FAULTS

Fractures are planar discontinuities, i.e. interruption of the rock physical continuity, due to stresses. The geological fractures occur at every scale so that any large volume of rock has some or many. These discontinuities are attributed to sudden relaxation of elastic energy stored in the rock.

The geological fractures have their economic importance. The loss of continuity in intact rocks provides the necessary permeability for migration and accumulation of fluids such as groundwater and petrol. Fractured reservoirs and aquifers are typically anisotropic since their transmissivity is regulated by the conductive properties of fractures, which the local stress field partially controls. Geological fractures may be partially or wholly healed by the introduction of secondary minerals, often giving rise to ore deposits, or by recrystallization of the original minerals.

Planar discontinuities along which rocks lose cohesion during their brittle behavior are:

- **joints** if there is no component of displacement parallel to the plane (there may be some very small orthogonal parting; joints are extension fractures).
- **faults** if rocks on both sides of the plane have moved relative to each other, parallel to the plane (faults are shear fractures).
- **veins** if the fractures are filled with secondary crystallization.

Joints and faults divide the rocks into **blocks** whose size and shape must be taken into consideration for engineering, quarrying, mining, and geomorphology.

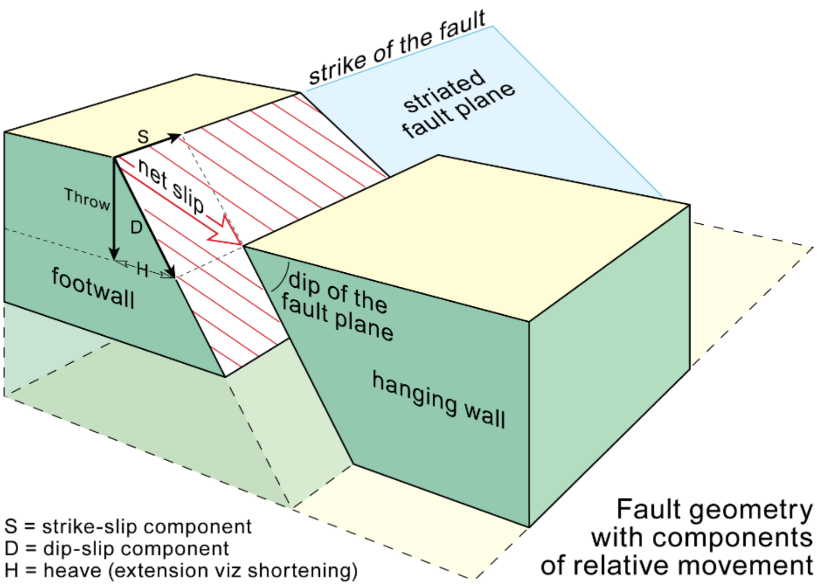
Fault terminology

Definitions

Faults separate two adjacent blocks of rock that have moved past each other because of induced stresses. The notion of localized movement leads to two genetically different classes of faults reflecting the two basic behaviors of rocks under stress: brittle and ductile.

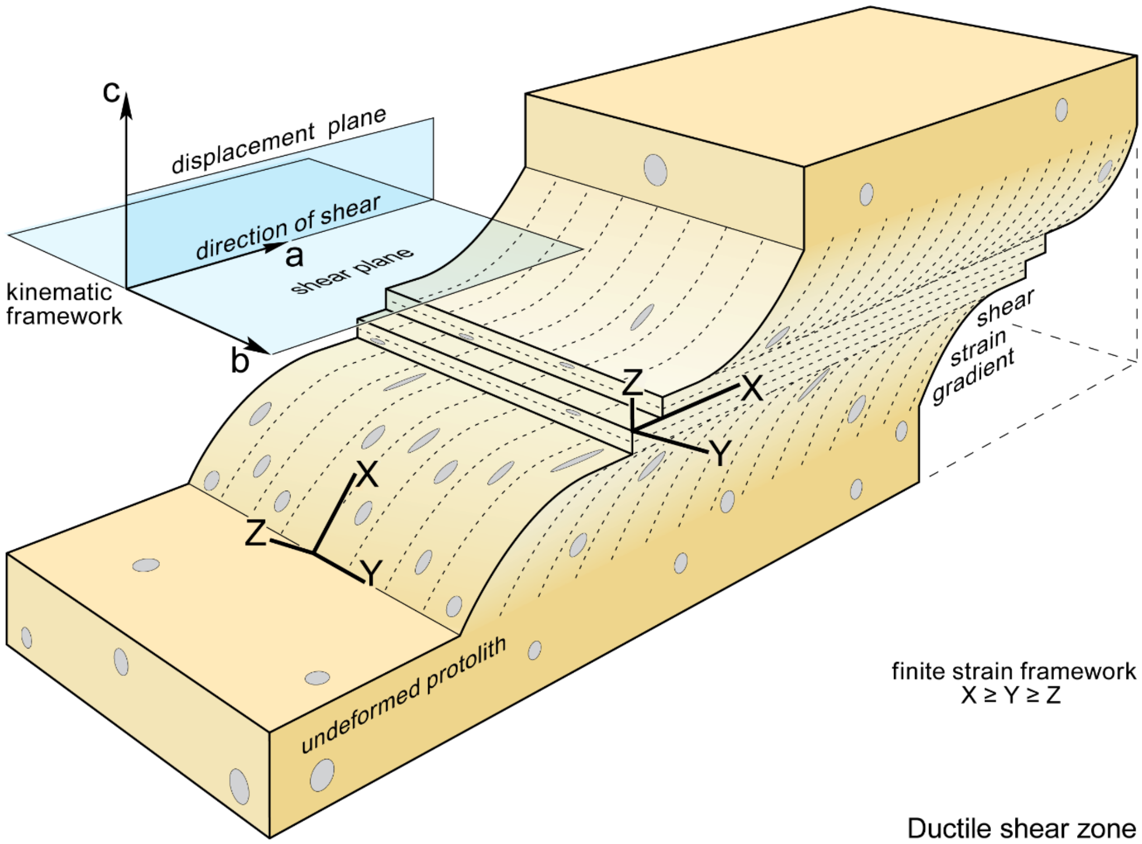
Brittle fault

A **fault** is a discrete fracture between blocks of rock displaced relative to each other, in a direction parallel to the fracture plane. A **fault zone** is a region containing several parallel or **anastomosing** (i.e. branching and reconnecting) faults. Any fault-bounded sliver in a fault zone is a **horse**. Fault and fault zones are identified where either an earthquake occurs or by geological mapping, showing that motion across a discontinuity has occurred in the past. Geologic maps usually show only faults that affect the outcrop pattern.



Ductile fault

Shear zones are the analogs in a ductile material of faults in a brittle material. Shear zones are regions of localized but continuous ductile displacement, formed under conditions of elevated temperature and/or confining pressure, in contrast to fault zones that are regions of localized brittle deformation. Shear zones are thus ductile faults, by contrast to the brittle faults.

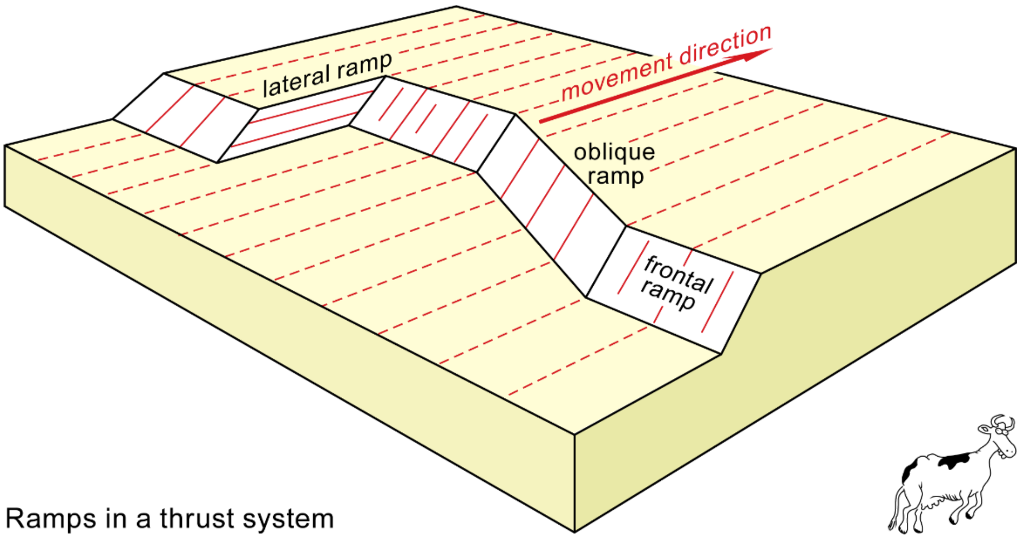


Geometrical classification

Fault plane

High angle faults dip more than 45; Faults dipping less than 45° are **low angle faults**. Most long faults are **segmented**, each segment having its individual history; fault segments are usually not coplanar. In general, fault surfaces undulate, as commonly seen in 3D seismic data. The fault **corrugations** thereby identified are attributed to the linkage of fault-segments. A **listric fault** is curved, concave upward, that is, it gradually flattens with depth.

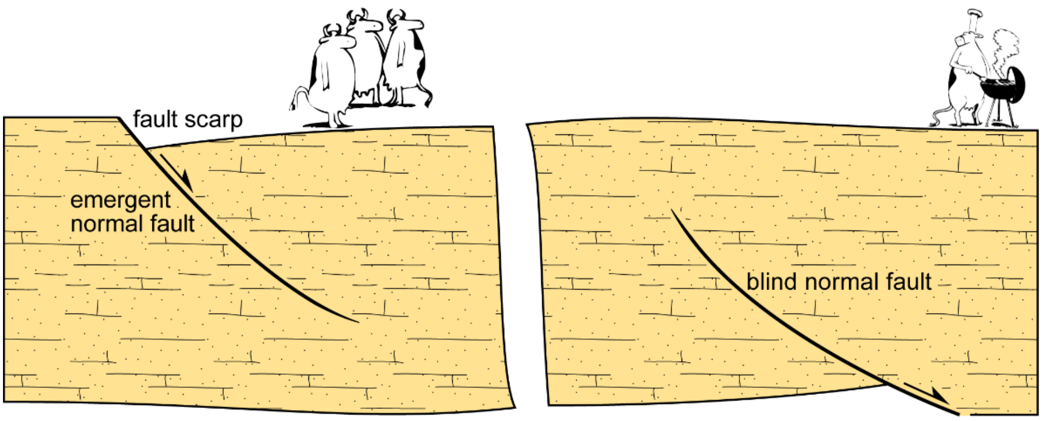
Where low-angle faults affect a set of nearly horizontal bedded rocks, they generally follow a staircase path made up of alternating **ramps** and **flats**. The flats are where the overlying rocks slide along a relatively weak bedding plane also called a **décollement plane,** which refers to a surface across which there is a discontinuity in displacement, strain, and/or fold style. The ramps are fault sections climbing through the stratigraphic sequence, typically at around 30° to the horizontal, across stiff, competent layers. Ramps do not necessarily strike perpendicular to the movement direction (**frontal ramp**). They also can be **oblique** or parallel to the transport direction (**lateral ramp** or **tear fault**).



Ramps in a thrust system

The fault that intersected the ground surface while it was active is an **emergent** fault, by opposition to **blind** faults that did not break the surface. Emergent faults produce a topographic step, the **fault scarp**. Some blind faults are identified as seismogenic streaks with no corresponding fault plane mapped on the Earth's surface.

Attention: An emergent fault is not an exhumed fault. Erosion reaching a fault makes also a fault trace on the Earth's surface.



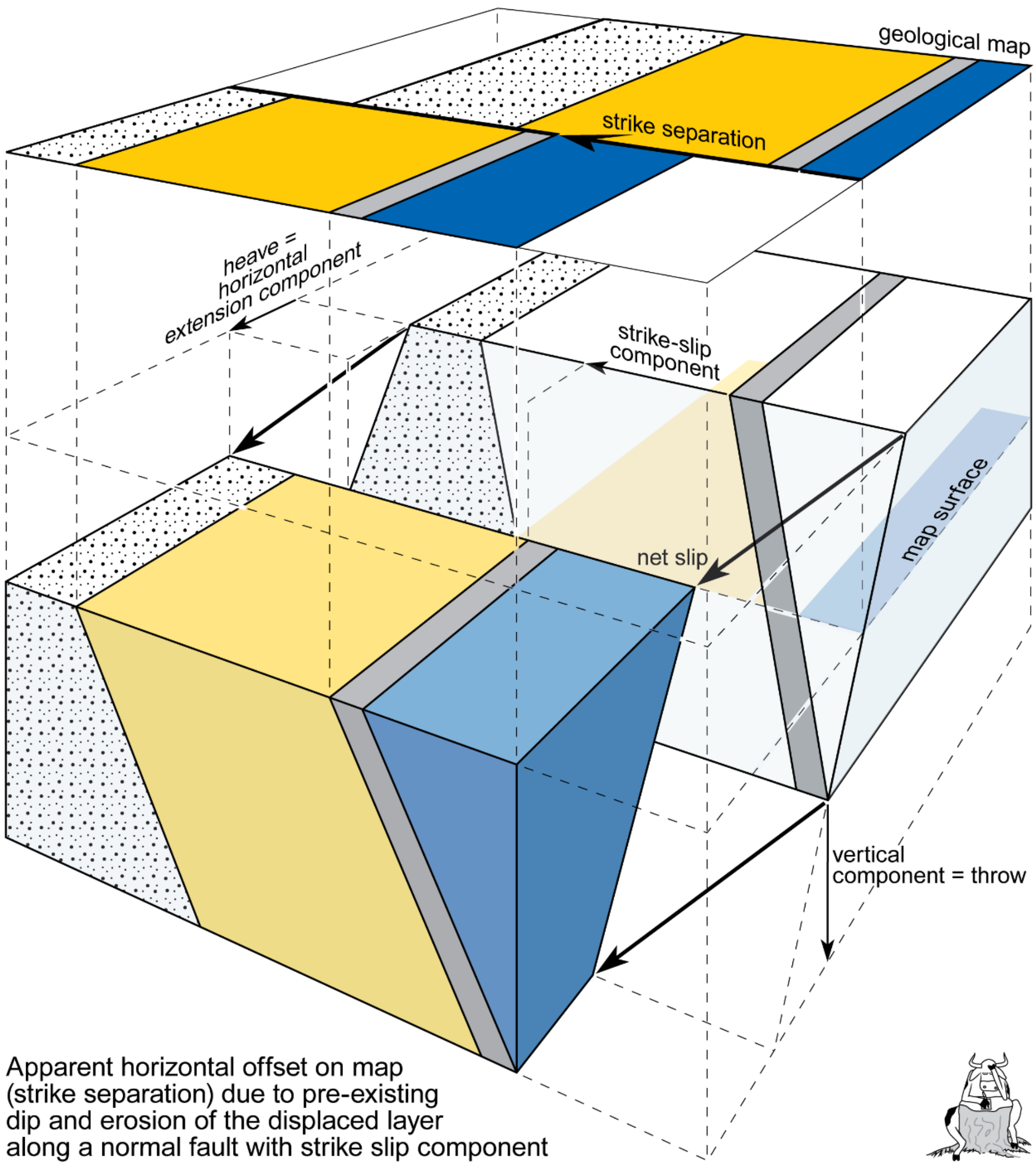
Fault blocks

The **hanging-wall** and the **footwall** designate the rock immediately above and below a non-vertical fault or shear zone, respectively. Rocks that have been translated great distances away from their original site are **allochthonous**. Allochthonous rocks that have lost connection with their original site are **rootless**. They come to rest on **autochthonous** rocks, which have retained their original location. **Parautochthonous** refers to locally transported rocks.

Kinematic classification

Slip

Slip is the direction of movement of one wall relative to the other. The **net slip** is the displacement vector connecting originally coincident points (the **piercing points**) on opposite sides of the fault plane. Its length provides the amount of displacement on the fault, which generally is the addition of several movements.



The components of the net slip parallel to the strike and dip of the fault are the **strike-slip** and the **dip slip**, respectively. The **rake** is the angle measured within the fault plane down from the strike direction to the line of slip. The **plunge** is the angle measured in the vertical plane that contains the slip line between the horizontal in this plane and the slip line.
The offset shown by a planar feature in a vertical cross-section perpendicular to the fault is the **dip separation**. The vertical component of the dip separation is the **throw** and the horizontal component (perpendicular to the fault strike) is the **heave**. Notice that the dip separation is not equivalent to the dip-slip, the former depending on the orientation of the offset surface as well as on the nature of the fault displacement.

