences:

-Movements of the African plate during the Jurassic impacting sedimentation and biogeographic patterns.

-Evidence of rift basins and the early opening of the Atlantic Ocean affecting species migration and habitat distribution.

Key Sites and Discoveries:
-Notable fossil sites in Morocco, Algeria, Tunisia, or Libya that have contributed to understanding Jurassic evolution.
-This subject bridges paleontology, geology, and evolutionary biology, providing insights into how Jurassic life adapted to the dynamic environments of North Africa (Aubouin *et al.*, 1968).

1.4.2.2. A fault is a discontinuous deformation that is a break in the layers of the terrain, accompanied by a displacement of the two compartments thus created. The key elements of a fault include the two compartments:
*** The elements of the fault are:** The two compartments: **the footwall -** the uplifted compartment (below the fault).
* **The hanging wall -** the down-dropped compartment (above the fault) (Cailleux, 1977; Tricart, Cailleux, 1963, 1964).

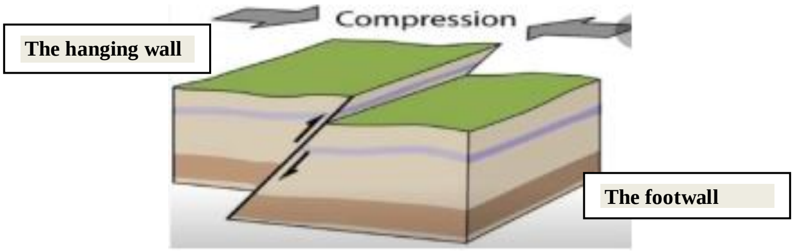


Figure 19: A fault

1.4.2.2.1. Fault elements

***The fault plane** is the surface along which the two compartments have slipped, either obliquely or vertically. It is accompanied by a polished surface known as the fault mirror. **The fault plane** can be described by measuring its inclination or dip angle (q) with respect to the vertical.
***Fault Displacement:**
***Vertical Displacement (R):** It is the difference in altitude between the two blocks.
***Horizontal Displacement (r):** It measures the sliding of the blocks against each other (Cailleux, 1977).

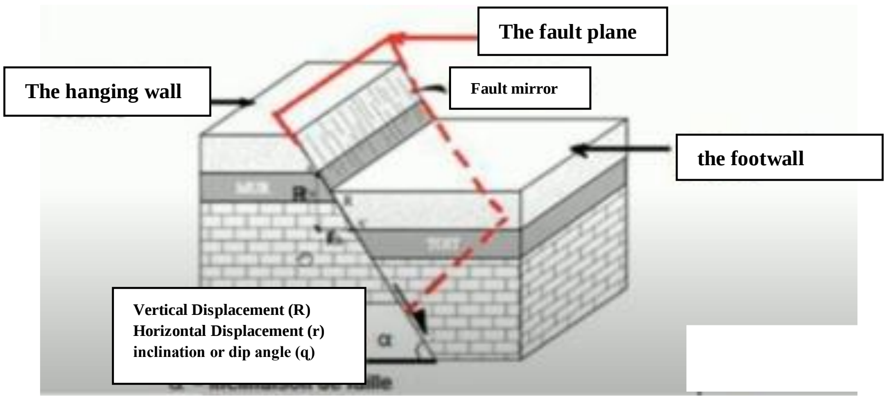


Figure 20: Fault elements

1.4.2.2.2. Different Types of Faults:

*** Normal Fault:**

A normal fault is a fault along which rocks above the fault plane move downward relative to rocks below the fault plane. Normal faults form when two blocks of rock move away from each other due to stretching (extension) (Tricart, Cailleux, 1963; Cailleux A.,1977; Viers, 2003).

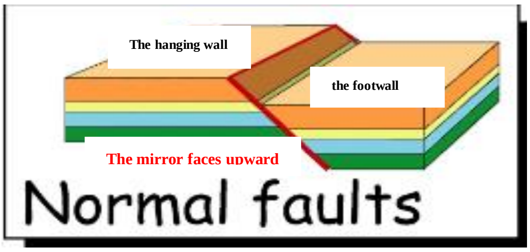
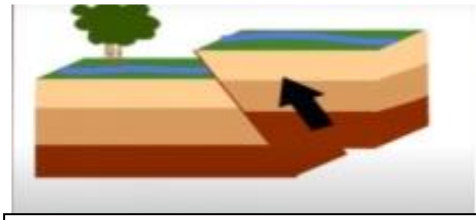


Figure 21: Normal Fault

***Reverse Fault:**

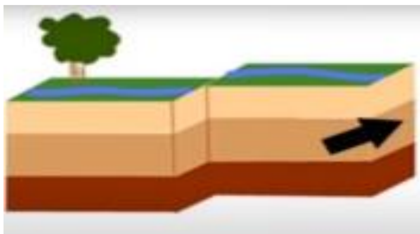
A reverse fault is a fault along which rocks above the fault plane move upward relative to rocks below the fault plane. Reverse faults form when two blocks of rock are pushed toward each other due to compression.



Reverse Fault (mouvements convergents)

***Strike-Slip Fault:**

A strike-slip fault is a fault along which the relative horizontal movement occurs along the fault plane, separating adjacent blocks of rock. It is noted as either right-lateral strike-slip (clockwise sense) or left-lateral strike-slip (counterclockwise sense).



Transform fault" ou simplement "strike-slip fault"

***Fold-Thrust Fault:**

A fold-thrust fault refers to a folded or tilted fold whose opposite limb has been flattened by a thrust fault (Intermediate deformations.) (Cailleux,1977; Viers, 2003).

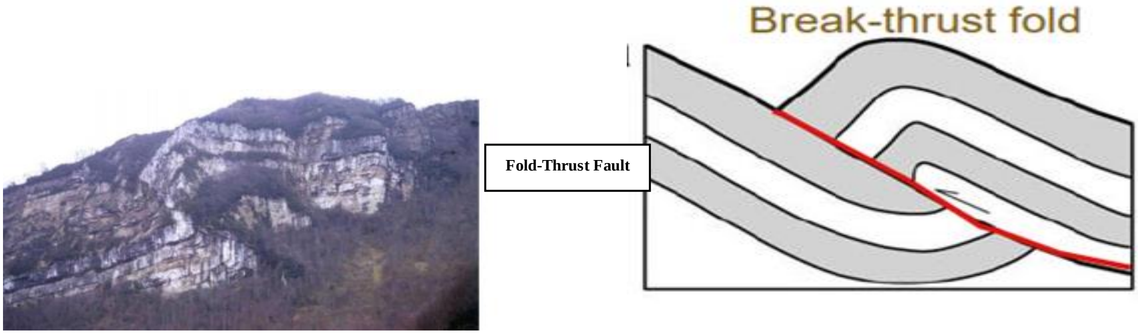


Figure 22: Fold-Thrust Fault (Photographie Pierre Thomas).

***Overthrust:**

An overthrust is a tectonic movement or a series of rocks that overlap another through an abnormal contact, typically an inverse fault. Generally characterized by a inclined fault and limited extent (several kilometers) (Cailleux,1977; Viers, 2003).

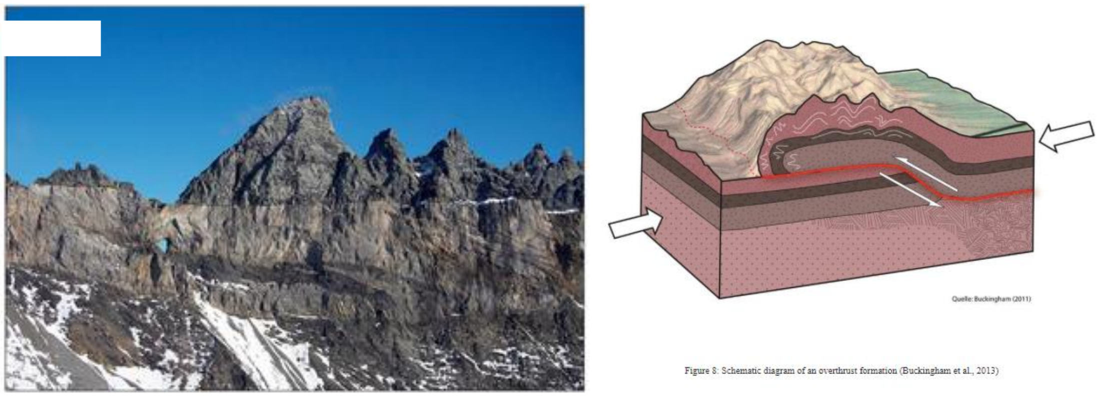


Figure 23: The Glarus thrust seen from the Tschingelhomer region (imper, 2011).

Note: The combination of numerous normal faults can give rise to tectonic features such as **Graben** (a type of rift valley formed by normal faulting) and **Horst** (an elevated block of the Earth's crust bounded by faults) (Tricart, Cailleux, 1963 ; Cailleux, 1977; Viers, 2003).

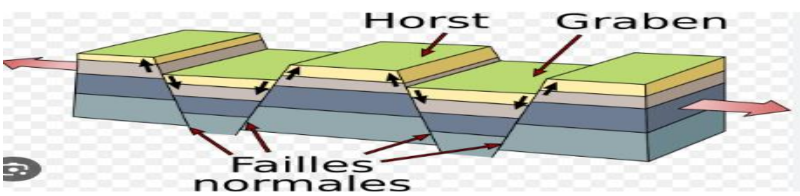


Figure 24: Graben

***Thrust Sheet:** Thrust sheets correspond to much larger tectonic units with a range that can extend from several tens to over a hundred kilometers. They move several kilometers, and in this case, there is a distinction between the unit that remains in place, called autochthonous, and the unit that moves, called allochthonous, under the influence of compressive forces (Tricart, Cailleux, 1963 ; Cailleux, 1977; Viers, 2003).

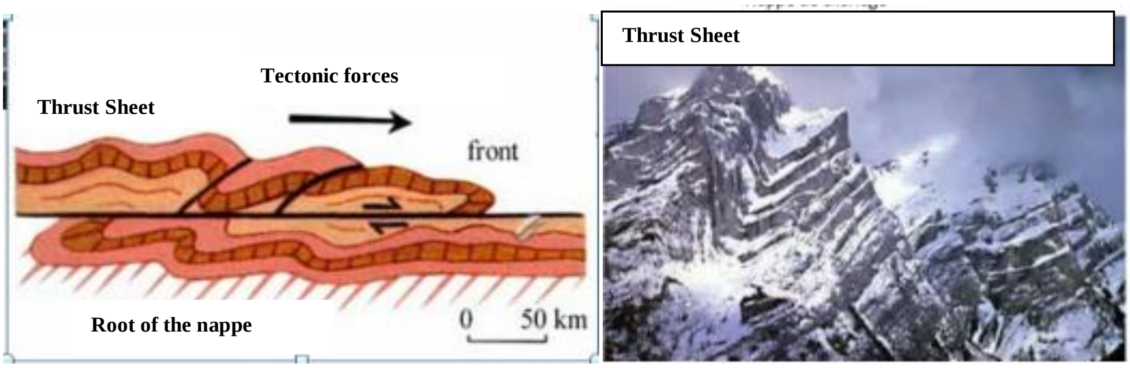


Figure 25 : Thrust Sheet (alpin style).

1.5. rock is an assemblage of minerals defined by its chemistry, mineralogical composition (the minerals it contains, e.g., pyroxene, feldspar, quartz), and structure (the mode of assemblage of the minerals that constitute it) (Cailleux ,1974).

1.5.1. Different types of rocks, such as liquid or gaseous rocks like petroleum and natural gas, loose solid rocks like sand and clay, and coherent solid rocks like limestone, sandstone, and coal. Ex: Solid rocks are composed of a mixture of minerals (Cailleux , 1974).

1.5.2. Classifications of rocks:

*** Igneous Rocks (Endogenous): Rocks** formed from the cooling of volcanic magma.
*** Sedimentary Rocks (Exogenous):** Rocks formed at the Earth's surface, resulting from the action of erosion and transport agents leading to deposition.
***Metamorphic Rocks:** Rocks formed, without melting, from other rocks (igneous or sedimentary) through recrystallization due to increased temperature and pressure (Pomerol et Fouet, 1975).

1.5.2.1. Igneous Rocks (Ignées = of fire):

Igneous rocks result from the crystallization of magma. Magma (mineral matter in a molten state) is generated by the local melting of deep rocks. Rocks formed from the cooling of magma are of two types: extrusive or intrusive.

1.5.2.1.1.Extrusive Igneous Rocks (or Volcanic Rocks):

Magma erupts onto the surface, exposed to the air, and is then referred to as lava. It cools rapidly and becomes an extrusive rock. The gases contained in the magma do not have time to escape, explaining the porosity of this type of rock (numerous small holes related to gas bubbles, as seen in pumice). Crystallization is low or nonexistent. These rocks are often dark, such as basalt (Pomerol et Fouet, 1975; Macdonald,1982).

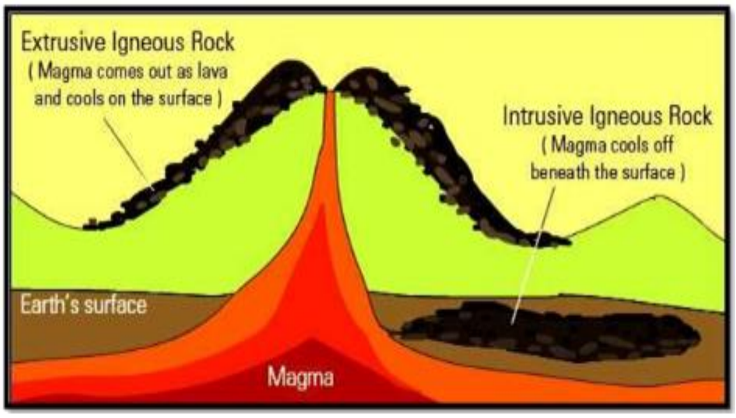


Figure 26: Mode of occurrence of Igneous rocks.

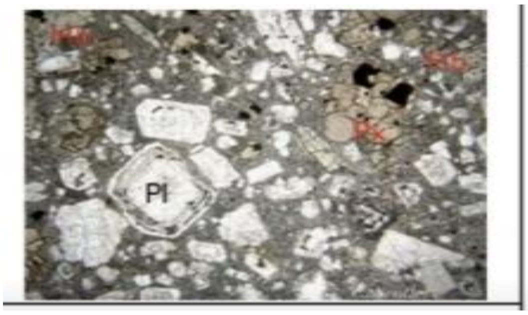
Pyroxene

Plagioclase

Olivine

Characteristics of basalt:
-Macrocrystals
-Microcrystals
-Glassy texture
Semi-crystalline rock with a microlitic structure

Photos 3: -Extrusive Rocks (Volcanic): Formed from lava cooled on the Earth's surface. Example: basalt



Characteristics of andesite:
-Macrocrystals (plagioclase, mica, amphibole)
-Microcrystals (microliths)
-Volcanic glass

Photos 4 : -Extrusive (volcanic) rock: formed from intermediate composition lava.
Example: andesite

Table 1: Comparison between basalt and andesite:

	basalte	andésite
With the naked eye	The basalt is a dense, dark rock that contains few large crystals and a significant portion of non-crystalline material (glass).	Roche compacte, noire ride, gros cristaux, verre volcanique microlithes
Under a polarizing microscope	Large crystals (plagioclase and olivine), small crystals (microlites), and non-crystalline material (volcanic glass)	This description indicates a mixed texture in the rock. The term "macrocristaux" refers to larger crystals like plagioclase, mica, and amphibole, while "microcristaux" points to smaller crystals or microliths. The presence of "verre volcanique" signifies volcanic glass within the rock.
Petroraphic structure	microlitic structure	microlitic structure

1.5.2.1.2. Intrusive magmatic rocks (or plutonic) - Endogenous (rocks formed in depth). After rising in the Earth's crust, magma accumulates in a chamber at a certain depth. Through slow cooling, it becomes an intrusive rock. This slow cooling allows for the release of gases (making the rocks non-porous) and the formation of well-defined crystals (crystallization more or less significant depending on the cooling time). An example is granite, which has a "speckled" appearance due to the numerous minerals it contains (Pomerol et Fouet, 1975 ;Macdonald,1982).

