3. Tectonic deformations

Tectonic deformation refers to the processes by which Earth's crust changes shape, volume, or position due to internal geological forces. These alterations, occurring over vast timescales, directly influence the stability of landforms and subsurface resources crucial for sustainable development. Such geological movements, including folding, faulting, and fracturing, reshape the planet's surface and subsurface architecture. Understanding these dynamics is essential for assessing long-term environmental stability and human infrastructure resilience against natural hazards.

The term 'tectonic' originates from the ancient Greek 'tektonikos,' signifying 'pertaining to building or construction,' reflecting the Earth's crustal architecture. 'Deformation' stems from the Latin 'deformare,' meaning 'to disfigure' or 'spoil the form of.' Together, these terms accurately describe the geological construction and subsequent alteration of Earth's lithosphere, highlighting the powerful, ongoing forces that shape our planet's physical environment.

3.1 Isostatic equilibrium

The concept of **isostasy**, proposed in **1889 by Clarence E. Dutton**, explains why mountain ranges exert less gravitational pull than expected. Isostasy corresponds to a pressure equilibrium in the lithosphere: at a certain depth called the compensation depth, the pressure is the same everywhere, despite variations in surface relief.

This equilibrium depends on differences in density between the materials in the crust and mantle. However, it is characterised by considerable inertia: during rapid changes in load (such as the appearance or disappearance of an ice cap), an isostatic imbalance can persist for a long time.

A current example is Scandinavia, which sank under the weight of the ice cap during the last glaciation. Since the rapid melting of the ice cap around 10,000 years ago, the region has continued to rise by about 1 cm per year. The negative gravimetric anomaly indicates that the readjustment is not complete: there is still a gap of about 200 metres to reach isostatic equilibrium.

