Chapter III

Tectonic Deformation

Introduction

Tectonic deformation involves all modifications in the shape, position, or orientation of rocks due to internal forces within the Earth. These deformations can be **ductile** (without breaking) or **brittle** (with fracturing). They explain the formation of major geological structures such as **folds**, **faults**, and **thrust sheets**.

I.1 Continuous Deformation (Folds):

Continuous deformation occurs when rocks bend without breaking, usually under **compressive stress**.

a) Folds

Folding is a common form of deformation observed in layered rocks (as in Figure 7.1a). Folds occur when an originally planar structure, such as a sedimentary bed, is bent into a curved structure. The bending can be produced by either horizontally or vertically directed forces in the crust, just as either pushing together the opposite edges of a piece of paper or pushing up or down on one side or the other can fold it.

Folds form under varied conditions of stress, hydrostatic pressure, pore pressure, and temperature as evidenced by their presence in sediments, sedimentary rocks, the full spectrum of metamorphic rocks, and in some igneous rocks. Folds may result from a primary deformation, which means that folding occurred during the formation of the rock, or a consequence of a secondary, tectonic deformation.

Slumps in soft sediments and **flow folds** in lavas are examples of primary folds. Structural geology is concerned with the tectonic folds that are produced, in general, by a shortening component parallel to the layering of the rocks. Their spectacular presence in shear zones and mountain belts indicates that distributed, ductile deformation has resulted in gradual and continuous changes in a rock layer both in its attitudes and internally. However, the absence of folds does not demonstrate the absence of pervasive deformation.

Like faults, folds come in all sizes. In many mountain belts, majestic, sweeping folds can be traced over many kilometers (Figure 1). On a much smaller scale, very thin sedimentary beds can be crumpled into folds a few centimeters long (Figure 1). The bending can be gentle or severe, depending on the magnitude of the applied forces, the length of time over which they were applied, and the resistance of the rocks to deformation.

Folds in which layered rocks are bent upward into arches are called **anticlines**; those in which rocks are bent downward into troughs are called **synclines** (Figure 1). The two sides of a fold are its **limbs**. The **axial plane** of a fold is an imaginary surface that divides the fold as symmetrically as possible, with one limb on either side of the plane. The line made by the lengthwise intersection of the axial plane with the rock layers is **the fold axis**. A symmetrical horizontal fold has a horizontal fold axis and a vertical axial plane with limbs dipping symmetrically away from the axis.

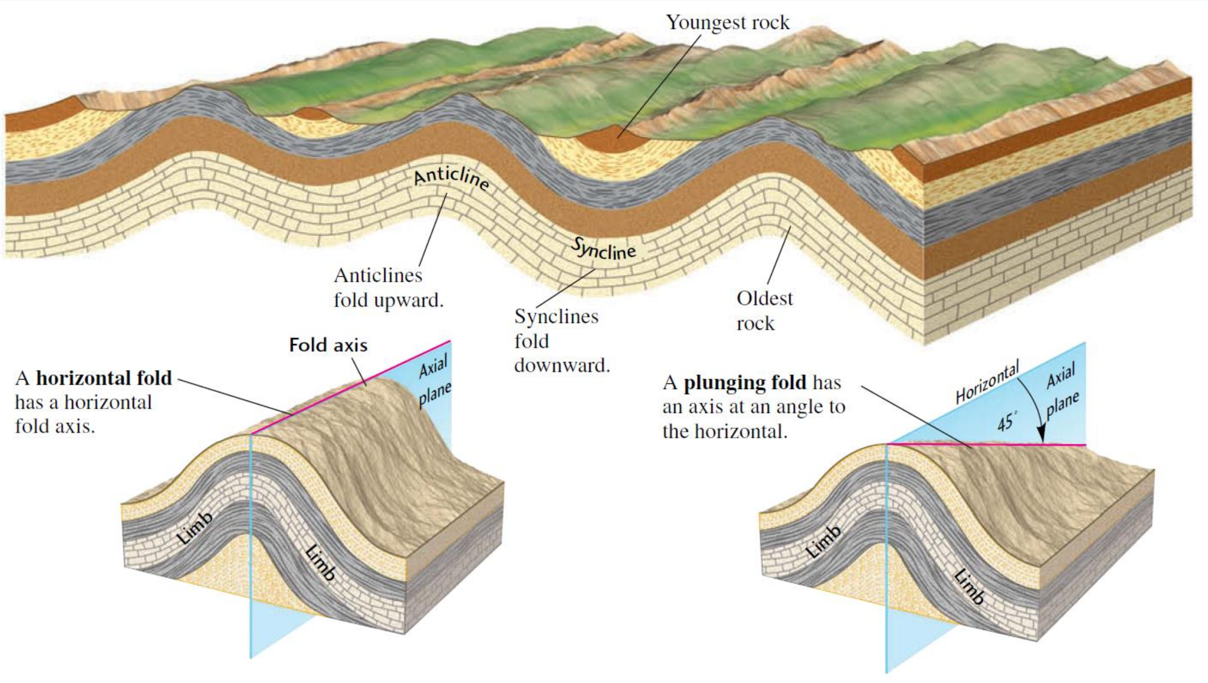


FIGURE .1. The folding of rock layers is described by the direction of folding (upward or downward) and by the orientation of the fold axis and the axial plane.

Folds rarely stay horizontal, however. Follow the axis of any fold in the field, and sooner or later the fold dies out or appears to plunge into the ground. If a fold's axis is not horizontal, it is called a ***plunging fold***. Figure 3 diagrams the geometry of plunging anticlines and plunging synclines.