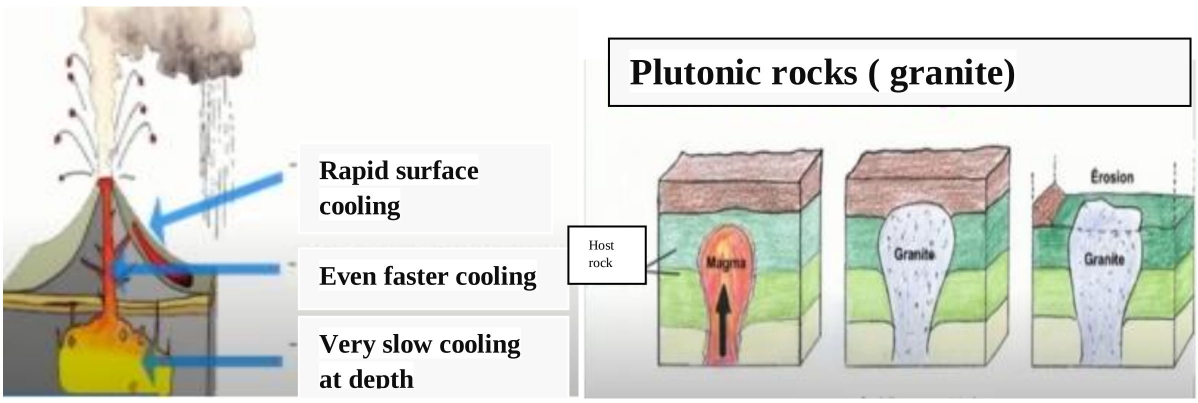
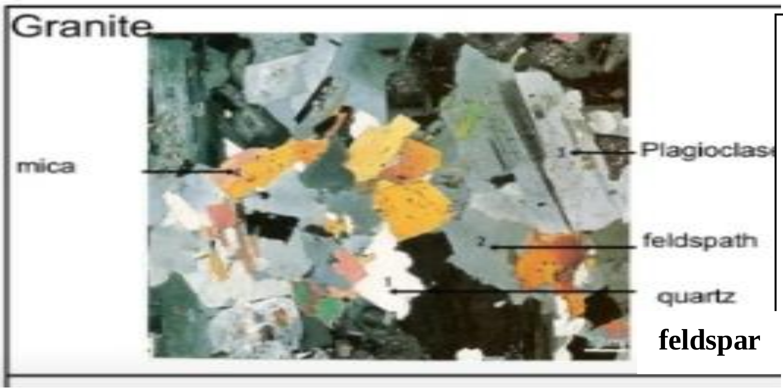


Figure 27: Plutonic rocks (granite)

Photos 5: Intrusive (plutonic) rocks: form at significant depths within the Earth's crust. Their slow cooling allows for the growth of crystals (**E.g:** gabbro)



Characteristics of basalt:

Large crystals (quartz, feldspar, mica, amphibole, pyroxene)

Photos 6: Intrusive (plutonic) rock: slow cooling of magma deep within the Earth **(E.g: Granite)**

Table 2: Comparison between gabbro and granite

	Gabbro	**Granite**
With the naked eye	**Gabbro is a compact rock, ranging in color from green to black, composed of large-sized crystals.**	**A very hard, compact rock that is entirely composed of large crystals.**
Under a polarizing microscope	**Large crystals (plagioclase and pyroxene)**	**Large crystals (quartz, feldspar, mica, amphibole, pyroxene)**
The petrographic structure	**Granular**	**Granular**

1.5.2.2. Sedimentary rocks

Sediments are deposits, most often at the bottom of bodies of water. They can be classified based on their size (grain size).

Sedimentary rocks formed from these sediments can be either unconsolidated (composed of separate elements, e.g., sand) or consolidated (composed of fused elements, e.g., sandstone) (Boulvain, 2015 a,b) :

-Grain size classes (diameters):

Pebbles (boulders, cobblestones, gravel): > 2mm

Sand: 0.05mm to 2mm

Silt: 0.002mm to 0.05mm

Clay: < 0.002mm

1.5.2.2.1. Sedimentary Rocks Classification

1.5.2.2.1.1. Detrital rocks (diagenesis): sandstone, shale, clay, and schist.

They result from the accumulation and compaction of debris from the breakdown of other rocks.

-Sediments deposited at the bottom of the sea: Larger debris settles closest to the coast, while finer debris settles farther away in less turbulent regions (Pomerol et Fouet, 1974; Cojan et Renard, 2013; Boulvain, (2015a, b).

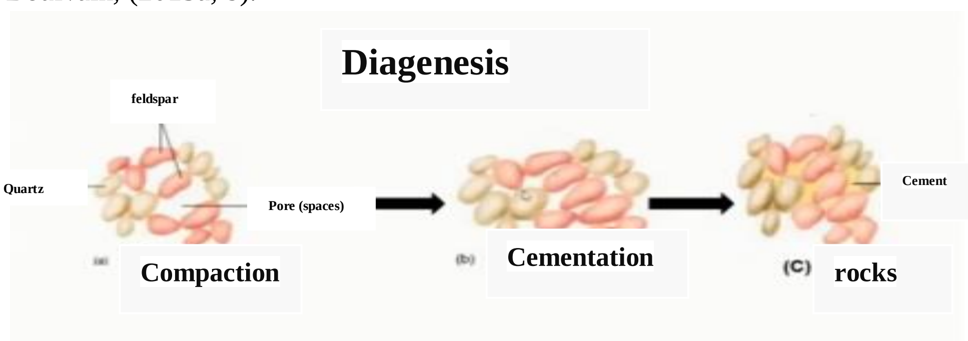


Figure 28: Diagenesis

A) Organic Rocks: (e.g., chalk, limestone)

After the death of marine organisms, soft parts decay or are eaten, while hard parts (shells, pieces of skeletons, coral structures) remain.

Organic rocks result from the accumulation of these organism debris at the bottom of the sea (Jules Desnoyers, 1829 ; Pomerol et Fouet, 1974; Cojan et Renard, 2013; Boulvain, (2015a, b).

B) The organic rocks (coal, petroleum) result from the transformation of animal and plant organic matter and are rich in carbon.

C) Evaporitic rocks (gypsum, NaCl) originate from the precipitation of salts following the evaporation of salty water. This precipitation results from the evaporation and concentration of salts until reaching the point of saturation (Pomerol et Fouet, 1974; Cojan et Renard, 2013; Boulvain, (2015a, b).

1.5.2.2.2. Some characteristics of sedimentary rocks:

*** Stratification:** They are arranged in strata, successive layers with variations in composition, grain size, and color.

*** Subsidence:** Sedimentary layers are often stacked to considerable thicknesses, reaching several kilometers. The deposition of sediments is accompanied by a very slow progressive subsidence of the Earth's crust. This movement is called subsidence (Pomerol et Fouet,1974)

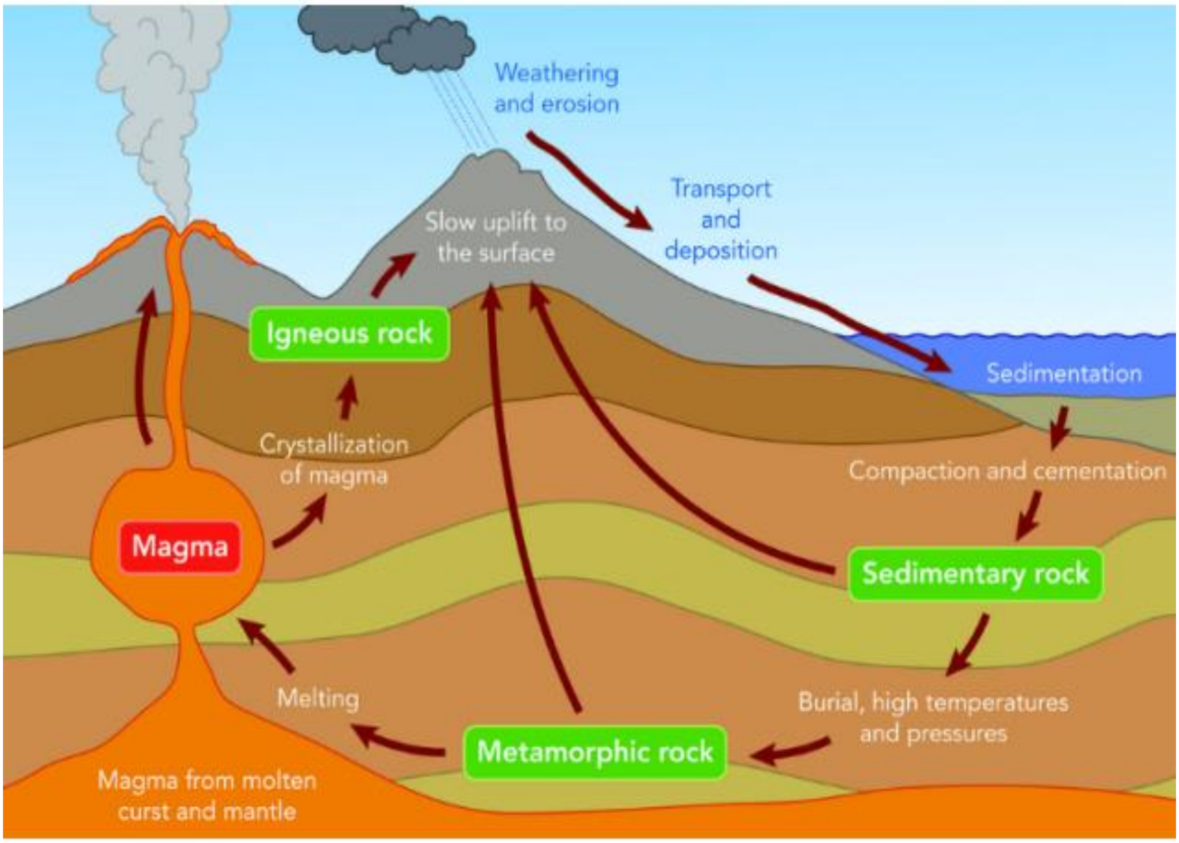


Figure 29: sedimentary cycle.

1.5.2.3. Metamorphic Rock

Metamorphic rock is a type of rock formed from the physical and/or chemical transformation of a pre-existing rock, known as the parent rock, under the influence of heat, pressure, or hydrothermal fluids. This process, called metamorphism, alters the mineralogical structure and texture of the original rock without completely melting it.

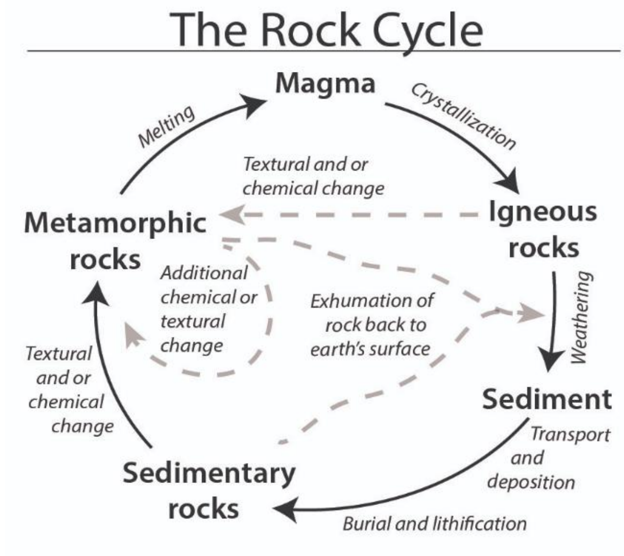


Figure 30: Rock cycle showing the five materials (such as igneous rocks and sediment) and the processes by which one changes into another (such as weathering) (Source: Peter Davis).

1.5.2.3.1. Definition of Metamorphism:

Metamorphism is a geological process that induces changes in the mineralogical composition and texture of a pre-existing rock. It is characterized by the disappearance of old minerals and the formation of new, neoformed minerals, as well as modifications in the rock's structure, often marked by an alignment of minerals along parallel planes, resulting in a foliated texture. This phenomenon arises from variations in the temperature and pressure conditions to which the rock is subjected, leading to mineralogical and structural transformations. In summary, metamorphism encompasses all the modifications undergone by a parent rock due to changes in temperature and pressure (Tricart, J., Cailleux, 1964;Pomerol et Fouet, 1976 ;Marshak, 2009, 2010).

For instance, taking a parent rock, whether it's sedimentary, igneous, or metamorphic, it will invariably be composed of a set of minerals. These minerals represent the fundamental structures that make up rocks, whether sedimentary, igneous, or metamorphic. If this parent rock is subjected to high pressure and temperature conditions or a combination of pressures and temperatures, it will undergo a series of mineralogical and structural transformations.

These transformations are not limited solely to the structure of the parent rock. Indeed, not only will the structure of the rock undergo changes, but also its mineralogical composition. Thus, rocks will undergo changes both in their structural arrangement and mineralogical composition when subjected to specific pressure and temperature conditions (Marshak, 2009, 2010).

Figure 31 : Metamorphism

1.5.2.3.2. Structural Characteristics of Metamorphic Rocks:

The structural characteristics of metamorphic rocks can be illustrated by considering the example of a parent rock subjected to high or increasing pressure. Under such conditions, the rock undergoes a structural transformation known as schistosity. Schistosity is characterized by the formation of multiple layers or strata in the rock, with each layer designated as a schistosity plane. These **schistosity** planes represent an evolution from the rock's initial structure and can be easily separated. Importantly, these strata exhibit a similar mineralogical composition, thus constituting the first distinctive structure of metamorphic rocks (Marshak, 2009,2010).

If the rock undergoes even higher pressure than during the initial transformation, it will progress to another structure called **foliation**. In foliation, the formation strata are no longer composed of the same mineralogical composition, marking a difference from schistosity (Pomerol et Fouet, 1976 ;Marshak, 2009, 2010).

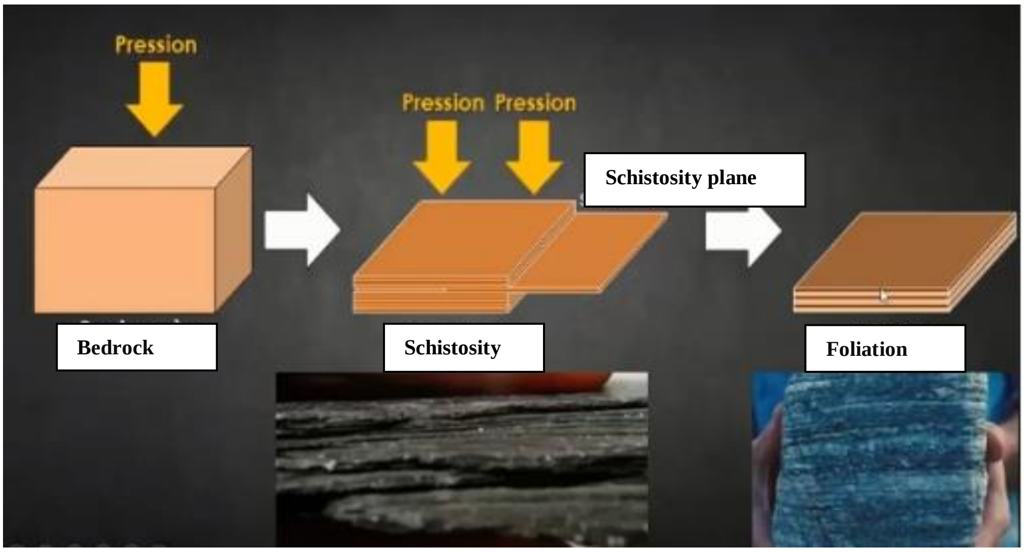


Figure 32: Structural Characteristics of Metamorphic Rocks.

1.5.2.3.3. Metamorphic Facies

A specific set of temperature and pressure conditions in which certain metamorphic rocks form. Each metamorphic facies is characterized by distinct thermodynamic conditions that influence the mineralogical composition of the rocks that develop within it.

The example of the "blue schist facies" you mentioned represents a specific domain in a pressure-temperature (P-T) diagram. This facies indicates the ideal conditions for the formation of blue schists, characterized by the presence of specific minerals such as glaucophane. This facies is often associated with subduction zones where rocks undergo high pressures at relatively low temperatures (Tricart, Cailleux,1964; Pomerol et Fouet, 1976; Marshak, 2009, 2010).

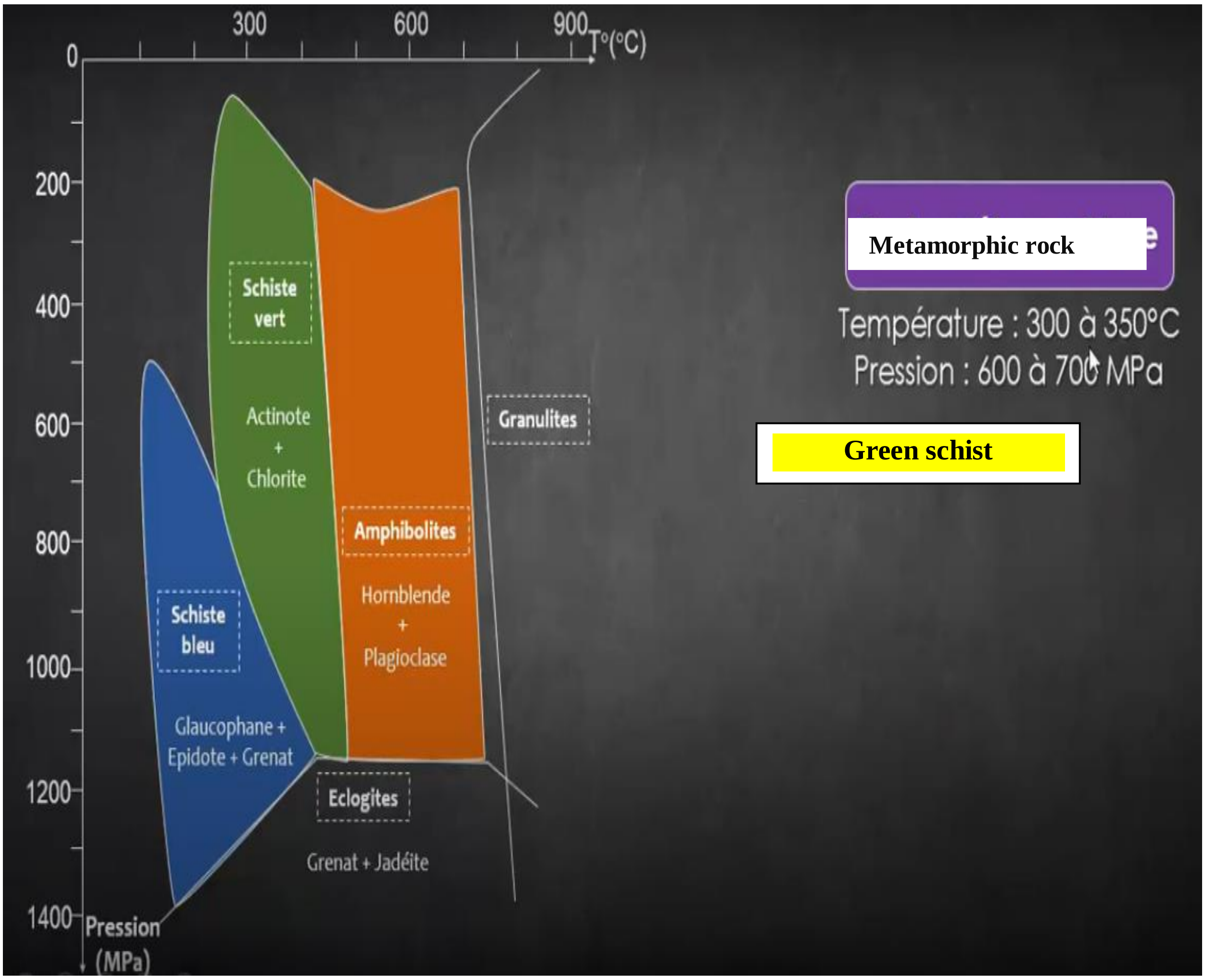


Figure 33: **Metamorphic Facies.**

1.5.2.3.4. Metamorphic Series

The concept of a 'metamorphic series' refers to the set of metamorphic facies experienced by a given rock during its metamorphic process. In other words, it represents the metamorphic path followed by a rock since the beginning of its metamorphism. This series reflects the various pressure and temperature conditions to which the rock has been subjected over time and is often associated with complex tectonic processes such as subduction or the collision of lithospheric plates.Pomerol et Fouet 1976 ;Marshak, 2009, 2010).