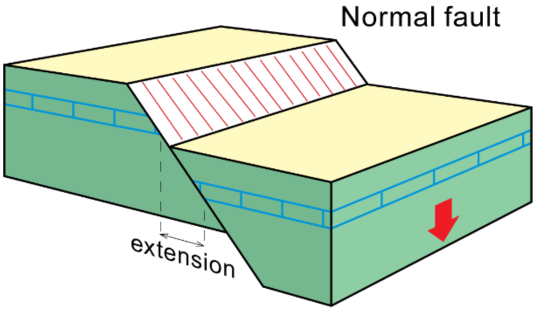
Note: A bedding surface alone can never be used to determine slip

Faults are classified according to the direction of the relative movement between fault blocks, which is related to the type of stress causing the fault.

Fault classes

Normal fault

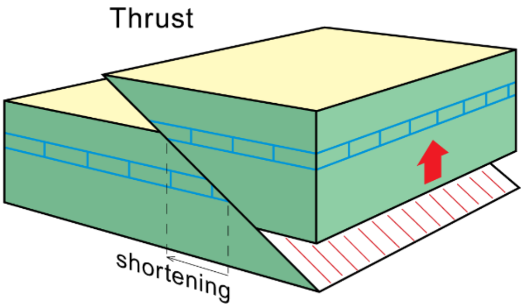
A **normal fault** is a high angle, dip-slip fault on which the hanging-wall has moved down relative to the footwall. A normal fault brings younger rocks over older ones. Because of the separation of geological horizons, normal faults are also termed **extension faults**.



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°.

Reverse fault

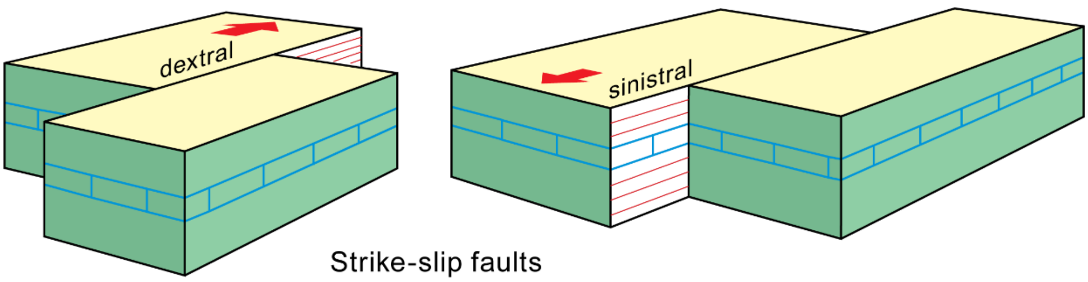
A **reverse fault** is a dip-slip fault on which the hanging-wall has moved up and over the footwall. Consequently, old rocks lay over younger ones. Such faults produce a repetition or overlap of a geological horizon and are accordingly termed **compression fault**.



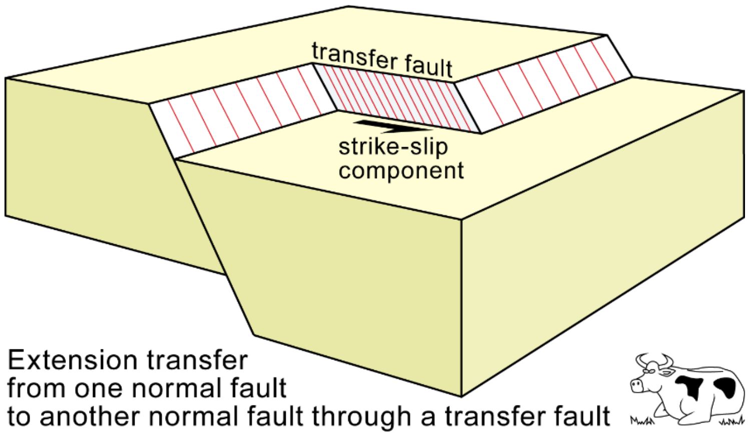
A **thrust fault** is a low-angle reverse fault along which the hanging wall forms **thrust-sheets (nappes)** of allochthonous rocks emplaced over the autochthonous or parautochthonous footwall. Most common, thrust faults ramp up section towards the surface in the direction of tectonic transport.

Strike-slip fault

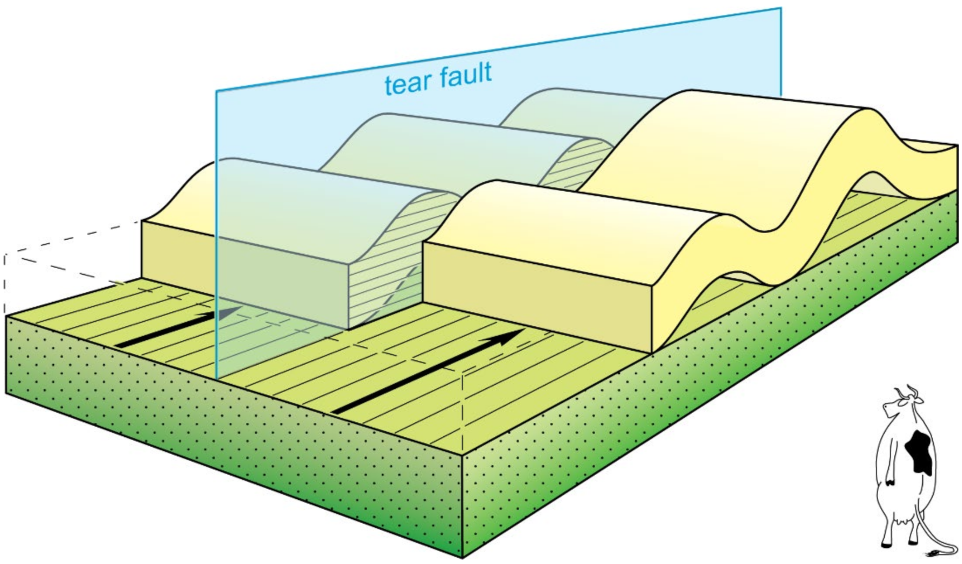
Strike-slip faults usually have very steep or vertical dips and the relative movement between the adjacent blocks is horizontal, parallel to the strike of the fault plane. Large strike-slip faults are referred to as **transcurrent faults** and **wrench faults**.



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.
A **transfer fault** is a strike-slip fault that transmits displacement between two similarly oriented fault segments (e.g. two normal faults). Transfer faults are usually confined to hanging walls of detached systems (i.e. not affecting the basement) and terminate where they connect the linked faults. Transfer faults or zones are lateral ramps that may accommodate differential displacement and/or strain in adjacent blocks (different amounts of shortening or extension on both sides of the fault).



Assuming that thrusts and normal faults strike at a high angle to the slip direction, transfer faults linking two thrusts or normal faults are therefore nearly parallel to the movement direction. Accordingly, transfer faults usually have strike-slip components that vary along strike if displacement changes across the transfer zone.
A **tear fault** is a strike-slip fault that runs across the strike of a contractional or extensional belt and accommodates differential displacement between two segments of the belt. Like transfer faults, tear faults are usually confined to hanging walls of detached systems (i.e. not affecting their basement).

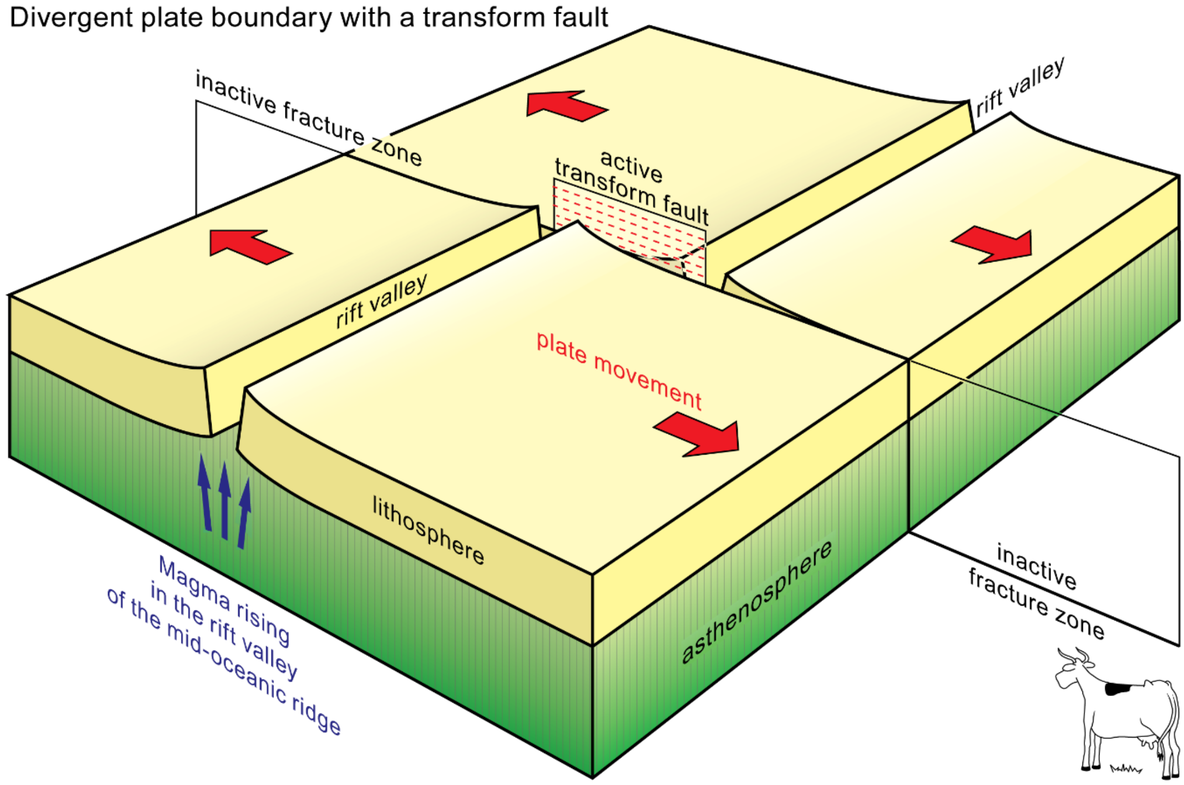


<u>Transform fault</u>

A **transform fault** is a strike slip fault at plate boundaries. There are three types:

Ridge-Ridge transforms link two segments of a constructive plate boundary.
Trench-Trench transforms link two segments of a destructive plate boundary.
Ridge-Trench transforms link a constructive plate boundary to a destructive one.

Ridge-Ridge transform faults are the most common. They are fracture zones striking at nearly right angles to the mid-oceanic ridges and seemingly offsetting the ridges. However, they differ from transcurrent faults in that the direction of horizontal movements is in the opposite direction to that required if the faults were strike-slip faults responsible for offsetting the ridges after formation of the latter.



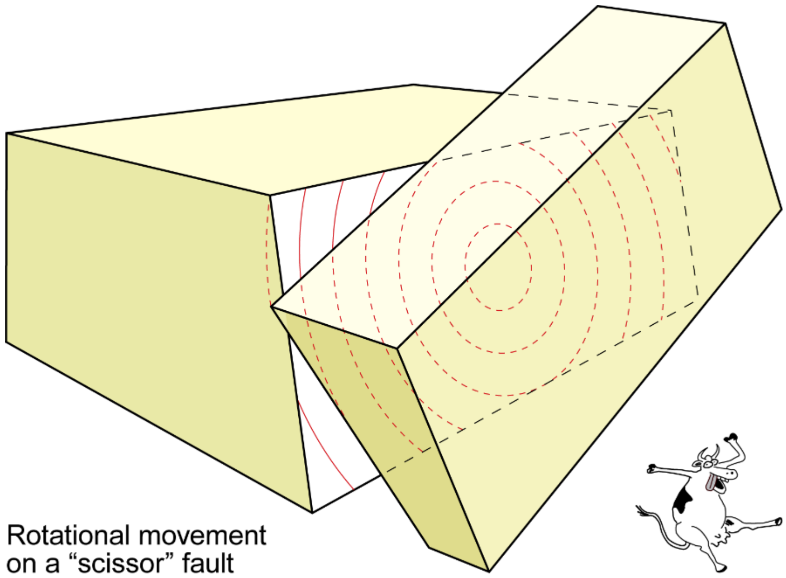
Transform faults are active between the ridges and dead beyond the offsets, and they are parallel to small circles centered at the poles of rotation of the plates. Displacement across them is much greater than the length of the active segment.

<u>Hybrid fault</u>

The terms normal fault and reverse fault, while strictly defined for faults with zero strike-slip displacements, also apply to faults with small strike-slip components accompanying much larger dip-slip displacements. Where the strike-slip and dip-slip displacements have similar magnitude, the fault may be called an **oblique-slip** fault.

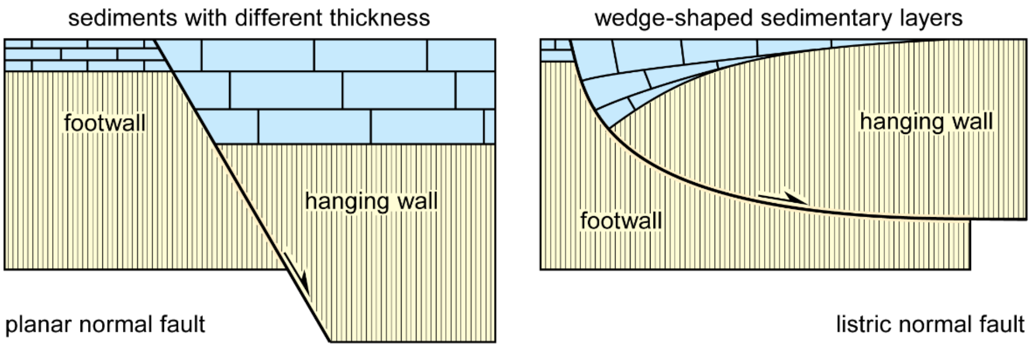
<u>Scissors fault</u>

One fault block can rotate around an axis perpendicular to the plane of **scissors faults.**



Growth fault

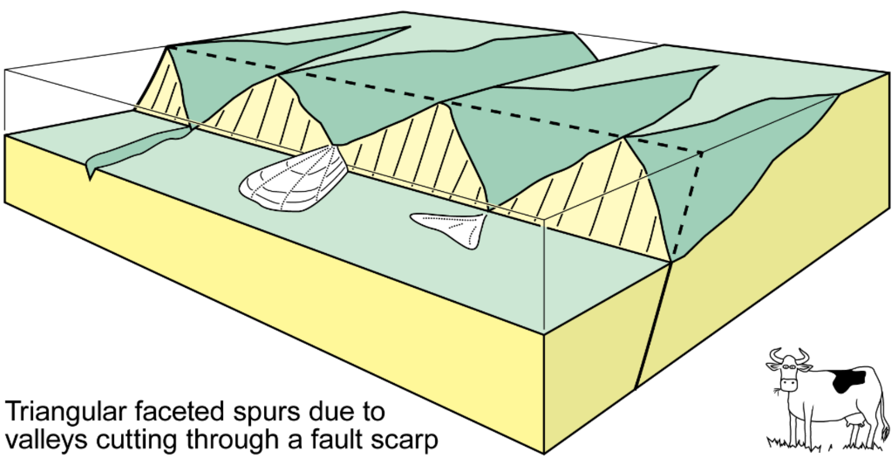
A thicker stratigraphic sequence on the hanging-wall than sedimentary layers of the same age on the footwall of a fault indicates fault movement during sedimentation. **Growth faults** form characteristically, but not exclusively, in unconsolidated sediments deposited in basins actively growing in breadth and depth.



Growth normal faults with associated sedimentary basins

Topographic effect

Recent vertical components of fault movement produce linear topographic steps, or **scarps**. Erosion dissecting fault scarps develops **triangular faceted spurs**.



Length/throw ratio

The general elliptical form of single-event movement planes suggests some relationship between the maximum length of the fault plane (ellipse long axis) and its maximum "down-dip" height (ellipse short axis). Slip distribution is further considered symmetrical about a central point of maximum slip. This geometrical vision has led to mechanical models based on the assumption that rocks are homogeneous elastic materials. These models relate the maximum displacement (D_{max}) at the fault midpoint to the length (L) of the fault. Their general expression is:

$$\frac{D_{max}}{L} = \frac{2\left(1-\nu^2\right)}{E}\left(\sigma_d - C\sigma_y\right)$$

in which σ_d is the shear "driving" stress (i.e. the shear stress leading to Coulomb frictional sliding), σ_y is the yield strength of the intact rock at the fault tip and C is a variable or a function that specifies how the theoretical stress singularity is removed at the fault tip ($C = 1/\pi$ in linear displacement models). E and ν are the Young's ratio and the Poisson's ratio of the rock, respectively.

The general equation given above shows that the maximum displacement/length ratio of faults reflects three properties of the host rock: its shear modulus, its elastic strain limit, and the shear driving stress. Typical ratios for isolated, small normal faults in sedimentary rocks range from 0.002 to 0.04, with an average of 0.01. Ratios of 0.4 to 0.004 and an average of 0.02 were reported for strike-slip faults in turbidites. Lithological variations may account for the range of values, with weak rocks allowing higher strain gradients at the fault tips, hence higher D_{max}/L ratios than stronger rocks.