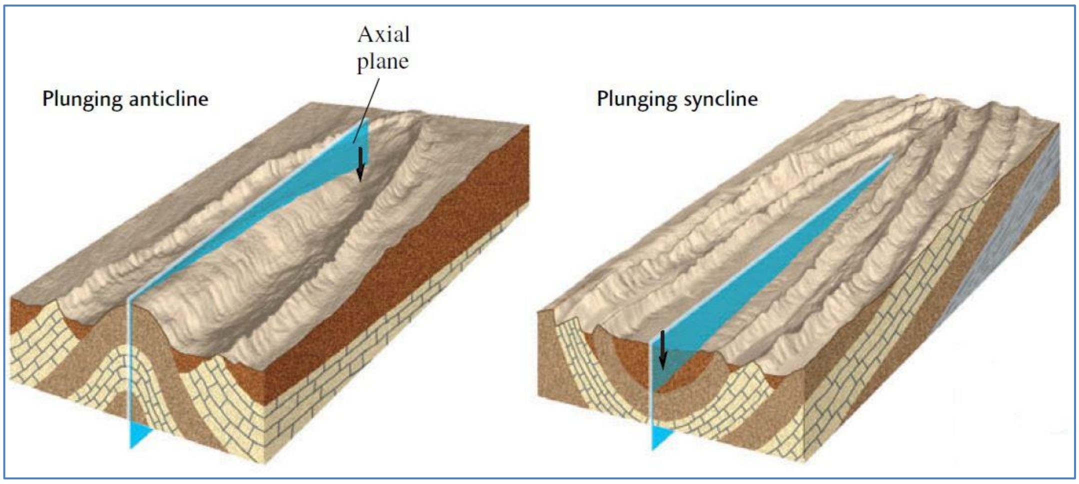


FIGURE 3 .The geometry of plunging folds. Note the converging pattern of the layers of rock where they intersect the land surface.

In eroded mountain belts, a zigzag pattern of outcrops may appear in the field after erosion has removed much of the surface rock from the folds. The geologic map in Figure 4 shows this characteristic pattern. Nor do folds usually remain symmetrical. With increasing amounts of deformation, folds can be pushedinto asymmetrical shapes, with one limb dipping more steeply than the other (Figure 4).

Such ***asymmetrical folds*** are common. When the deformation is so intense that one limb has been tilted beyond the vertical, the fold is called an ***overturned fold***. Both limbs of an overturned fold dip in the same direction, but the order of the layers in the bottom limb is precisely the reverse of their original sequence that is, older rocks are on top of younger rocks.

Observations in the field seldom provide complete information about folds. Bedrock may be obscured by overlying soils, or erosion may have removed much of the evidence of former structures. So geologists search for clues they can use to work out the relationship of one bed to another.

For example, in the field or on a geologic map, an eroded anticline might be recognized as a strip of older rocks forming a core bordered on both sides by younger rocks dipping away from the core.

An eroded syncline might appear as a core of younger rocks bordered on both sides by older rocks dipping toward the core. These relationships are illustrated in Figures 4 and 3. Determining the subsurface structure of folds by surface mapping has been an important method for finding oil, as described in the Practicing Geology exercise at the end of the chapter.

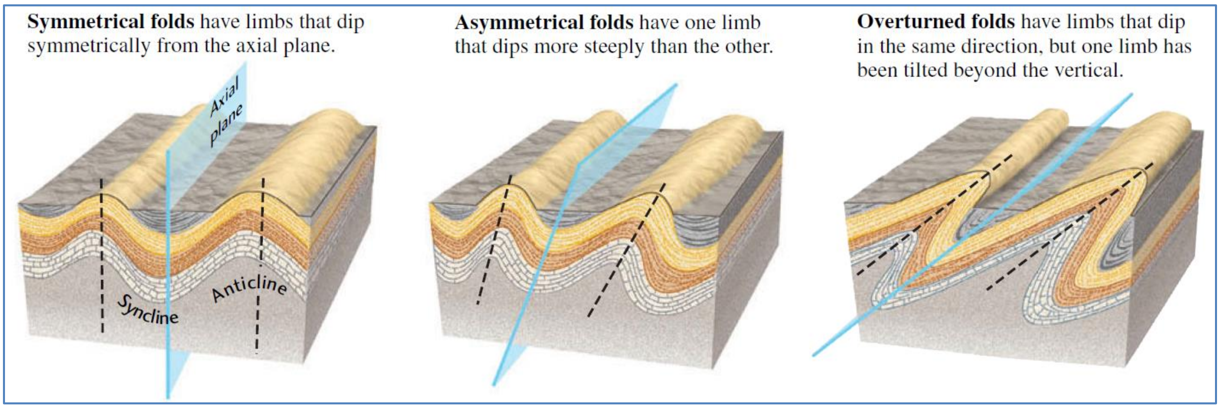


FIGURE 4 . With increasing deformation, folds are pushed into asymmetrical shapes.

Conclusion

A fold is a bend in a layered rock caused by compressive stress (buckling) or passive draping of layers over a deeper structure (including normal faults) or around a resistant object.

Folds display a wide range of shapes and result from a wide range of processes that all largely reflect the rock behavior. Therefore, geometrical characteristics commonly change within the same fold from layer to layer.

Folds represent a large-scale flow of material and record periods of rock deformation. Therefore, generations need to be distinguished and dated. For these reasons, structural geologists have to document the layer configurations as clues to conditions of deformation and folding history. This information has economic and geologic hazard applications; folds form associated with faults and thus can signal earthquake hazards. Folds host ore deposits in hinge areas due to the flow of fluids to those localities (for example, antiforms are hydrocarbon reservoirs).

b) Monocline structures

A **monocline** is a geological structure characterized by **gently inclined sedimentary rock layers dipping in a single direction**, forming a type of **simple flexure** or **local bend**.

Main features:

- **Gentle inflection**: The rock layers remain parallel but are locally bent.
- **Single-direction dip**: The strata tilt uniformly in one direction.
- **“Stair-step” appearance**: The structure resembles a simple step in the landscape.
- **Not a full fold**: Unlike anticlines or synclines, a monocline involves only one bend.

Common causes:

- **Localized uplift** due to tectonic stress.
- **Presence of a deep fault** or **shearing**, causing tilting of the overlying block.
- **Reactivation of ancient basement faults**.