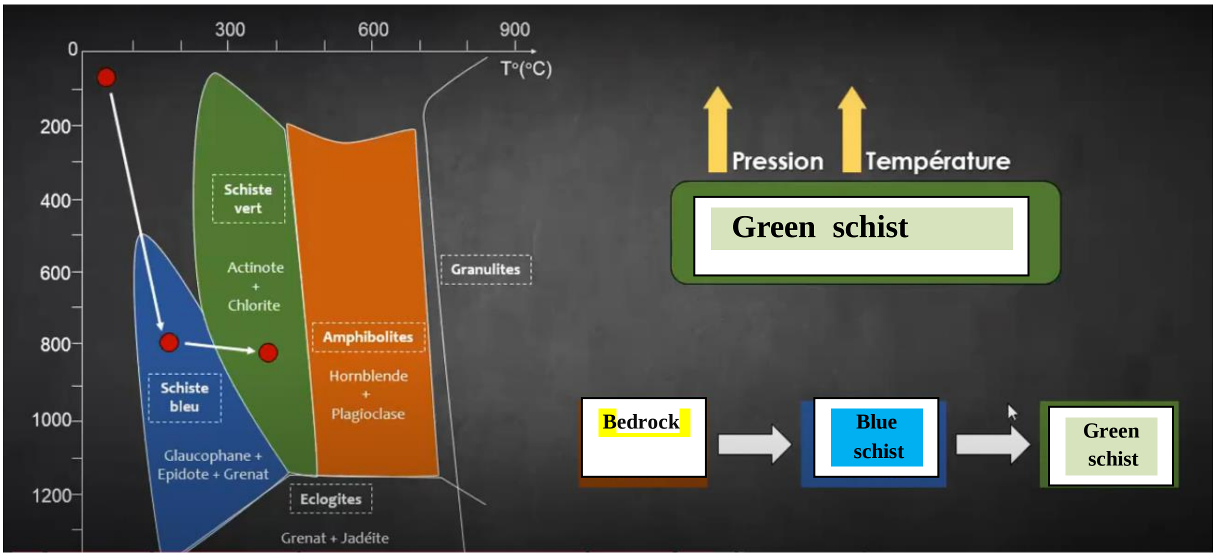


Figure 34: Metamorphic Series

A)The metamorphic series associated with subduction zones, comprising basalt or gabbros, green schists, blue schists, and finally eclogite, is characterized by high-pressure and low-temperature conditions. This specific type of metamorphism is referred to as dynamic metamorphism (Marshak, 2009).

Basalte ou gabbros ⟶ Green schist ⟶ Bleu schist ⟶ Eclogite

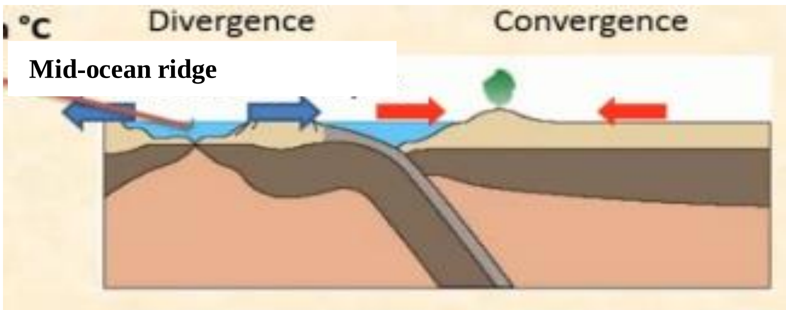


Figure 35: The metamorphic series associated with subduction zones

B)The metamorphic series associated with collision zones, comprising gneiss, mica schist, schist, and clay, is characterized by high-pressure and high-temperature conditions. This specific type of metamorphism is referred to as thermo-dynamic metamorphism (Marshak, 2009).

Gneiss ≤--------Micashist ≤-----Shist≤---------clay

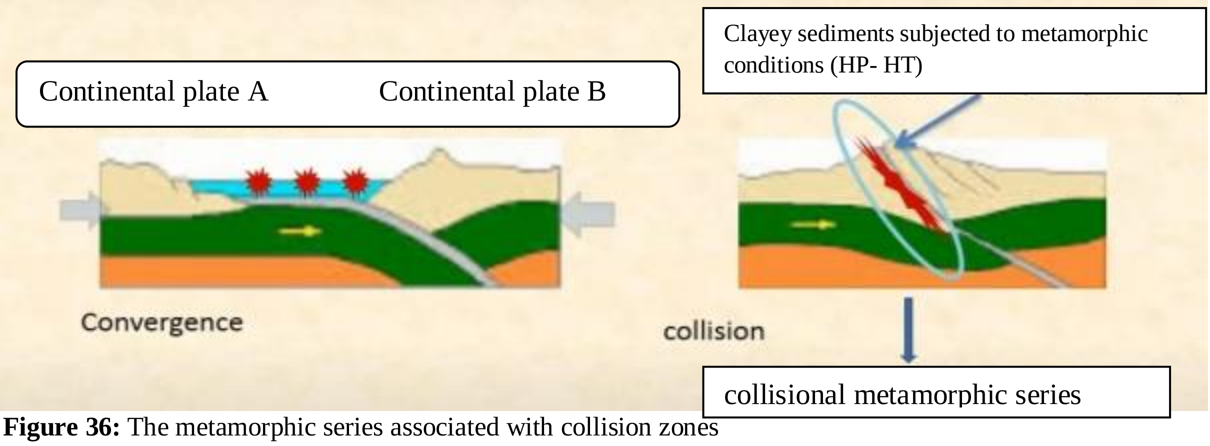


Figure 36: The metamorphic series associated with collision zones

C) Metamorphic series and types of metamorphism characterizing the metamorphic aureole.

Gneiss ≤--------Micashist ≤-----Shist≤---------clay

The metamorphic series associated with the metamorphic aureole resulting from a collision process includes gneiss, mica schist, schist, and clay. When the gneiss, located at significant depths where the temperature is high, undergoes partial melting, it generates magma. This magma, still at a high temperature, is then injected into a sequence of cooler rocks, causing a heat transfer and inducing cooking of the surrounding rock along its borders through contact metamorphism (Marshak, 2009).

The resulting contact aureole exhibits a transformation of the surrounding rock into schist, under conditions of low pressure and high temperature. This specific process of metamorphism is termed thermal or contact metamorphism, emphasizing the significance of the thermal input from the partially molten magma. The interaction between the hot magma and the cold surrounding rock leads to mineralogical and textural changes in the surrounding rock, giving rise to **the metamorphic aureole (**Pomerol et Fouet, 1976 ; Marshak, 2009).

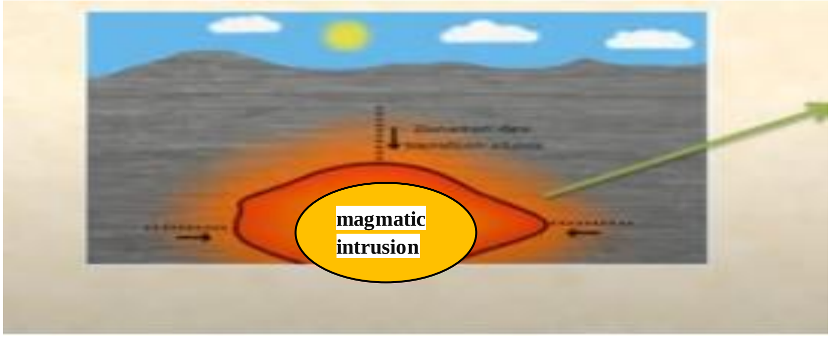


Figure 37:Metamorphic series and types of metamorphism characterizing the metamorphic aureole.

1.5.2.3.5. The types of metamorphism, namely thermal metamorphism, thermal-dynamic metamorphism, and dynamic metamorphism, are linked to orogenesis processes, which involve tectonic movements leading to mountain formation. Each of these types of metamorphism is associated with specific geological conditions that occur during the phases of orogenesis (Marshak, 2009).

a)Thermal Metamorphism:

***Geological Conditions:** High temperature, low pressure.

***Relationship with Orogenesis:** Thermal metamorphism is often associated with the early stages of orogenesis, where the accumulation of sediments or magmatic intrusions causes temperature increases without requiring very high pressure. **For example,** sediments deposited at depth may undergo thermal metamorphism when buried by new layers of sediments (Pomerol et Fouet, 1976 ;Marshak, 2009).

B)Thermo-Dynamic Metamorphism:
***Geological Conditions:** High temperature, high pressure.
***Relationship with Orogenesis:** This type of metamorphism is closely associated with the later stages of orogenesis, where rocks undergo both elevated temperatures and increased pressures. Rocks at significant depths in the Earth's crust can undergo this type of metamorphism during tectonic collisions, forming mountain ranges (Marshak, 2009).

C)Dynamic Metamorphism: *Geological Conditions: Low temperature, high pressure.
***Relationship with Orogenesis:** Dynamic metamorphism is often associated with subduction zones, where one lithospheric plate descends beneath another. Rocks undergo intense deformation at significant depths, resulting in high pressures without a significant increase in temperature. This frequently occurs during collision and subduction phases associated with orogenesis (Pomerol et Fouet, 1976 ;Marshak, 2009).

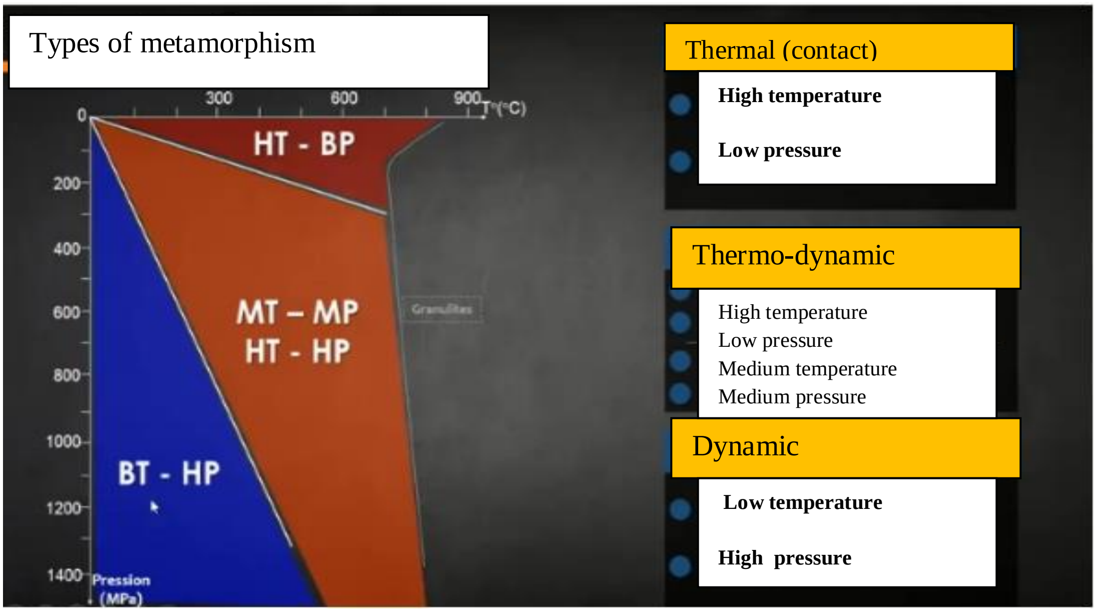


Figure 38: Dynamic Metamorphism

1.5.2.3.6. Metamorphism - Orogenesis

*** In the case of subduction,** rocks from the oceanic crust, initially at the surface, undergo a burial process, moving towards increasingly deeper zones. These rocks, due to their surface origin, maintain relatively low temperatures even at considerable depths, as indicated by thermal anomalies. However, rapid burial leads to a significant increase in pressure compared to a relatively small increase in temperature (Marshak, 2009). This combination of conditions, characterized by a rapid increase in pressure and a slower increase in temperature, leads to a specific metamorphism called dynamic metamorphism. In the context of subduction, dynamic metamorphism is the only type of metamorphism encountered in this region.

It is characterized by low-temperature and high-pressure conditions. Thus, rocks from the oceanic crust undergo mineralogical transformations in response to these specific subduction conditions, generating dynamic metamorphism. This metamorphic process is essential for understanding the evolution of rocks in subduction zones, where tectonic plate movements result in significant changes in thermal and pressure conditions (Pomerol et Fouet, 1976 ;Marshak, 2009).

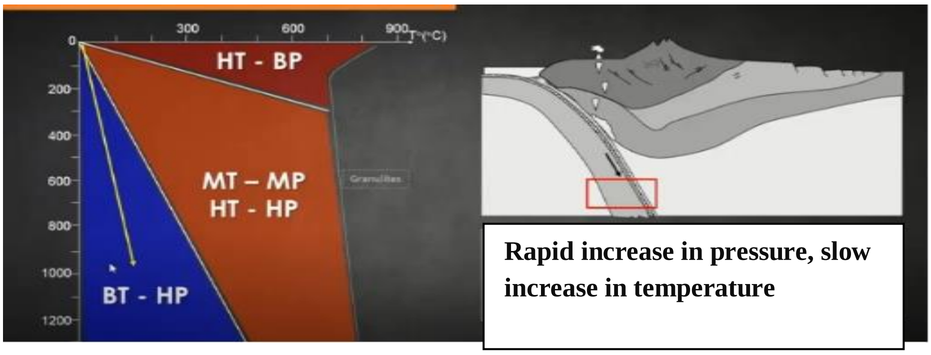


Figure 39: Metamorphism – Orogenesis (In the case of subduction)

***In the case of collision**

In the context of collision, the process can be divided into several key stages:

Fig 1-Subduction: The first stage involves the convergence of two lithospheric plates, leading to the subduction of a portion of the oceanic lithosphere.

Fig 2-Rift and Displacement: The second stage shows a rift in the oceanic lithosphere, creating a fragment of oceanic crust trapped between the two continental masses. Tectonic forces and faults contribute to the formation of this fragment.

Fig 3-Uplift and Continued Subduction: In the third stage, a part of the continental crust rises over the oceanic crust, followed by the continued subduction of this zone of oceanic crust.

Fig 3-Collision of Continental Masses: The last stage is marked by the collision of the two continental masses, forming a mountain range (Marshak, 2009).

The metamorphic evolution of these rocks during these stages is noted by red stars:

-Initially at the surface (low pressure and low temperature).

-Extension to increasing depths during subduction, causing low-temperature and high-pressure metamorphism (Marshak, 2009).

-Movement to greater depths during collision, inducing tectonic deformations and metamorphism.

The overall process is marked by changes in pressure and temperature, impacting the metamorphism of rocks. Variations in rock transformation provide clues about the events that shaped these regions, with some parts having undergone metamorphism, while others are still undergoing this complex process. These clues are often observable through the different metamorphic phases that rocks go through in their geological history (Pomerol et Fouet, 1976 ;Marshak, 2009).

