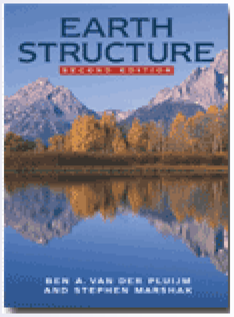
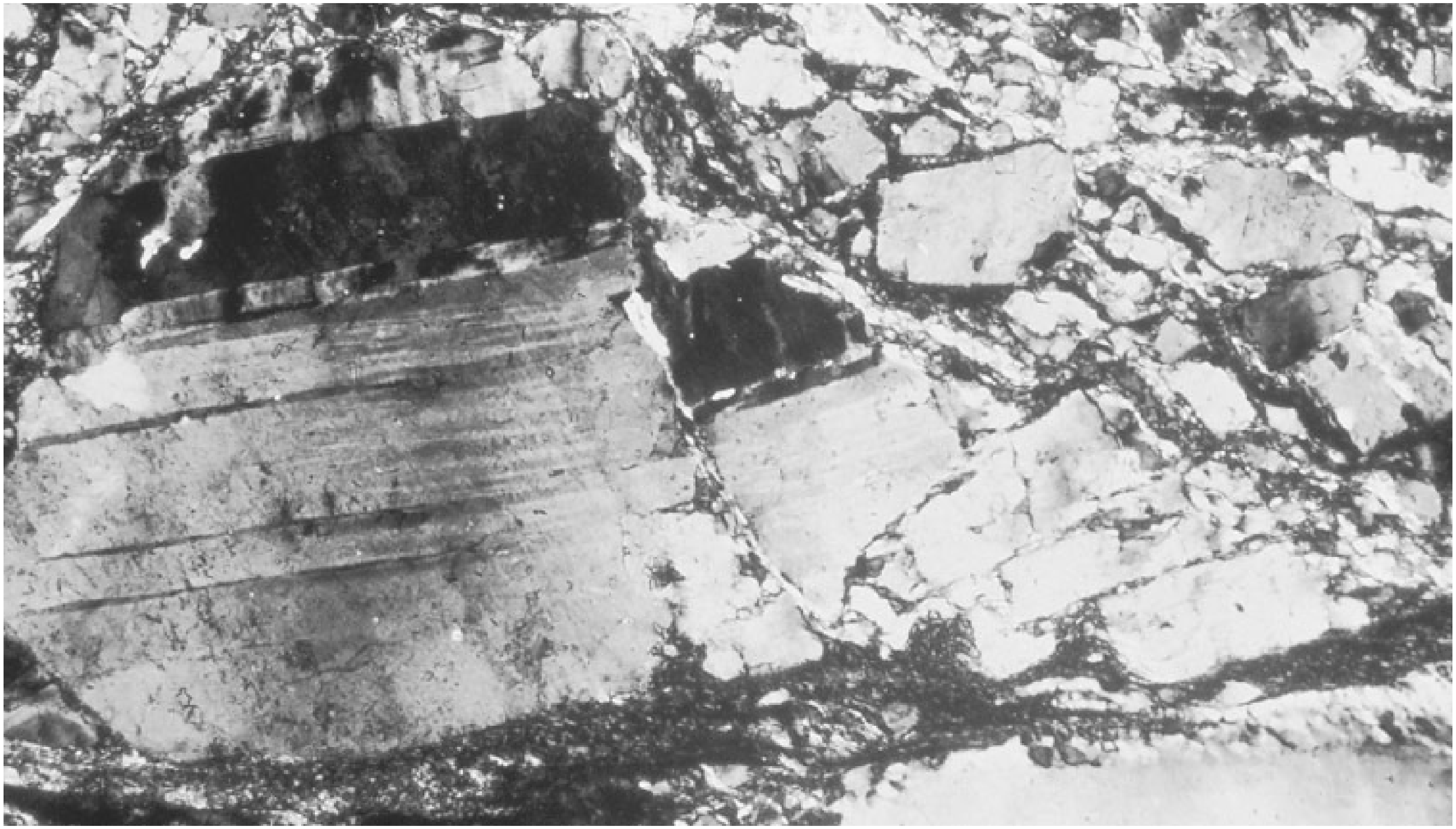
Lecture 8