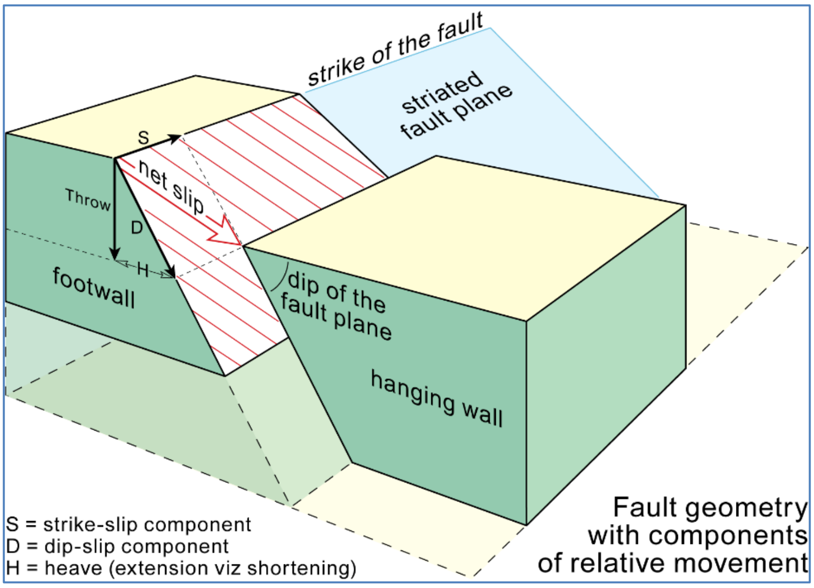
I.2. Discontinuous Deformation: Faults

Discontinuous deformation is associated with brittle rocks that break under stress.

A **fault** is a discrete fracture between blocks of rock that have been displaced relative to each other, in a direction parallel to the fracture plane. A fault zone is a region that contains several parallel or anastomosing faults. Any fault-bounded sliver of rock within a fault zone is called a *horse*. Faults and fault zones are identified either where earthquakes occur or through geological mapping, which shows that movement across a discontinuity has taken place in the past. Geological maps usually show only those faults that affect the outcrop pattern.

a) Elements of a Fault

- **Fault plane**: This is the flat or gently curved surface along which the rock breaks and slips. It represents the zone of rupture where the movement occurs. The orientation of the fault plane (its dip and strike) helps classify the type of fault.
- **Blocks (compartments)**: These are the large masses of rock located on either side of the fault plane. Depending on the direction of movement, one block may move upward, downward, or horizontally relative to the other. The block above the inclined fault plane is known as the *hanging wall*, while the one below is the *footwall*.
- **Displacement (throw)**: This is the relative movement or offset between the two blocks along the fault. It can be vertical, horizontal, or oblique, and its magnitude helps determine the amount of deformation the area has experienced.
- **Fault mirror**: This is a smooth, shiny surface that forms on the fault plane due to friction during fault movement. It often shows linear striations or grooves (called slickensides) that indicate the direction of movement.



b) Fault Nomenclature

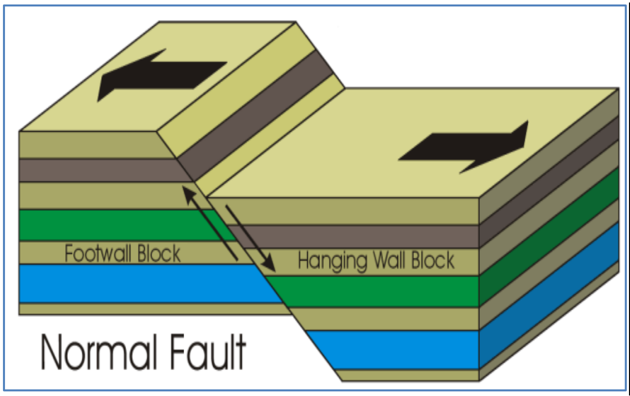
1. *Normal Fault*

A **normal fault** is a high angle, dip-slip fault on which the hanging-wall has moved down relative to the footwall. A normal fault brings younger rocks over older ones. Because of the separation of geological horizons, normal faults are also termed **extension faults**.

Extensional ramps termed detachments cut down section in the direction of transport, although a typical detachment has no roots and follows a stratigraphic horizon. Some call a lag or denudation fault a normal fault with a dip less than 45°.

Key features of a normal fault:

- The block above the fault plane (the *hanging wall*) moves **downward** relative to the block below (*footwall*).
- This type of fault forms under **tensional stress**, when rocks are being stretched apart.
- Common in rift zones or areas of crustal thinning.

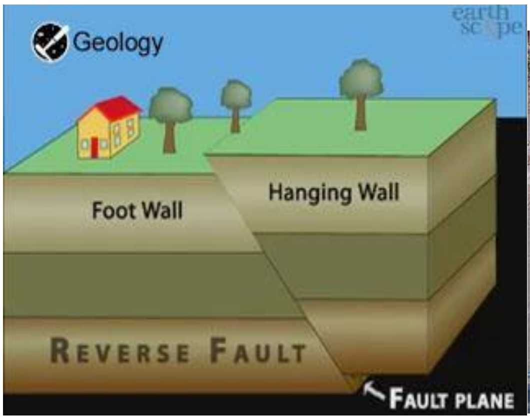


2. Reverse Fault

A **reverse fault** is a dip-slip fault on which the hanging-wall has moved up and over the footwall. Consequently, old rocks lay over younger ones. Such faults produce a repetition or overlap of a geological horizon and are accordingly termed **compression fault**.

Key features of a reverse fault:

- In this case, the hanging wall moves **upward** relative to the footwall.
- It results from **compressional stress**, where rocks are pushed together.
- Typical in mountain-building regions.

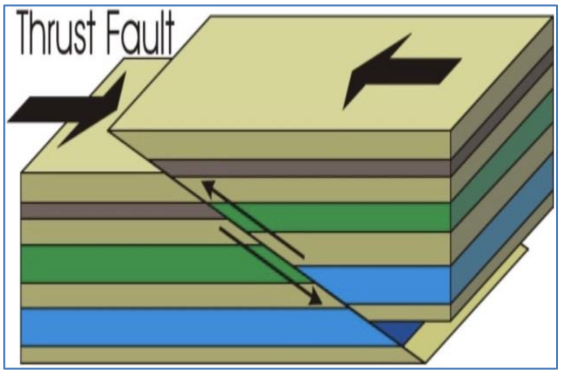


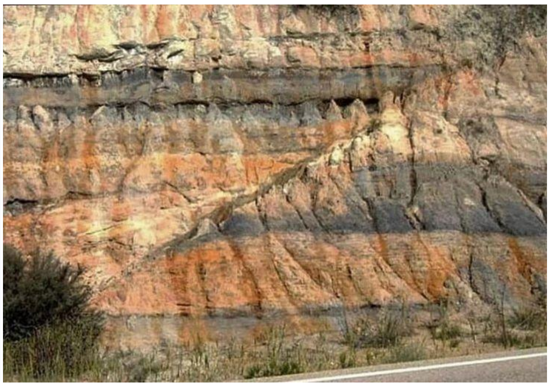
3. *Thrust Fault*

A **thrust fault** is a low-angle reverse fault along which the hanging wall forms **thrust-sheets (nappes)** of allochthonous rocks emplaced over the autochthonous or parautochthonous footwall. Most common, thrust faults ramp up section towards the surface in the direction of tectonic transport.