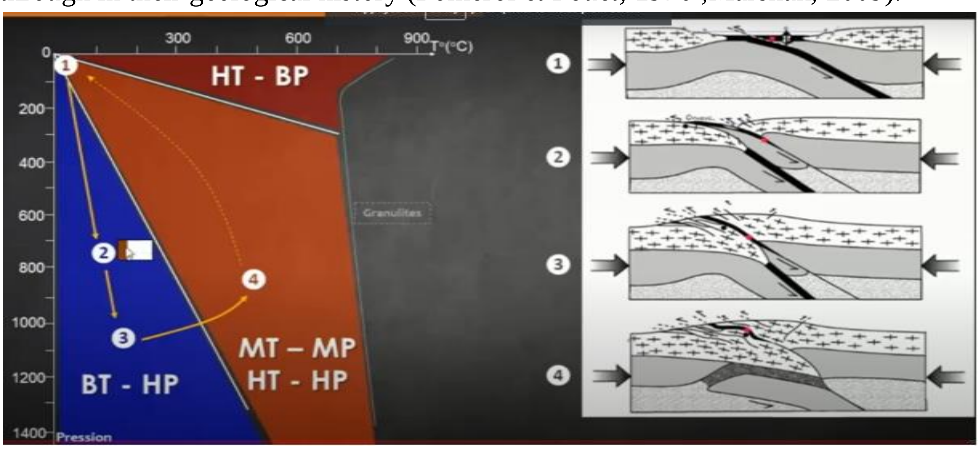


Figure 40: Metamorphism – Orogenesis (In the case of collision)

Chapter 3: Tectonic Deformations

1- Isostatic Equilibrium

At the continental scale, erosion processes, such as runoff, ice, and wind erosion, tend to flatten reliefs toward a base profile corresponding to sea level. According to the principle of isostasy, which emphasizes that the lithosphere "floats" on the asthenosphere, the removal of materials at the surface of a continent leads to a rebalancing of masses, causing the uplift of the entire continental lithosphere. This process gradually results in the thinning of the continental crust, evolving towards the formation of a peneplain and a crust thickness compatible with that of oceanic crust, taking into account the respective densities of the two crusts. Simultaneously, the accumulation of sediments on the oceanic lithosphere creates an overload leading to subsidence.

The formation of minerals results from the crystallization of supersaturated solutions in various chemical elements, and rocks are the product of various physical, chemical, and biological processes. A large geological cycle begins and ends with mantle magma, primarily fueled by the heat generated by the radioactive decay of certain elements contained in rocks. The surface layers contain mineral resources originating from surface processes. Weathering produces altered rocks, including saprolite, a decomposing rock.
Weathering breaks down rocks into soluble ions and grains, mobilized by erosion and residual deposition. Three types of mechanisms are involved: physical or mechanical processes, such as aeolian, fluvial, and glacial erosion; chemical processes by water, involving alteration and dissolution; and morphodynamic processes influenced by external agents such as water in solid and liquid forms, temperature, and biogenic agents.
The concept of isostasy, explaining that mountain ranges exert less attraction than expected, is based on an isostatic equilibrium where elements of the lithosphere at limited depths experience the same pressure, regardless of topographical irregularities on the surface. Isostatic equilibrium has significant inertia, persisting even in the presence of rapid loading and unloading phenomena on a geological scale. Current examples, such as post-glacial rebound in Scandinavia, illustrate the dynamic adjustment of the altitude of the continental crust relative to the geoid, although perfect isostatic equilibrium is only possible when the mantle material is at rest (Aubouin et *al.*,1968; Tricart et Cailleux, 1964).

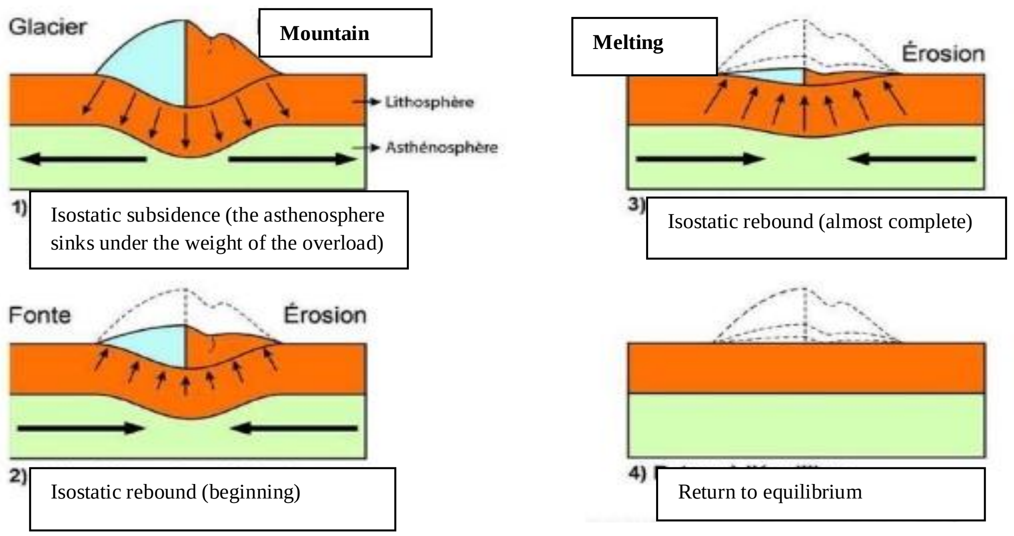


Figure 41: Isostatic Equilibrium

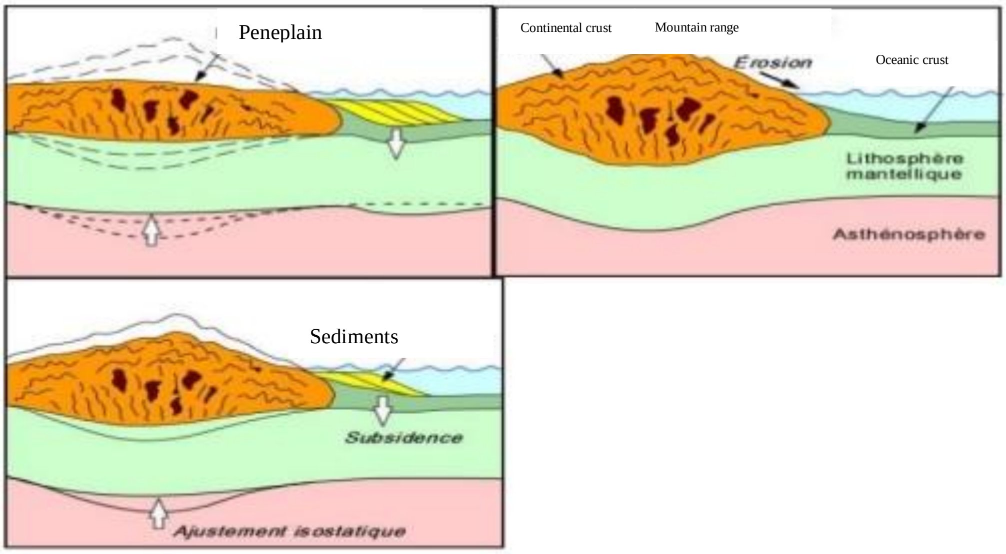


Figure 42: Isostasy Scandinavia

1.2. Continental Drift and Plate Tectonics

These are tectonic forces induced by the slow convective movements of the mantle and the subsequent movements of the Earth's crust (movements of rigid plates through tectonic processes) (Grataloup, 2009).

1.2.1-Plate Tectonics Theory

The plate tectonics theory, based on Alfred Wegener's theory of continental drift in 1912, suggests that it is not the continents but rather the tectonic plates that move. Tectonic plates are pieces of the Earth's lithosphere and crust that float on the asthenosphere. Wegener's idea was a major advance in understanding Earth's dynamics, marking the beginning of plate tectonics, a fundamental theory explaining movements and changes on the Earth's surface (Macdonald, 1982; Grataloup, 2009).

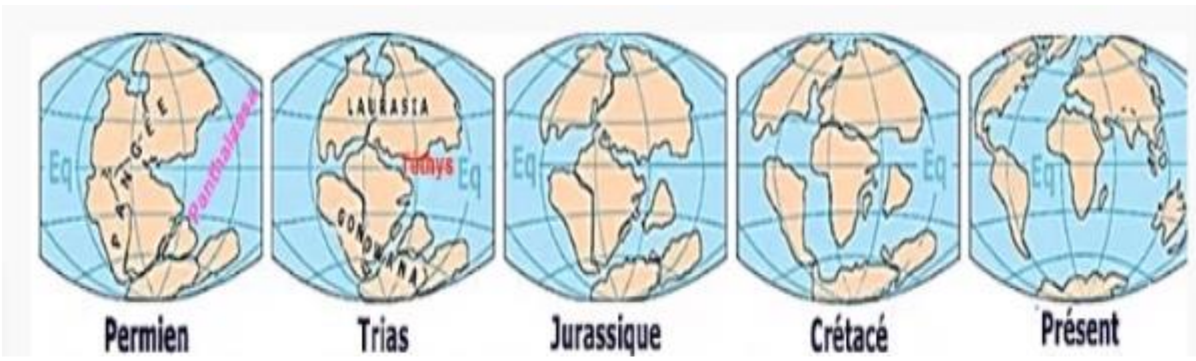


Figure 43: Plate Tectonics Theory.

a) The morphological argument: The morphological argument refers to the complementary geometric shapes of the coastlines of certain continents (Aubouin *et al.*,1968;Grataloup, 2009).

Figure 44 :**The morphological argument**

b)The paleontological argument: The paleontological argument refers to the presence of the same fossils on two different continents(Macdonald, 1982; Aubouin et al., 1968; Grataloup, 2009).

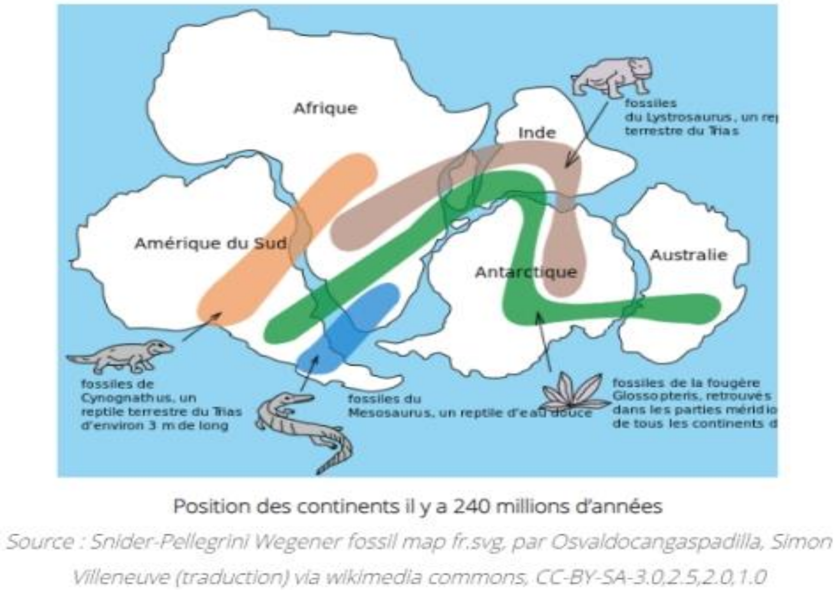


Figure 45: The paleontological argument.

c)The petrographic argument: The petrographic (or geological) argument refers to the similarity in the geological composition of shields (a shield is a region containing rocks over 2 billion years old) on certain continents (Aubouin, *et al.*,1968; Grataloup, 2009).

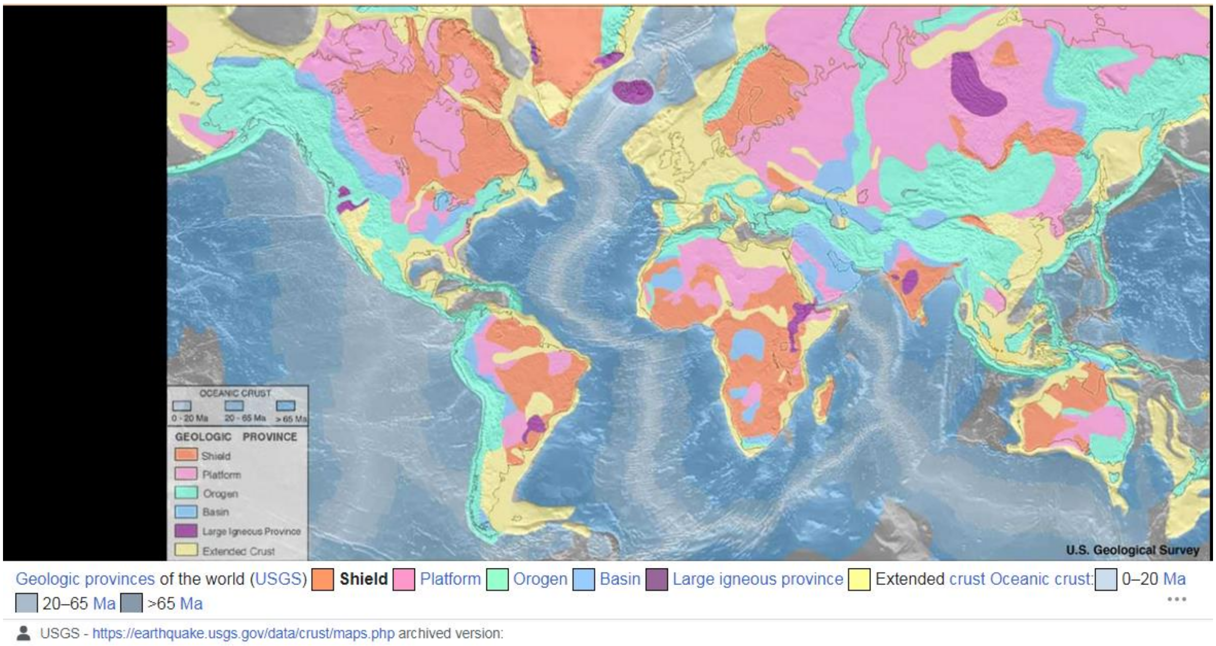


Figure 46: The petrographic argument

Plate tectonics is the result of the slow convective movements of the Earth's mantle, leading to successive displacements of the Earth's crust. These forces are primarily linked to thermal dynamics caused by the release of heat from the radioactive decay of specific elements. The plate tectonics model describes the Earth's lithosphere as being composed of rigid plates, both oceanic and continental, floating on the asthenosphere, a more ductile part of the upper mantle. The movements of these plates, facilitated by the rigidity of the lithosphere, give rise to various major geological phenomena such as earthquakes, volcanoes, oceanic trenches, and the formation of mountain ranges.

Each tectonic plate is associated with the asthenosphere, with a thickness of about 100 km. Overall, there are 12 essential tectonic plates, exhibiting diversity in their composition. Some plates include both continental and oceanic parts, such as the African Plate, while others, like the Nazca Plate, are exclusively oceanic. The latter are categorized as oceanic plates, indicating that the lithosphere is entirely oceanic. It is noteworthy that purely continental plates are rare; for example, the Arabian Plate is often considered continental, although it may also contain oceanic parts. Thus, we observe mixed plates, comprising both continental and oceanic regions, as well as exclusively oceanic plates. The surface of the Earth is thus made up of 12 distinct lithospheric plates (Aubouin, 1968; Grataloup, 2009).

Lithospheric plates can be either entirely oceanic (e.g., Pacific Plate) or oceanic-continental (e.g., African Plate).

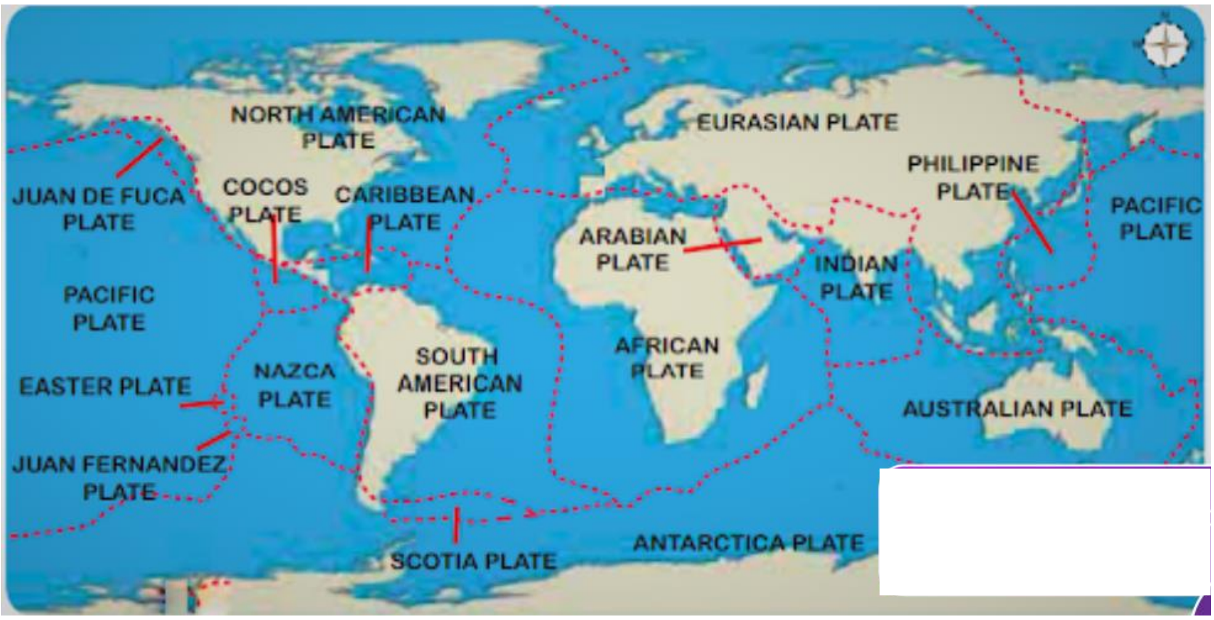


Figure 47: **Plate tectonics**

Plates are bounded by narrow and highly active zones (volcanic and seismic activity) (Aubouin, 1968; Grataloup, 2009).