https://www.youtube.com/watch?v=3rk2jx3eRDE

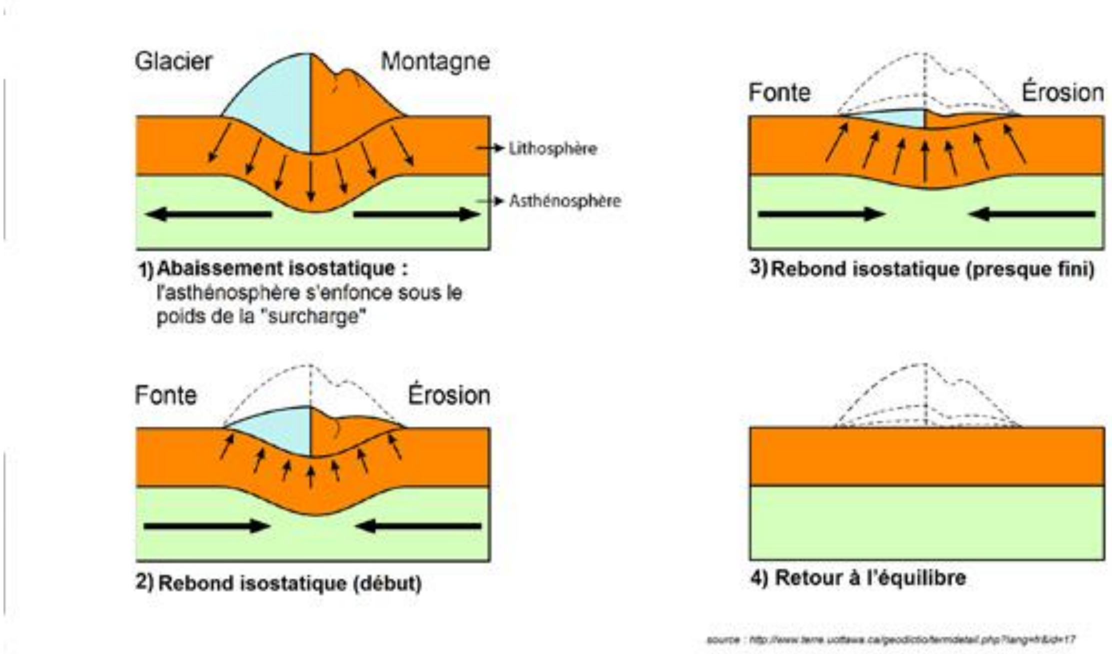


Diagram illustrating isostatic rebound following the melting of ice caps

3.2. Continental drift and plate tectonics

- **Continental drift**

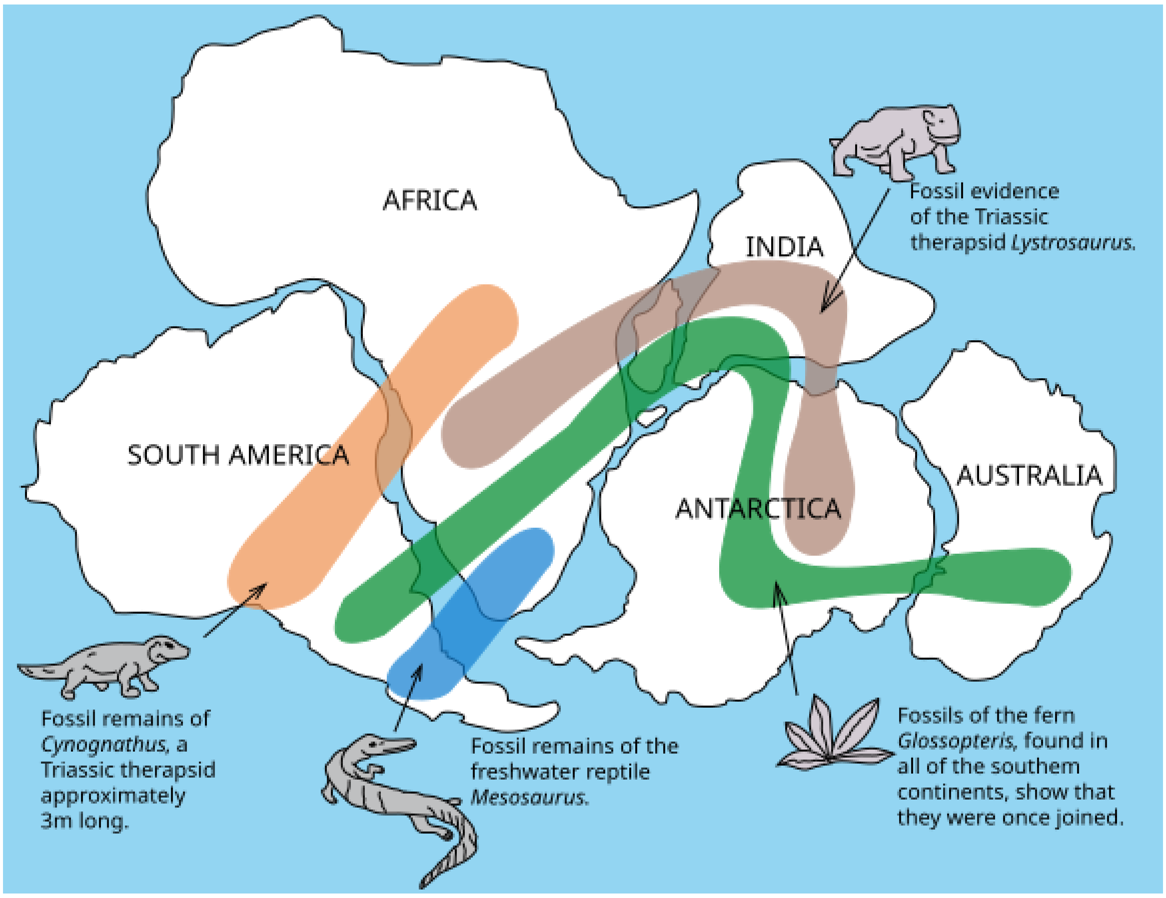
It was not until the early 20th century that German scientist **Alfred Wegener** proposed the idea that the Earth's continents were moving in a process he called "continental drift". He was not the first or only person to formulate this hypothesis, but he was the first to make it public.

Wegener came up with this hypothesis because he noticed that the coasts of West Africa and East South America resembled pieces of a jigsaw puzzle that had broken apart and drifted away from each other. Looking at all the continents, he hypothesised that they had all once been joined together in a single **supercontinent** (later named **Pangaea**) nearly 225 million years ago.

Pangaea is not the only supercontinent that is believed to have existed. It is thought that there may have been others before it.

The concept of moving land masses seems obvious now, but it took several years **for the theory of continental drift** to be accepted. Why? First, Wegener could not convincingly explain the cause of the drift (he thought that the continents moved because of the Earth's rotation, which was later proven false). Second, he was a **meteorologist** (a weather specialist). Geologists therefore believed that he did not know what he was talking about.