Key features of a thrust fault

- A special type of reverse fault with a **low-angle dip** (a gently inclined fault plane).
- The movement is mostly horizontal over long distances.
- Characteristic of orogenic belts, where large sheets of rock are stacked.





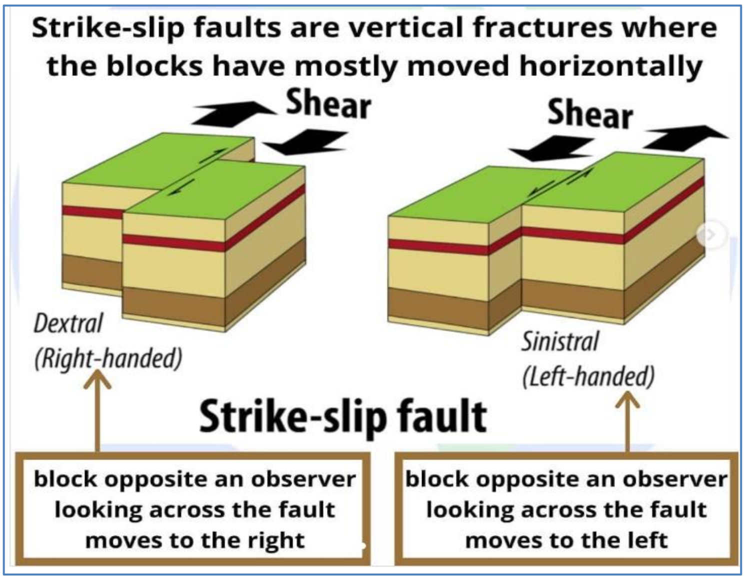
4. *Strike-slip Faults*

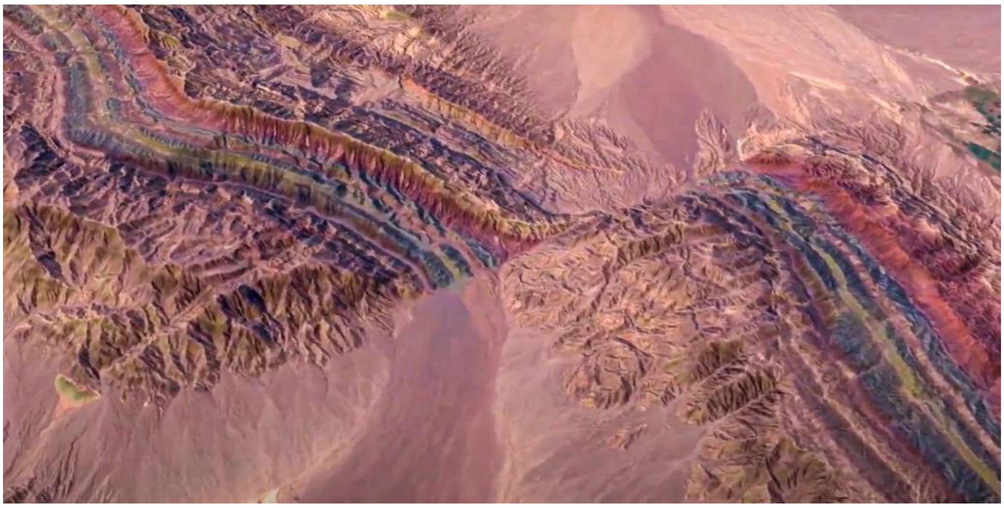
Strike-slip faults usually have very steep or vertical dips and the relative movement between the adjacent blocks is horizontal, parallel to the strike of the fault plane. Large strike-slip faults are referred to as transcurrent faults and wrench faults.

The terms sinistral (left-lateral) and **dextral** (right-lateral) describe the sense of the strike-slip displacement. A fault is sinistral if, to an observer standing on one block and facing the other, the opposite block is displaced to his left. Conversely, the fault is dextral if the movement is to the right.

Key features of a Strike-slip fault

- Here, the movement between the blocks is **horizontal**, along the fault plane.
- There are two types depending on the direction of movement:
  - **Dextral (right-lateral)**: the opposite block moves **to the right**.
  - **Sinistral (left-lateral)**: the opposite block moves **to the left**.
- Common along major transform boundaries (the San Andreas Fault).