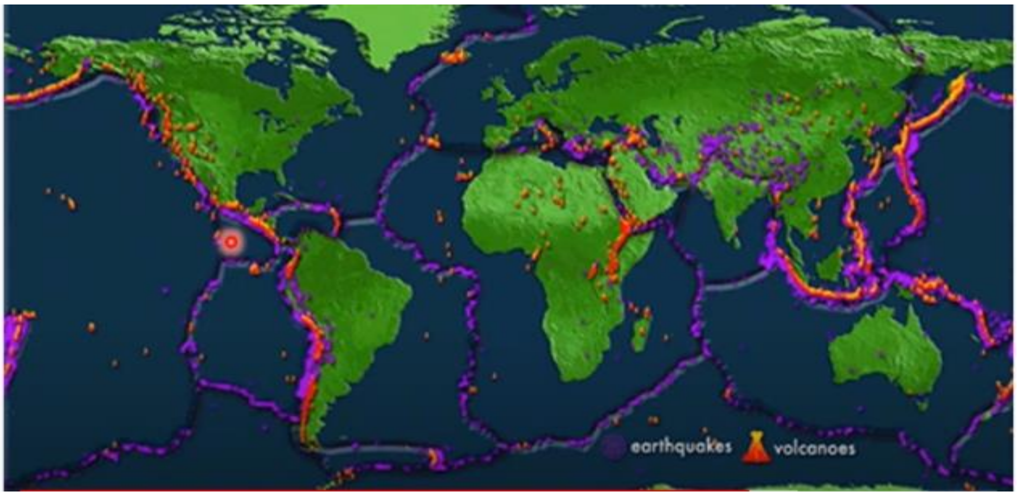


Figure 48: volcanic and seismic activity

1.2.2-The different tectonic movements of lithospheric plates can be classified into three main categories:

***Divergent movements:** These movements occur at mid-oceanic ridges, where plates move apart. Oceanic accretion takes place, forming oceanic crust and leading to the opening and widening of oceans. Divergent movements result in oceanic expansion, generating the creation of oceans and the widening of oceanic ridges.

***Convergent movements:** Convergent movements, illustrated by subduction and plate collision, result in deformations of the lithosphere. These deformations cause the thickening of the lithosphere, leading to the formation of mountain ranges.

-Subduction occurs at oceanic trenches, where oceanic plates dive beneath continental lithosphere. Subduction reduces the oceanic surface and can lead to the complete closure of an ocean, resulting in the collision between two continental plates.

-Continental collision forms mountain ranges such as the Himalayas and the Alps, resulting from the pressure and deformation of rocks.

-Obduction is a particular case where an oceanic plate sinks beneath a continental plate and then rises above it, forming obducted mountain chains (Wegener, 1912; Thomas, 2011).

***Transform movements:** Transform faults allow for divergent movements of plates along a spherical structure, shifting the axis of oceanic ridges. These transform movements manifest as transform faults, facilitating the displacement of lithospheric plates.

In summary, divergent, convergent, and transform movements contribute to the dynamics of the Earth's lithosphere, shaping the planet's surface over geological time.

When two tectonic plates move apart, creating a divergent boundary, a gap is formed between them, primarily in the oceanic regions. This region, known as the oceanic ridge, is the site where new oceanic crust is generated. The process begins with the upwelling of magma from the asthenosphere to the surface through the divergent boundary (Wegener, 1912; Thomas, 2011).

12.2.1.At the oceanic ridge, the lava emitted by the magma solidifies to form new oceanic crust. The newly formed oceanic crust accumulates along the divergent boundary, creating an underwater mountain range. This expansion of the oceanic floor is a continuous process, fueled by the influx of fresh basaltic magmas from the asthenosphere. The age of the oceanic crust increases symmetrically as it moves away from the oceanic ridge. Although this expansion process is slow, averaging about 2 cm per year (reaching up to 10 cm/year in the East Pacific Rise), it significantly contributes to the formation of underwater topography and the dynamics of tectonic plates (Cotton, 1950 ; Tricart et Cailleux,1964;Thomas, 2011).

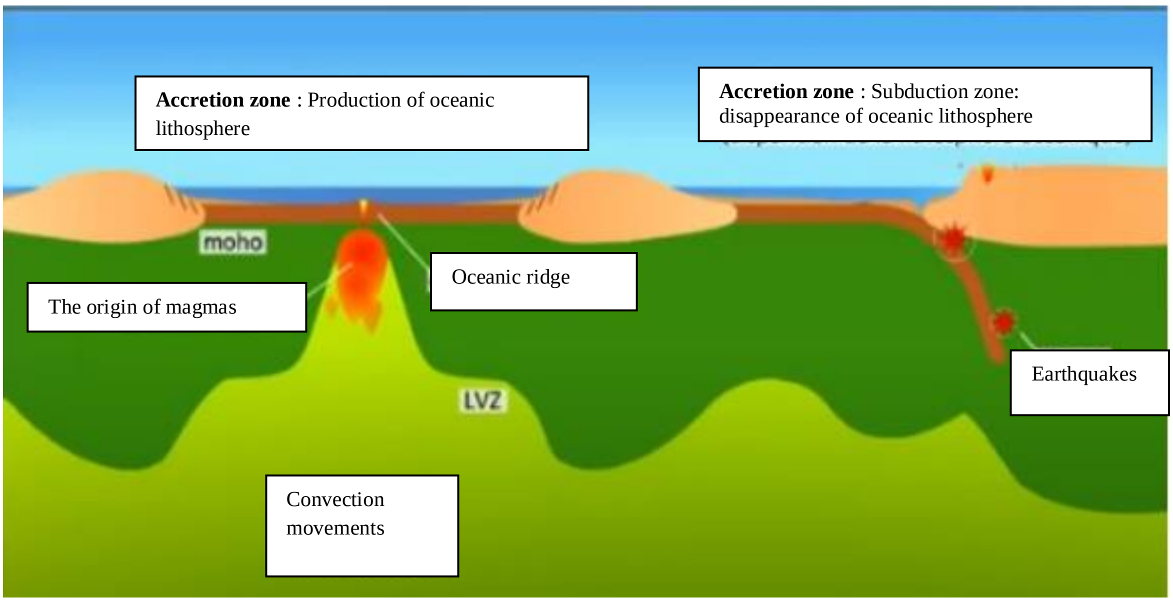


Figure 49: At the oceanic ridge

The Mid-Atlantic Ridge is an underwater feature located in the middle of the Atlantic Ocean and in the Arctic Ocean. In the North Atlantic, it lies at the divergent boundary between the North American Plate and the Eurasian Plate. In the South Atlantic, it lies at the divergent boundary between the South American Plate and the African Plate (Wegener, 1912; Aubouin et *al.*,1968; Thomas, 2011).

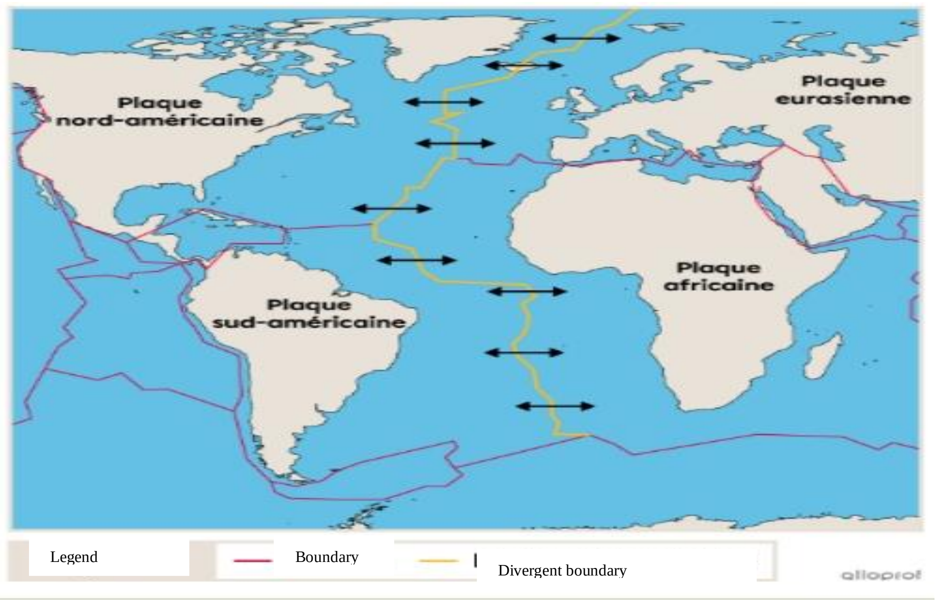


Figure 50: The Mid-Atlantic Ridge

****Tectonic Accidents:**

1.2.2.2. Collision (Subduction) between an Oceanic Plate and a Continental Plate:

During this process, the denser oceanic plate subducts beneath the continental plate. The oceanic plate sinks into the mantle, leading to its melting, which can result in the formation and ascent of magma beneath the continental plate.

The magma that rises to the surface within a continental plate promotes the formation of terrestrial volcanoes along the boundary between the two plates. The Andes Mountains, the world's longest and highest mountain range, are an example of such a region where several of its peaks are volcanic. The Andes are located along the convergent boundary between the Nazca Plate and the South American Plate (Wegener, 1912; Thomas, 2011; Pomerol et *al*., 2002).

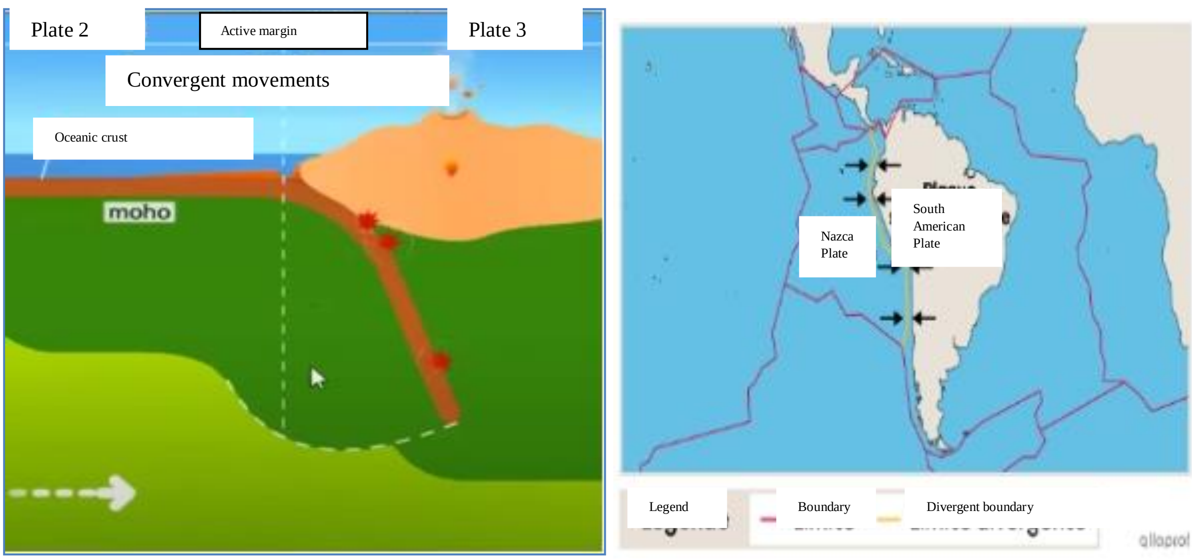


Figure 51: Collision (Subduction) between an Oceanic Plate and a Continental Plate.

- The case of subduction where a lighter oceanic plate sinks beneath a denser continental plate or one oceanic plate sinks beneath another oceanic plate. The area of collision is called the subduction zone. Subduction leads to the formation of oceanic trenches, volcanic eruptions, earthquakes, metamorphism, and the formation of subduction mountain chains (Thomas, 2011).

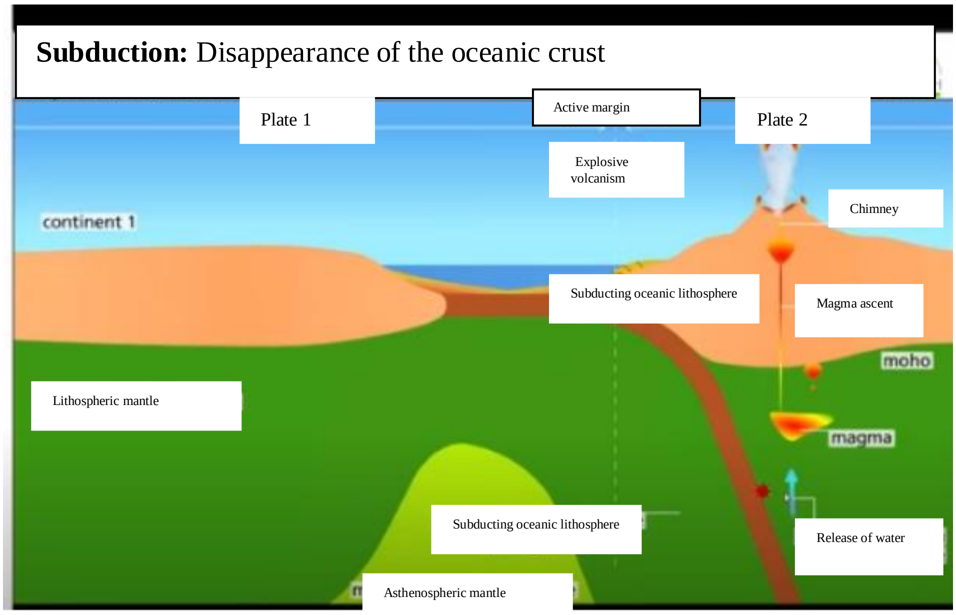


Figure 52:The case of subduction.

Subduction chains result from subduction, a process induced by converging forces. The oceanic lithosphere, denser than the continental lithosphere, sinks beneath it, causing tectonic deformations such as folds, faults, and thrusts. These deformations give rise to the distinctive features of subduction mountain chains (Wegener, 1912; Pomerol, et *al.*, 2002; Thomas, 2011).

1.2.2.2.1.The characteristics of subduction chains include tectonic deformations, oceanic trenches, accretionary prisms, earthquakes along the Benioff zone, thermal anomalies, partial melting, and andesitic volcanoes.

-Tectonic deformations result from the subduction of the oceanic lithosphere beneath the continental lithosphere, leading to folds, faults, and thrusts (Thomas, 2011).
-Oceanic trenches, formed in subduction zones, are deep structures resulting from the overlapping of the oceanic and continental lithospheres.
-The accretionary prism is an accumulation of marine sediments deposited on the continental lithosphere.
-Earthquakes along the Benioff zone are caused by friction between the two lithospheres in contact, generating seismic foci.
-Thermal anomalies are detected in subduction chains, marked by initially low-temperature rocks at the surface that are buried at high depths.

-Partial melting of peridotite in the upper mantle, due to the release of pressurized water, forms andesitic volcanoes on the surface, while the magma that remains trapped in the continental crust can solidify, creating granites (Cotton, 1950; Wegener, 1912).

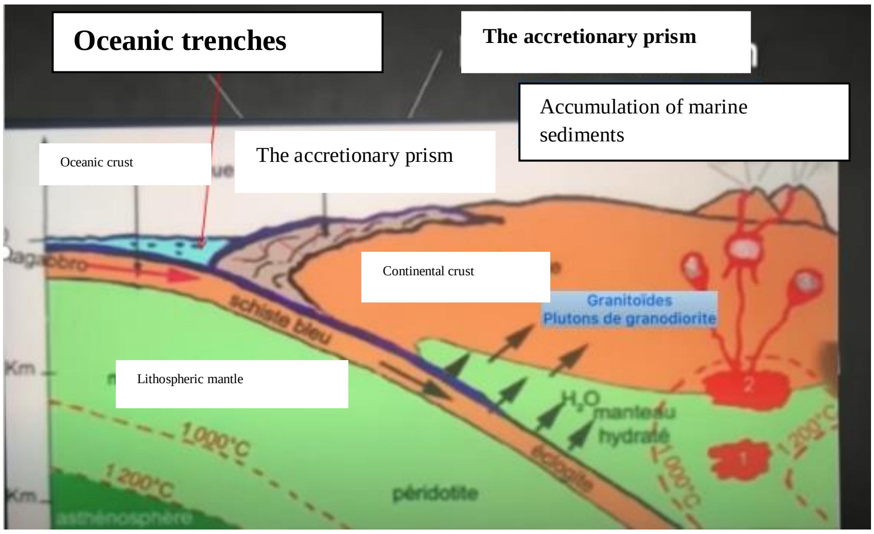


Figure 53: The characteristics of subduction chains

-For the process of partial melting in the upper mantle, the rock involved is peridotite. This rock undergoes transformation into magma at temperatures of around 2000 degrees Celsius in the absence of water. However, in the presence of water, peridotite can transform into magma at temperatures as low as 1200 degrees Celsius. In subduction zones, where the oceanic crust is being subducted, rocks experience high pressures, triggering mineralogical reactions.
The rocks of the oceanic crust, composed of various minerals, are subjected to increasing pressure during subduction. This pressure induces mineralogical reactions that release water molecules (Thomas, 2011).

-The hydration of peridotite, resulting from this release of water, leads to partial melting.
In the absence of hydration, the existing temperature in the upper mantle, which ranges between 1000 and 1200 degrees Celsius, is not sufficient to transform peridotite into magma. However, in subduction zones, the sufficient release of water allows for the partial melting of peridotite, thus transforming this rock into magma (Thomas, 2011).

