CHAP VI

DEFORMATION OF THE EARTH CRUST
“CRUSTAL DEFORMATION”

In this chapter we will try to answer the following questions:

1-What causes rocks to deform? Quelle est la cause de la déformation des roches ?

2- How do rock déformes ? Comment les roches se déforment ?

3- Folds : Rock structures formed by ductile deformation. Les plis : formés suite à une déformation ductile,

4- Faults : Rock structures formed by brittle déformation. Les failles et les joints : formés suite à une déformation cassante,

SMARTFIGURE 10.1 Deformed sedimentary strata These deformed strata are exposed in a road cut near Palmdale, California. In addition to the obvious folding, light-colored beds are offset along a fault located on the right side of the photograph. (Photo by E. J. Tarbuck)

Any rock, no matter how strong it is, has a stress threshold where it deforms by bending or breaking. **Deformation** (تشوه) is then a general term that refers to a change in the shape or position of a body of rock in response to differential stress.

Most crustal **deformation** occurs along plate boundaries. Plate movements and interactions along plate boundaries generate the tectonic forces that cause rocks to deform.

The basic geologic forms that result from deformation are called geologic structures (Fig. 10.1). **Geological structures** include **folds**, **faults and joints**. Other small structures associated with metamorphic rocks are **foliation and cleavage** of rocks.

I- Concept of stress

Geologists use the term stress to describe the forces that deform rocks. Whenever stress acts on a rock body, it usually deforms through folding, flow, or fracturing.

Stress is by definition the force exerted on a surface.

$$\vec{\sigma} = \frac{\vec{F}}{\vec{S}}, \qquad \vec{F} \text{ force et } \vec{S} \text{ surface}$$

The stress is a vector quantity has the unit of pressure kgf/m^2.

The magnitude of stress is not simply a function of the amount of force applied but also relates to the area on which the force acts.

There are three types of stresses:

I.1- Compressive stress:

In this case, the rock is compressed if it was placed in a vice. The stress is known as **compressive stress**. For example :

When tectonic plates collide, the Earth's crust is generally shortened horizontally and thickened vertically. Over millions of years, this deformation produces mountainous terrain.

A. Undeformed rock

B. Compressional stress (shortening)

I.2- Tensile stress:

The stress that pulls apart or elongates a rock body is known as tensile stress.
Along divergent plate boundaries where plates move apart, tensile stresses stretch and elongate the rock.

C. Tensional stress (stretching)

I.3- Shear stress

Differential stress can also cause rock shearing. Shearing involves the movement of one part of a rock's body relative to the other part. Shearing is similar to the sliding that occurs between individual playing cards when the top of the deck is moved relative to the bottom.

D. Shear stress (sliding and tearing)

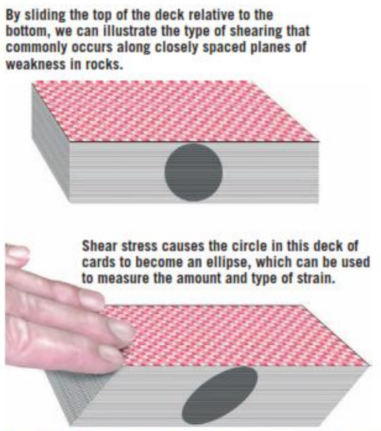


FIGURE 10.3 Shearing and the resulting deformation (strain)
An ordinary deck of playing cards with a circle embossed on its side illustrates shearing and the resulting strain.

II-Deformation (strain: a change in shape caused by stress)

In geology, “deformation” is a generic term that describes changes in shape, position or orientation of a body subjected to stress. It is the only element that can be described from geological objects.

II.1-How rocks deform

When rocks are subjected to stresses beyond their strength, they deform, usually by bending or breaking. It's easy to visualize how rocks break because they are fragile. But how can large masses of rock be folded into complex folds without breaking apart in the process? To answer this question, geologists performed laboratory experiments where rocks were subjected to differential stresses under conditions experienced at various depths in the Earth's crust. Geologists have determined that rocks deform depending on loading conditions into three types of deformation: elastic, brittle and ductile.