Faults and Faulting

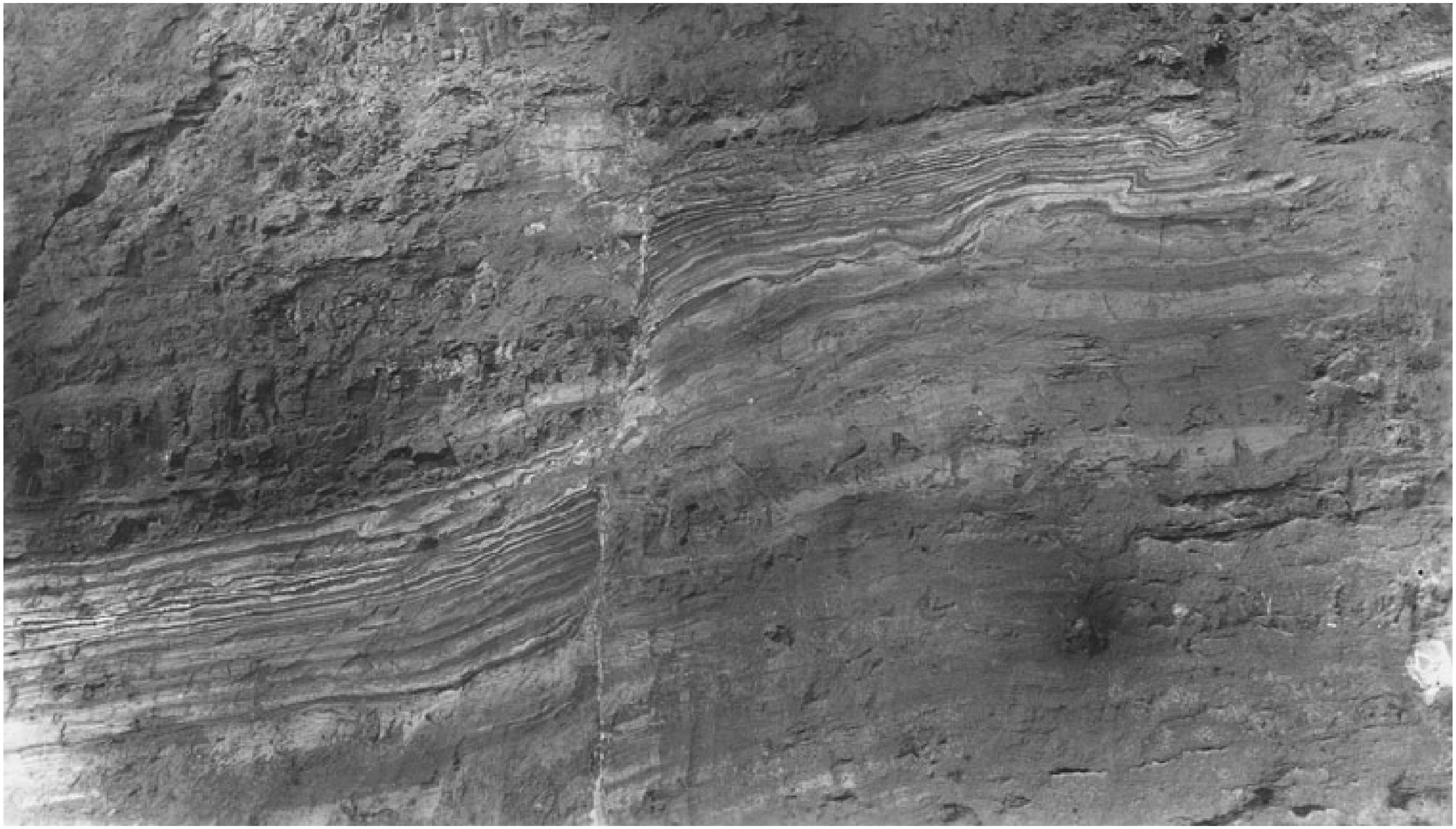


Earth Structure (2nd Edition), 2004
W.W. Norton & Co, New York
Slide show by Ben van der Pluijm