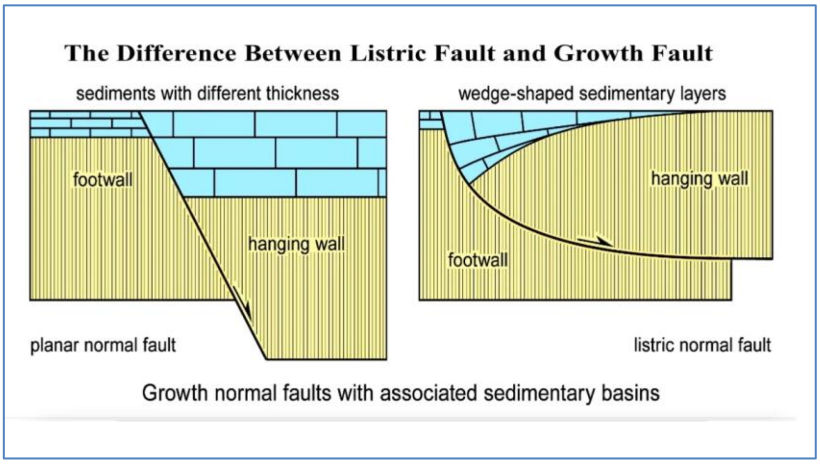
5. ***Other types of faults:***

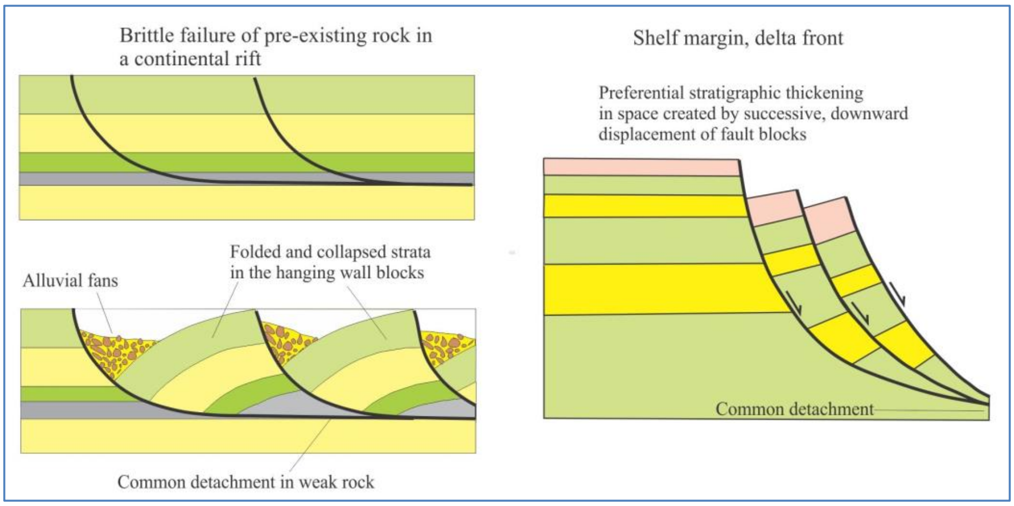
a. **Listric fault:** A **listric fault** is a specific type of fault that shows an upward concave curvature. In other words, its dip decreases progressively with depth, meaning the fault becomes more horizontal as you go deeper into the Earth's crust. This type of fault is commonly found in **rift zones** or **oceanic ridges**, where the Earth's crust is being stretched.

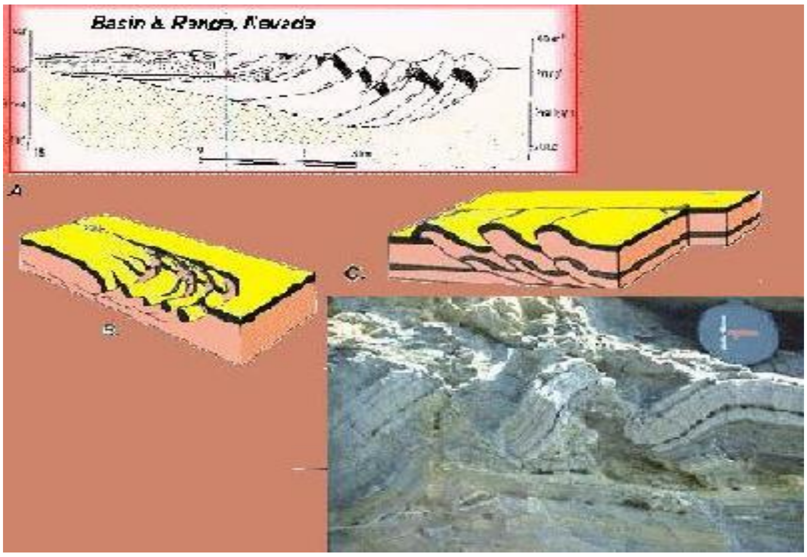
Key features of a listric fault:

- **Concave curvature**: The surface of the fault is curved upwards, and its dip becomes shallower with depth.
- **Movement distribution**: The fault movement is typically vertical in the upper part and becomes more horizontal as you go deeper.
- **Transitioning shape**: It can connect more vertical and pronounced fault segments, transitioning into low-angle faults.

This type of fault is often observed in environments where the Earth's crust is undergoing extensional forces. **Listric faults** are important for understanding deformation mechanisms in rift zones and sedimentary basins.







b. **A crush zone (zone de broyage): A crush zone** is a geological region where rocks have been intensely deformed by shear movement, typically along faults or fracture zones. In these areas, rocks are crushed, fragmented, and often reduced to fine materials such as powders or small debris. These deformations often result from tectonic forces, particularly in active fault zones or subduction zones.

Features of crush zones:

- **Fragmented texture**: Rocks are broken into small fragments or powder.
- **Shear movement**: The relative movement of rock blocks creates intense deformation that crushes the material.
- **Presence of fine materials**: The resulting debris can include breccias or powders, sometimes called **mylonites** when they are strongly metamorphosed.

These zones are commonly observed in strike-slip or compressional fault environments and often indicate significant tectonic activity.

So, a **fault zone** refers to a brittle structure where continuity is lost and slip occurs on multiple discrete faults within a definable band. In contrast, **shear zones** are ductile structures where rocks do not lose continuity and strain is distributed across the band.

A fault zone is typically divided into three components:

1. **Host rock**: Undeformed rock with low fracture frequency (<4 fractures/m).
2. **Transition zone**: Contains undeformed rock but with increased fracture frequency (up to 9 fractures/m).
3. **Fault core**: Characterized by fault rocks or intensely fractured rock, with fault rocks occurring in lenses alternating with relatively undeformed rock.

The width of the transition zone and fault core varies depending on the fault zone size and deformation style, ranging from centimeters to meters. Fault rocks provide primary evidence for the deformational processes, influenced by factors like lithology, strain rate, temperature, pressure, and the presence of fluids. The classification of fault rocks is essential for understanding faulting processes and mechanisms, and Braathen et al.'s (2004) classification scheme is used in this study.

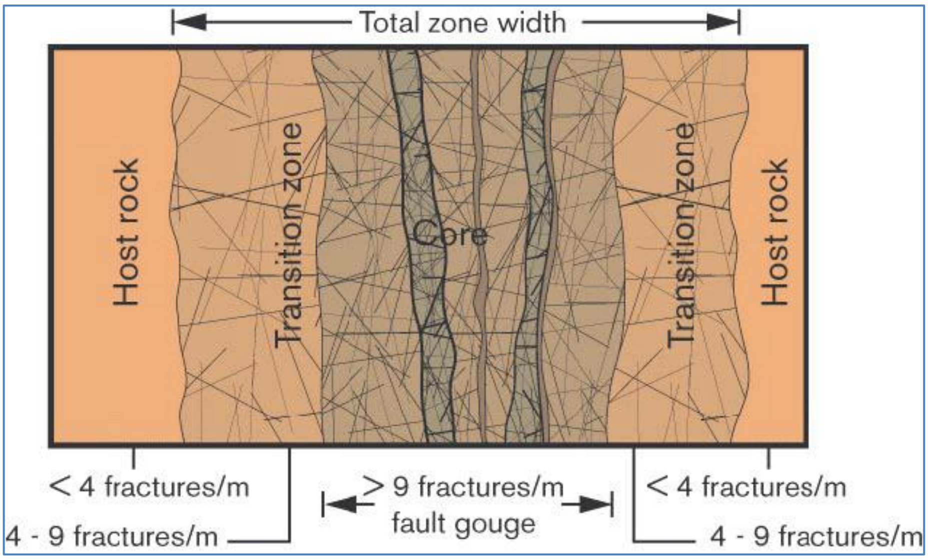


Figure. Schematic illustration of a brittle deformation Fault zone.