II.2, brittle and ductile

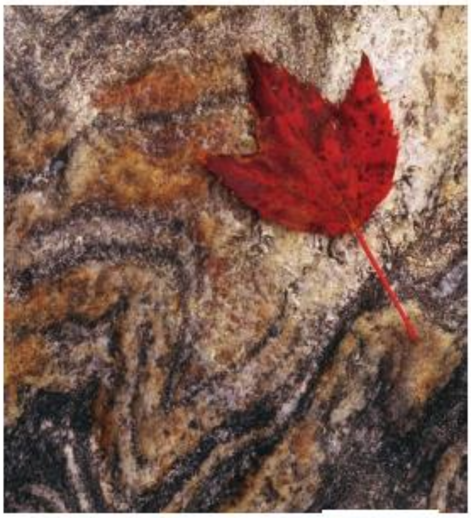
Elastic deformation:

When stress is applied gradually, rocks initially respond by deforming in an **elastic** manner. The resulting deformations are recoverable (like a rubber band, the rock returns to its original size and shape when the stress is removed. During **elastic deformation**, the chemical bonds of minerals in a rock are stretched but do not break. When the stress is removed, the links return to their original length.

Once a rock's **elastic limit is exceeded**, it bends or breaks. Rocks that break exhibit a **brittle deformation**). Ex: glasses, porcelain plates break once their strength is exceeded.

Ductile (plastic) deformation

Ductile deformation, on the other hand, is a type of deformation that produces a change in the **shape** of an object **without fracturing** (Fig. 10.5). Example: modeling clay, beeswax,. **Ductile deformation** can occur by sliding along planes of weakness such as bedding surfaces and foliations in rock bodies.



Rocks exhibiting ductile deformation

II.3Factors influencing rock strength

The main factors that influence a rock's resistance to fracture and the manner in which it deforms are: temperature, confining pressure, rock type, and time.

a- Temperature :

At low temperatures the rocks are fragile when the temperature increases the deformation of the rock becomes more and more **ductile** until the rock flows when it reaches its melting temperature.

b- Confinement pressure:

As the confining pressure increases the strength of the rocks increases and the rocks tend to deform in a ductile manner.

c-The type of rock:

Magmatic rocks are hard and tend to break under stress while metamorphic and sedimentary rocks deform in a **ductile** manner before breaking while evaporitic salt and gypsum rocks exhibit **ductile** deformation.

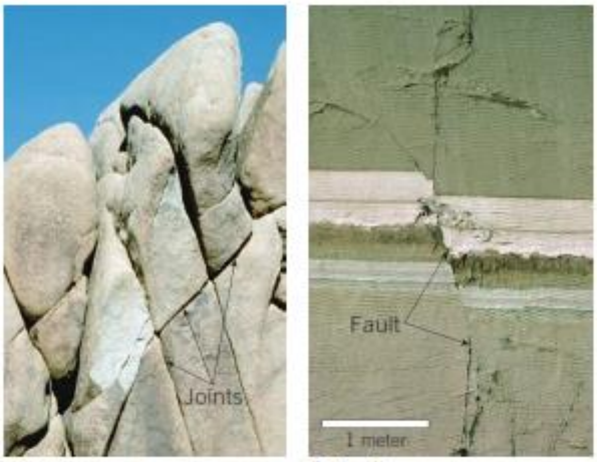
d- Rate of loading:

When stresses are applied quickly, the resulting deformation is often fragile (brittle). When the speed of load application is low, rocks tend to deform in a ductile manner.

III- Brittle and ductile deformations and the resulting rock structures

When a drinking glass falls onto a hard surface it breaks into pieces. This type of deformation is known by **brittle deformation** it is the similar to the brittle deformation within the Earth's crust, near the surface.

When tectonic forces cause crustal reworking, rocks near the surface are stretched and pushed apart, forming **fractures called joints** (Fig. 10.7A). **Faults are fractures** in the Earth's crust where rocks on one side of the fault are displaced relative to the other side (Fig. 10.7B).



A. Joints B. Fault

FIGURE 10.7 Joints versus faults

Folds, on the other hand, are one of the most spectacular manifestations of **ductile deformation.** The following figure shows brittle and ductile deformations as a function of depth and type of stress (compression, tension and shear).