Fossil evidence strongly supports the theory of continental drift. Fossils of similar plants and animals have been found in rocks of similar age on the coasts of different continents, which could prove that these continents were once joined together. For example, fossils of Mesosaurus, a freshwater reptile, have been discovered in Brazil and West Africa. Fossils of the land reptile Lystrosaurus have also been found in rocks of the same age in Africa, India and Antarctica.



Map of fossil evidence

- **Tectonic plates**

The theory of plate tectonics is based on Wegener's theory of continental drift. In this new theory, it is the tectonic plates, rather than the continents, that move.

Tectonic plates are pieces of lithosphere and crust that float on the asthenosphere. There are currently seven major plates that make up most of the continents and the Pacific Ocean.

These are :

The African plate

The Antarctic plate

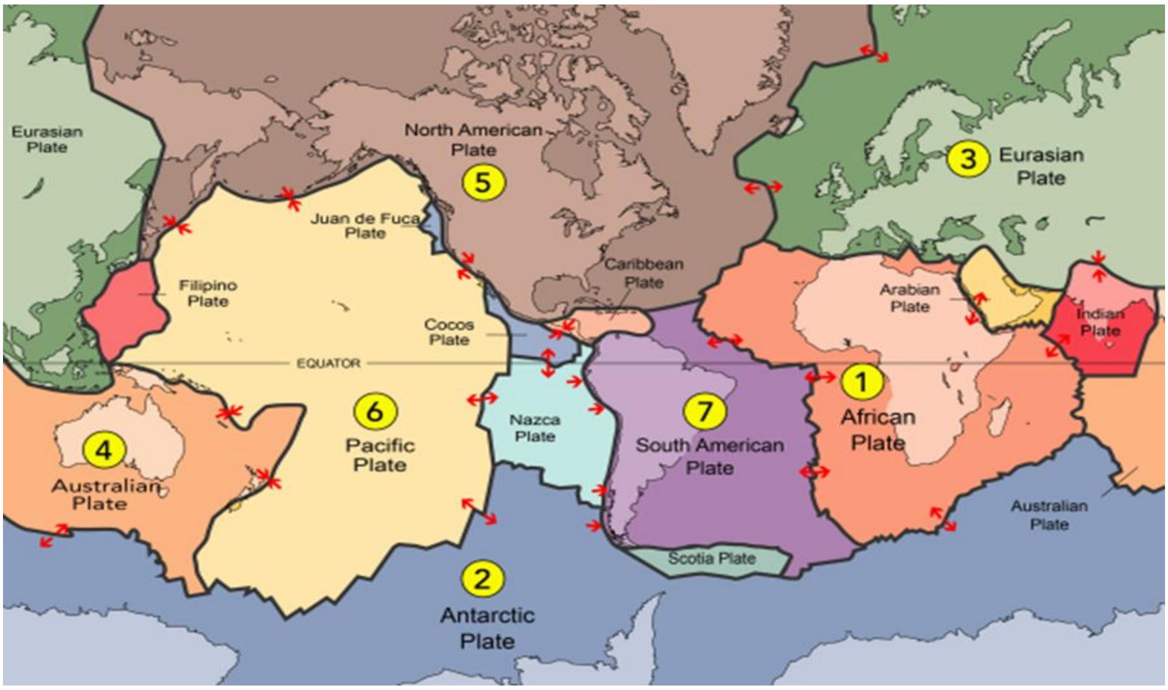
The Eurasian plate

The Indo-Australian plate

The North American plate

The Pacific plate

The South American plate



Tectonic plates

There are eight other smaller secondary plates. There are also other microplates, which are very small.

Geologists accepted the theory of plate tectonics in the late 1950s and early 1960s after understanding the concept of **seafloor spreading**. Seafloor spreading occurs on the ocean floor where oceanic plates are moving away from each other. We say that these plates are **diverging**. When this happens, cracks occur in the lithosphere. This allows **magma** to rise and cool, forming new seafloor.

The opposite of divergence is **convergence**. This occurs when plates move towards each other. The material can push upwards to form mountains or downwards into the mantle. When material from one plate is pushed on top of another, we call this **obduction**. When the material is pushed downwards, we call this **subduction**. The material lost through subduction is roughly balanced by the formation of new oceanic crust through seafloor spreading.