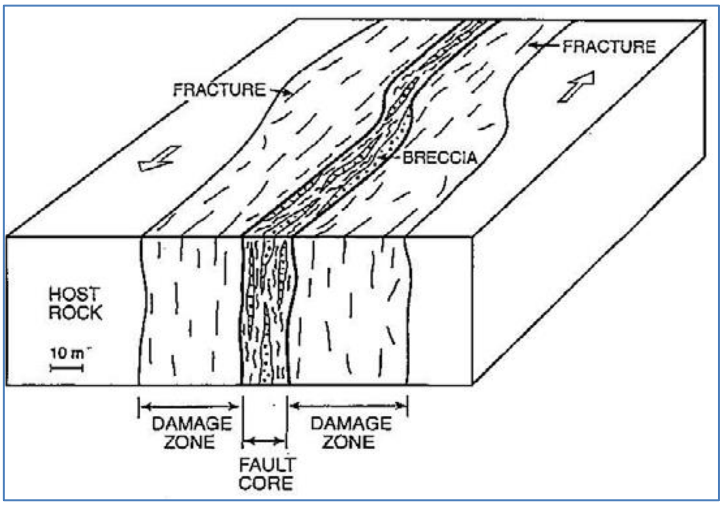


Figure 4-3. Schematic illustration of the architecture of an idealized fault zone.

c) Shear joint, Tension vein (or tension gash) et Joint (or fracture) (Joints de cisaillement, fentes de tension et diaclases)

Shear joints, **tension fractures**, and **diaclases** are geological structures related to rock fracturing caused by tectonic stresses. Here are their key characteristics:

1. Shear Joints

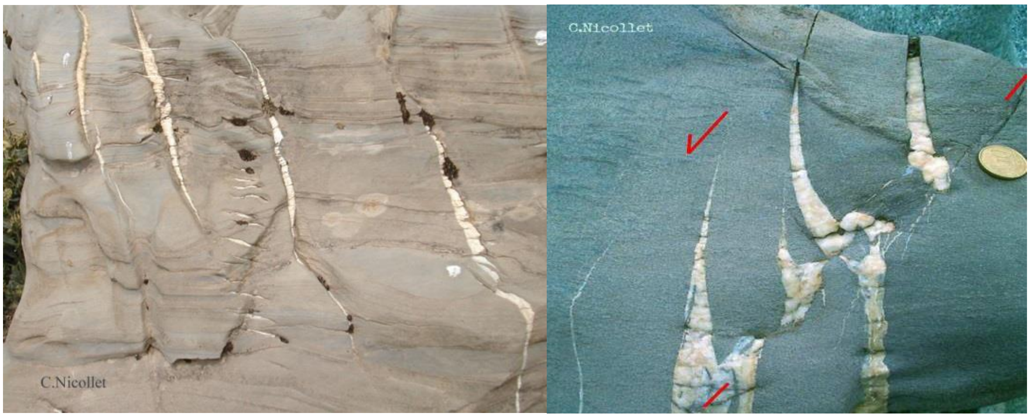
Definition: Fractures resulting from shear stresses (tangential forces). They are often smooth and striated (slickensides) and May show grooves or striations due to block movement. They can be resulted by **compressional or strike-slip tectonic regimes**.

A shear joint is a fracture in rock where sliding has occurred between the two parts, without significant visible separation or opening between the blocks. The displacement is often subtle and parallel to the fracture plane, distinguishing it from more prominent faults. This type of joint reflects shear deformation, often observed in areas subjected to lateral tectonic stress.

2. Tension Fractures

Definition: Fractures formed by extensional stresses (rock stretching). We can say it like an openings perpendicular to the extension direction with irregular edges, often filled with secondary minerals (e.g., calcite, quartz). They origin linked to stress relaxation (e.g., erosional unloading) or extensional tectonics.

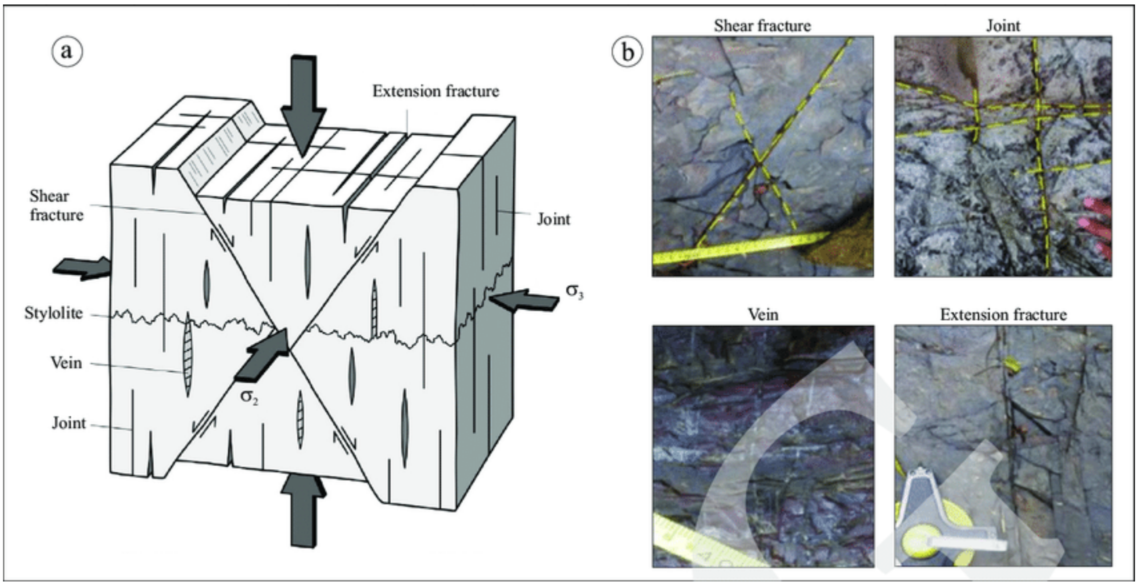
A tension vein is an open fracture in rock, formed under extensional (tensile) stress. It is usually filled later by minerals (such as quartz or calcite) precipitated from circulating fluids. These structures are often oriented perpendicular to the principal stress direction and are indicative of extensional environments.