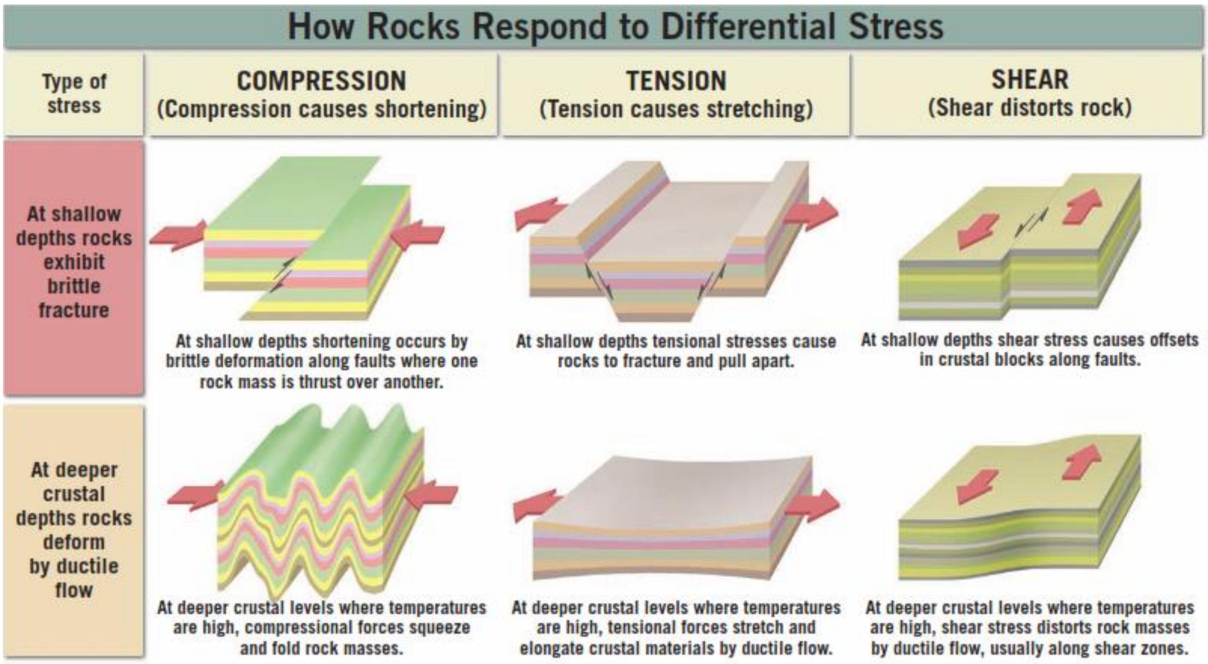


FIGURE 10.8 Deformation caused by three types of stress

IV- Rock structures formed by ductile deformation

IV.1- The folds

Along convergent plate boundaries, flat sedimentary strata, tabular intrusions, and volcanic rocks are often folded into a series of undulations called **folds**. In nature, **folds** come in a wide variety of sizes and configurations.

Folds are geological structures consisting of initially horizontal sedimentary layers which have been **folded** as a result of **permanent ductile deformation**. Each layer is curved around an imaginary axis called **the fold axis or hinge**.

Two basic **fold** geometries are common—**anticlines and synclines** (figure 6.11).
An **anticline** is a fold shaped like an arch with the oldest rocks in the center of the fold. Usually the rock layers dip away from the **hinge line** (or *axis*) of the fold.
The counterpart of an anticline is a **syncline,** a fold shaped like a trough with the youngest rocks in the center of the fold.

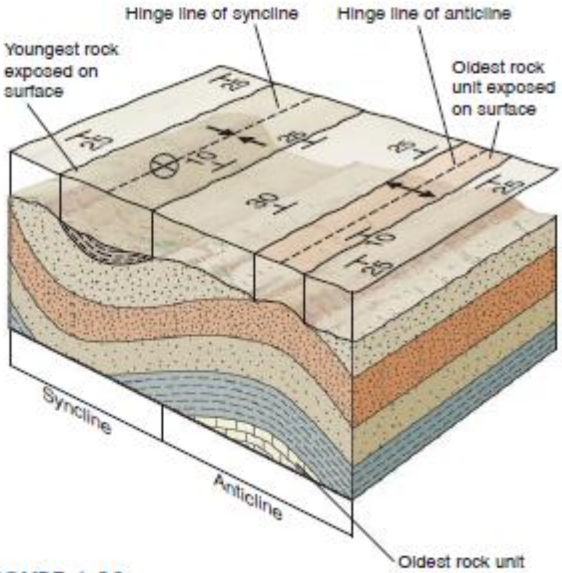


FIGURE 6.12
By measuring the strike and dip of exposed sedimentary beds in the field and plotting them on a geologic map (top surface) geologists can interpret the geometry of the geologic structure below the ground surface.