3D seismic data indicate that the D_{max}/L ratio varies over a limited range around a nearly constant value that depends on the tectonic setting:

* D/L= 12-40: Several fault sets, faults frequently abut against each other
* D/L= 25-75: One dominant fault set. Normal or reverse faults with a limited strike-slip component
* D/L= 50-150: Large component of strike-slip and shallow levels in deltaic (growth fault = synsedimentary fault) settings.

Systematically smaller maximum displacements for normal and thrust faults on Mars (by a factor of ca. 5) and Mercury are related to the reduced gravity on these planets relative to the Earth.

Fault activity

Although every fault has moved and can be reactivated, geologists have developed a qualitative three-term classification to appreciate seismic risks.

- An active fault has moved during the past 10 000 years.
- A potentially active fault has moved during the Quaternary
- An inactive fault has had movement older than the Quaternary.

However, it is difficult to prove that a fault is active without the historical record of earthquakes on the fault. Any fault is a weakness "capable" of reactivation.

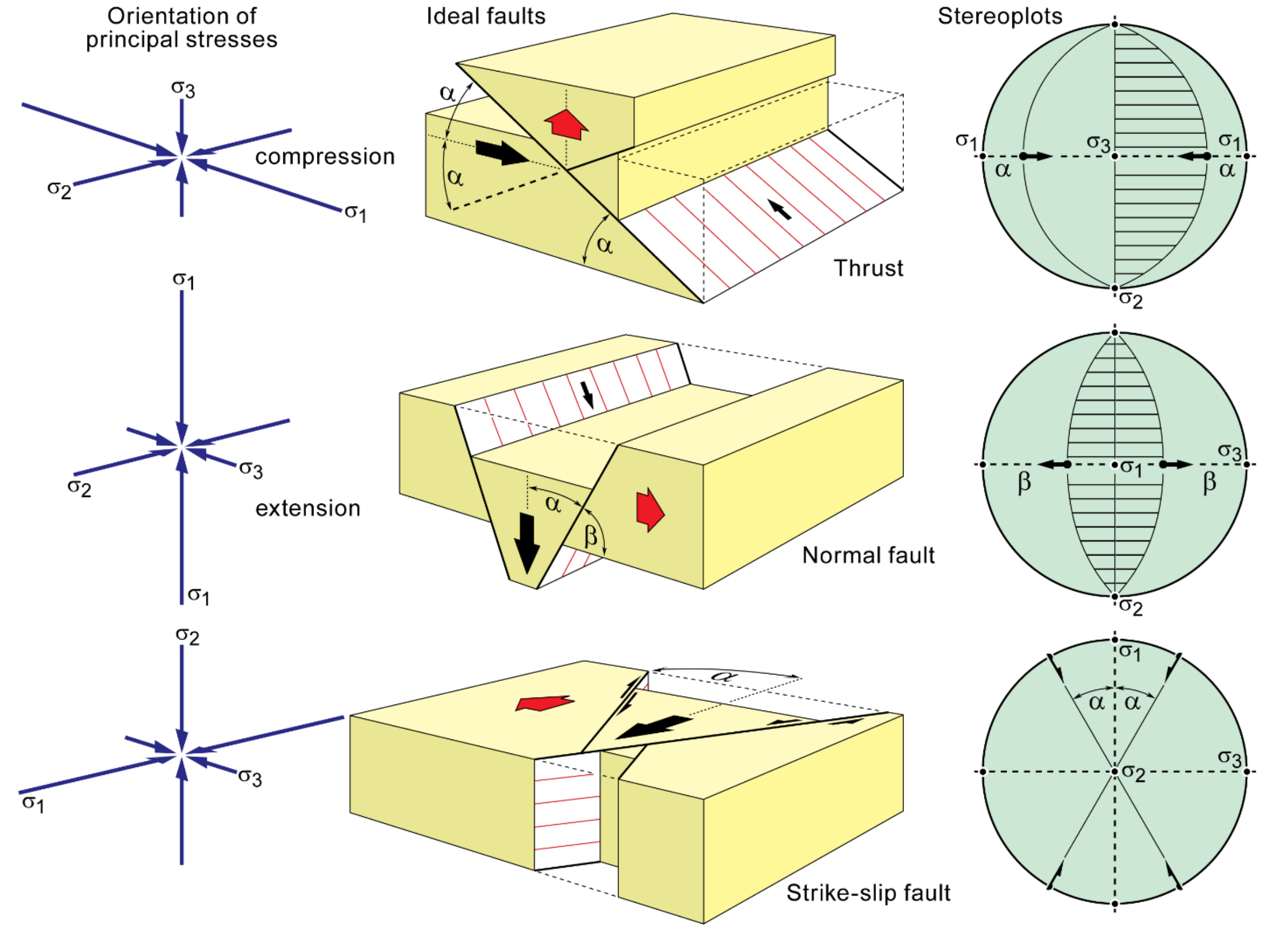
Fault associations

Faults are rarely isolated. **Subsidiary** faults of a lesser extent often accompany the major, **master** fault. They are usually found in groups of the same type, often parallel and dividing the area into **blocks**.

Conjugate faults

Major blocks may be bounded by sets of **conjugate faults,** which means that faults of the same type and formed during the same deformation episode occur in two symmetric sets with parallel strikes, opposite dips and opposite or reciprocal sense of movement to each other.

Triaxial experiments (the three principal stresses have non-zero magnitudes) show that Mohr-Coulomb shear fractures (i.e. faults) are oriented systematically with respect to stress directions.
- Conjugate faults intersect in a line parallel to the intermediate principal stress axis σ_2.
- The greatest principal stress σ_1 bisects the acute angle between the conjugate faults.
- Striation orientations on a given fault are movement directions defined by the intersection of the fault surface with the (σ_1, σ_3) plane.
- The material shortens parallel to σ_1 and expands parallel to σ_3.



Dynamic interpretation of faults: Anderson's "standard" relationship between stresses and ideal faults

These observations are the basis for a dynamic interpretation of fault systems. In addition, Anderson emphasized that the earth surface is a free surface with a fluid, the air, and fluids are unable to support any shear stress (it is a physical definition of fluids). Therefore, the earth surface is a principal plane of stress (remember that a principal stress is per definition orthogonal to a no-shear plane). Assuming a bulk horizontal attitude of the surface of the earth (which is nearly true in low relief regions), one of the three principal stresses is close to the vertical. The type of conjugate fault that develops near the surface depends on which of the three principal stresses is sub-vertical:

- σ_1 vertical: Normal faults dipping about 60°.
- σ_2 vertical: Vertical strike-slip faults.
- σ_3 vertical: Thrusts dipping about 30°.

This interpretation involves that the vertical stress is the lithostatic pressure and that regional stress variations are due to changes in the magnitude of the horizontal stresses relative to the vertical gravitational load. There are three possible ways:
- Both horizontal principal stresses decrease by different amounts in magnitude.
- Both horizontal principal stresses increase by different amounts in magnitude.
- One horizontal principal stress increases while the other horizontal principal stress decreases.

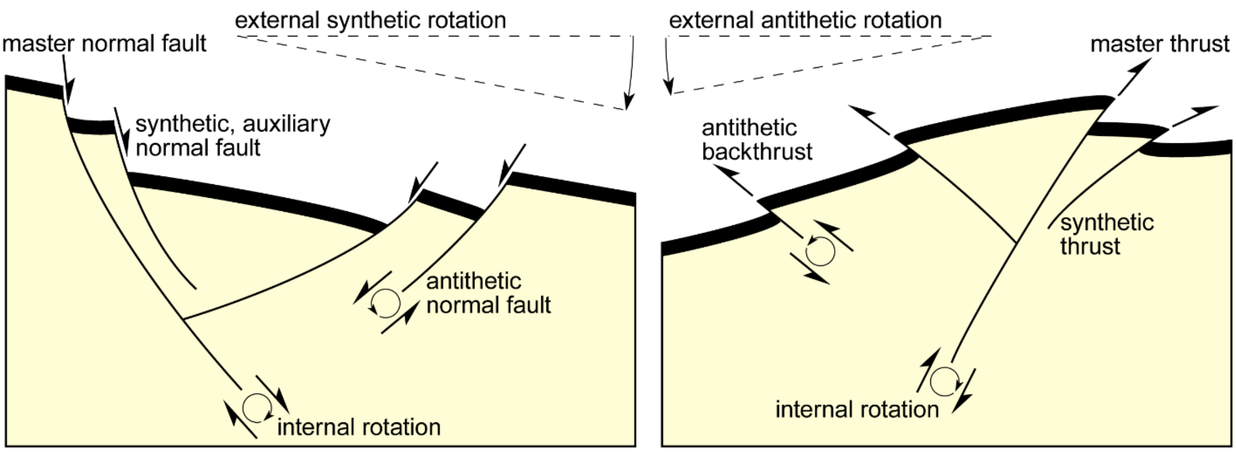
Exercise

Assuming that one of the principal stresses is the gravitational load, draw three Mohr diagrams with the same Coulomb criterion, the same vertical stress, and corresponding to the three "standard states" of stress postulated by Anderson. Comment in terms of differential stresses involved in normal, thrust, and strike-slip faulting.

This formulation explains many fault systems but low-angle normal faults and high-angle thrusts are cases that do not abide by Anderson's rules. Explanations can be the role of anisotropies or pre-existing fractures in natural rocks, which affect fault orientation, and possible strain along the σ_2-direction. Other explanations involve the rotation of fault planes towards non-conventional attitudes.

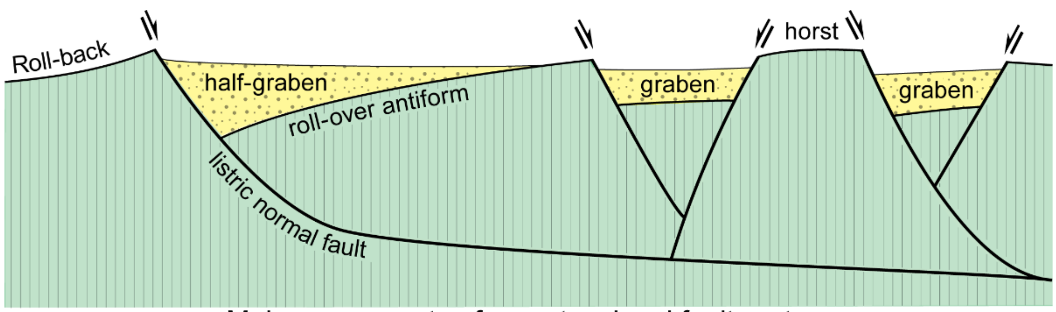
Synthetic and antithetic faults

Synthetic faults are parallel and have the same relative movement as the master fault. The subsidiary yet genetically related set of conjugate faults, dipping in the opposite direction to the master fault, is **antithetic**.



Normal faults

A down-dropped block bounded by conjugate normal faults dipping toward each other is a **graben** and a relatively elevated block bounded by outward-dipping normal faults is a **horst**. **Rifts** are major grabens that extend for long distances. A graben bounded by a single set of normal faults on one side of a tilted fault block has a triangular profile; it is a **half-graben**.

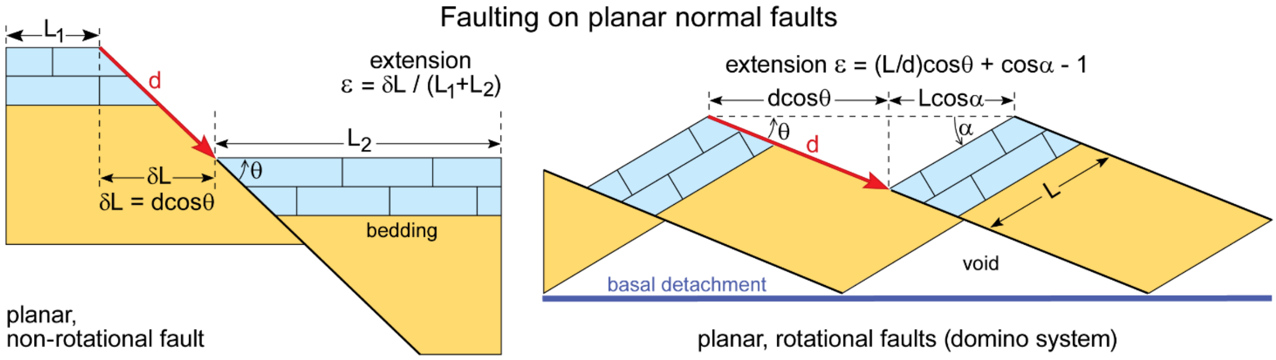


Main components of an extensional fault system

In ideal graben and horst systems, the growth rates of the faults are equal so that the fault blocks do not rotate and the grabens remain symmetric throughout the extension event. In natural fault systems, however, faults grow at different rates and therefore give rise to asymmetric grabens and block rotation. In fact, faulting is usually associated with rotation, which can be important along two types of normal-fault : Planar and listric faults.

Planar faults

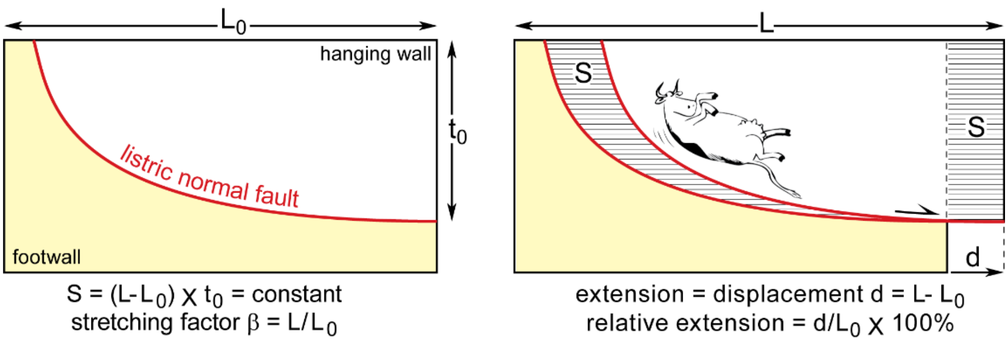
Planar, rotational normal faults occur above a basal detachment or a brittle-ductile transition. They separate juxtaposed and tilted blocks without internal deformation. Both the faults and fault-blocks rotate simultaneously about an axis roughly parallel to the strike of the faults (rigid body rotation resulting in **domino** or **bookshelf faulting**).



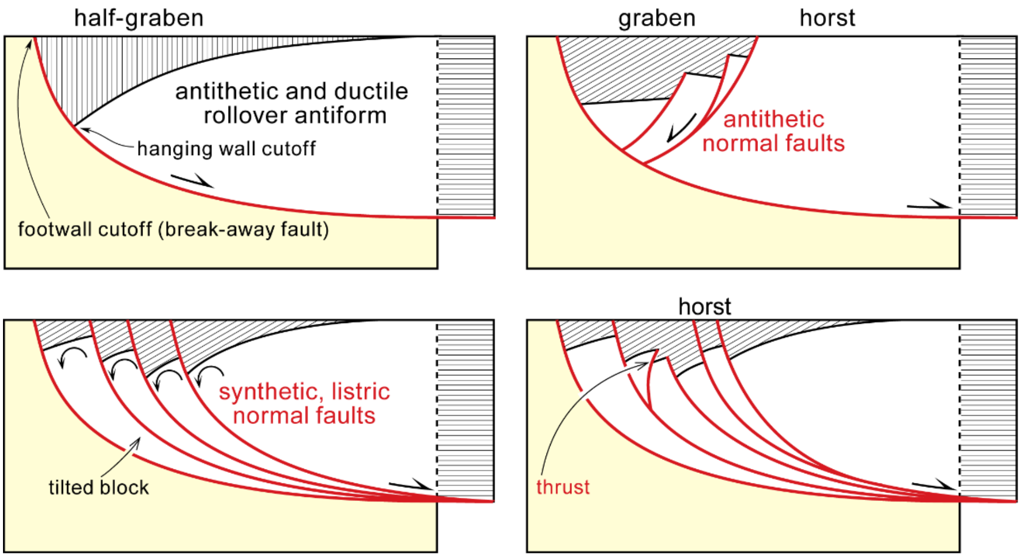
Each fault block has its half-graben. Each fault must have the same amount of displacement and tilt and/or voids open at the bottom of the system. Planar, rotational faults and blocks generally abut against transfer, scissors faults.

Listric faults

Normal faults, in particular the master faults, are in general **listric** (concave upward). They may look steep on the surface outcrops, although they are subhorizontal at depth, which gives rise to space problems if the adjacent blocks are rigid: when the opposing blocks are displaced, they cannot remain uniformly in contact and a gap must develop between the hanging-wall and the footwall.