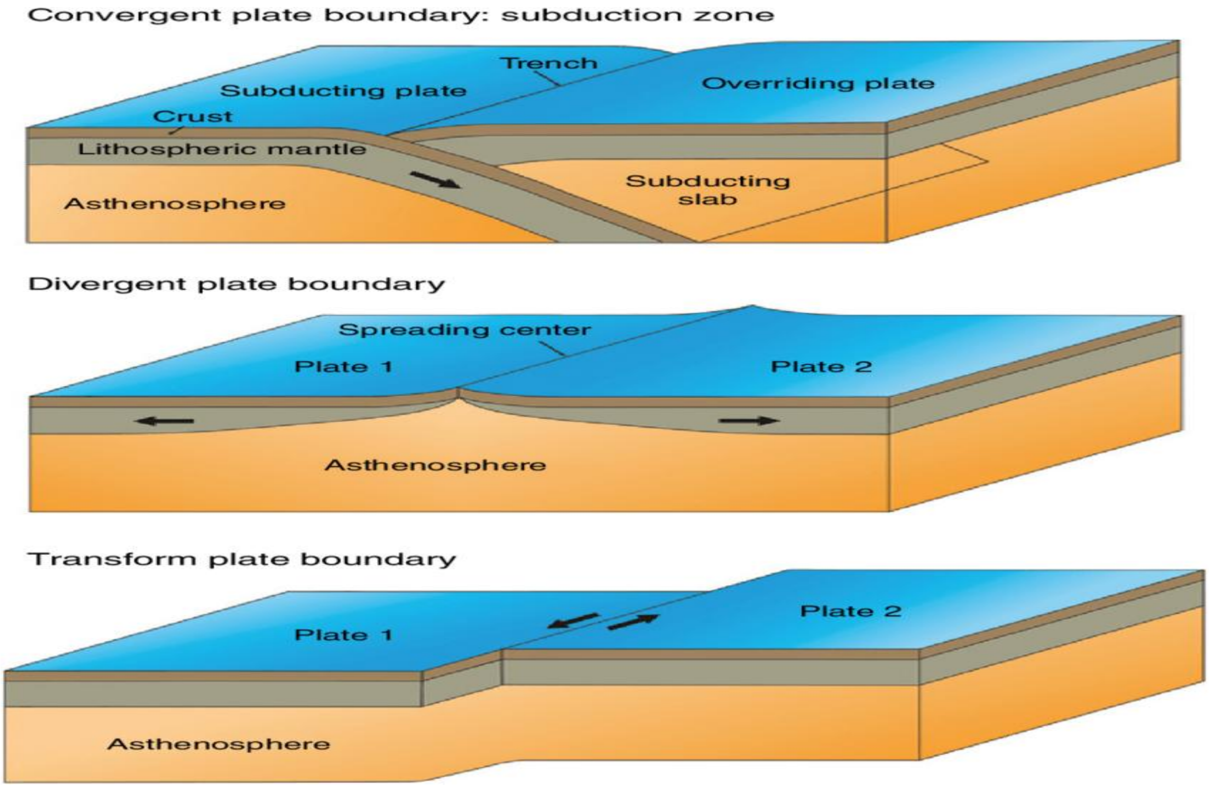


Plate movement

3.3. Relief formation

The formation of landforms is a geological process that shapes the Earth's surface, creating diverse landscapes such as mountains, valleys and plateaus. It results from several natural phenomena that act together to transform the Earth's crust.

The Earth is a dynamic planet, and the formation of landforms is a fundamental process that creates varied landscapes such as mountains, plateaus and valleys. These landforms are the result of complex interactions between several internal and external forces that alter the Earth's crust over time.

Landforms are shaped by a variety of natural causes. Here are the main ones:

Plate tectonics: The movement of tectonic plates can cause mountains to form through orogenesis or create tectonic rifts.

Volcanism: Volcanic eruptions deposit lava and ash, altering the contours of the Earth's surface.

Erosion: Water, wind and glaciers wear away soil and rock, shaping and reshaping existing landforms.

Each of these causes acts over different geological periods, collectively contributing to the Earth's morphology.

Definition of landform formation: geological process that modifies the Earth's crust to create various geographical structures such as mountains and valleys.

Landform formation process: combination of internal forces (tectonic movements) and external forces (erosion) that modify the Earth's surface.