Folds are also classified by **their axial plane**. **The axial plane** is the surface which passes through all the hinge line of the folded layers.

a- **Upright fold** has a vertical axial plane which divides the fold into two symmetrical **limbs**.

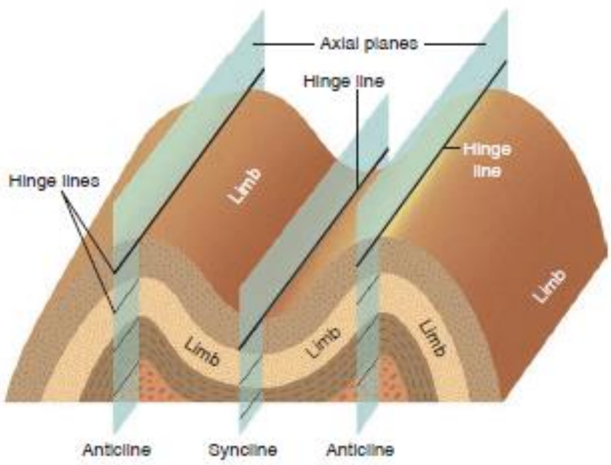
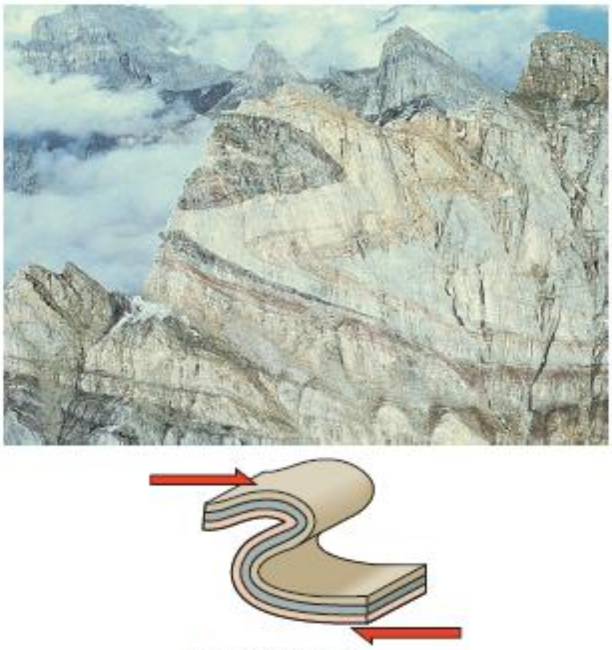


FIGURE 6.11
Diagrammatic sketch of two anticlines and a syncline illustrating the axial planes, hinge lines, and fold limbs.

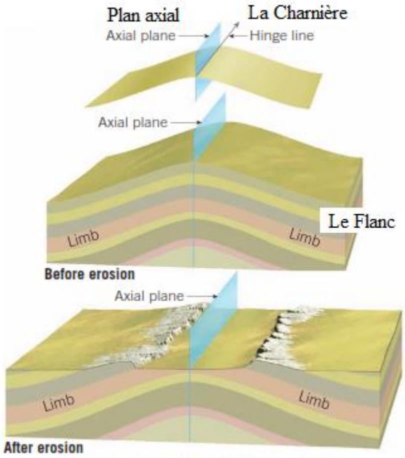
b- Overturned Fold: If the axial plane is inclined to such a degree that the fold limbs dip in the same direction, the fold is classified as an **overturned fold** (figure 6.17*C*).