Faults

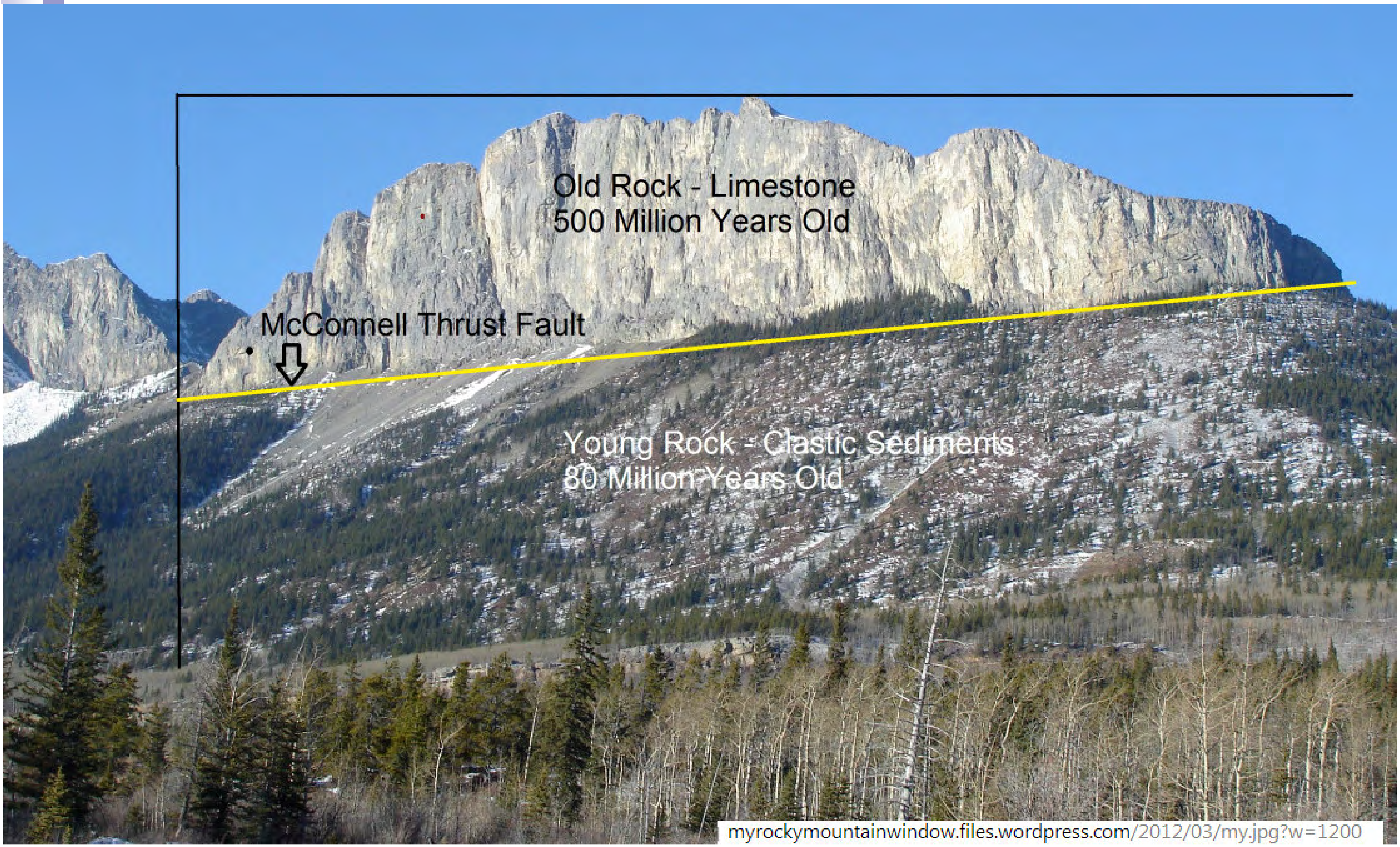


Microscopic faults, showing fractured and displaced feldspar grains.