-The partial melting of peridotite, also known as **andesitic magma**, results in the ascent of magma to the surface. This gives rise to andesitic volcanoes, although in some cases, the magma may remain trapped in the continental crust, solidifying to form what is called granite. This process gives rise to **granitic plutons** within the continental crust (Cotton, 1950; Wegener, 1912; Thomas, 2011).

1.2.2.3. Obduction: The collision between two oceanic plates

The denser oceanic plate, typically the older one, sinks beneath the other oceanic plate.
The oceanic plate that sinks into the mantle undergoes disintegration, which can trigger the formation and ascent of magma.
The magma that rises to the surface of an oceanic plate leads to the formation of underwater volcanoes along the boundary between the two plates (Cotton, 1950; Wegener, 1912; Thomas, 2011).

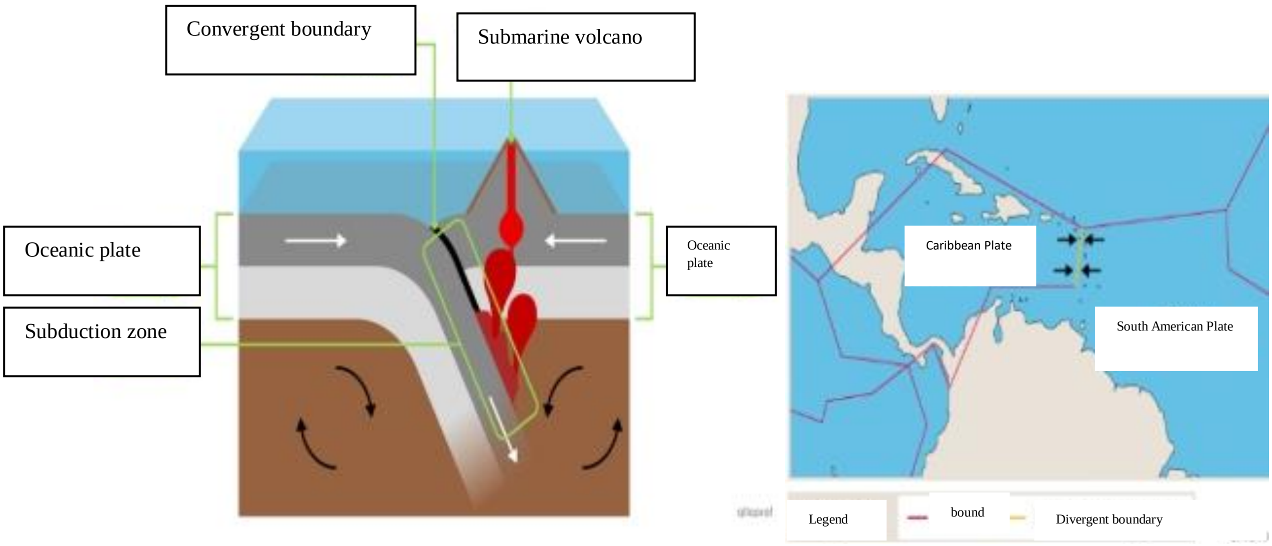


Figure 54: Obduction: The collision between two oceanic plates

1.2.2.3.1.The characteristics of Obduction chains represent the reverse of the subduction process, involving the uplift of oceanic lithosphere above continental lithosphere. A notable example of obduction chain is observed in the collision between the Eurasian plate and the Arabian plate, as exemplified by the Oman chain. Initially, obduction begins with intra-oceanic subduction, where one oceanic lithosphere sinks beneath another oceanic lithosphere, a process known as intra-oceanic subduction. This phase of intra-oceanic subduction continues until the subducted oceanic lithosphere is exhausted, marking the complete end of subduction for that oceanic lithosphere. At this stage, when subduction reaches the continental margin, it ceases, but ongoing tectonic forces lead to the uplift of the oceanic lithosphere onto the continental lithosphere (Cotton, 1950; Wegener, 1912; Thomas, 2011).

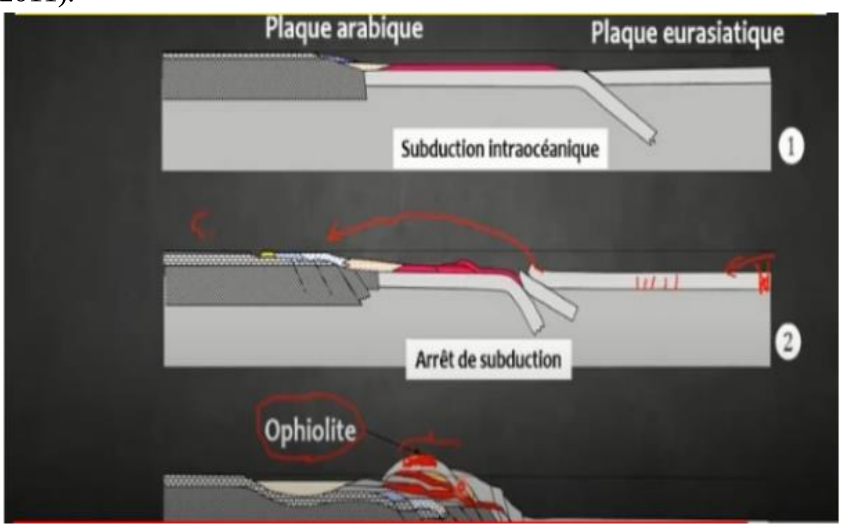


Figure 55: The characteristics of Obduction chains

This phenomenon leads to **the formation of what is called an ophiolite**, **a complex that characterizes** oceanic crust and is exclusively found at oceanic ridges, not forming in continental regions. Thus, the presence of an ophiolite in a continental zone indicates an obduction process, suggesting that oceanic lithosphere has been uplifted above continental lithosphere. Obduction chains are distinguished by the widespread distribution of the ophiolite complex, indicating an abundance of ophiolites, as well as the frequent occurrence of thrust faults and nappe structures. **These nappe structures** involve the displacement of certain rocks away from their original location.

-Indications of subduction can also be observed in obduction zones because obduction is always preceded by subduction. During subduction, the partial melting of rocks leads to the formation of magma, which, after solidification, can appear as granite masses. Therefore, the presence of these granite masses provides evidence of previous subduction prior to obduction, illustrating the connection between these two geological processes (Cotton, 1950; Wegener, 1912; Thomas, 2011).

1.2.2.4. The collision between two tectonic plates occurs when they are moving towards each other. The boundary between two colliding tectonic plates is called a convergent boundary.

-In the case of a collision between two continental plates, neither plate is dense enough to sink beneath the other. As a result, both plates compress and uplift, forming high mountain ranges (Cotton, 1950; Wegener, 1912; Thomas, 2011).

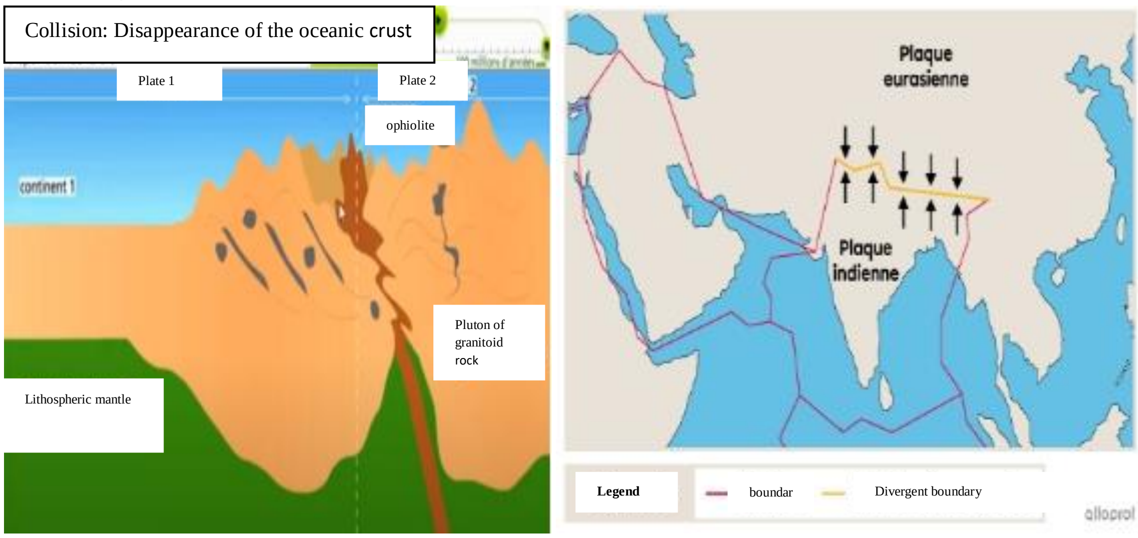


Figure 56: The collision between two tectonic plates

Collision chains occur when two continental masses, represented here as continent 1 and continent 2, collide. The process of approach between these two continents is initiated by subduction, a phase where subduction leads to earthquakes and partial melting of peridotite. This subduction process continues until the subducting lithosphere is exhausted, meaning that the lithosphere moving towards the continental lithosphere is fully buried. At this stage, the burial stops, the partial melting ceases, and magma consolidates, forming granitic plutons (Thomas, 2011).

The collision of the two continents results from this phase, giving rise to collision chains. It should be noted that a portion of the lithosphere, originating from the oceanic crust, becomes trapped between the two continental masses. Within the collision chains, a section of oceanic crust is also captured, leading to the emergence of ophiolites, which are exclusively found in collision chains (Wegener, 1912;Thomas, 2011).

During these collisions, marine sediments become trapped between the two rocky masses, indicating that this area was once occupied by an ocean. In the case of collision, the ocean tends to disappear due to the approach of the two continental masses (Cotton, 1950; Wegener, 1912).

1.2.2.4.1. Characteristics of collision chains include the presence of ophiolitic sutures, the specific location of the chain, and the high intensity of tectonic deformations.

-Ophiolitic sutures form between the two rocky masses involved in the collision. It is important to make a distinction in the distribution of ophiolites between subduction chains and collision chains. In obduction chains, ophiolites cover the entire chain, while in collision chains, although they exist, they do not extend across the entire chain. **The location of the chain** is specified by its position between two continental margins.

-The violence of tectonic deformations within collision chains is marked by considerable amplitudes, indicating powerful tectonic forces at work. These tectonic deformations manifest as substantial modifications in the geological structure of the region.

-Friction between two tectonic plates occurs when they are moving in parallel but opposite directions. The boundary between two tectonic plates in friction is called a transform boundary.
The plane along which two tectonic plates slide past each other is called a fault. Friction along the fault releases enormous amounts of energy, which can lead to earthquakes.
The San Andreas Fault is a zone of friction at the boundary between the Pacific Plate and the North American Plate. The large amounts of energy released by the movement of these plates are the cause of numerous earthquakes in California (Cotton, 1950; Wegener, 1912; Thomas, 2011).

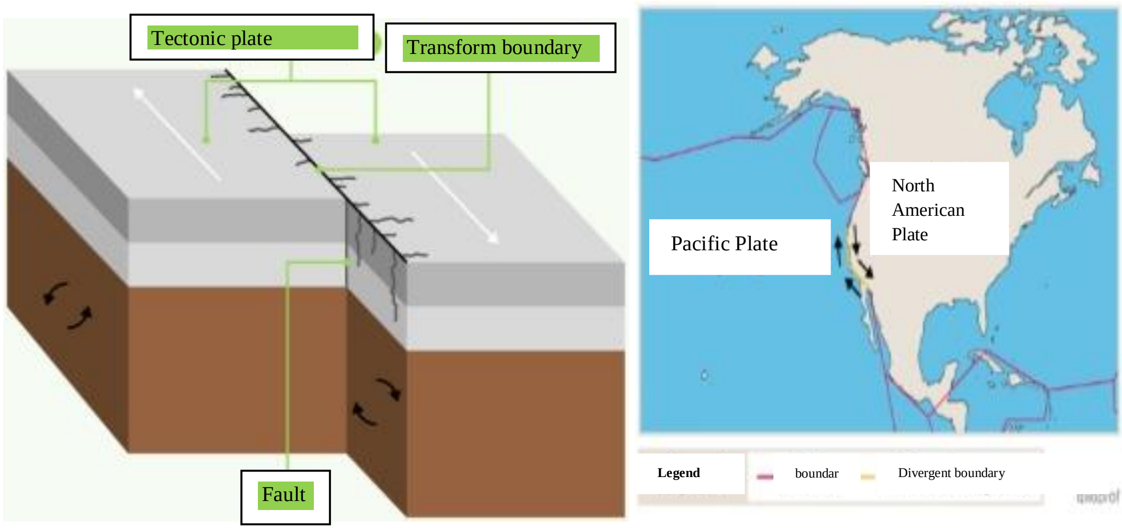


Figure 57: Characteristics of collision chains

1.2.2.2. Regarding tectonic deformations, two major types are discussed: faults and folds.
Faults, whether normal or reverse, result from forces of divergence or convergence between rock masses. Normal faults cause expansion, while reverse faults lead to shortening and thickening of rock layers, often associated with the formation of mountain ranges.
Furthermore, **folds** are continuous deformations without rock rupture and are considered ductile formations. In addition to faults and folds, other minor deformations, such as thrust faults and nappe de charriage (overthrust sheets), are mentioned. Thrust faults involve the uplifting of one rock mass over another, while nappe de charriage results from convergent forces, causing the displacement of one rock mass over another, often influenced by factors such as erosion (Cotton, 1950; Wegener, 1912; Thomas, 2011).

Chapter 4: External Factors of Morphology

The Earth's crust undergoes lateral and vertical modifications resulting from two types of phenomena. On one hand, internal geodynamics encompasses deep movements related to orogenic or tectonic stresses. On the other hand, external geodynamics involves erosive or sedimentary processes. In geomorphology, the explanation of landform shapes always relies on an analysis, at least qualitatively, of the erosion processes responsible for sculpting rock volumes and transporting debris to their final deposition sites, thereby contributing to the formation of accumulation plains.

1-Definition of Erosion:

Erosion is a physical phenomenon that shapes the landscape, primarily through the action of agents such as wind, water, temperature variations, and gravity. Due to the diversity of structural components, rock responses to erosion vary. For instance, shales are highly susceptible to regressive erosion caused by water, unlike sandstones, which are porous rocks facilitating water infiltration. Limestones, on the other hand, are sensitive to dissolution and, in the presence of fractures, to frost action, etc. These variations in responsiveness to erosion based on lithologies and geological structures are collectively referred to as differential erosion.

1.1-The modalities of erosion encompass various manifestations of the erosion process in the field. The main modalities include water erosion, induced by water through runoff, river erosion, and coastal erosion due to waves. Wind erosion, caused by the wind, is characterized by the movement of soil particles, forming sand dunes and altering the landscape. Glacial erosion, associated with glaciers, sculpts the terrain by moving rocks and creating glacial formations. Thermal erosion, resulting from temperature variations, can cause rock exfoliation. Anthropogenic erosion, caused by human activities such as deforestation and urbanization, alters vegetation cover and the landscape. Finally, chemical erosion involves the dissolution of rocks through chemical processes, such as the dissolution of limestone rocks by acidic water. Understanding these modalities is crucial for implementing conservation and sustainable land management strategies (Cotton, 1948).

1.2-Erosion Process

The erosion process is complex and involves several stages. Here is a general description of the main erosion processes:

-Detachment: Soil particles are detached from their original location. This can occur due to various factors such as rain, wind, waves, or water runoff.

-Transport: Particles are transported to other locations by erosive agents such as water, wind, glaciers, or waves. The type of transport depends on the environment; for example, water transport can occur through surface runoff or in river channels.

-Sedimentation: When erosive agents lose their energy, transported particles begin to settle. This sedimentation process can occur in rivers, lakes, oceans, or even on hillslopes.

-Compaction: Deposited sediments often undergo a compaction process, where pressure from upper layers leads to a reduction in spaces between particles.

-Weathering: This process involves the disintegration or modification of the characteristics of rocks and soils due to various agents such as temperature changes, chemical action of water, or other substances (Cotton, 1948).

1.3-Formation of Geomorphological Features: Over time, erosion can shape the landscape by creating geomorphological features such as valleys, canyons, dunes, cliffs, etc.

a-Thermal Weathering:

Thermal weathering results from uneven heating and cooling of rocks.

b-Mechanical Weathering:

Water infiltrates into joints, fractures of lesser resistance whose origin is linked to temperature and pressure variations during tectonic movements (Cotton, 1948).

1-Oxidation:

Oxidation is caused by the presence of free active oxygen, and its effectiveness is enhanced when it occurs within an aqueous environment. Oxidation phenomena occur at the expense of almost all ferromagnesian minerals.

Exemple pour un minéral d'olivine : olivine + oxygène -----> oxyde ferrique + silice.

Fe_2SiO_4 + 1/2 O_2 -----> Fe_2O_3 + SiO_2

2-Hydration:

The absorption of water by minerals is observed, particularly in silicates and alumino-silicates, resulting in an increase in volume.

- Plagioclase + Pyroxène + Eau ------------> Amphibole (Hornblende verte)
- Plagioclase + Hornblende + Eau ------------> Chlorite + Actinote

3-Dissolution:

The complete dissolution of minerals by water, accompanied by carbon dioxide which significantly enhances its dissociation power, is observed in salt beds, gypsum, and especially in limestone formations. Example: karstic topography (Cotton, 1948; Birot et *al*,1962).

Elle produit la solubilisation des calcaires et des dolomies sous l'action du CO_2 dissous dans l'eau.