C Overturned folds

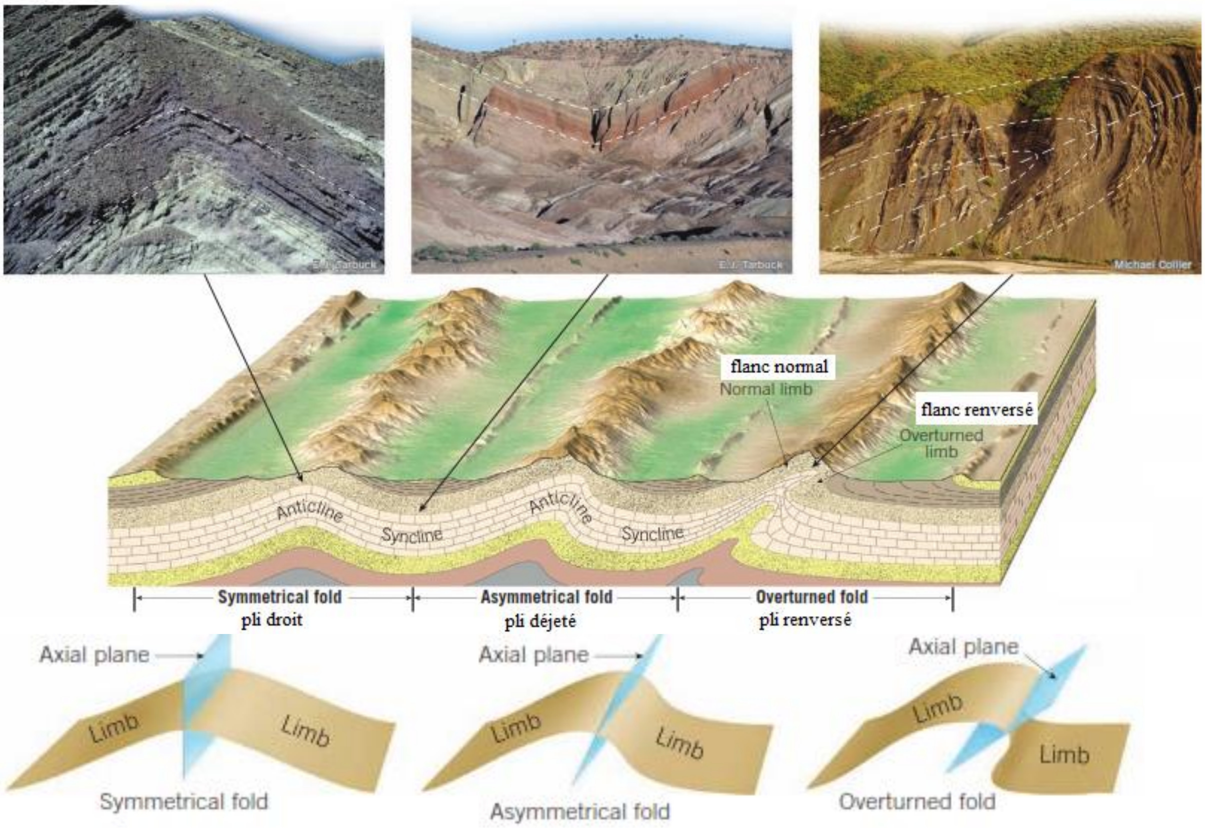
c- Recumbent folds are overturned to such an extent that the limbs are essentially horizontal (figure 6.17*D*).



D Recumbent folds



Features associated with symmetrical folds



The most common fold types

"FAULTS AND JOINTS: rock structure formed by brittle deformation"

Faults form when **brittle deformation** causes rocks in the Earth's crust to fracture and displace relative to each other. **Faults** can cause displacements of a few centimeters (fig. 10. 18) as they can have displacements of several hundred kilometers, for example: the **San Andreas fault** in California.

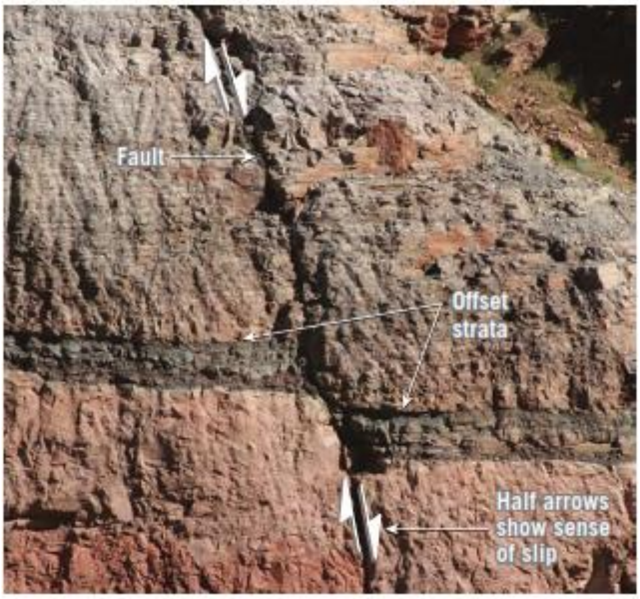
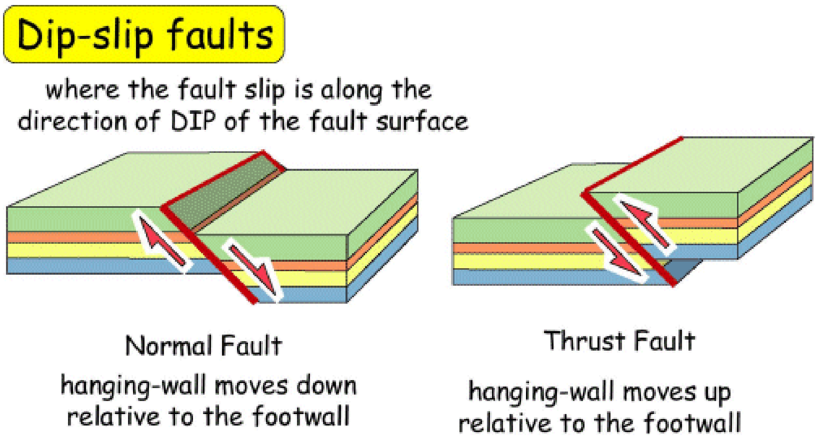