3. Diaclases (Joint Fractures)

Definition: Fractures without visible displacement, formed by various processes (tectonic, thermal, unloading). They are typically clean and parallel planes and may form orthogonal or parallel networks. Their origin was can be; **Tectonic, Thermal.**

These structures are crucial for understanding a region's tectonic history and rock properties.



I.3 Thrust sheets (Les nappes de charriage)

Thrust sheets (or nappes) are large geological units made up of rocks that have moved over long distances as a result of tectonic forces. This phenomenon generally occurs in zones of plate convergence, where one continental plate slides over another, often leading to the formation of mountain chains. Their study is essential for understanding the building of orogenic belts and the tectonic evolution of the Earth.

During mountain building, detachment between different rock units can occur, leading to the development of independent tectonic units that may stack atop one another along **thrust planes**, which are often subhorizontal.

Thrust faults may taper out laterally and rapidly; in such cases, they reflect only limited displacements. When the relative displacement between two rock masses across the fault plane becomes significant, the term **thrusting** (or **overthrusting**) is used—particularly when the basement rocks override their sedimentary cover (see Fig. 25).

Thrust sheets are therefore **allochthonous formations**, hundreds to thousands of meters thick, that lie atop an **autochthonous basement** through zones of shearing and deformation, which indicate movement (known as the **thrust plane** or **tectonic contact**). The point of origin corresponds to the **root zone of the nappe**, while the leading edge, or **forefront**, becomes embedded in the underlying basement. These thrust sheets are often affected by folding and secondary tectonic structures, such as **nappe-scale anticlines** and **synclines**.

Allochthonous / par-autochthonous / autochthonous

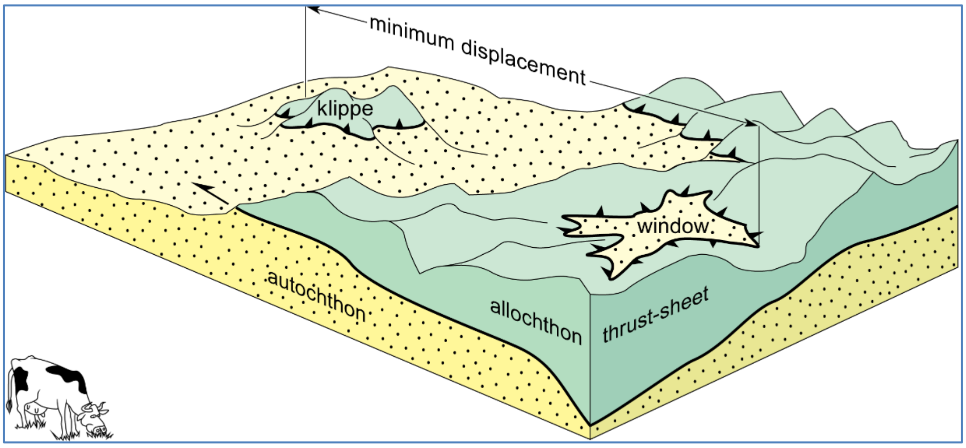
Overthrusting involves the displacement and tectonic emplacement of hanging-wall rocks forming **thrust-sheets (nappes)**. Rocks within thrust sheets have been translated great distances away from their original site; they are **allochthonous**. Allochthonous units often consist of subordinate thrust sheets that possess a common displacement history. They come to rest on **autochthonous** rocks, which have retained their original location, or on **par-autochthonous** footwall material if it has been moved close to its original location.

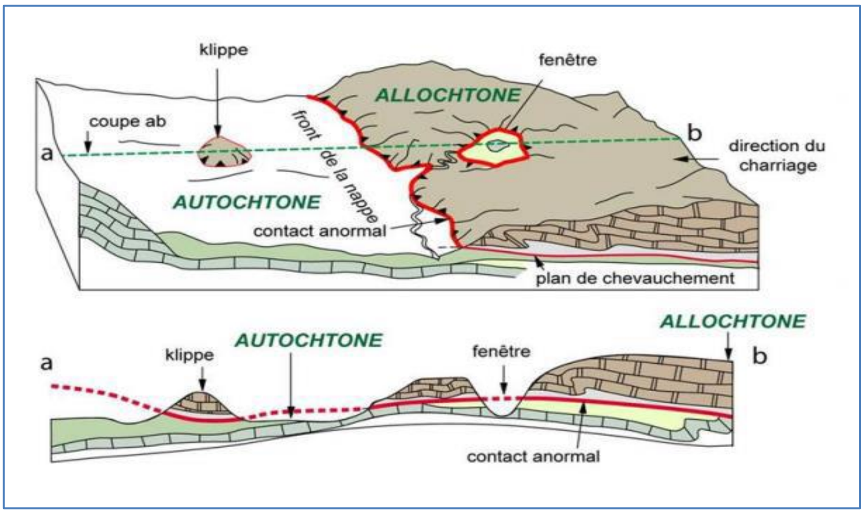
Erosion exposures: window and klippe

A **window** (or **fenster**) is produced when erosion made a hole through a thrust-sheet to expose the footwall rocks beneath the thrust fault; autochthonous or para-autochthonous rocks are completely surrounded in map view by rocks of the allochthonous hanging-wall.

A **klippe** is an isolated, erosion remnant of a thrust sheet completely surrounded in map view by rocks of the footwall.

Both klippen and windows are indicators of minimum displacement.





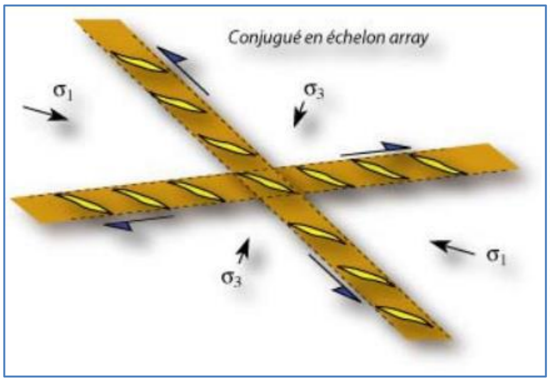
I.4 Concept of Microtectonics

Microtectonics refers to the study of small-scale tectonic structures, often visible in outcrops or thin sections of rock. It involves examining features like fractures, faults, folds, and other deformation structures at a microscopic or mesoscopic scale. Microtectonics focuses on understanding the local and regional stress and strain history of rocks, often to interpret their tectonic environment and the processes that affected them.