To maintain geometric compatibility, beds in the hanging wall must rotate and dip towards the fault. Collapse and rotation of the hanging-wall fills the gap and antithetic and/or synthetic normal faults soling into the low-angle master fault eventually accommodate the resulting flexure (**rollover**). Voids may be filled by broken rocks of the fault walls or may provide sites at which minerals are subsequently deposited from circulating fluids. Note that the triangular shape of the half-graben over a rollover defines the dip of the associated listric fault.



Models of collapse-deformation filling the gap between the hanging wall and the footwall of a major listric normal fault

The listric fault geometry is important because it can accommodate a much larger amount of extension than planar faults for the same amount of slip. The bounding steep part of the listric extensional system is the **break-away fault**.

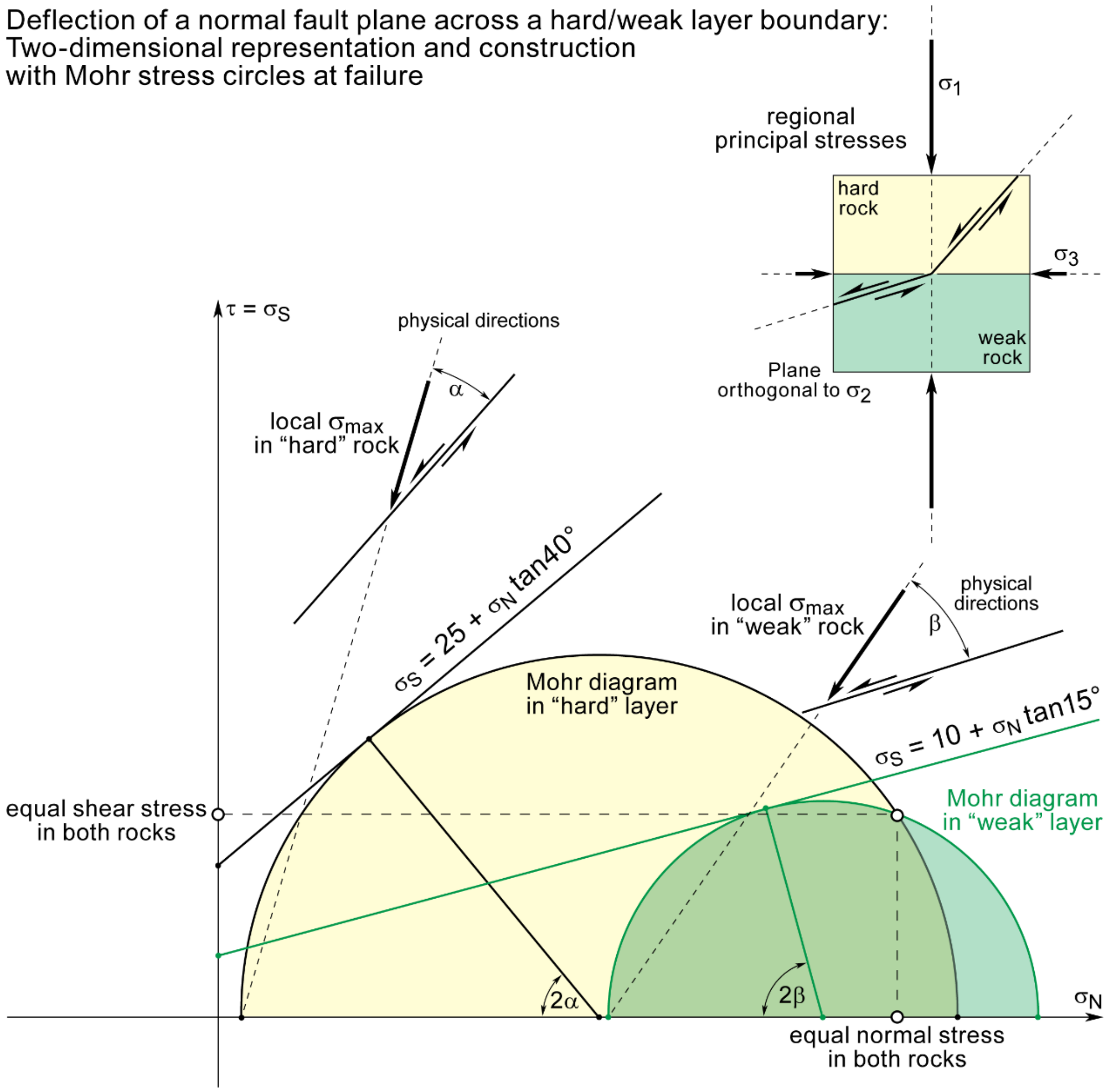
Curved and ramping fault planes

In general, fault surfaces are curved. Variations in fault plane attitude in a consistent stress field meet several explanations.

One is inherent to the shape of the Mohr envelope (see the chapter on Faulting). Its progressively decreasing slope with increasing confining pressure implies that the fault orientation flattens with depth.

Another one concerns the material properties. Different rocks possess different friction angles. The failure (Coulomb) criterion of a rock with high friction angle and likely high cohesion (e.g. sandstone) differs from that of a rock with a lower friction angle and cohesion (e.g. clay). These conditions plotted in a Mohr-Coulomb diagram show that a fault should change orientation with respect to σ_1 across the layer boundary if these rocks are interlayered. Both rocks have to be at the rupture state. This implies that the two rocks are under different states of stress. Assuming the same pore pressure in both, the normal and shear components must have the same values on the layer boundary. This is true only at the point where the two Mohr circles at failure intercept. The σ_N and σ_S axes coincide with the $x-$ and $z-$ axes of real (physical) space, respectively. Therefore, one should be able to represent stress and physical spaces together on the same diagram. Consider normal faulting with σ_1 normal to horizontal bedding. A horizontal line through the (σ_N, σ_S) stress point is the trace of the horizontal bedding plane on which the considered σ_N and σ_S stress components are acting. The intersections of this line with the Mohr circles are **poles**. The chords connecting poles to stress point σ_1 define the real orientation of the plane orthogonal to the local σ_1, hence the local direction of the maximum stress in the corresponding rock. Knowing from 2θ the angle of the fault plane to this local σ_1, one can construct the fault in the two adjacent rocks and readily see how variations in shear strength deviate fault planes.

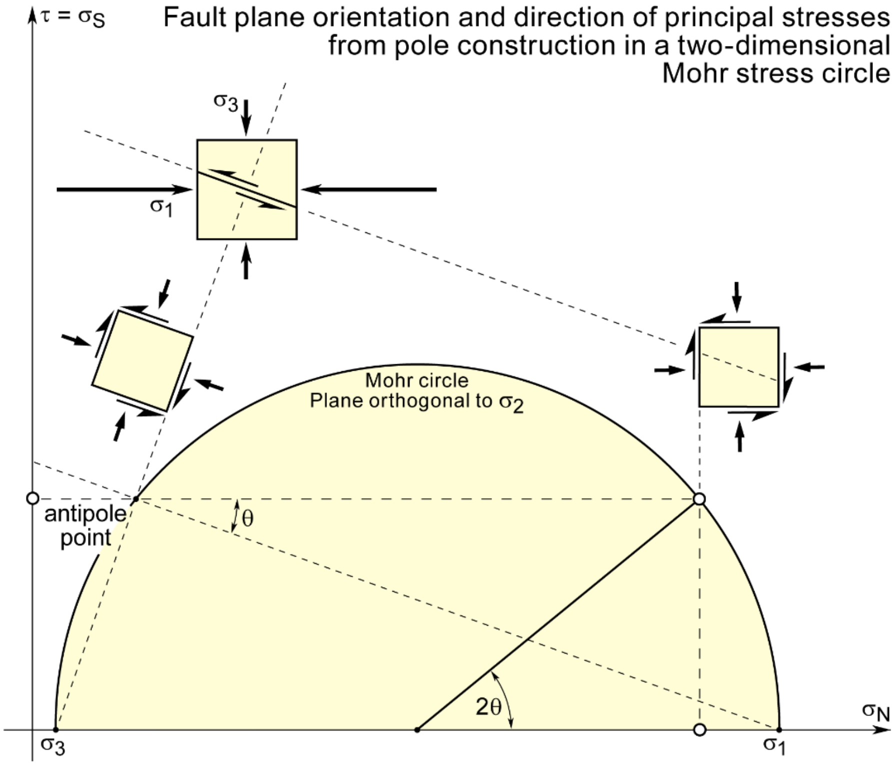
The same game can be played for thrusting conditions. Fault plane deviation is even more pronounced if layer-parallel shearing is involved, as it can happen when beds are inclined to regional maximum compressive stress after folding or tilting, or when a viscous layer (salt, or molten middle crust on a larger scale) laterally flows below a brittle cover. Then the fault tends to follow the ductile layer.



More in Mohr: Physical space in Mohr diagram

Displaying angles twice their physical value is a visual inconvenience of Mohr diagrams. Representing the real orientation of the planes on which stresses act consists in defining the **pole** on the Mohr's circle. The easiest way to locate this pole is to draw a horizontal line through the (σ_N, σ_S) point under consideration. This line represents a plane parallel to the σ_N axis, parallel to the σ_1 direction and containing σ_2. In terms of stress and space axes, the line is parallel to the normal of a plane on which σ_1 is known. Drawing a vertical line parallel to the normal of a plane on which σ_3 is acting yields a diametrically opposite intersection pole, the **antipole** in the lower semi-circle. Discarding sign conventions and being interested in orientations only, the upper semi-circle is sufficient.

An elementary theorem of Euclidean geometry states that an inscribed angle extended from any point on a circle is one-half of the angle subtended at the center from the same arc. A special situation is that an angle inscribed in a semi-circle is a right angle. Therefore, the two lines drawn from the pole or the antipole to the σ_1 and σ_3 points are perpendicular and one of these two lines defines with the horizontal line through the (σ_N, σ_S) point an angle $= \theta$. These two lines, from the antipole ~~point~~ to the principal stresses, thus physically represent the orientation of the two perpendicular planes on which σ_N and σ_S are normal and shear stresses, respectively.

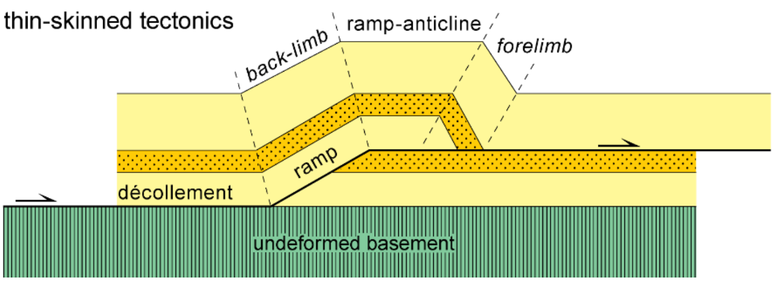


Thrusts

Two styles refer to the degree of basement involvement in the considered thrust system: **thin-skinned** and **thick-skinned** tectonics.

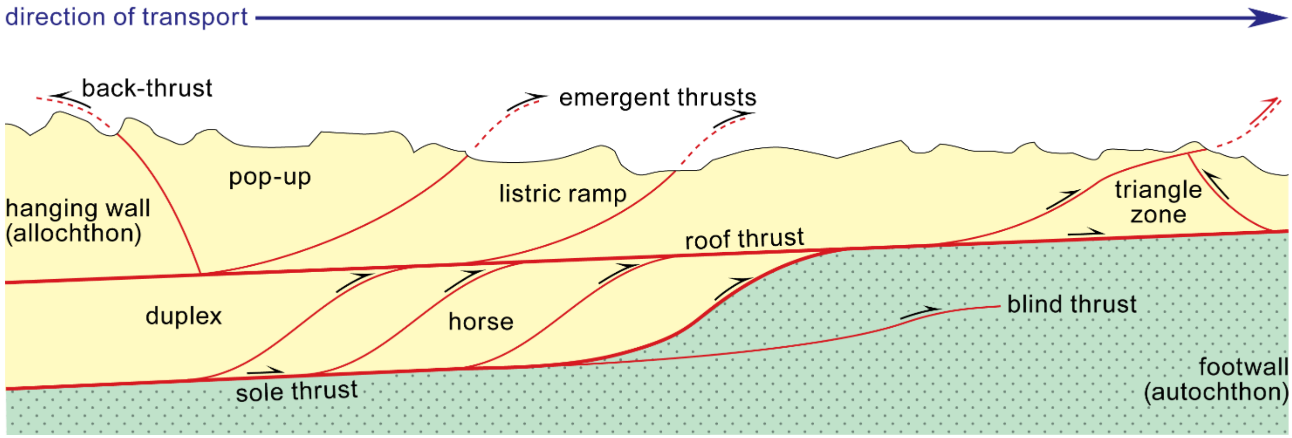
Thin-skinned tectonics

In many foreland fold-and-thrust belts, bedding plays a controlling factor in generating staircase, flat–ramp systems. The sedimentary cover is detached from the basement typically along the **sole thrust**, which remains above the strong crystalline basement left undeformed. Thin-skinned tectonics describes this style of deformation.



Thin-skinned tectonics implies large horizontal displacements whereby the stratigraphic sequence above the floor décollement can be piled up several times, thrust sheet upon thrust sheet. Thrust sheets are generally thin compared to their lateral extent. Thrust faults may develop in sequence either forward (which is termed **prograding**) or backward from the first thrust. Where the younger thrust develops in the footwall of the original thrust, the earlier, higher thrust sheets are carried forward on the later, lower ones, which earned the name of **piggyback** thrusting. Conversely, if the thrust development migrates backward, an **overstep** sequence develops.

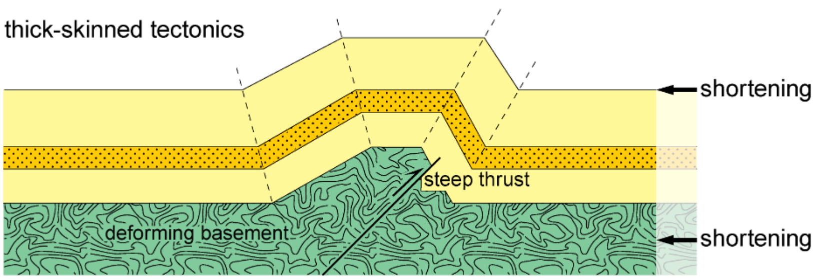
Thrust sequences often result in the stacking up of a series of thrust sheets separated by subparallel thrust faults making up an **imbricate zone** or **schuppen structure**. When master thrusts or décollement surfaces delimit at the top and bottom of an imbricate zone, the whole package is a **duplex**. Individual imbricate sheets within the duplex are **horses**, typically lens-shaped in cross-section. The duplex structure, therefore, consists of a flat-lying **roof thrust** and a **floor thrust** (also **sole thrust**) enclosing a stacked-up pile of horses.



Backthrusts are subsidiary thrusts with a displacement opposite to that of the main thrust. The uplifted hanging-wall block between a thrust and a backthrust forms a **pop-up**. If the backthrust truncates an earlier thrust, a **triangle zone** is formed.

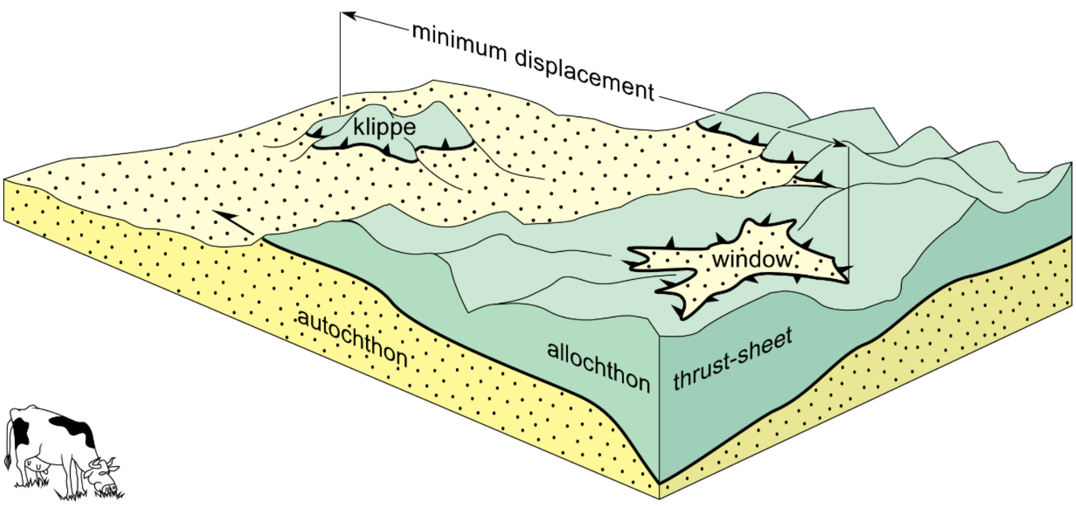
Thick-skinned tectonics

In metamorphic regions, thrusting is commonly associated with intense and distributed ductile deformation. The staircase, flat and ramp geometry is not respected. Major sole thrusts extend steeply down to the basement. Although thrust zones tend to follow surfaces of rheological contrast, they involve the basement. This style is termed thick-skinned tectonics.