Mesoscopic faults cutting thin layers in an outcrop.

The trace of the San Andreas (strike-slip) Fault across the countryside.


Old Rock - Limestone
500 Million Years Old
McConnell Thrust Fault
Young Rock - Clastic Sediments
80 Million Years Old
myrockymountainwindow.files.wordpress.com/2012/03/my.jpg?w=1200

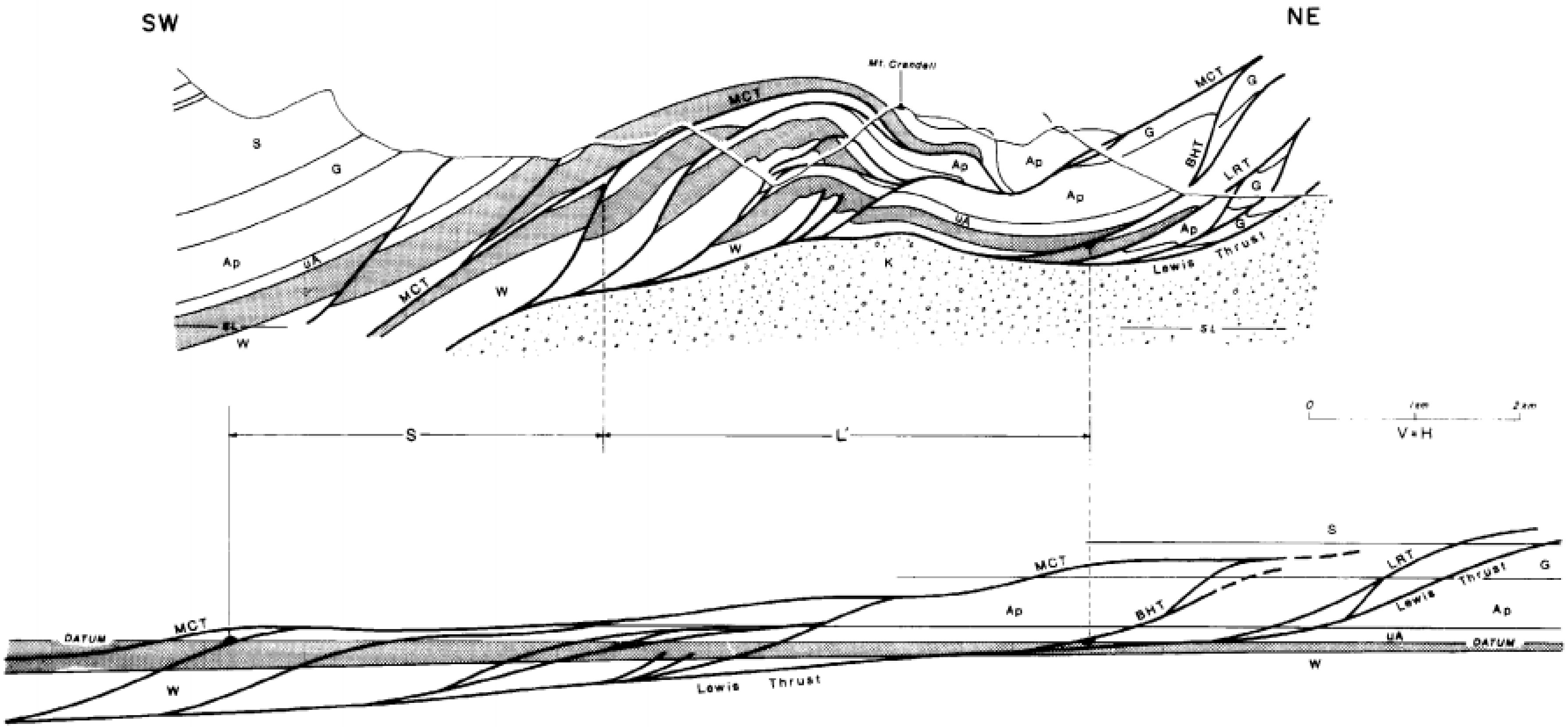
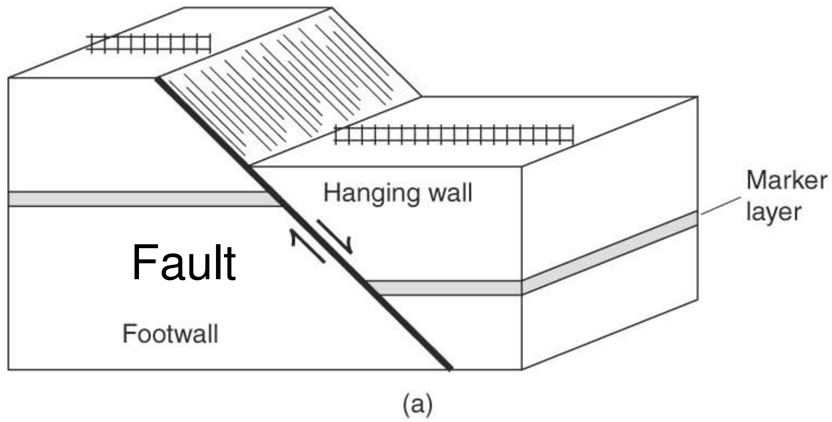
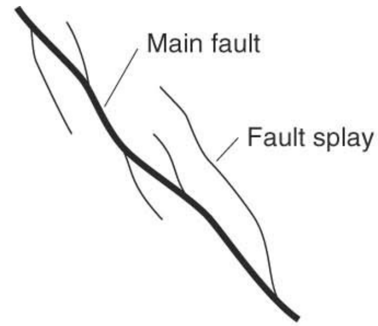