$CaCO_3$ + nbsp; CO_2 + H_2O ----------> $Ca(HCO_3)2$ soluble

4-Hydrolysis:

Hydrolysis, carried out jointly by water containing carbon dioxide, leads to the decomposition of silicates, especially feldspars, which are the most widespread minerals in plutonic (igneous) pockets. Ferromagnesian minerals decompose more vigorously than feldspars (Birot et *al*,1962).

c-Role of Living Organisms:

The role of organisms in chemical weathering should not be overlooked. Plants exert not only a mechanical action through their roots but also a chemical action by releasing organic acids from rootlets, absorbing the mineral elements necessary for their development, emitting oxygen and carbon dioxide, and releasing humic acids during their decomposition (Birot et *al*,1962).

1.4. The Different Types of Erosion:

1.4.1. Erosion on Interfluves, or Sheet Erosion:

Sheet erosion, also known as rill erosion, represents the initial stage of soil degradation by erosion. It is characterized by extensive deterioration of the soil surface, indicating a form of diffuse erosion that is often not very visible from year to year. Distinctive signs of sheet erosion include bare areas with a lighter color and the emergence of rocks at the surface through agricultural tools. This type of erosion primarily affects low-slope areas, leading to the loss of fine elements in the surface layers of the soil.

The landscape resulting from sheet erosion consists of eroded surfaces exposing the bedrock, interspersed with areas where silts and fine sands accumulate. A frequent network of small, anastomosing channels, characterized by sheet flow with a depth not exceeding 1 cm, is often observed. This process gradually contributes to soil degradation and can have significant repercussions on the local ecosystem (Cotton, 1948; Pardé, 1951; Birot, 1981).

Figure 58: Erosion on Interfluves, or Sheet Erosion

1.4.2. Wind Erosion:

Wind erosion is a geological process influenced by the action of the wind, which transports and erodes soil particles, contributing to the formation of distinctive geological features. A key aspect of wind erosion is deflation, a phenomenon where the wind can only move fine particles, such as silts, at a speed of about 3 m/s, while sands require a speed of about 10 m/s (Pardé, 1951).

As part of erosive action, there are two types of wind erosion:

C1-Examples of Wind Erosion by Corrosion:

Wind erosion by corrosion involves quartz grains transported by the wind, polishing residual rocks characterized by flat facets joined by blunt angles

Figure 59: Wind Erosion by Corrosion. Death Valley (USA)

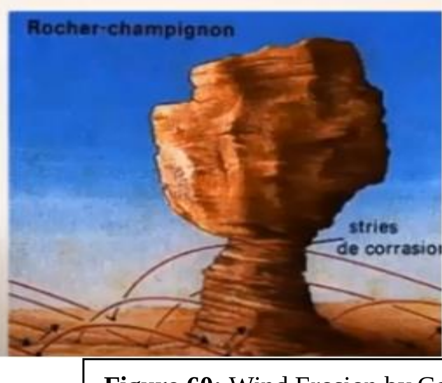


Figure 60: Wind Erosion by Corrosion Sinai (Egypte)

C2-Examples of Wind Erosion by Abrasion: The wind transports elements like sand, for example, which cuts and polishes the surface of exposed rock, generating wind-carved patterns on the surface. This process creates distinctive rock forms known as ventifacts, **yardangs**, tafoni, and mushroom rocks.

***Yardangs:**

Yardangs are rock formations resulting from wind erosion in desert regions. These structures, which can take the form of columns or pillars sculpted by the wind, are eroded ridges in cohesive materials. Several processes contribute to the formation of yardangs, including wind **abrasion**, deflation, fluvial incision, desiccation features, weathering, and mass movements.

Abrasion is significant in the lower parts of yardangs, indicated by polished slopes, flutes, sand-stripped slopes, and undercutting on the windward face. Deflation and fluvial incision also play a role, creating initial depressions that channel the wind. The steep slopes of yardangs facilitate mass movements along their flanks. These formations exhibit a specific ratio of volume, length, width, and height.

Yardangs vary in size, ranging from a few centimeters to several tens of meters in height and several kilometers in length. Formed by strong, unidirectional winds carrying suspended materials, yardangs are characterized by elongated crests, often composed of sandstone, limestone, or consolidated rocks. They can be isolated or clustered in fields, typically larger on the windward side and smaller on the leeward side (Goudie, *et al.,* 1999).

Photos 7:Yardangs Kaluts in Iran

Photos 8: Yardangs Koukour in tunisia

Corrasion refers to the process of shaping rock through the abrasive action of sand grains. Corrasion delineates elongated mounds with aerodynamic longitudinal profiles, sometimes reaching several meters in height, known as "yardangs."

C3-Examples of Wind Erosion by Deflation: Another aspect of wind erosion, deflation occurs when the wind removes fine soil particles, creating depressed hollows. This process eliminates the finest fraction of the soil, leaving behind a rocky desert landscape, also known **as reg.** Deflation is responsible for the formation of vast desert depressions, such as the **chotts** of the Sahara or the playas in American deserts. This phenomenon plays a crucial role in desert morphology and influences the distribution of materials on these desert surfaces.

In wind erosion by deflation, the wind blows, sweeping, dragging, or lifting particles from the ground. There are three types of deflation or transport (explained below): saltation, suspension, and rolling. With this type of wind erosion, three types of deserts can be formed: Reg or rocky, Erg or sandy, and finally, Rocky or mountainous.

***Hamadas** are tabular rocky plateaus in deserts, exposed by wind erosion resulting from deflation, where the wind carries away fine particles, revealing the rocky surface. These plateaus, often of sedimentary origin, are primarily composed of limestone, sometimes covered with sandstone, earning them the name "tassilis." A notable example is the Tassili N'Ajjer in Algeria. These hamadas feature surfaces smoothed by wind erosion, creating a lunar landscape characterized by highly eroded rock formations, sometimes reminiscent of the ruins of ancient cities (Capot- Rey, 1970).

Photos 9: Hammada de Taghit with the Aghlal Mountains

Le Reg: A Desert Landscape

***Le Reg** is a type of desert resulting from deflation, which removes the finest fraction of the soil, leaving behind a rocky desert landscape paved with pebbles. It consists of stretches of rounded stones and gravel, creating particularly inhospitable conditions. This type of desert, also known as "serir" in Libya, is the most widespread. Regions of Reg, such as the Tanezrouft in Algeria, the Ténéré of Tafassasset in Niger, or the Libyan Reg, are only conducive to the survival of a few very rare species, such as the addax and thorny acacia (Capot- Rey, 1970).

Photos 10: Pebble Reg in the Anti-Atlas, Morocco

***Erg: Vast Sand Dune Desert**

Contrary to a rocky desert, L'Erg represents the final stage of relief erosion and consists of an extensive array of sand dunes constantly reshaped by the wind. Although it covers only 20% of the Sahara's surface, the dunes in L'Erg are typically grouped in ridges, several tens of meters wide and can reach over 300 meters in height.

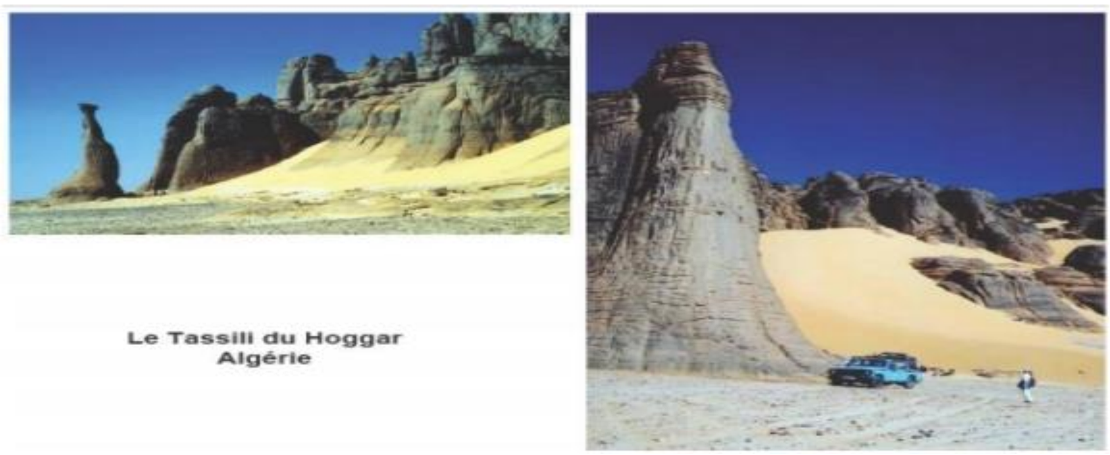
These dunes are continually in motion, shifted by the wind, with sand grains propagating through saltation. Some of the major ergs include the Grand Erg Oriental, the Grand Erg Occidental, the Erg de Mourzouk, the Erg Admer, the Ténéré, the Erg Oubari, the Erg Mehediebat, among others (Capot-Rey, 1970; Coque, 1962).

Photos 11: The Grand Erg Oriental of Tunisia

***Les Playas: Desert Depressions**

Deflation, an aeolian process, is responsible for the formation of vast desert depressions such as the chotts of the Sahara or playas in American deserts. This phenomenon persists until the water table is reached. Playas are flat areas that form when aeolian sediments cover low-lying surfaces.

In deserts, permanent water bodies are rare. When it rains, water runs off the hills, creating temporary rivers in low-lying areas before evaporating or percolating deep into the ground. When these waters reach very flat areas, they may converge and accumulate in a depression, forming a small lake that can persist for some time. What remains after the evaporation or percolation of water are sediments such as clays, silts, and salt, creating a vast cracked surface called a playa (Capot- Rey, 1970; Birot, 1981).



Photos 12: The Tassili of Hoggar in Algeria.

***The term "Chott"** in Arabic refers to a salted land surrounding a closed depression housing a temporary lake. This depression, also called sebkha, is the site of salt precipitation and, consequently, the formation of evaporites. The waters contributing to this phenomenon come from runoff, groundwater, or even periodic inputs of marine water (Capot- Rey,1970; Blanchard et Richard,1890; Encyclopædia Universalis, 2020).

Photos 13: Chott

1.4.3. Linear Erosion (by Running Water)

Linear erosion is characterized by the formation of linear incisions, such as scratches, channels, and ravines, that cut into the surface of the soil. This phenomenon occurs when sheet runoff concentrates, giving rise to channel erosions marked by the concentration of runoff in depressions. At this stage, channels form into parallel streams. This process contributes to the creation of linear features in the landscape, such as gullies, grooves, and canyons, resulting from the concentrated effect of water flowing over the soil. Linear erosion is influenced by various factors, including topography, soil nature, precipitation, and human activities, and can have a significant impact on the terrain's morphology.

In summary, linear erosion encompasses the linear excavations that form when sheet runoff organizes, with channels transforming into parallel streams in the landscape depressions (Birot *et a.l*,1962).

Photos 14 : Linear Erosion (by Running Water)

The main linear erosions are: runoff erosion and calm fluvial erosion, and aggressive torrential erosion.

1.4.4. Runoff and Fluvial Erosion:

Runoff erosion and fluvial erosion are two distinct erosion processes influenced by soil type. In clayey or shale areas, runoff leads to the formation of parallel channels that merge through ridge collapse, creating formations known as "badlands." In limestone areas, wear and rock dissolution by acidic waters create lapiez, excavated surfaces characterized by grooves and sharp blades (Birot *et a.l*,1962).

Runoff erosion occurs when rainwater or snowmelt carries soil particles and other materials over exposed, vegetation-deprived terrain. It can cause gullies, furrows, and alter the landscape, leading to sediment transport to rivers, lakes, and oceans.

Fluvial erosion, on the other hand, results from the movement of water along rivers, carrying materials from soils and rocks to contribute to the formation of valleys and canyons. Factors such as terrain slope, the volume of moving water, and human activities like deforestation can influence this process. The construction of dams and intensive agriculture can also worsen fluvial erosion. In summary, these two processes shape the landscape by transporting materials through the action of water, emphasizing the importance of responsible land and water resource management (Pardé, 1951;Birot *et a.l*,1962).

Photos 15 : Runoff and Fluvial Erosion (Water as the main agent)

Fairy chimneys, or hoodoos, form due to the presence of a highly resistant rock at the top, covering softer rocks below. Mechanical erosion caused by runoff alters the underlying softer rocks, creating characteristic needle-like structures. These formations are common in mountains, especially on steep slopes composed of moraines left by glaciers. These heterogeneous deposits contain resilient blocks that act as a protective cap, as seen in the fairy chimneys of Colorados de Russtrel (Pardé, 1951).

Photos 16 : Fairy Chimney or Hoodoo in Canada (Differential Erosion in Heterogeneous Terrain)

Photos 17 : Fairy Chimneys in Cappadocia, Göreme, Turkey

1.4.5. Periglacial Erosion

Periglacial erosion is a type of erosion that occurs in the peripheral regions of glacial areas, typically in cold environments where permafrost (permanently frozen soil) plays a crucial role. Here are some characteristics and processes associated with periglacial erosion: (Birot, 1981).

-Climatic Context: Periglacial erosion occurs in regions where the climate is cold, with average annual temperatures close to freezing. Subarctic regions and high latitudes are often associated with this type of erosion.

-Permafrost: Permafrost is a key component of periglacial erosion. It is a layer of soil or subsoil that remains frozen permanently. Periodic thawing and freezing of permafrost contribute to erosive processes.

-Freeze-Thaw of Soil: Freeze-thaw cycles are essential processes. When water in the soil freezes, it expands, exerting pressure on the surrounding soil. Upon thawing, this pressure decreases, leading to soil fragmentation.

-Frost Heaving: This is the uplift of the soil caused by the freezing of water in the intergranular spaces. This process contributes to the creation of micro-reliefs and characteristic forms known as "frost heave polygons."

-Cryogenic Landsliding: When masses of frozen soil slide on inclined surfaces, it is referred to as cryogenic landsliding. This can result in the denudation of large areas and the formation of distinctive deposits**.**

-Solifluction: This is a slow movement of water-saturated soil, typically influenced by gravity, occurring on gentle slopes. Solifluction is particularly common in periglacial regions.

-Formation of Deposits: Eroded materials can be transported and deposited as accumulations, such as alluvial deposits and periglacial moraines.

-Wind Erosion: In periglacial regions, wind can also play a role in transporting eroded materials over long distances, contributing to erosion (Pardé,1951 ;Birot, 1981).

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Photos 17: Alpine glacier (The Perito Moreno Glacier in Argentina is one of the only glaciers in the world that continues to grow).

1.4.6. The karst model

This section explains the karst model, a geological phenomenon related to erosion by groundwater in soluble rocks such as limestone, dolomite, and sometimes gypsum. Karst features include an underground network (endokarst) influenced by geological discontinuities, as well as surface forms (exokarst) such as sinkholes, canyons, and shafts. The formation of karst is guided by processes such as the chemical dissolution of soluble rocks by slightly acidic water, forming caves, conduit networks, underground rivers, karst depressions, and speleothem formations.

Key elements associated with the karst model include the geological formation in regions where soluble rocks are present, the dissolution process due to carbonic acid in water, the formation of caves and conduit networks, lapiaz resulting from runoff, karst depressions such as sinkholes, underground rivers emerging at the surface, and speleothem formations like stalactites and stalagmites.

Karst can also manifest at the surface with features such as sinkholes, poljes, and intermittent rivers. Karst landscapes are diverse and spectacular, influencing regional hydrology, biodiversity, and human activities, including water supply (Fénelon, 1954).

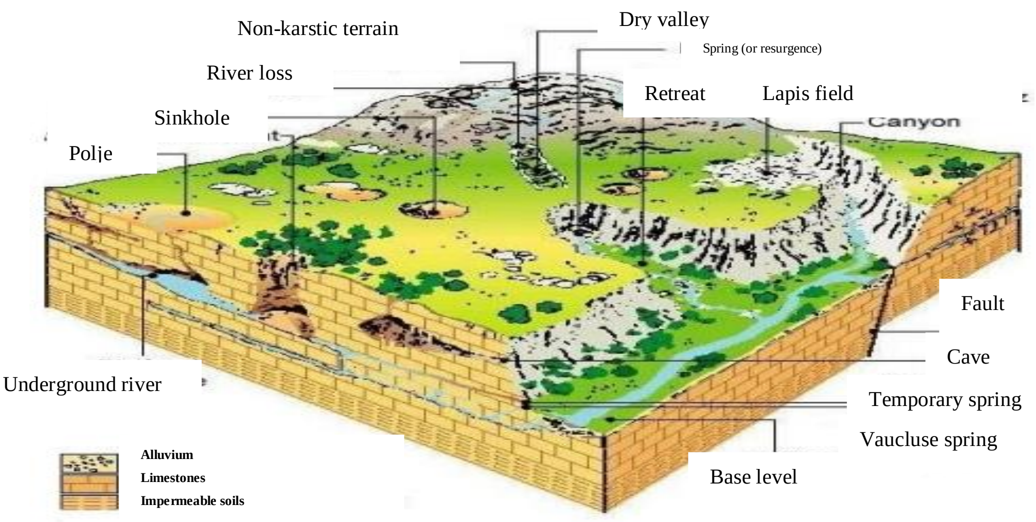

Figure 61: The karst model

1.4.7. Wind-hydro basins: Daya

Wind-hydro basins, also known as "dayas," are circular depressions formed by the on-site weathering of rocks or by the deposition of materials through runoff. These depressions can range in diameter from a few tens of meters to several kilometers. In the context of renewable energy, wind-hydro basins can play a significant role. They may fill with water during precipitation, acting as water catchment areas in arid regions. Furthermore, they can be utilized in pumped hydro storage, where water is pumped into an upper basin during periods of excess electricity to be released later to generate electricity during peak demand. The interaction between natural processes such as rock weathering and wind-driven accumulation, along with human activities in the context of renewable energy, contributes to the morphogenesis of wind-hydro basins. These depressions hold ecological interest, promoting plant growth and can be exploited for agriculture with satisfactory yields due to the presence of some moisture resulting from localized stream convergence. However, intense deflation contributes to the deepening of these depressions.