Causes of landform formation: include plate tectonics, volcanism and erosion.

Techniques for landform formation: geological mapping, remote sensing, seismic analysis, computer modelling.

Significance of landform formation: importance for understanding the evolution and dynamics of terrestrial landscapes.

Examples of landform formation:

Mountain: high regions with long, steep slopes connecting high ridges and deep valleys.

Plain: horizontal surface bounded by two slopes of varying steepness, with rivers flowing close to the surface (flat).

Plateau: flat surface or enclosed water where the contour lines diverge at the summit.

Valleys: furrows sloping in the same direction from upstream to downstream. Valleys are the hollows between two mountains.

Vallon: a short, shallow valley.

Hill: circular summit, closed depression basin, highest point of a relief feature, steep relief fan dominating the sea or lake water surface

Island : A body of land surrounded by water. Islands are smaller than continents and can be found in many types of water bodies such as oceans, lakes, and rivers.

Mesa : A naturally elevated, flat-topped area of land with steep sides. It is larger than a butte but smaller than a plateau.

Canyon : A deep, narrow passage bounded by steep cliffs on both sides. Canyons are like valleys but with much steeper walls.

Sand Dune : A hill of loose sand commonly found along coasts and in deserts.

Volcano : A mountain or hill with a crater through which lava is projected.

Beach : gradually sloping land along the edge of a body of water; usually covered with sediments like sand, pebbles, or cobbles.

Butte : a small flat-topped mountain; not as large as a mesa.

Moraine:landform feature created by the loose rocks and sediments plowed into piles by a glacier.

Cave : A naturally formed, underground chamber, below the earth's surface or on the side of a hill or cliff.

Cliff : A steep rock face where the land's surface abruptly drops off.

Isthmus : A narrow strip of land with water on two sides, connecting two bodies of land.

Examples of landform formation

3.4. Tectonic accidents

Tectonics is the study of the deformation of the rocks that make up the Earth's crust.

There are two types of deformations:

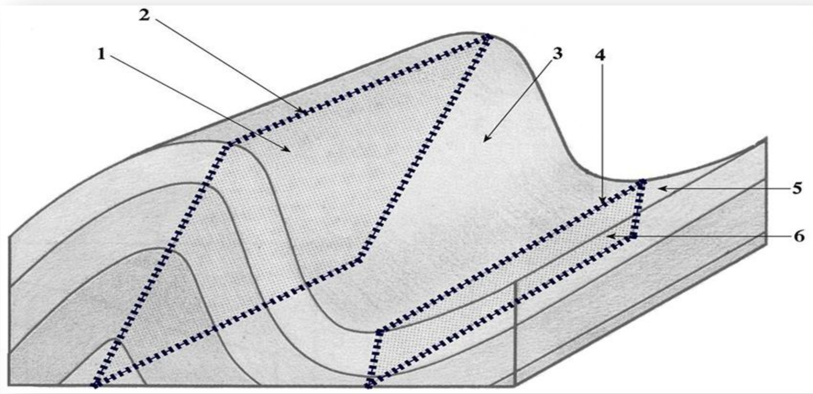
Brittle deformations (faults and fractures)

Flexible deformations (folds).

These two categories of deformation depend mainly on the physical conditions (primarily pressure) exerted during deformation, and on the properties of the rocks (ductility; the ability to deform without breaking).

a) Flexible deformations

When ductile rocks are subjected to tectonic stresses, these rocks generally deform in a flexible (non-brittle) manner. This results in undulations called folds.



1- Axial plane of the anticline fold

2- Anticline hinge

3- Fold flank

4- Syncline hinge

5- Fold flank

6- Axial plane of the syncline fold

Fold elements

The different types of folds :

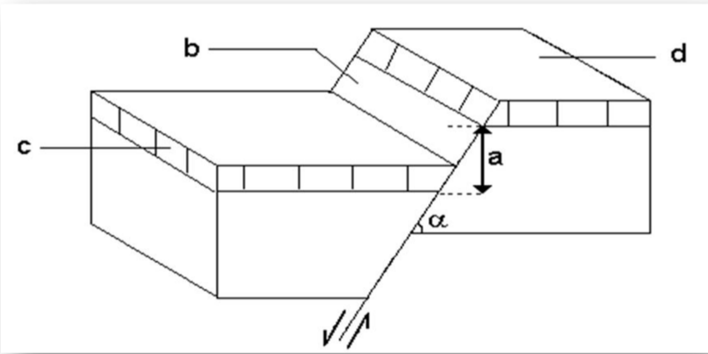
A <u>syncline</u> is a fold whose concavity faces upward.