In practice, microtectonics might involve analyzing features such as:

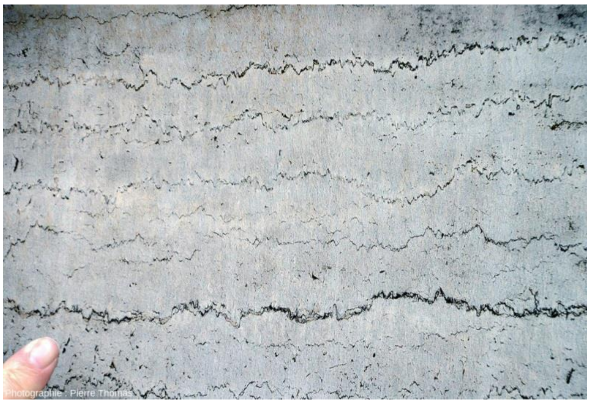
- Faults (normal, reverse, strike-slip, etc.)
- Fractures (including joints and stylolites)
- Folds (small-scale, often related to regional deformation)
- Shear zones and microstructures formed due to tectonic activity.

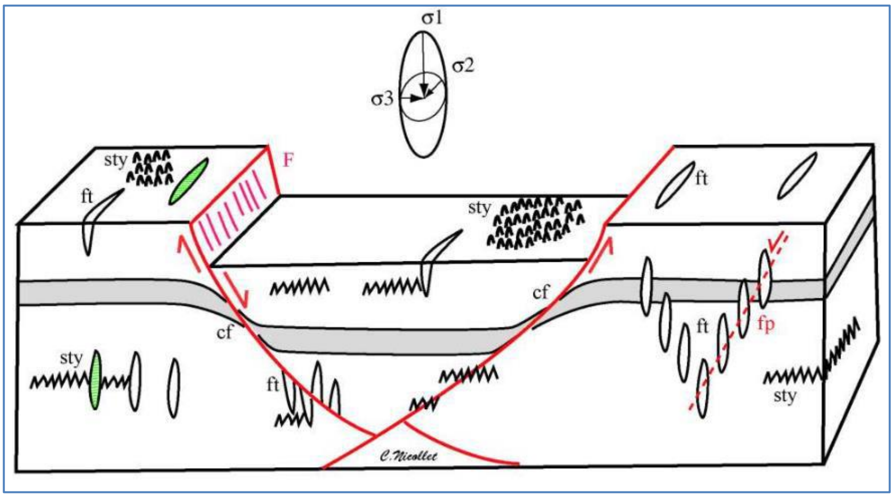
a. **Tension gashes (Fentes de tension):** are generally small veins (on the order of a few tens of centimeters, although analogous structures can reach kilometer-scale dimensions) filled with minerals such as **calcite** or **quartz**. They are **tensile fractures** that open in the direction of **σ_3** (the minimum principal stress).
These structures are often associated with **faults**, forming **en-echelon systems** (*en-echelon tension gashes*) along fault planes, or sometimes in areas where a fault **could have** developed.



b. **Joints (les joints):** are fractures that are often the most visibly recognizable geometric features on an outcrop. They result from **brittle fracturing**, without displacement (or with only minimal displacement) along the fracture planes. When fracture systems are filled with minerals (often **quartz** or **calcite**), they are referred to as **veins**.

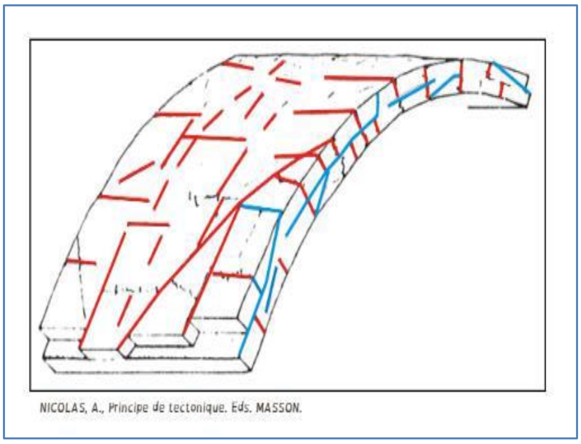
- **Stylolitic joints** (**Joints stylolitiques)** are generally associated with open fractures. They are irregular structures characterized by stylolitic peaks, ranging in size from millimeters to centimeters.
These are pressure-solution surfaces, with the peaks indicating the direction of the maximum principal stress σ_1.

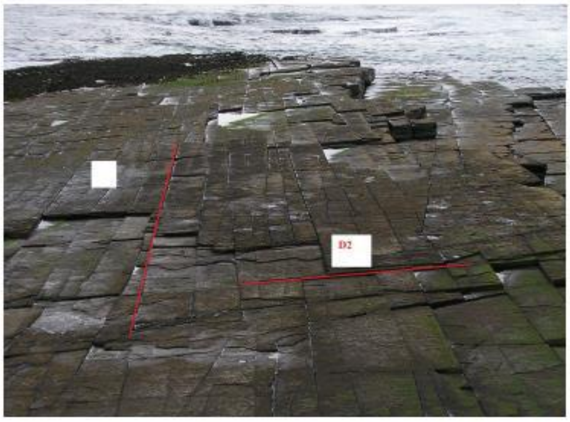




A **graben** or **rift** is bounded by a system of conjugate normal faults (**F**). Associated microstructures include **stylolites** (**sty**), **tension gashes** (**ft**), **fault jogs** (**cf**), and **potential faults** (**fp**).

c. **<u>Diaclasis (Diaclases);</u>** the term **diaclasis** (from the Greek *dia*, meaning "through," and *klassis*, meaning "break" or "fracture") is generally used for fractures with no displacement or filling. They are most often perpendicular to the bedding joints of a sedimentary unit, forming a network that divides the rock into coarse prisms.





Diaclases perpendicular to stratification.