FIG. 17—Precambrian Belt Supergroup, comprising Waterton (W), lower Altyn (fine stipple), mid and upper Altyn (uA), Appekunny (Ap), Grinnell (G), and Siyeh (S), is thrust over Cretaceous siliciclastics (K, with pebble pattern) by Lewis thrust. Mount Crandell thrust (MCT) is roof and Lewis thrust is floor to duplex, and folded horse just northwest of Mount Crandell suggests that duplex developed toward foreland. Cross section is balanced (with current distance L′ between points recording a shortening of S), and is based on excellent control provided by over 2 km of local relief. Modified from Douglas (1952).

www.efn.uncor.edu/departamentos/GeoBas/materias/geologiatectonica/material/Thust%20Systems.pdf

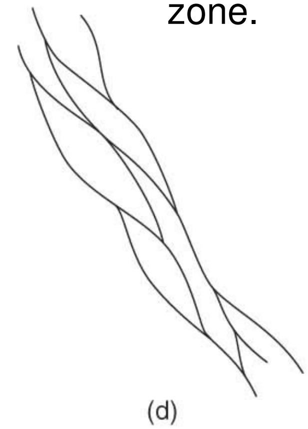
Faults, fault zones and shear zones Fig. 8.1

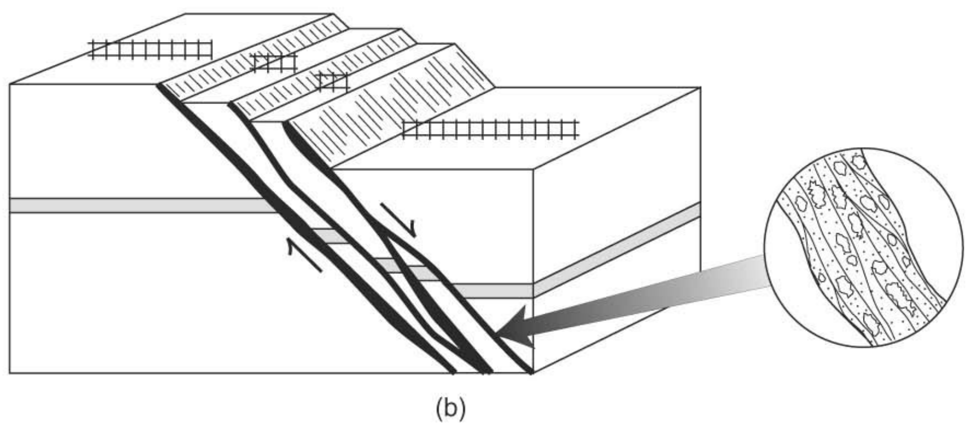




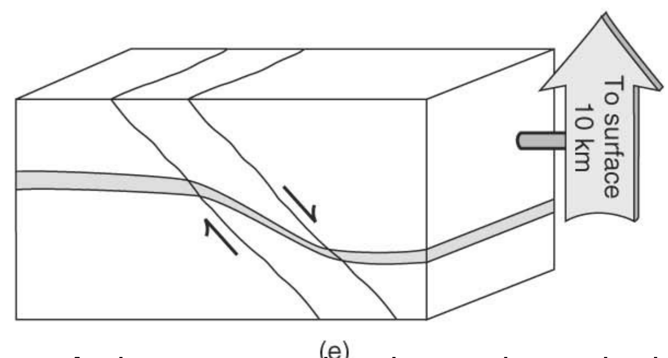
Sketch illustrating the relation between a principal fault and fault splays.

Anastomosing faults in a fault zone.



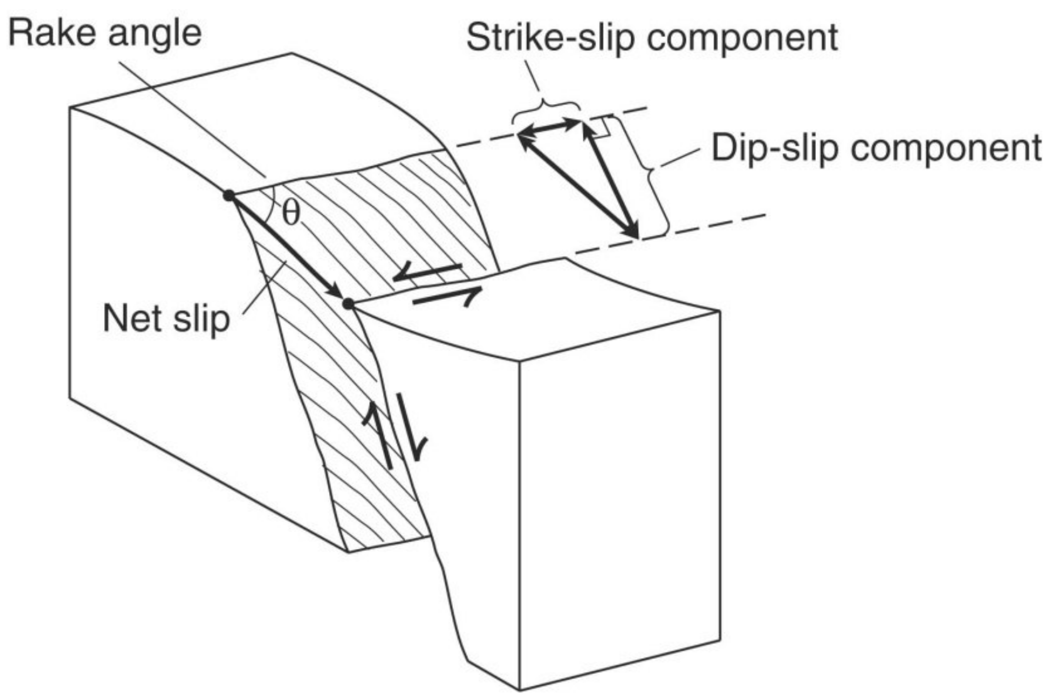


Fault zone, with inset showing cataclastic deformation adjacent to the fault surface.