Wind-hydro basins or deflation basins: Closed circular depressions, often saline, where fine materials produced by weathering (hydro- and haloclasty) are exported by deflation. Example: sebkhas in North Africa and the Middle East.

1.5. Human Impact and Landscape Formation

Soil degradation, through erosion and other factors such as compaction, reduced organic matter, structural deterioration, insufficient drainage, salinization, and acidification, poses a significant problem. Erosion, primarily caused by water and wind, can occur imperceptibly or escalate to alarming proportions, leading to a significant loss of arable soil. Human activities such as urbanization, intensive agriculture, and mining exacerbate the vulnerability of cultivated and pastoral lands. Human-induced changes, such as the conversion of forests into cultivated lands, overgrazing, and anthropogenic pollution, intensify erosion at the expense of valuable surfaces. Bioerosion by living organisms on rocky substrates is relatively limited. Anthropogenic pollution, with its greenhouse gas emissions, also contributes to the erosion of landforms and environmental degradation. The interaction between human action and landscape formation, the process of shaping the landscape, is crucial. Human activities alter the structure and appearance of the natural environment, from local soil transformations to global impacts on ecosystems. Understanding this relationship is essential for sustainable environmental management (Desanges et Riser, 2012).

Chapter 5: Azonal Climatic Geomorphology

1-Climatic Variations: The Quaternary

During the recent geological period known as the Quaternary, spanning approximately 3 to 4 million years, the Earth experienced significant climatic changes. This era is marked by cycles of glaciation, during which ice covered up to 30% of the Earth's surface with thickness ranging from 1500 to 3000 meters. These cycles are dominated by cold periods, alternating between glacial phases and warmer interglacial phases.

Manifestations of these climatic changes include glacier expansion, variations in sea levels, valley carving, alluvial deposits on terraces, freeze-thaw processes, and aeolian deposits. Glacial periods are characterized by modifications in topography, changes in wind patterns, alterations in sedimentary deposits, as well as shifts in fauna and flora.

During glacial periods, sea levels could have dropped by 100 to 200 meters, leading to the carving of "U"-shaped river valleys and the formation of alluvial terraces composed of rounded stones, gravel, and sand. These complex geological modifications reflect the influence of climatic changes on various aspects of the terrestrial environment (Tricart, 1953).

2-Morphological System of Algeria:

The climate in Algeria is diverse due to its vast land area. The northern part has a Mediterranean climate, while the rest of the country experiences a desert climate, and in between, there is a semi-arid climate (Mediterranean climate with a dry period) (Hadjiat, 1997; Desanges et Riser, 2012).

Algeria exhibits a variety of climatic domains that define its distinct ecological characteristics:

2.1-Humid and Subhumid Mediterranean Domain: This area, including Kabylie and the Tell Constantinois, is characterized by rivers, lakes, dams, and a wide variety of bird species. With a typical Mediterranean climate, it features hot and dry summers along with mild and rainy winters. The vegetation is rich, with over 300 species, fueled by high precipitation and significant humidity. Maritime influences contribute to mild winters, with an average of 15°C, and the biological diversity is accentuated by the presence of rivers, lakes, dams, and chotts (Desanges et Riser, 2012).

2.2-Arid and Semi-Arid Southern Domain: Encompassing the high plains of Algiers and Oran, the Hodna Basin, and the Saharan Atlas, this region is characterized by aridity, promoting salt concentration. Poorly evolved soils and the presence of alluvial deposits define this arid domain, where climatic conditions impose specific adaptations on vegetation and animal life.

2.3-Desert Domain: The Sahara, with its stretches of dunes (Eastern Erg and Western Erg), rocky plains (regs), and oases, forms the desert domain. The Saharan Atlas, extending from the Moroccan to the Tunisian border, features NE-SO-oriented reliefs. This desert region is also rich in hydrocarbon resources. Rocky masses like the Eglab Massif in the west and the Hoggar Massif in the east mark the southern boundary of the Algerian Sahara (Hadjiat, 1997;Desanges et Riser, 2012).

3-Evolution of landforms in the three climatic domains related to climates and soil:

The climatic dynamics on the Earth's surface, in constant evolution, experience both warm and cold periods, with a specific focus on the Quaternary, a geological era influenced by variations in the Earth's orbit for approximately 2.6 million years. Dynamic geomorphology, a discipline studying the creation and evolution of landforms at different scales, relies on external agents such as water, temperature, and biogenic agents.

3.1-In a cold climate, mechanical weathering due to freezing predominates, with low chemical decomposition and a cheluviation process enriching the soil with silica. In a temperate climate, various weathering factors come into play, with significant chemical alteration occurring within the soil.

3.2-In a hot and dry climate, mechanical fragmentation is limited, but chemical decomposition intensifies after rare rains, causing significant rock disintegration.

3.3-In a hot and humid climate, mechanical disintegration is minimal, but chemical decomposition becomes highly active due to consistently high temperatures, promoting an increased presence of H+ ions in groundwater (Desanges et Riser, 2012).

Chapter 6: Ecological Preponderances of the Geomorphological Factor

This section addresses the formation and evolution of soils, emphasizing the influence of ecological factors such as climate and vegetation on soil genesis. Ecological factors directly impact all living organisms at different stages of their development. Dynamic geomorphology studies the creation and evolution of terrestrial landforms, with a focus on the interaction between external agents such as water, temperature, and biogenic agents.

Several branches of geomorphology are presented, each focusing on specific factors influencing landform shapes. These branches include climatic geomorphology, fluvial geomorphology, slope geomorphology, wind geomorphology, glacial geomorphology, structural geomorphology, coastal geomorphology, and biogeomorphic domains such as bioweathering and fluvial biogeomorphology. Bioweathering explores the impact of microorganisms on landforms, while fluvial biogeomorphology examines the relationships between geomorphological processes and living communities.

Finally, the section emphasizes the importance of integrating geomorphological and ecological domains, highlighting benefits for both fundamental research and environmental management. It concludes by addressing dynamic geomorphology as a discipline that goes beyond observation, utilizing various measurement methods and modeling to understand erosion processes and landscape evolution (Le juge Stallins, 2006; Urban et Daniels 2006).

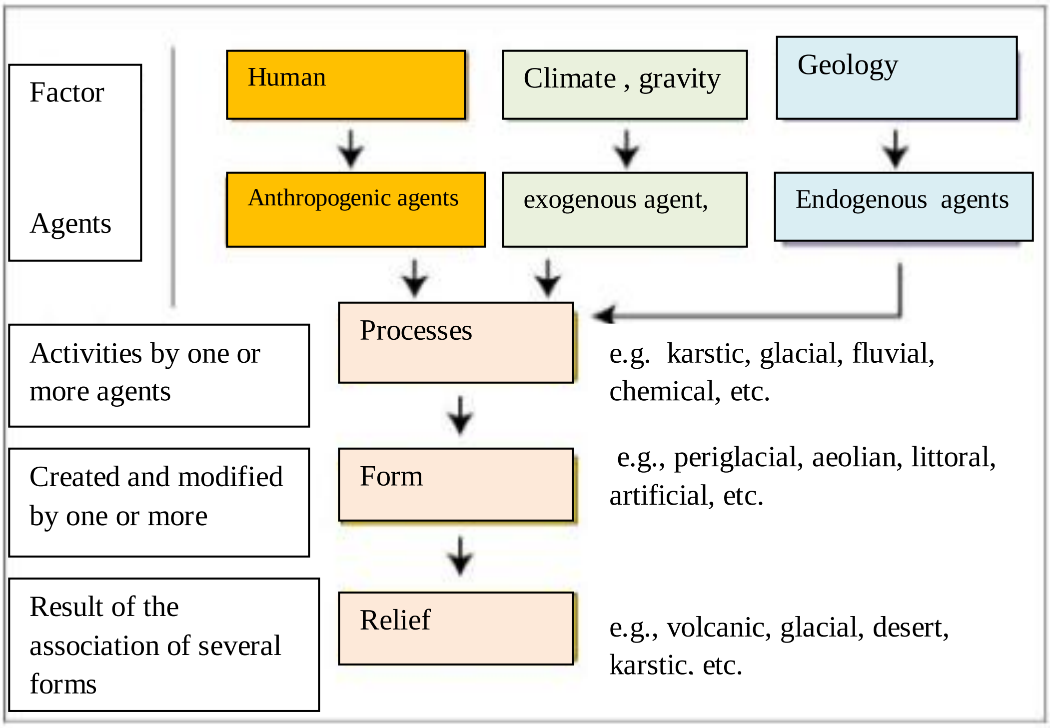

Figure 62 : Ecological Preponderances of the Geomorphology Factor.

Conclusion:

Geomorphology, in constant interaction with ecology, profoundly influences the structure and evolution of terrestrial landscapes. Through this overview, we observe an integrated approach, ranging from basic principles (lithology, erosion) to tectonic processes and external factors shaping landforms. The relationship between geological structures and landform features highlights how geomorphological processes—such as tectonic deformations, various types of erosion, and climatic influences—shape diverse environments, from arid to desert regions, as seen in Algeria.

Each geographic domain exhibits specific morphological characteristics influenced by climatic factors (humid, arid, and Saharan zones) as well as natural and anthropogenic processes. This diversity is essential to understanding the interactions between geomorphology and ecosystems, illustrating how Earth's physical structure impacts ecological dynamics and morphogenesis.

In summary, this exploration of geomorphological and climatic themes underscores the critical importance of these factors in shaping terrestrial forms, driving their evolution, and maintaining ecosystem balance.

Reference

Aubouin, J., Brousse, R., Lehman, J.P. (1968). Précis de Géologie, 3 tomes (Tome 1 : Pétrologie, Tome 2 :Paléontologie-stratigraphie, Tome 3 : Tectonique, Morphologie, Le globe terrestre), éditions. Dunod, 1 ère édition en 1968.

Birot , P., (1940). le relief de cuesta, information géographique, V, n°1,P12-15.

Birot, P., et coll. (1962). contribution à l'étude de la déségrégation des roches, Paris, CDU., 1962, 232P.

Birot, P. (1981). Les processus d'érosion à la surface des continents. Masson, Paris, 608 p.

Boulvain, F. (2015a). Eléments de Sédimentologie et de Pétrologie sédimentaire, Université de Liège (Belgique), 2015, 100 p.

Boulvain, F. (2015b). Une introduction aux processus sédimentaires, Univ.de Liège (Belgique), 2015, 113 p.

Blanchard, R., Richard, J (1890). Sur les crustacés des Sebkhas et des chotts d'Algérie.

Cailleux A., (1977). la geologie, n° 525, 8e éd.,1977P.

Cailleux A.(1974). les roches, : n° 519, 7e éd.,1974P.

Cotton, C.A. (1950). Tectonic scarps and fault valley, Bull.géol.Soc.Am., LXI, p 717-758.

Coque R., (1962). la tunisie présaharienne, Paris, A.Colin, 476p. sur les dépressions fermées, voir p.123-90 ; sur les glacis d'ablation, voir p. 247-309.

Capot- Rey R. (1970). remarque sur les ergs du sahara, Ann.Géogr.LXXIX, n°431,P.2-19.

Coque. R. (1977) .Géomorphologie.1V. PP—1-430.

Coque, R. (2000). «Géomorphologie » Ed. A Colin, coll. U ; 503 p.

Cowles, H.C. (1899).Les relations écologiques de la végétation sur les dunes de sable du lac Michigan. Gazette Botanique 27, 95-117.

Cotton, C. A. (1948). Landscape, as Developed by Processes of Normal Erosion, Second ed., London, Australiaand New Zealand, Whitcombe and Tombs.

Cojan, I. Renard,M. (2013). Sédimentologie, Dunod, 2013, 35 p.

Desanges J., Riser,J. (2012). « Atlas », in Encyclopédie berbère, 7 | Asarakae – Aurès En ligne [archive], mis en ligne le 01 décembre 2012, consulté le 23 février 2015.

Dylik ,J. (1957). dynamical geomorphology, its nature and methods.bull.Soc.Sc.Lettres, Lodz, ch. III, VII, n°12, 1-42P.

Encyclopædia Universalis, (2020). « Chott [archive] », sur Encyclopædia Universalis (consulté le 3 avril 2020).

Fénelon, P., (1954).le relief karstique, Norois, I, 1954, P. 51-77.

Grataloup, C. (2009). L'invention des continents, Larousse, 2009 (ISBN 978-2-03-582594-0).

Goudie, A.S., Stokes, S. et al (1999). Yardang landforms from Kharga Oasis, south-western Egypt. Zeitschift für Geomorphologie, Supplementbände 116: 97-112.

Jules Desnoyers. (1829). « Observations sur un ensemble de dépôts marins plus récents que les terrains tertiaires du bassin de la Seine, et pouvant constituer une Formation géologique distincte », Annales des sciences naturelles, vol. 16, p. 171-214, 402-491.

Jouty, S. et t Odier, H. (2009). Dictionnaire de la montagne, Omnibus, 2009, 883 p. (ISBN 978-2-258-08220-5 et 2-258-08220-X, lire en ligne [archive).

Le juge Stallins (2006). Géomorphologie et écologie : thèmes fédérateurs pour les systèmes complexes en biogéomorphologie. Géomorphologie 77, 3-4, 207-216. La Terre - Mers • Continents • Univers, Cerise Bleue, coll. « Savoir Compact », 2008 (ISBN 978-2-7583-0197-

Macdonald, K. C (1982). « Mid-Ocean Ridges: Fine Scale Tectonic, Volcanic and Hydrothermal Processes Within the Plate Boundary Zone », Annual Review of Earth and Planetary Sciences, vol. 10, no 1, 1982, p. 155–190 (DOI 10.1146/annurev.ea.10.050182.001103, Bibcode 1982AREPS..10..155M)

Marsha, S., (2010). Terre, portrait d'une planète. Traduction de la 3ème édition américaine par Olivier Evrard. 833P.

Marshak, S., (2009). Essentials of Geology, 3rd or 4th Edition:

Hadjiat K., (1997) . Etat de dégradation des sols en Algérie, Rapport d'expertise, Plan National d'Action Environnementale PNAE, Banque Mondiale, Washington DC, 45 p.

Pomerol, Ch., Lagabrielle Y. et Renard M. (2002). Eléments de géologie, éditions Dunod, 12ème édition, 744p.Stern, R. J. (2002). « Subduction zones », Rev. Geophys, vol. 40, no 4, 2002, p. 1012 (DOI 10.1029/2001RG000108).

Pomerol, ch., Fouet R., (1975). Les roches éruptives, n°542, 6e éd., 1975, 128P.

Pomerol, ch., Fouet R. (1974). Les roches sédimentaires, n°595, 6e éd., 1974, 128P.

Pomerol, ch., Fouet R. (1976). Les roches métamorphiques, n°647, 6e éd., 1976, 128P.

Pardé, M. (1951). sur le mécanisme des transports solides effectués par les rivièeres et sur l'altération consécutive des lits fluviaux, Rev, Géogr, alp., 5-40, 289-315, 757-788.

Renard, R., Lagabrielle. Y., Martin, E., de Rafelis, M. (2015). Eléments de géologie : 15é édition du pomerol. 1142 p.

Tricart J. (1953). climat et géomorphologie, cahier inf.géogr., 39-51P.

Tricart, J., Cailleux A. (1964). cours de géomorphologie. Premiere partie : géomorphologie structurale ; Fascicule II. Géomorphologie des régions de platformes.Centre de document universitaire 5, place de la Sorbonne, Paris-V. 252P.

Tricart, J., Cailleux A. (1964). cours de géomorphologie. Premiere partie : géomorphologie structurale ; Fascicule I. Le relief des cotes (cuestas) avec travaux pratiques. Centre de document universitaire 5, place de la Sorbonne, Paris-V. 135P.

Tricart, J., Cailleux A. (1963). cours de géomorphologie. Preiere partie : géomorphologie structurale ; Fascicule III. Le modele des chaines plissées avec travaux pratiques.Centre de document universitaire 5, place de la Sorbonne, Paris-V. 330P.

Thomas, P. (2011). « La tectonique des plaques de 1970 à 2011 : qu'est ce qui a changé dans le modèle et n'a pas (assez) changé dans sa transmission depuis l'époque des pères fondateurs ? [archive] », sur planet-terre.ens-lyon.fr, 9 juin 2011 (consulté le 24 septembre 2018).

Urban M.A., Daniels M. (2006). Introduction : explorer les liens entre géomorphologie et écologie, Geomorphology 77, 3-4, 203-206.

Viers, G. (2003). « Eléments de Géomorphologie ». 2è. éd., Coll. Universités, Ed. Nathan, 208 P.

Wegener, A. (1912). « La formation des continents », Revue Géologique, Journal de Géologie Générale, troisième volume, p. 276-292 (en allemand).

Les liens

https://www.youtube.com/watch?v=Fl6lxfS_AII

http://www2.ggl.ulaval.ca/personnel/bourque/s1/tectonique.pl.html

https://www.alloprof.qc.ca/fr/eleves/bv/sciences/les-plaques-tectoniques-s1375