An <u>anticline</u> is a fold whose concavity faces downwards.

An asymmetrical syncline linked to an anticline on a beach

b) Brittle deformations

A fault is a break in the ground with relative displacement of the compartments thus separated.



a- fault rejection

b- fault mirror

c- upper compartment (roof)

d- lower compartment (wall)

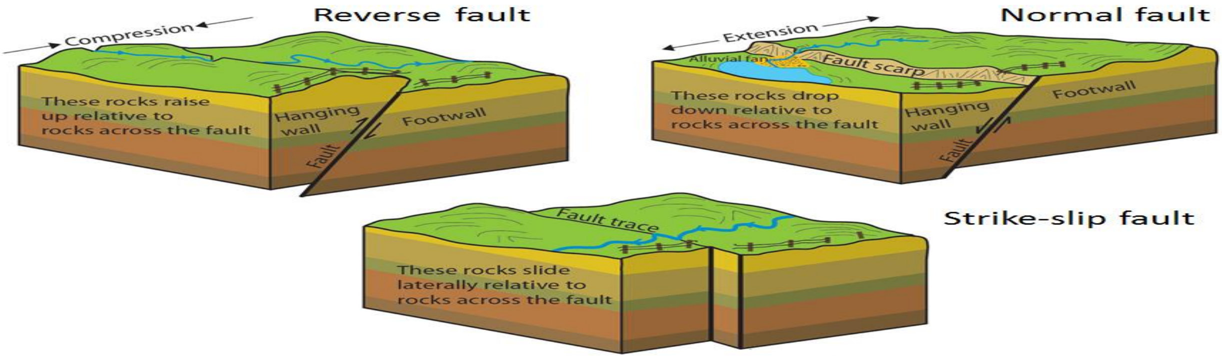
α- fault dip

Elements of faults

The different types of faults

There are three types of faults, depending on the movement of the compartments on either side of the fault.

1. Normal faults : involves a slip that results in the separation of the two compartments.
2. Reverse faults : involves a slip that results in the two compartments moving closer together.
3. Strike-slip fault: An offset fault (offset or detachment fault) involves horizontal slippage of the two compartments in a direction parallel to the fault.

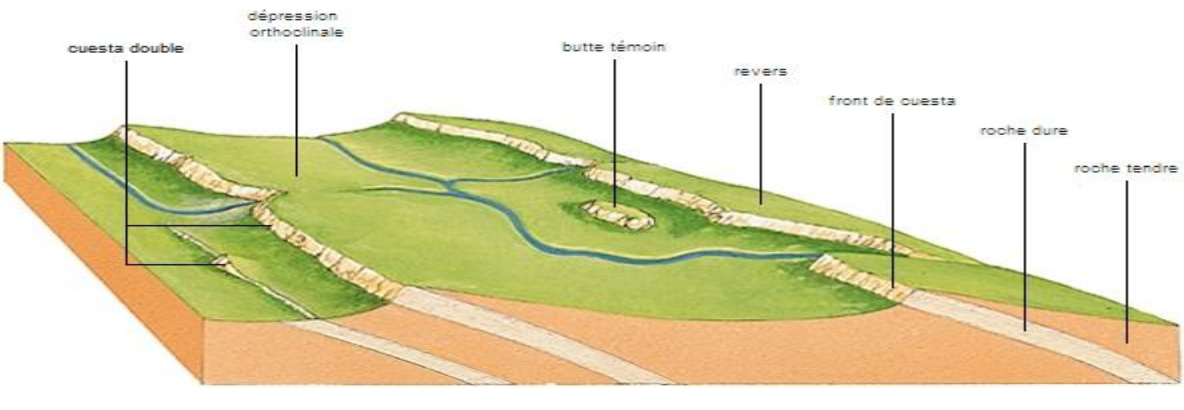


Depiction of reverse, normal, and strike-slip faults.

3.5. Reliefs of simple structures: cuestas

The cuesta relief, a term popularised by W. M. Davis, is characterised by a steep cliff called a cuesta front and a gently sloping reverse side facing in the opposite direction. When erosion exposes a second soft layer on the reverse side, a split cuesta may form, which is distinct from a double cuesta, which has a plateau due to an intercalated resistant layer. In certain geological configurations, the term false cuesta (discordant structure) or pseudo-cuesta (hard sedimentary rock on a soft crystalline base) is used.