FIGURE 10.18 Faults are fractures where slip has occurred

Sudden movements along **faults** are the cause of most earthquakes. However, the vast majority of faults are traces of past deformation and are inactive. On some **fault mirrors**, rocks become highly **polished** and **striated**, or **grooved**, as crustal blocks slide past each other. These polished, ridged surfaces, called **slickensides**, provide geologists with clues to the direction of the most recent movement along the fault.

Dip-Slip fault "Fault with the direction of dip"

Faults in which the movement is primarily parallel to the **deep of the fault plane** are called **normal faults**.



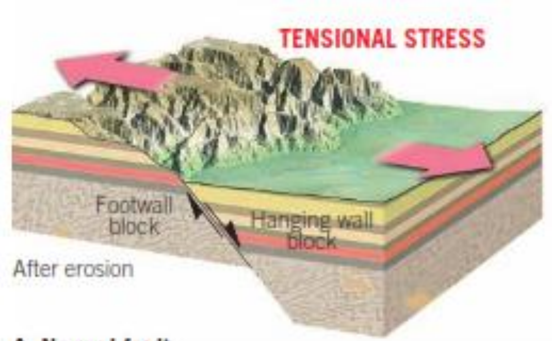
Geologists identify the block of rock immediately **above the fault plane** as the **hanging wall** and the block of rock **below the fault plane as the foot wall**.

Hanging wall block and footwall block

Le bloc Bloc Toit et Bloc Mur d'une faille

Normal faults (les failles normales)

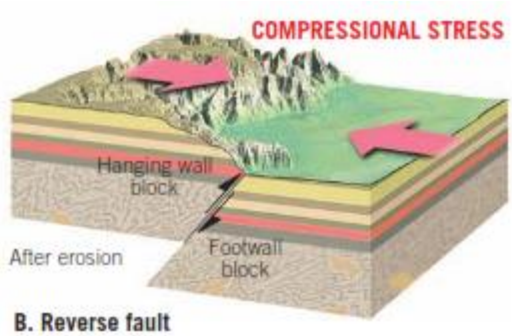
Dip slip faults are classified as **normal faults** when the **hanging wall block** moves down relative to the **foot wall block** (Fig. 10.22A). **Normal faults** tend to be associated with tensile stresses that stretch rocks, thereby elongating the crust.



A. Normal fault

Reverse faults (les failles inverses)

Dip-Slip faults in which the **hanging wall block** rises relative to the **foot wall block** are called **reverse faults**.

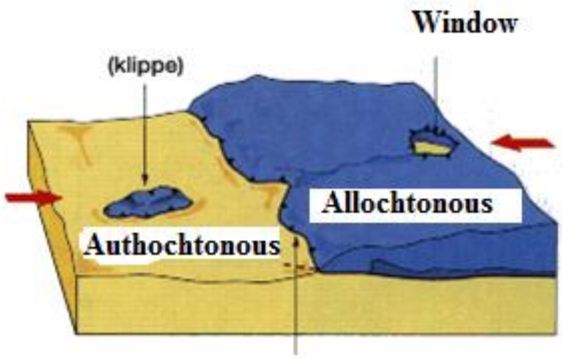


B. Reverse fault

Une Faille Inverse

Thrusts and overthrusts (les chevauchements et les charriages)

Thrusts are a type of **reverse fault**s whose plane is inclined at an angle less than 45 degrees. The **hanging wall block** moves almost horizontally over the **foot wall block**. **Reverse faults** and **thrust faults** result from compressive stresses that produce horizontal shortening of the crust. When the **hanging wall block** moves over **foot wall block** for several tens of kilometers, we speak about **overthrust**. Thrusting can bring sheets uprooted from their source called **allochtonous terrain**, into contact over, stable in place, **autochthonous terrain**.