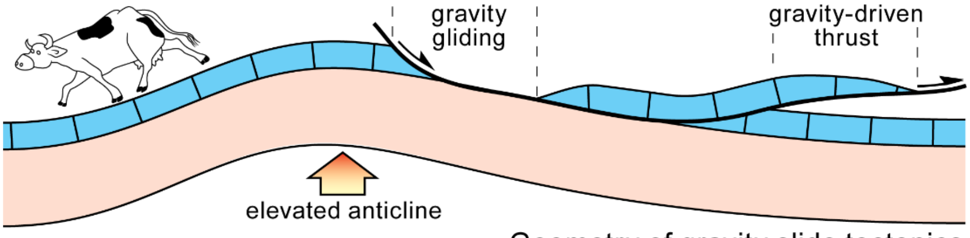
Eroded thrusts

A **window** (or **fenster**) is an erosion exposure of the rocks below a thrust fault surrounded by rocks above the thrust. A **klippe** is an isolated, erosion remnant of a thrust sheet surrounded by rocks of the footwall.



Gravity-driven thrusts

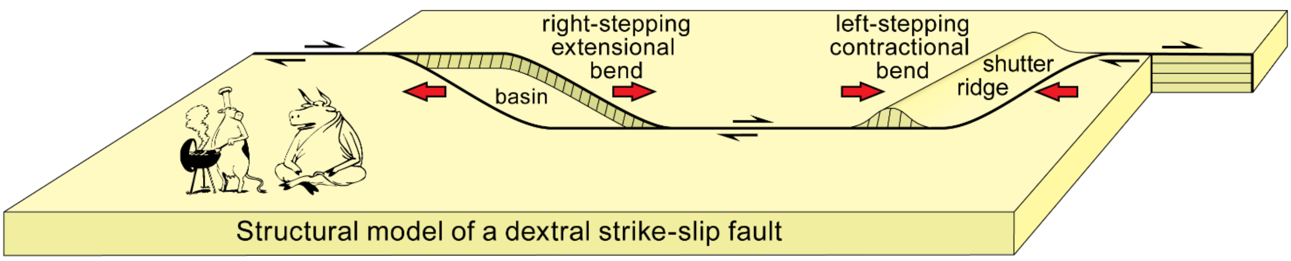
Slip-sheets are coherent parts of a series slipped away, as gravity collapse, from an anticline to rest on an eroded surface within one of the adjacent synclines.



Geometry of gravity slide tectonics

Strike-slip faults

Strike-slip faults are in general vertical and develop at ca. 30° to the horizontal compression direction. Major strike-slip faults can be several hundred kilometers long and are not simple planar movement planes. They often develop a system of **right-stepping** and **left-stepping** faults. Where right stepping faults generate an extensional zone, left-stepping faults generate a compressive zone, and vice versa, according to the sense of displacement on the master fault.

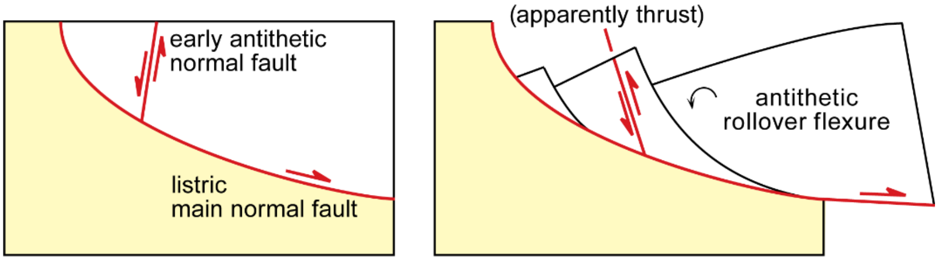


Structural model of a dextral strike-slip fault

Subsidiary faults of curviplanar master faults

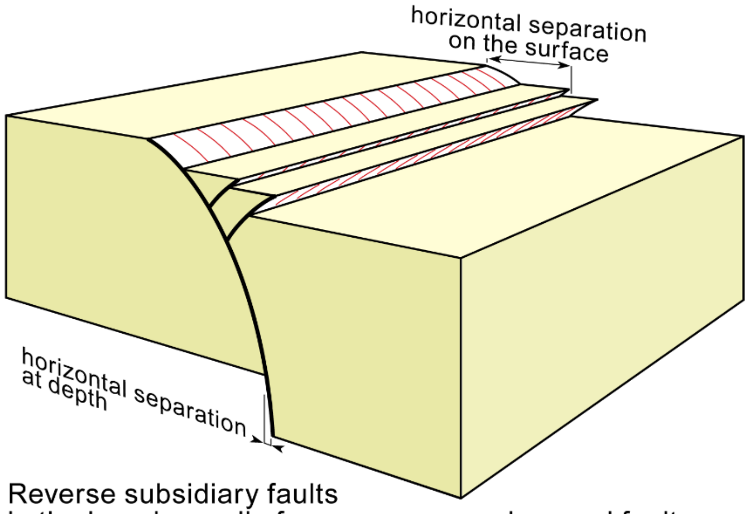
Usually, subsidiary faults belong to the same class as the host master fault. This relationship is not respected where the master fault is curviplanar, hence imposing a complex strain of the hanging wall through the development of accommodation faults.

- Rotation of the hanging wall of a listric normal fault may change a former antithetic normal fault into an apparent reverse one.



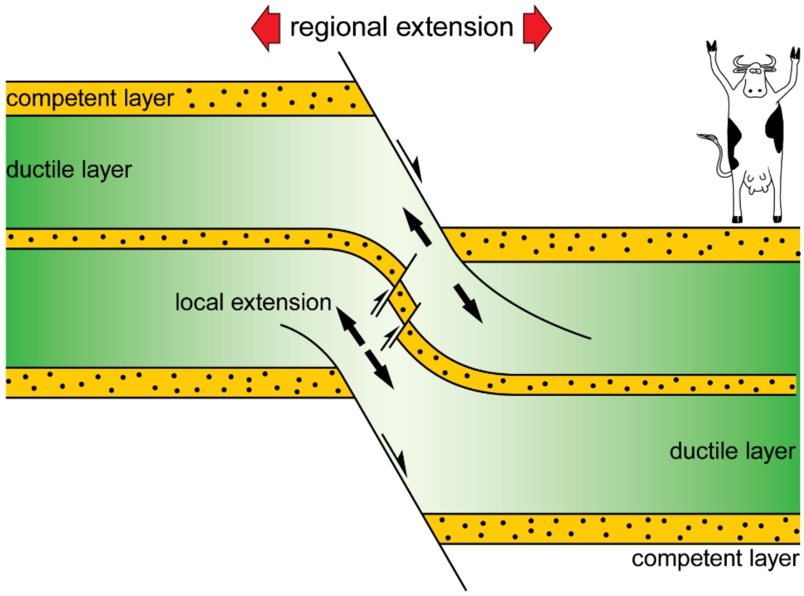
Back-rotation of an antithetic normal fault to the attitude of
an apparent reverse fault in the hanging wall of a listric normal fault

- Reverse faults may form in the hanging wall of a convex-upwards normal fault.



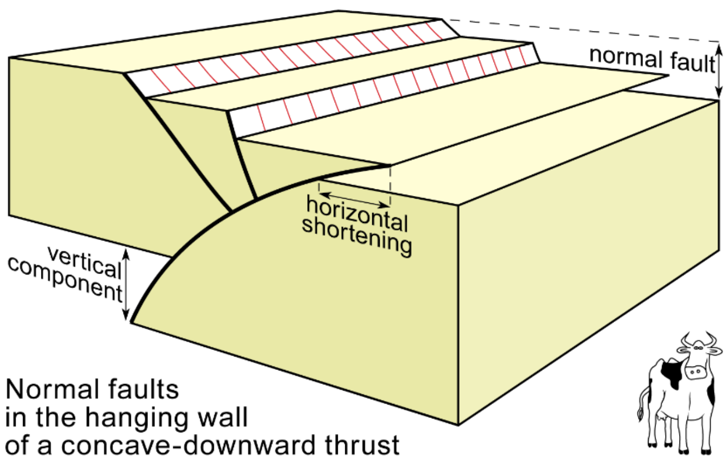
Reverse subsidiary faults
in the hanging wall of a convex-upward normal fault

- Reverse faults may form in tilted layers to accommodate layer-parallel stretching due to larger scale normal faulting.



Reverse fault accommodating local, layer-parallel extension
in a regional extension system

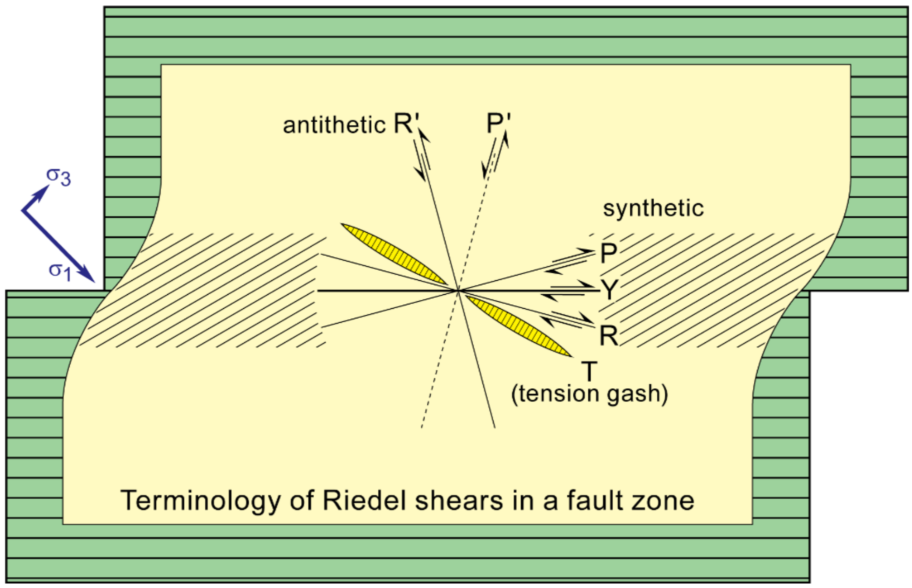
- Normal faults may form in the hanging wall of a convex-upwards thrust.



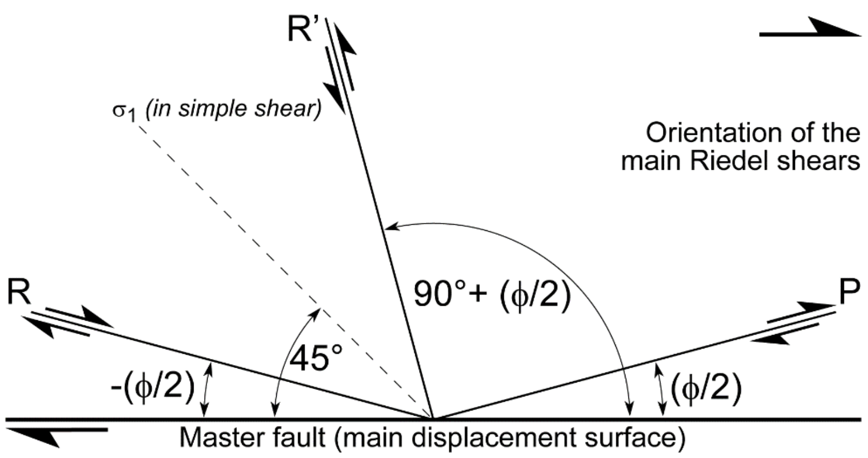
Normal faults
in the hanging wall
of a concave-downward thrust

Subsidiary fractures = Riedel shears

Subsidiary **Riedel shear** fractures propagate a short distance out of the main fault and make a network commonly developed during the embryonic stages of faulting. Riedel shears form a systematic array apparently self-similar for a wide variety of materials over a wide scale-range. The basic geometry consists of conjugate R and R' fractures whose acute bisector is the direction of maximum compressive stress.



- **R** Riedel shears develop at a small angle (typically 10-20°) to the main fault, often in an *en échelon* array, and are synthetic to the main fault. *En-échelon* describes the aligned pattern of a series of parallel, short fractures arranged like rungs of a ladder seen in perspective. In simple shear, the principal stress σ_1 is at 45° to the main slip plane. The Mohr-Coulomb failure criterion predicts that conjugate failure surfaces are optimally inclined at $\pm(45° - \phi/2)$ to σ_1, where ϕ is the angle of internal friction. The acute angle of R Riedel shears with the main fault is $-\phi/2$. This angle points in the direction of the relative sense of movement on the master fault.
- **R' shears** are conjugate, antithetic to the R(iedel) shears (i.e. with offsets opposite to the bulk movement), oriented at a high angle $[90° + (\phi/2)]$ to the main fault plane. They preferentially occur between two parallel R shears. R and R' shears intersect at an acute angle $\beta = 90° - \phi$.
- **P shears** are synthetic minor faults symmetrically oriented to the R shears with respect to the fault plane (at $+\phi/2$ from the fault plane). P shears generally link R shears and tend to occur for large displacements.



- As for R Riedel shears, there may be **P' shears** conjugate with P shears (at $-45° - \phi/2$ from the fault plane) but these have relatively minor importance.
- **Y shears** are microfaults subparallel to and slipping coherently with the main fault.

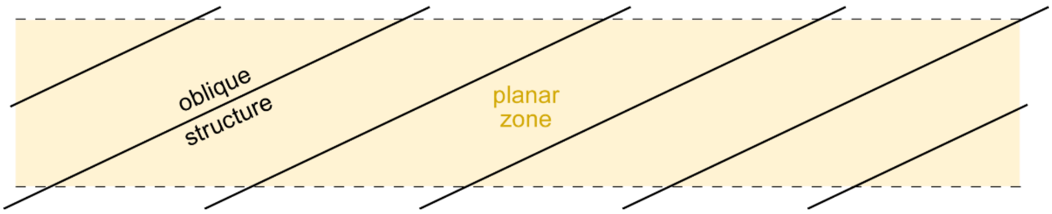
Fault population and networks

The analysis of fault populations has shown that faults exhibit many characteristics of **fractals**; a fractal is an entity that has geometrical properties (e.g. shape) either independent of its size (self-similar) or exhibiting a simple relation with its size (self-affine). This characteristic means that a pattern of faults viewed from satellite pictures looks the same as the pattern of faults seen in an outcrop. It implies that some fault properties (e.g. the length/throw ratio) are relatively independent of fault size. However, the analysis of faults on 3D data sets has shown that, in log-log space, there is a simple linear relationship between fault frequency and fault size. This relationship between fault size (length or maximum throw) and the number of faults with a certain size (few large faults, many small faults) can be used to predict the density of small, sub-seismic (i.e. below the limit of seismic resolution) faults.
There are a few important terms describing fault arrays in map view.

En échelon pattern

« ***En échelon*** » means "in step-like arrangement" and describes a consistently overstepping and overlapping alignment of subparallel, closely spaced structures oblique to the planar zone in which they occur. Such patterns commonly denote potential faulting.

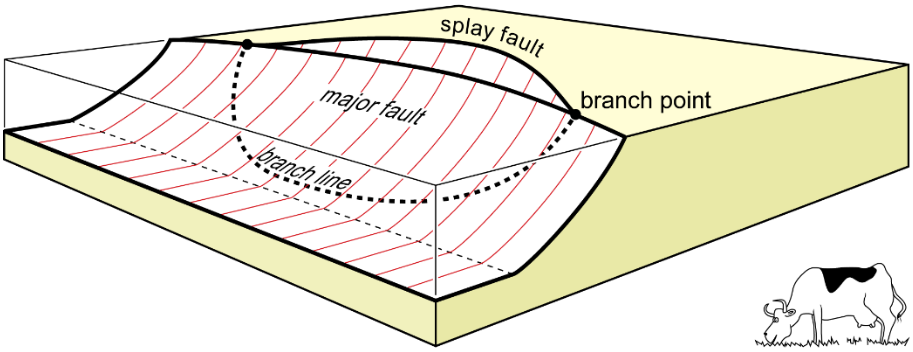
En échelon pattern



Fault linkage

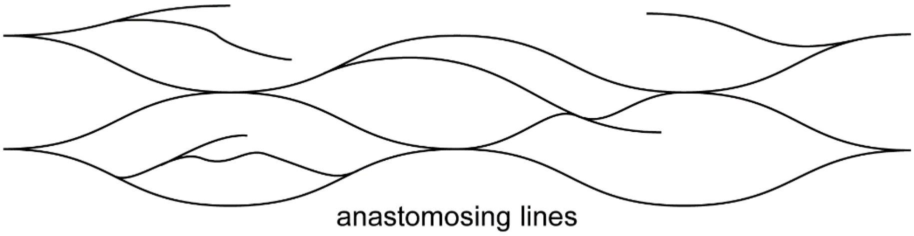
In brittle regions and damage zones, faults frequently splay into complex arrangements of smaller faults that curve away at an acute angle from the direction of the master fault. The line of connection where a fault splits into two fault surfaces of the same type is a **branch line**. Beyond this line, branching **splay faults** have the same sense of relative movement as the master fault. They form an **imbricate fan** that spreads the displacement over a volume of rock. A splay is a small, often inactive, fault segment or branch created during fault coalescence (**hard linking**) or propagation (**branching**). **Soft-linkage** refers to offset fault segments that are not connected.