Cuestas appear mainly in sedimentary basins, particularly where the layers are well differentiated and arranged in concentric arcs, as in the Paris Basin. In continental basins, more uniform sedimentation limits their regularity. Their formation requires differential erosion associated with tectonic reversal, which interrupts subsidence and allows the dissection of sedimentary series.



Reliefs of cuestas

3.6. Evolution of Jurassic forms

The Jura is a mountain range stretching 300 km between the Rhône and the Rhine, on the border between France and Switzerland.

The Jurassic is the second period of the Mesozoic geological era or secondary era. The Jurassic lies between the Triassic, which is the oldest period of the Mesozoic, and the Cretaceous, which is the third and last period of the Mesozoic. It follows the Triassic and precedes the Cretaceous.

The Jurassic period is divided into three epochs: the Lower Jurassic, the Middle Jurassic and the Upper Jurassic.

Lower Jurassic (Lias):

Located in the depressions of Haute-Saône, in the Avants-Monts anticline or in the Jura-Bresse overlap zone.

Thickness of approximately 200 m, constant from west to east.

Dominant rocks: grey marl with blue marl, schist and limestone.

Abundance of marine fossils indicating deposition in a sea rich in organisms.

Small changes in the marine environment resulted in deposition with varied facies. Terrain suitable for the Savagnin grape variety.

Middle Jurassic (Dogger):

Present on the western plateaus of the range.

Main rocks: limestone with oolite, marl-limestone and some iron ore.

Thickness of approximately 250 m over four stages: Callovian, Bathonian, Bajocian and Aalenian.

Rock visible on the cliffs of the recoils of the outer plateaus of the Jura.

Upper Jurassic (Malm):

Predominant in the massif with a thickness of over 500 m.

Present in the folds of the Haute-Chaîne, in the Petite Montagne, on the internal plateaus of the Jura, the

internal beams, in the plateaus of the Haute-Saône and the plateaus between Doubs and Ognon.

Rocks mainly limestone, sometimes dolomitic, sometimes marly, sometimes compact.

In the Purbeckian, small lignite deposits formed in the Haut-Doubs and Bresse regions.

Dinosaur footprints:

Several dinosaur footprint tracks discovered in the Upper Jurassic of the Jura Mountains. Mainly identified in north-eastern Switzerland, in the Reuchenette Formation (Kimmeridgian). Corresponds to a foreshore environment subject to occasional emergence where dinosaurs left their footprints.

3.7. Reliefs of complex structures

Thrust faults (Reliefs of thrust sheets) :

a vast slab of rock that breaks away and moves horizontally over other geological formations. This phenomenon is often caused by compressive forces resulting from tectonic plate movements. Here are some key characteristics:

- Shear zones can extend over several hundred kilometres.
- They usually form in mountainous regions where tectonic plates meet.
- They are frequently found in the Alps, the Rockies and the Himalayas.

Discontinuous ridges, overlapping series, shear surfaces.

Polyphase reliefs (folds and faults) :

The term ‘polyphasic’ indicates that at least two episodes of deformation affected the region, leaving behind folded and faulted structures inherited from different tectonic phases.

Anterior fold folded or broken by a more recent tectonic phase. Fractured anticlines, inverted synclines, zigzag folds.

Complex metamorphic reliefs :

Are geological features formed by the stretching and thinning of Earth's crust. They are characterized by a domed, uplifted core of hot, deep crustal rocks that has been brought to the surface by a process involving low-angle detachment faults. Above these faults, the upper crust breaks into brittle, tilted blocks that slide away from the dome.

Domes and core-mantle zones (e.g. gneiss surrounded by schist). Metamorphic domes, horns, labyrinthine ridges.

Relief features in areas of ophiolitic or magmatic accumulation:

These are mainly mountain ranges (orogenesis) and volcanoes. Ophiolites are remnants of the sea floor that rise up when tectonic plates collide, forming mountain ranges. Magmatic zones create volcanoes in subduction zones, volcanic mountains and volcanic sea plateaus, which are emerging relief features.

Intrusions + tectonics + differential erosion. Mosaic ranges, granite chaos, tors.