When erosion removes part of an **overthrust sheet** and allows the autochthon to reappear, this is called **a window**. If, however, erosion isolates a part of the **overthrust**, this is called a **klippe** (see the figure above).

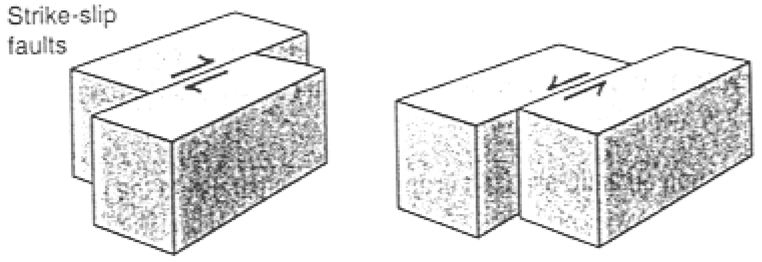
Some definitions

An **autochthon or authochtonous terrain,** in structural geology is a large block or mass of rock which is in the place of its original formation rooted to its basement rock

An **allochthon or allochtonous terrain** is a block or nappe which has been relocated from its site of formation. While an autochthon is in it's place of formation, an allochthonous block will have moved at least a few kilometres away from its root source.

Strike-Slip Faults

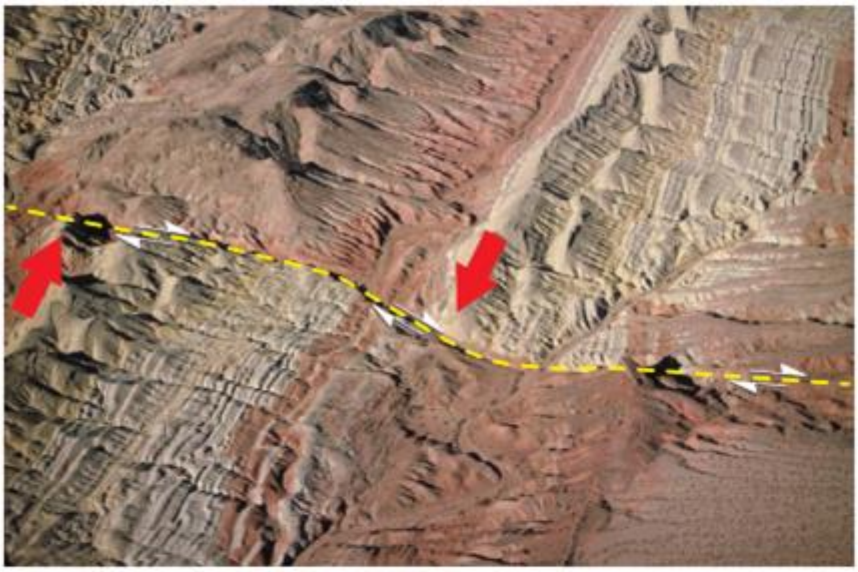
A fault in which the dominant displacement is horizontal and parallel to the *trend* (direction) of the fault surface is called a **strike-slip fault** (Figure 10.26).



(c) Right-lateral (or dextral) — (d) Left-lateral (or sinistral)

decrochement dextre — **decrochement senestre**

Faille decrochante (strike slip fault)



Aerial view of a strike-slip fault

Vue aérienne d'une faille décrochante (dextre)

"Notice that the ridge of light-colored rock in the top-right portion of the photo was offset to the right relative to the portion of the same ridge that appears at the bottom left of the image".

Notez que la crête de la roche de couleur claire dans la partie supérieure droite de la photo était décalée vers la droite par rapport à la partie de la même crête qui apparaît en bas à gauche de l'image.

Oblique-Slip Faults

Faults that exhibit both dip-slip and strike-slip movement, called **oblique-slip faults**, are caused by a combination of shearing and tensional or compressional stress (**Figure 10.29**).

Nearly all faults have minor components of both dip-slip and strike-slip movement, so defining a fault as oblique requires that both types of slip be significant enough to be observed and measured.