Tectonic wedge terminating at a branch line and two branch points



Anastomosing pattern

Riedel shears of any scale may merge to form an anastomosing network of fractures in a fault zone whose bulk borders are parallel to the main fault. **Anastomosing** refers to a branching and re-joining network of irregular surfaces or lines interlaced like braided streams or veins.



Scaling of fault distribution

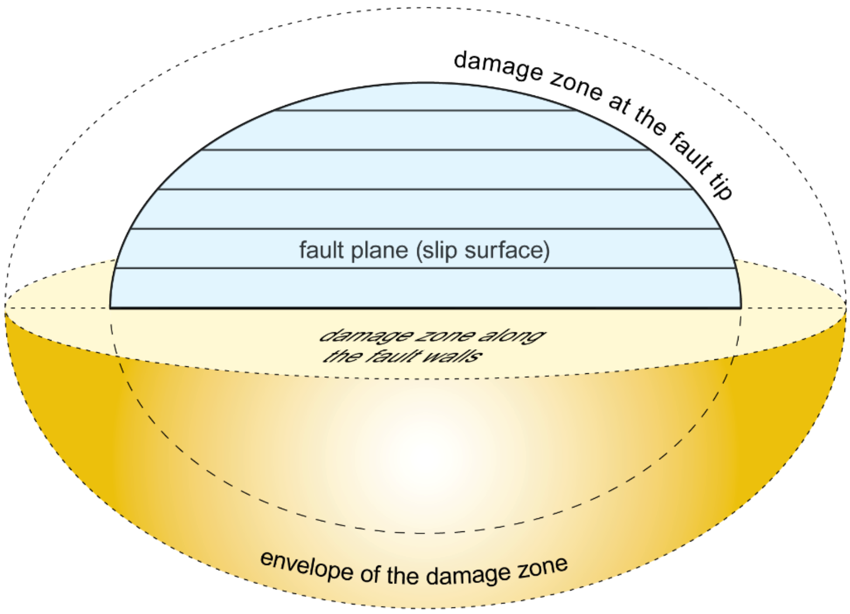
A power law distribution is frequently advocated to describe fault distributions. In practice, the significance of a single power-law exponent might reveal hierarchical patterns in a complex fracture system that includes all sorts of fractures with different scales.

Fault anatomy

Faults have finite extents. They consist of the slip surface (**fault core** for "thick" faults made of anastomosing shear fractures) and an enveloping **damage zone** spread over some width. These two elements either simply die out along their strike or terminate against other faults. In the latter case, faults either merge with or are truncated by the other faults. Because of fault growth and coalescence, faults develop into a **fault network**.

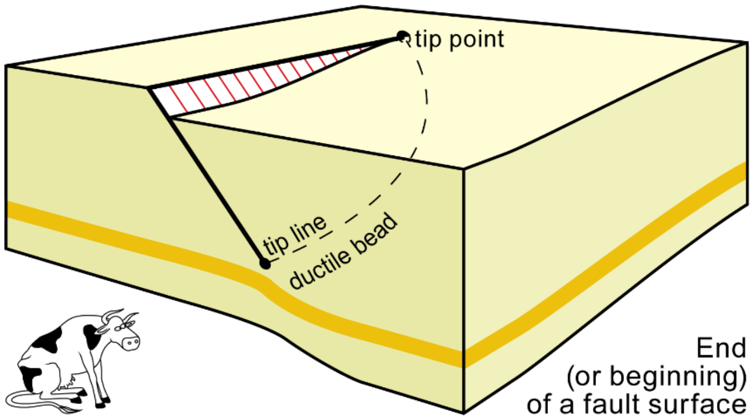
Tip line and tip zones

Single, isolated faults are approximately elliptical surfaces along which most of the slip has taken place; this elliptical shape is broken if the fault intersects the earth surface. The aspect ratios between length and width of the elliptical normal-fault planes tend to be >1 and <5.

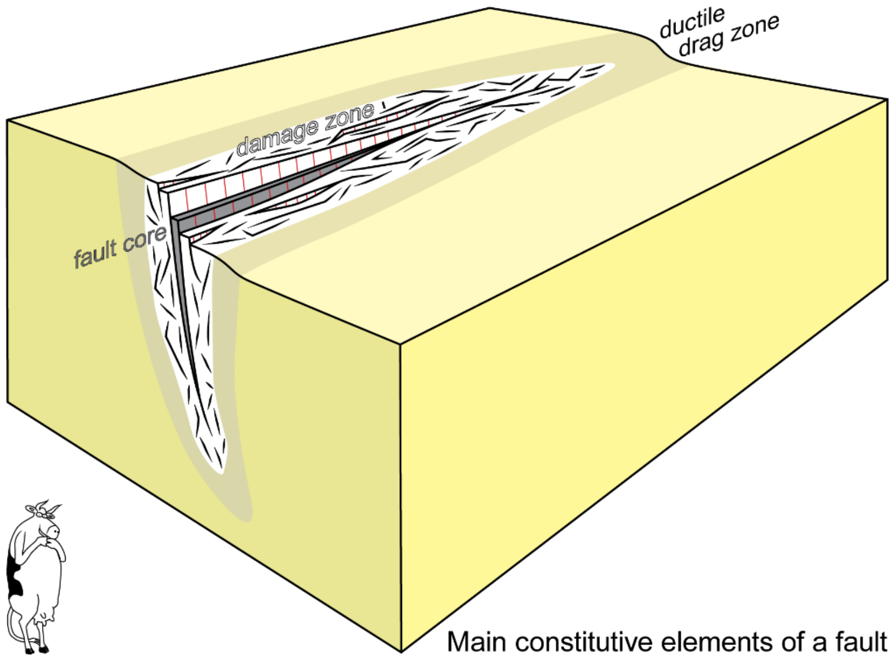


3D conceptuel model of a damage zone around a fault

The relative displacement must fade out outward. It drops to zero at the **tip line,** which encloses this movement plane. In other words, the tip line separates slipped from non-slipped rocks. Beyond this limiting line, the fault displacement is accommodated and dies out across a **tip zone** in various ways, depending on the ratio of fault length to fault displacement.



- If displacement is very small relative to the dimensions of the active segment, space and continuity problems are accommodated by the gradual reduction in displacement toward the fault extremities and suitably distributed, non-brittle deformation (penetrative strain and/or folding) through the surrounding solid rock along the fault tip, the **ductile bead,**
- Where displacement is bigger relative to fault dimensions, clusters of smaller faults and additional fractures within a **damage zone** can accommodate strain around the fault, particularly in hanging-walls.



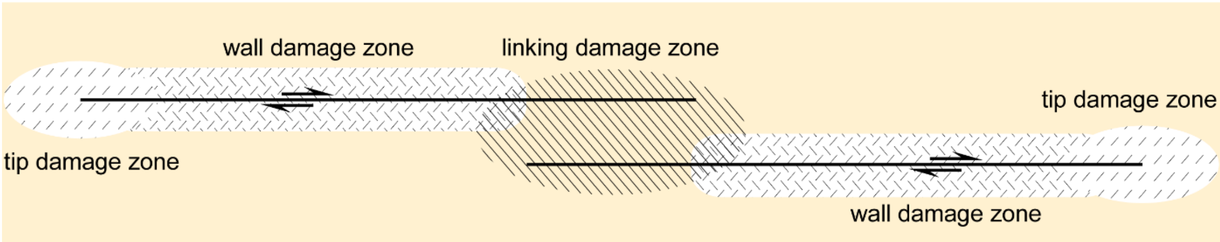
Main constitutive elements of a fault

Damage zones

Damage zones are arrays of entangled minor faults and fractures along larger fault planes. The density of faults and fractures ideally decays exponentially away from the master fault. Damage zones occur because of stress concentration, particularly at fault tips and in linking zones; Damage zones also occur to accommodate displacement variations into or along faults. Initiation, propagation, and interaction classify damage zones into tip-, wall- and linking-damage zones based on position within and around a fault zone.

- A tip damage zone develops in response to stress concentration at a fault termination.

- Wall damage zones can be distributed along the whole trace of a fault. They may represent tip damage zones abandoned in the wall rocks as faults propagated through the rock. They may also represent wall-rock deformation associated with the build-up of slip on faults.



Map view of the location of damage zones within a fault zone

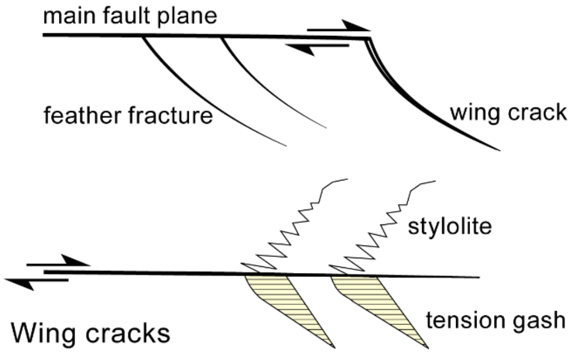
- Linking damage zones are caused by the interaction and linkage of fault segments in a relatively small region. They are complicated due to the cumulative displacement and interaction of the tip and wall damage zones of two neighboring faults. Consequently, linking damage zones can develop a wide range of fracture patterns depending on the interaction between the two fault segments.

Fault termination

Mesoscopic tip damage zones in front of tip lines are categorized into four subdivisions according to the nature and orientation of faults and fractures developed: wing cracks, horsetail splays, synthetic and antithetic splay faults. Tip-damage zones are easy to recognize, even at a large scale.

Wing cracks

Wing cracks occur where there is a rapid decrease in the slip at the fault tip, at fault plane irregularities such as bends, steps, or relay zones and at points of variable frictional properties along the fault surface. Wing cracks are extension fractures that abut fault planes and tend to curve towards parallelism with the local maximum principal stress direction, in dilational quadrants of the fault front.



Anticracks

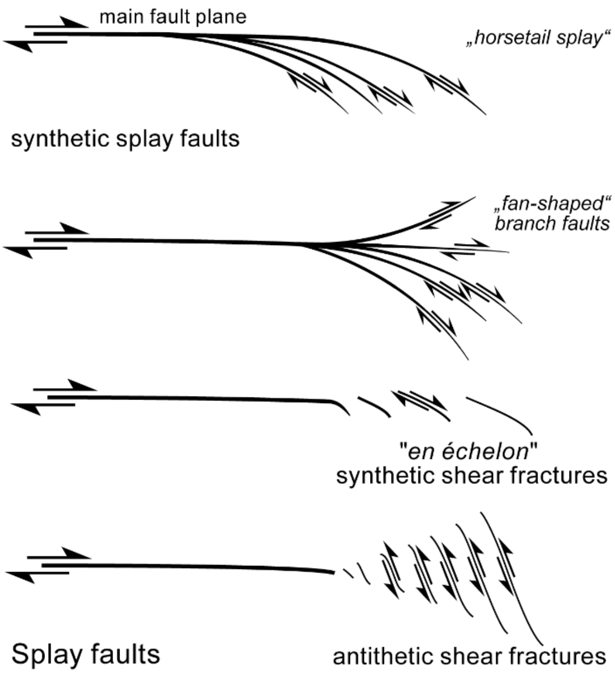
Anticracks are solution surfaces (**stylolites**) symmetrical to wing cracks with respect to the main shear surface. They are orthogonal to the local σ_1 direction in compressional quadrants of the fault front.

Pinnate fractures

Feather (or **pinnate**) fractures are extension fractures that form *en échelon* arrays along slip surfaces. **Tension gashes** are pinnate fractures filled with mineral crystallization.

Synthetic splay faults

Synthetic splay faults are geometrically and mechanically similar to wing cracks but are finer and more closely spaced with relatively low angles to the master fault. They have the same sense of slip as the main fault and may link with a neighboring fault segment. **Horsetail** fractures splay asymmetrically out, often on one side of the main fault in a fan-shaped network. They tend to develop where slip dies out more gradually towards the fault tip than for wing cracks.

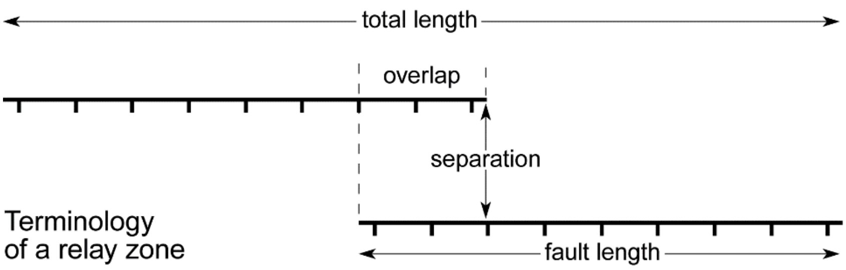


Antithetic splay faults

Antithetic splay faults have a sense of slip opposite to that of the main fault and tend to develop at high angles to the master fault. They are isolated fractures separated from the master fault and often increase their length and spacing away from the fault tip.

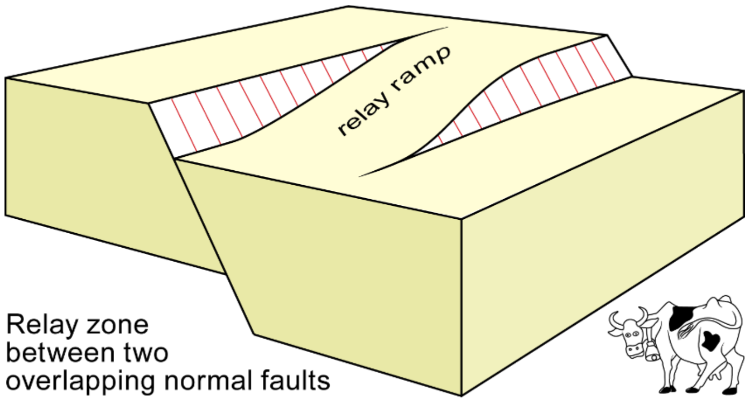
Relay zones; linking damage zones

A **relay zone** is a volume of rock through which the displacement is transferred from one fault termination segment to another fault termination segment. This transfer produces **relay structures** that accommodate local kinematic and strain complications. The discontinuous interval between two sub-parallel fault segments (strictly speaking between similar structures) is the **overstep**. If the normal to the tip of one overstepping fault intersects the other faults, there is **overlap**. The alternative is **underlapping**.

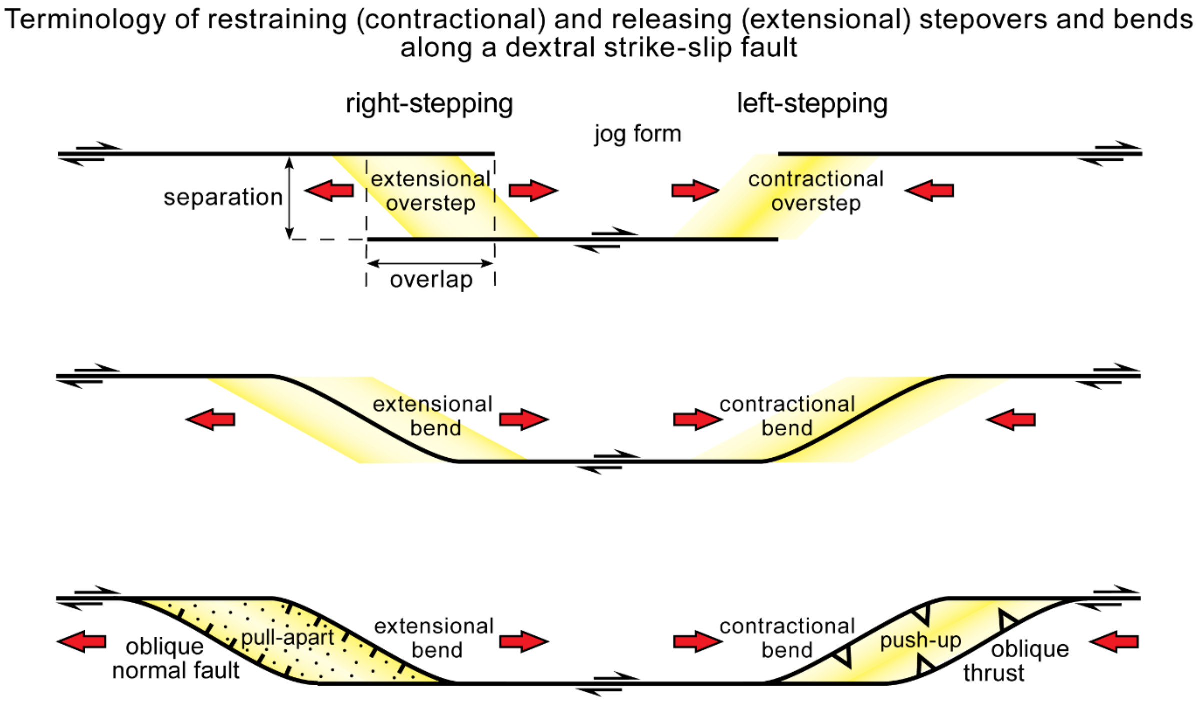


Overlaps are **right-** or **left-stepping**, depending on the sense the jump goes from one structure to the next. The **separation** is the distance between overlapping, parallel fault segments. Separation/overlap ratios provide a crude measure of fault interaction. The degree of interaction is better determined when separation and overlap values are normalized to the fault length of one and any of the two interacting faults.

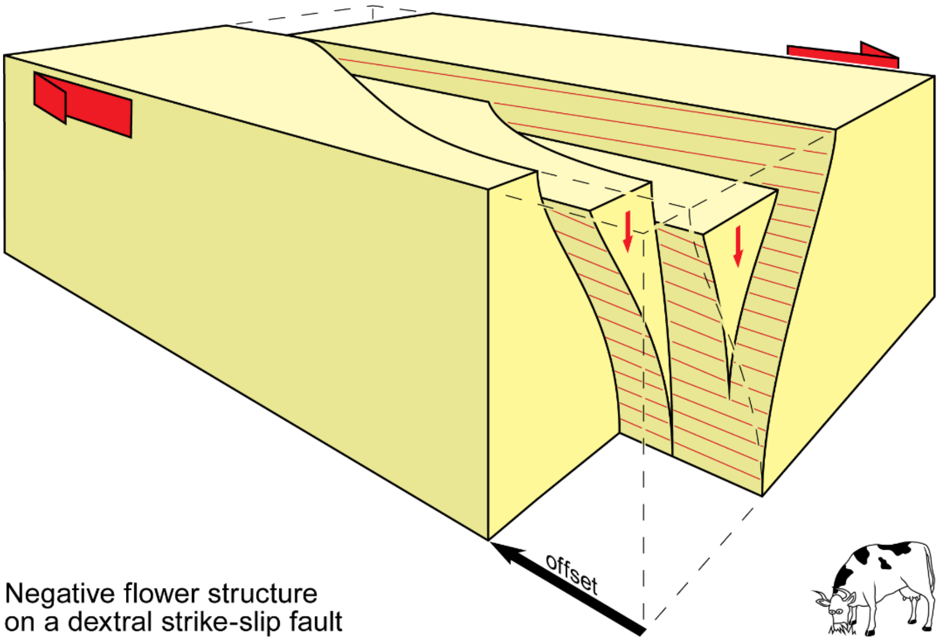
A **relay ramp** is an area of bent bedding that transfers displacement between two overstepping faults with the same dip direction.



Relay zones may form large structures. A **relay ramp** is an area of bent bedding that transfers displacement between two overstepping faults with the same dip direction. Whatever their scale, they are transient features, evolving during fault propagation until they are replaced by **breaching faults**, which connect the interacting fault segments (evolution from soft- to hard-linkage) to make a single, through-going fault surface. Single- and double-tip linkages are obvious patterns that will form fault **bends** and **jogs**, where both the dip and strike of a strike-slip fault change.



The changing attitude of a fault plane produces compressional or extensional stepping zones, according to the shape of the step with respect to the movement on the master fault. For example, if a dextral fault steps to the right, the **overlap zone** or the **transfer zone** where the fault segments run parallel is in extension. Transfer normal faulting forms voids filled with vein material or low topography areas with basin sediments (**rhomb-shaped basin**). Conversely, solution structures, anticlines, or some high topography mark a compressional overlap.
Overlap structures above strike-slip faults are **flower-structures** if several splay faults root into the main strike-slip zone. Fault **throw gradients** tend to be highest in relay zones.



Negative flower structure
on a dextral strike-slip fault

Fault rocks

Faulted rocks often fill fault zones. The accepted classification of fault rocks, i.e. rock types created by fault generation, uses cohesion at the time of fault movement and the presence of a planar fabric. There are two main types of fault rocks:

- Incohesive fault rocks in brittle fault zones. These rocks have a random fabric.
- Cohesive fault rocks in ductile shear zones. These rocks have a foliated fabric.

Incohesive, non-foliated fault rocks

Comminution (grinding) of rocks characterizes faulting in the brittle field. The resulting incohesive, non-foliated fault rocks are **cataclasites.**

Description - Definition

Cataclasites are randomly oriented aggregates of angular, broken fragments of the rocks composing the fault walls. The fragments range in size and may be held together by some cementing material, generally infilling minerals crystallized by precipitation from fluids circulating between the fragments. According to the size of the elements, one distinguishes**:**

* **Fault breccia** when visible, angular fragments constitute more than 30% of the rock volume. Breccia can be cemented or uncemented; rock fragments may range from sand-size to large boulder size and are commonly striated.
* **Microbreccia** if the fragments are microscopic;
* **Gouge** when more than 70% of the material consists of very fine-grained, clayey, and often dark powder containing small angular fragments. Clay minerals result from weathering and/or hydrothermal alteration of pulverized fault-wall rocks. Gouges and equivalent fine-grained fault wears are rarely consolidated.

Late movements may impart a distinct planar fabric in these crushed rocks, which, however, fundamentally remain incohesive, i.e. unconsolidated.

Setting

Major faults do not exhibit a discrete slip surface but a planar **core** up to several meters in thickness, essentially formed of wear detritus derived from the fault walls. Cataclastic and cracked rocks also constitute the damage zone, the broad volume of deformed wall rocks around the fault core. Many metalliferous veins occur in this setting, with hydrothermal minerals cementing the rock clasts. In that case, the cohesionless rock at the time of faulting has acquired a secondary cohesion.

Cataclasis

Cataclasis results from the initiation, propagation, interaction, and build-up of slip along the fault. The incohesive fault rocks are essentially formed by **cataclasis**, the deformation process involving fracturing of grains and grain boundaries along with **dilatancy** allowing rigid-body rotation between granular elements. Cataclasis is thus the mechanical granulation, crushing, and/or milling down to powder any coherent rock. The process is common in the upper crust where strain rates are fast and confining pressures and temperatures relatively low (< 500 MPa, 200-300°C).
The size-frequency of comminuted particles is a measure of the energy used for cataclasis. Fault gouges show size frequencies with fractal dimensions > 1.6.

Cohesive, foliated fault rocks

Cohesive, foliated, commonly lineated fault rocks belong to the **mylonite** series. They are characterized by a foliated or streaky structure, in thin section, and are typical of ductile shear zones. Grains of the parent rock have been reduced in size without the loss of primary cohesion. The fine grain-size and distinctive microstructure are due entirely to the ductile deformation (viscous creep) accompanied by recrystallization. Mylonites often contain larger fragments or relict minerals from the parent rock; these fragments are **porphyroclasts**. Mylonitization is a gradual process of grain size reduction in which three types of rocks are distinguished on the relative proportion of porphyroclasts to the fine-grain matrix:

* A **protomylonite** is a rock in the early stages of mylonitization, containing more than 50% porphyroclasts.

* A true **mylonite** contains 10-50% porphyroclasts.

* Extreme grain size reduction and dynamic recrystallization may produce a hard, flint-like, dark fault filling of ultramicroscopic grains containing less than 10% of tiny porphyroclasts. These rocks are **ultramylonites**.

* B**lastomylonite** describes extensively recrystallized rocks with strain grains annealed after mylonitization.

*** Phyllonite** is a mica-rich mylonite with the mesoscopic appearance of schist.

Fault rocks - Terminology

<table>
<tr><td>metamorphic conditions</td><td colspan="2">very low grade</td><td>low grade</td><td>medium</td><td colspan="2">high grade</td></tr>
<tr><td></td><td colspan="3">Cataclasite</td><td colspan="3">Mylonite</td></tr>
<tr><td rowspan="9">Principal types of fault rocks</td><td colspan="2">incohesive</td><td colspan="4">cohesive</td></tr>
<tr><td>Fragments %</td><td></td><td></td><td></td><td>Matrix %</td><td></td></tr>
<tr><td rowspan="3">>30</td><td colspan="2">Breccia</td><td>Protomylonite</td><td><50</td><td rowspan="7">recrystallised Blastomylonite</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Microbreccia</td><td>Mylonite</td><td>50<<90</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td><30</td><td>Gouge</td><td></td><td>Ultramylonite</td><td>>90</td></tr>
<tr><td colspan="2"></td><td></td><td></td><td></td></tr>
<tr><td colspan="2"></td><td colspan="2">Pseudotachylite (molten)</td><td>>85</td></tr>
</table>

Pseudotachylites

Pseudotachylites form thin, glassy, and dark veins of cohesive and non-foliated rock along some faults. They typically occur in a branching network of injection veins stemming from the fault zone into the usually crystalline wall rock. The glassy matrix, which contains rock inclusions and microscopic spherulites, attests that the vein was in a fluid state and abruptly chilled. In most cases, later devitrification has removed the glassy texture. Pseudotachylites are believed to form when a seismic movement and local decompression trigger swift melting followed by quenching and solidification of the molten material. Calculations of temperatures required for local friction melting of the wall rocks infer rapid movement (0.1 to 1 m/s) along the fault plane. Pseudotachylites are therefore recognized as indicators of paleo-seismic activity.

Fault rocks and depth

The different types of fault rocks tend to form at different depths:

Incohesive gouge and breccia:	0-5 km
Cohesive cataclasites and pseudotachalites:	10(15) km
Cohesive mylonites:	> 10(15) km

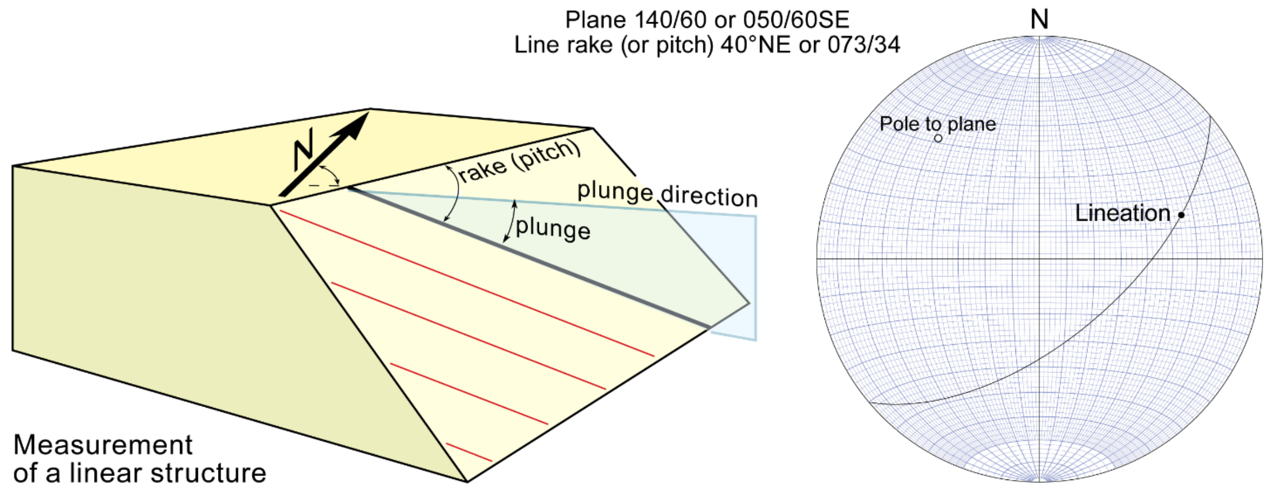
Determination of slip

Several methods may be employed, if possible in combination, to determine a fault displacement.

Offset of geological structures

The knowledge of the stratigraphic sequence provides a first indication for knowing a fault. Then, for example in a drill hole, a thrust is responsible for the **repetition** of strata, and a normal fault for the **omission** of strata. This simplification ignores, however, the possible strike-slip movement on strike-slip faults with an original dip.
The complete determination of displacement requires identifying the positions on either side of the fault of two originally coincident points, for example, the intersection of the fault plane and a linear element such as a pre-existing fold hinge line, which the fault has displaced. Where the intersection of two planar structures defines the offset linear marker, the planar structures must both predate the faulting. Offset contact lines on geological maps may be misleading because they are defined by the intersection of a geological plane that predates the fault and a topographic surface that post-dates the fault. The same may be true of offsets shown in cross-sections, or observed in outcrop surfaces of any orientation. To distinguish the offset of planar markers from the offset of linear markers the former is referred to as **separations**.
A lower limit can be placed on the net slip of a thrust fault where thrusting has brought older rocks over younger ones. For example, the distance between klippe and window places a minimum limit on the displacement of the fault. Note, however, that the klippe-to-window method is lousy if a line drawn from window to klippe is not at least approximately parallel to the direction of displacement.

Diagnostic movement structures within brittle fault planes

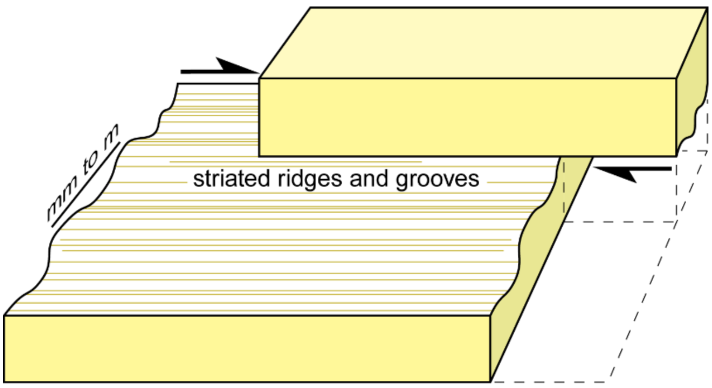


Rocks in contact at a fault plane often have smooth, shiny, or polished surfaces of mineralized material known as **slickensides**. Slickensides are due to abrasive action, may be featureless, but

sometimes feel smoother (under the finger) in the direction of slip. Parallel scratches **(striations)** are common on fault surfaces. These **cataclastic lineation**s (**slickenlines**) are parallel to the slip vector on the fault. The angle measured within the inclined fault plane between the horizontal line (the fault strike) and the line marked by striations is the **pitch** or **rake**. Associated asymmetric surface features are **kinematic indicators** of the sense of slip.
The most common and reliable fault kinematic criteria are:

Asperity plowing

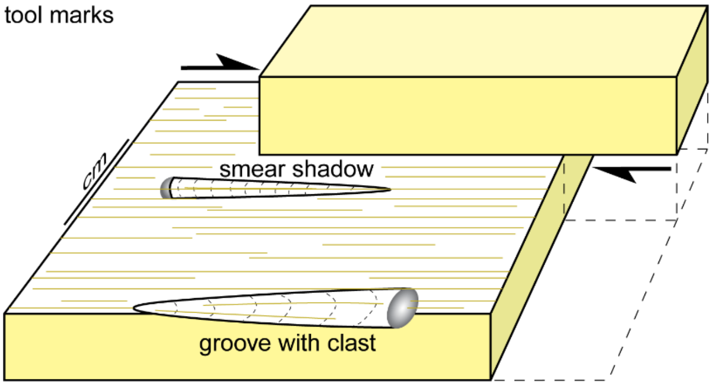
Slickensides commonly display a linear **striation** or **corrugation** (thereby describing parallel ridges and grooves that occur over a range of several scales) experimentally shown to be abrasion scratches parallel to the direction of relative fault movement. Mineral streaks in the fine-grained material along fault planes define most striations (**slickenlines**). Some **striae** may be **grooves** or **gutters** deeply furrowed on one side of a fault by hard particles drawn over it by the other side. **Ridges and grooves** can be long, linear, meter-scale undulations of the fault plane. On a microscopic scale, a dimensional preferred orientation of grains marks such lineations, in particular in soft sediments. These linear features indicate the slip direction but not its sense.



Movement structures within a brittle fault plane

Tool marks, tracks and debris streaking

A striating, erosive object can be pinned in one wall of the fault plane while matching depressions or indentations are present on the opposing surface. A spoon-shaped depression around a hard clast provides the sense of relative movement, with the hard object at the distal end of the pit it carved. Conversely, debris can be deposited in the direction of slip behind a protruding asperity, erosion-sheltering creating a tail of lightly cemented gouge material accumulated behind hard asperities, which is the movement direction.