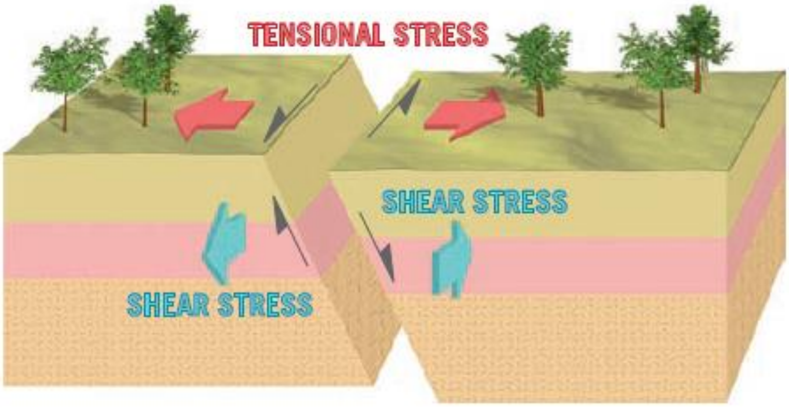


FIGURE 10.29 **Oblique-slip faults**
Oblique-slip faults exhibit a combination of dip-slip and strike-slip movement.

Joints, and veins

Among the most common rock structures are fractures called joints. Unlike faults, **joints** are fractures along which no appreciable displacement has occurred.

When fracture systems are filled with minerals (often quartz or calcite), we speak about **veins**.

Joints are vertical and parallel

Words to be remembered

Angle of dip, anticline, axial plane, brittle, compressive stress, dip-slip fault, direction of dip, ductile elastic, elastic limit, fault, fold, footwall, geologic cross section, geologic map, hanging wall, hinge line, isoclinal fold, joint, joint set, left-lateral fault, limb, normal fault, oblique-slip fault, open fold, overturned fold, plunging fold, recumbent fold, reservoir rock, reverse fault, right-lateral fault, shear stress, source rock, strain, stress, strike, strike-slip fault, structural basin, structural dome, syncline, tensional stress, thrust fault, tight fold, upright fold.

Testing Your Knowledge

Use the following questions to prepare for exams based on this chapter.

1. Most anticlines have both limbs dipping away from their hinge lines. For which kind of fold is this not the case?

2. What is the difference between a joint and a fault?

3. On a geologic map, if no cross sections were available, how could you distinguish an anticline from a syncline?

4. If you locate a dip-slip fault while doing field work, what kind of evidence would you look for to determine whether the fault is normal or reverse?

5. What factors control whether a rock behaves as a brittle material or a ductile material?

6. What is the difference between strike, direction of dip, and angle of dip?

7. Draw a simple geologic map using strike and dip symbols for a syncline plunging to the west.

8. How does a structural dome differ from a plunging anticline?

9. Which of the statements is true?

a. when forces are applied to an object, the object is under stress

b. strain is the change in shape or size (volume), or both, while an object is undergoing stress

c. stresses can be compressive, tensional, or shear

d. all of the preceding

10. The compass direction of a line formed by the intersection of an inclined plane with a horizontal plane is called

a. strike b. direction of dip

c. angle of dip d. axis

11. Folds in a rock show that the rock behaved in a _____ way.

a. ductile b. elastic

c. brittle d. all of the preceding

12. An anticline is

a. a fold shaped like an arch with the youngest rocks exposed in the center of the fold

b. a trough-shaped fold with the oldest rocks exposed in the center of the fold

c. a fold shaped like an arch with the oldest rocks exposed in the center of the fold

d. a trough-shaped fold with the youngest rocks exposed in the center of the fold

13. A syncline is

a. a fold shaped like an arch with the youngest rocks exposed in the center of the fold

b. a trough-shaped fold with the oldest rocks exposed in the center of the fold

c. a fold shaped like an arch with the oldest rocks exposed in the center of the fold

d. a trough-shaped fold with the youngest rocks exposed in the center of the fold

14. A structure in which the beds dip away from a central point and the oldest rocks are exposed in the center is called a

a. basin b. anticline c. structural dome d. syncline

15. Which is not a type of fold?

a. open b. isoclinal c. overturned d. recumbent e. thrust

16. Fractures in bedrock along which movement has taken place are called

a. joints b. faults c. cracks d. folds

17. In a normal fault, the hanging-wall block has moved _____ relative

to the footwall block. a. upward b. downward c. sideways

18. Normal faults occur where

a. there is horizontal shortening b. there is horizontal extension c. the hanging wall moves up d. where the footwall moves down

19. Faults that typically move older rock on top of younger rock are

a. normal faults b. thrust faults c. strike-slip faults