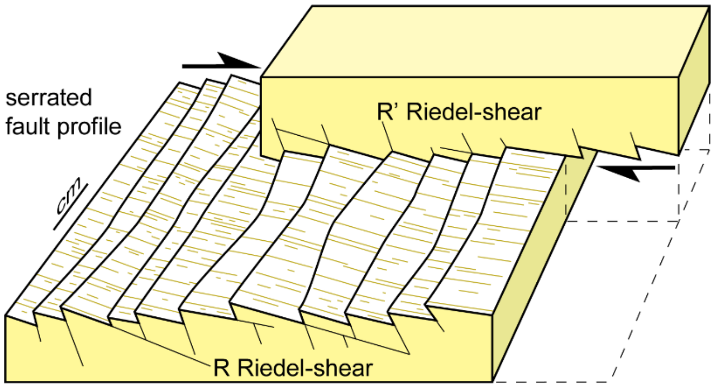
Movement structures within a brittle fault plane

Steps

Chatter marks are small, asymmetric **steps** facing in one direction and roughly perpendicular to the striations. These steps were traditionally interpreted as indicators of the sense of displacement, with the riser facing the relative displacement direction (**congruous steps**). However, experiments have shown that **incongruous** steps accompany frictional-wear striations or oblique-stylolite columns and form so that the risers of the steps are opposed to the movement vector. Therefore, there is no absolute rule about the kinematics significance of the steps alone.

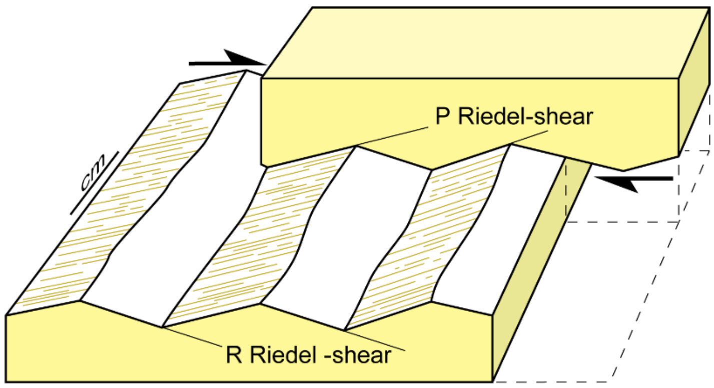
Riedel shears

Small and striated fractures in Riedel-shear attitudes commonly truncate fault planes nearly orthogonal to the slip direction. R and R' shears tend to be regularly spaced and impel a serrated profile to the fault plane, with steps facing the movement direction.



Movement structures within a brittle fault plane

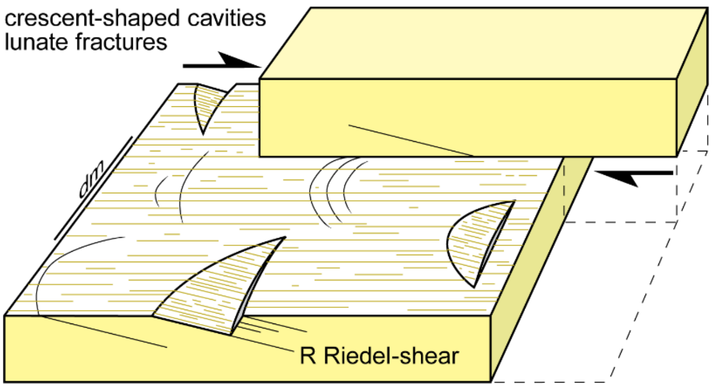
Combinations of R and P-Riedel shears, intersecting nearly perpendicular to the slip direction, result in alternating striated surfaces (P-shears facing in movement direction) and non-striated surfaces (R-shears in the lee side of asperities). The intensity of striation or non-striation depending on the attitude of topographic irregularities on the fault plane is a common kinematic criterion.



Movement structures within a brittle fault plane

Friction fractures

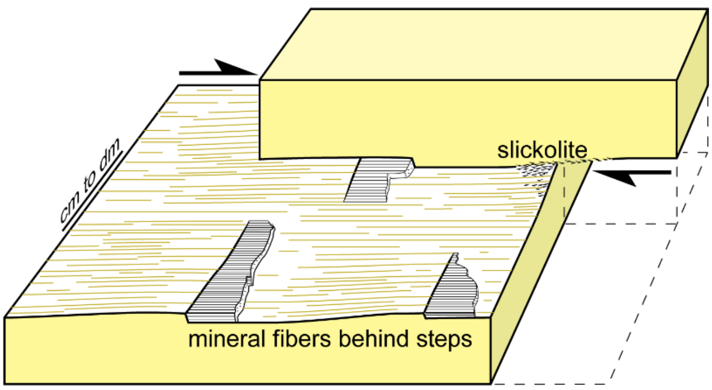
Friction fractures (R-Riedel shears) dip forward into the fault with respect to the movement direction. They are concave so that their intersections with the fault surface have **crescent-shapes** with their long axis transverse to the direction of movement. The two crescent tips indicate the movement direction of the missing block.



Movement structures within a brittle fault plane

Accretionary mineral steps

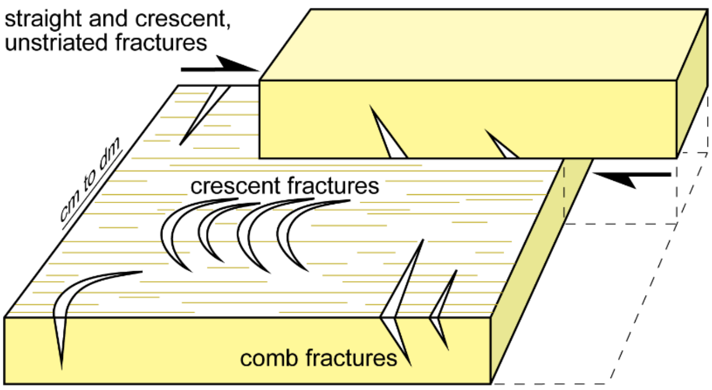
Preferred directional growth of minerals produces fibrous crystals as walls separate during faulting. Such minerals have their long axes parallel to the prevailing direction of slip and fill cavities on the lee side of congruous steps and asperities on fault surfaces. The rock-to-fiber relationship across a step makes these **slickenfibers** (or **accretionary growth fibers**) particularly valuable to deduce the direction and sense of movement. Curved or superposed crystal fibers can preserve a record of changes in the instantaneous direction of fault displacement. By contrast, ordinary slickenside striations may be erased and overprinted if changes occur in the direction of fault displacement. If so, ordinary striations may record only the latest uniform displacement.



Movement structures within a brittle fault plane

Unstriated, mineralized fissures

Straight, forward-dipping straight and lunate fractures form at a low angle to the fault plane and tend to rotate towards higher angle relationships during the deformation of wall rocks due to friction slippage. They open for secondary mineral crystallization during rotation. Straight fractures are named “comb fractures”. The two horns of crescent fractures point in the direction of slip.



Movement structures within a brittle fault plane

Slickolites

Surface irregularities or **asperities** may show a striated or stylolitic surface facing movement (compression) direction of the missing block and unstriated slopes towards the movement (extension) direction. Slickolite defines dissolution surfaces facing the displacement direction with microstylolitic peaks pointing in the upstream direction at a low angle to the fault surface.

Diagnostic movement structures within fault zones

Movement-related structures in fault zones and observed on erosion surfaces orthogonal to the fault plane and parallel to the slip direction are used in determining the fault kinematics.

Tension gashes

Tensile fractures or **tension gashes** (T fractures) normally parallel to the regional maximum principal stress (compression) may appear at an angle typically less than 45° to the fault plane, near the fault plane. Their intersection with the fault surface is nearly perpendicular to the cataclastic lineation. Their angular relationship may be helpful to infer the sense of slip, as discussed for the pinnate joints. Besides, they may take S or Z shapes depending on the leftward or rightward sense of shear along the fault, respectively.

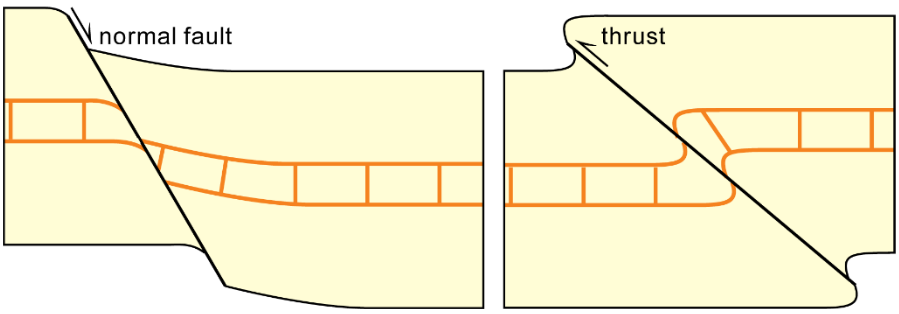
Exercise

Draw in two and three dimensions tension fractures related (1) to a normal fault, (2) to a thrust.

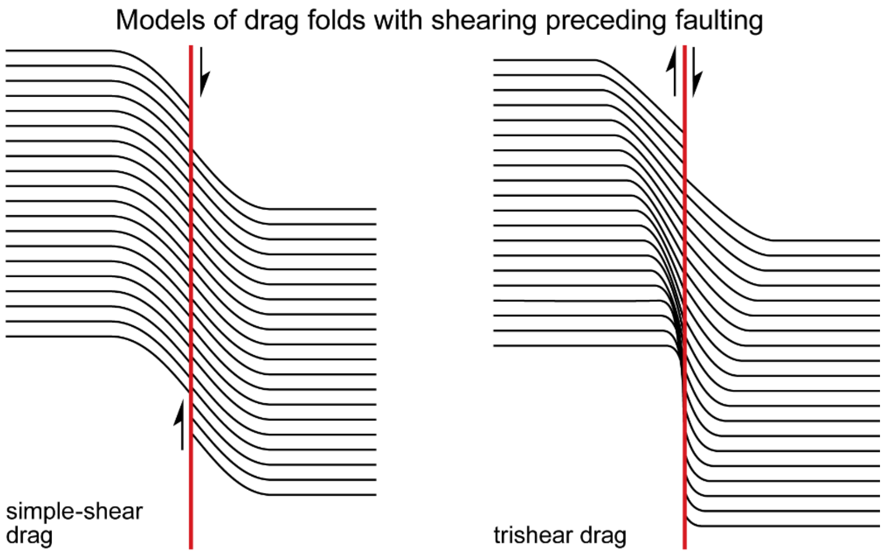
Drag folds

Drag folds are local flexures of initially flat or straight markers adjacent to faults curved in the direction of movement of the opposite block. The appellation encompasses the interpretation that faulting first initiates, and then shear deformation due to friction along the fault causes bending as one block is dragged along the other.

Drag folds against fault planes



The resulting geometry would not be different if fault-parallel, ductile shearing precedes faulting through a shear zone, whether this has a constant (simple shear) or a downward decreasing thickness (**trishear**, for strain distributed in a triangular zone).



The use of drag folds can be misleading because the curvature of the opposite sense to the displacement, termed **reverse drag**, is common. Reverse drag is independent of true drag effects but hardly distinguished from true drag when they appear separately. In addition, the orientation of such folds is often controlled by the intersection between bedding and the fault plane rather than the movement direction. Drags should be used with extreme care.

Riedel shears

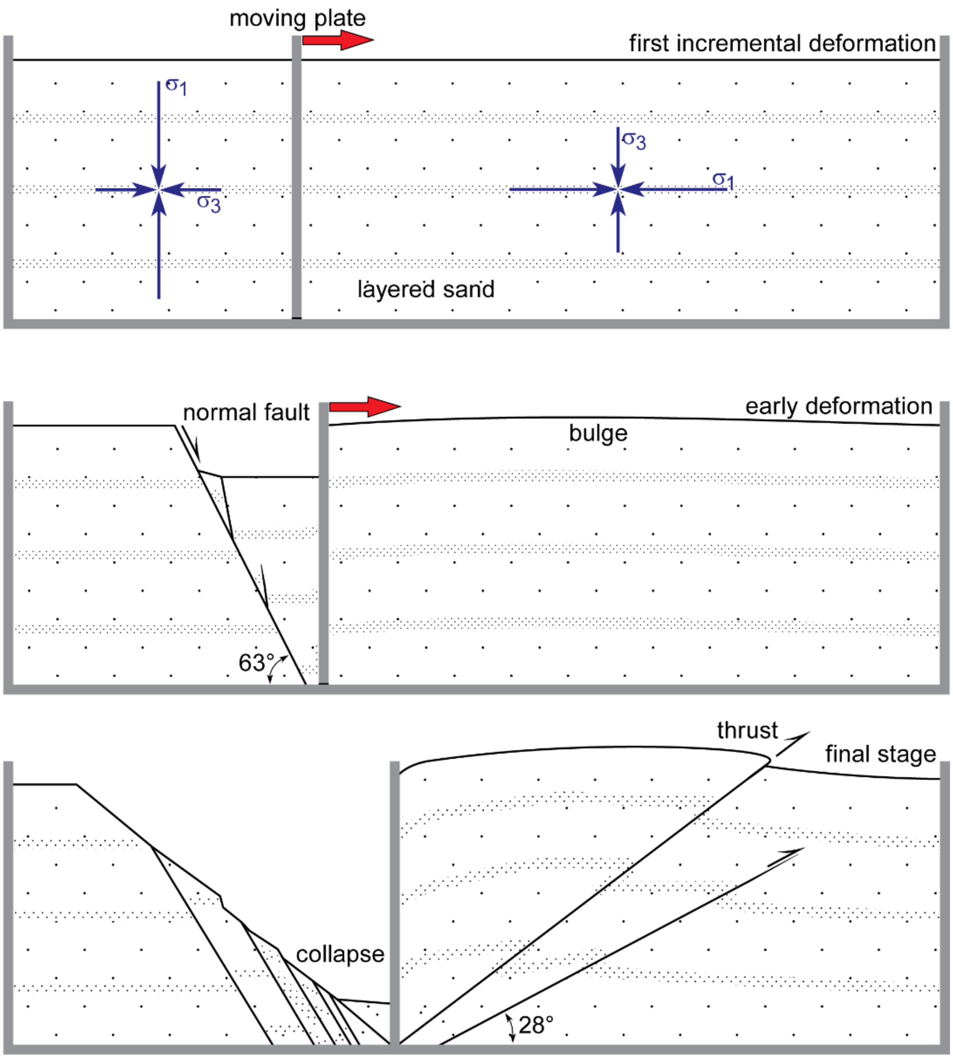
Riedel fractures dipping into the fault wall at a small angle to the main fault plane are diagnostic features. They are usually striated in the same direction as the main fault, intersect with this plane at a high angle to the slip direction and dip towards the movement direction.

Exercise

Discuss and sketch how conjugate Riedel-shears may help defining the sense of relative movement of the main fault.

Experimental faulting in sand

Very early, students of the mechanical behavior of rocks have noted that dry sand exhibits fault structures similar to those recognized in rocks. In effect, experiments verified that dry sand satisfies a yield criterion of Coulomb type behavior with an internal friction angle similar to those of rocks (30-40°, depending on close packing) and cohesion of the order of 100 Pa. Therefore, dry sand is an excellent analog for simulating brittle deformation of the upper crust in the Earth's field of gravity.
A famous experiment is due to M.K. Hubbert. He made a glass box divided into two compartments by a rigid, movable partition that he could translate parallel to the long axis of the box. The box was filled using loose plaster with different colors to visualize layers as horizontal markers. When the partition is moved to the right (with a screw), the left-hand side compartment is lengthened while the right-hand side compartment is shortened by the same amount.



Experimental faulting in sand
Experiment of Hubbert 1951 *Geol. Soc. Am. Bull.* **62(4),** 355-372

The first thing that happens is the development of a distinct normal fault that dips 60-65° in the lengthened compartment. In the meantime, nothing other than a slight bulging is observable in the shortened compartment. As the partition is cranked farther, reverse faults that dip 25-30° occur in the shortened side. These dip in the same direction and extend from the bottom of the box near the foot of the partition to the surface of the plaster where escarpments occur.
The behavior of the plaster, which sand can replace, is identical in both compartments. Thus, the double experiment illustrates that:

- 1) Rupture is reached faster in extension than in compression
- 2) Normal faults are steeper than reverse faults.
- 3) Anderson's classification of faults (fault plane orientation with respect to stress ellipsoid) is applicable in near-surface conditions.

Summary

Faults are fractures along which macroscopically visible slip has occurred. Slickensides, striations, and grooves caused by surface roughness (asperities) are used to define the offset directions of the walls. Three basic types are recognized 1) normal faults (hanging wall down), 2) thrust faults (hanging wall up), and 3) strike-slip faults (horizontal slip).
Faults are not theoretical planes of highest shear stress because a friction factor depending on each lithology plays some role in fault plane orientation in the local stress field. Besides, high pore pressures can promote faulting under conditions where it would not occur in dry rocks.

Large faults consist of a central fault core and an enveloping damage zone. Faults develop in the brittle regime and represent sudden displacement events producing earthquakes. They initiate with the nucleation of small shear fractures that propagate, interact, and link to form large faults. Their total movement generally results from the addition of many smaller slip events.

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