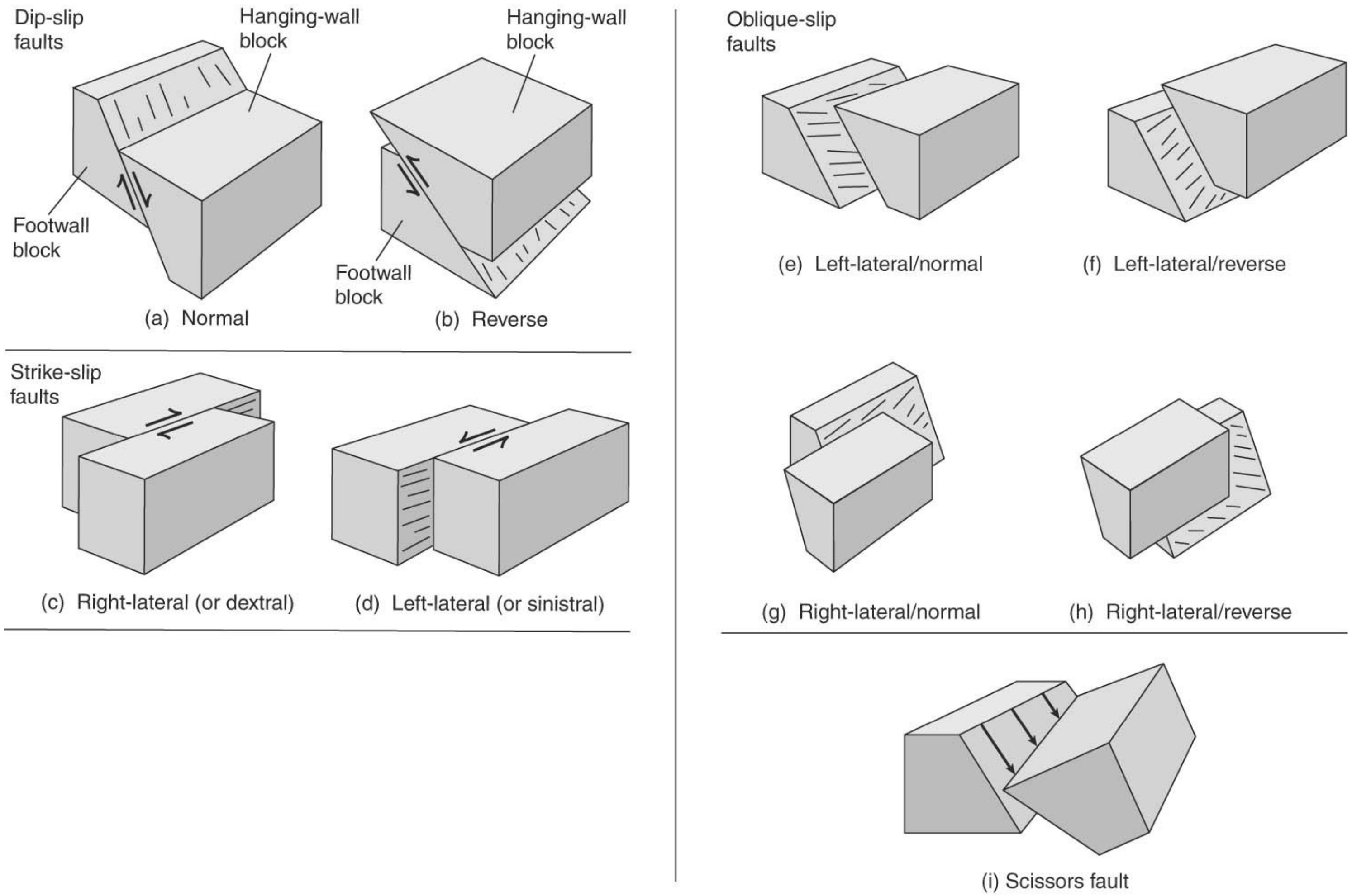
A shear zone, showing rock continuity across the zone. The displacements are shown to intersect the ground surface, whereas the shear zone occurs at depth in the crust.

Fault slip Fig. 8.3

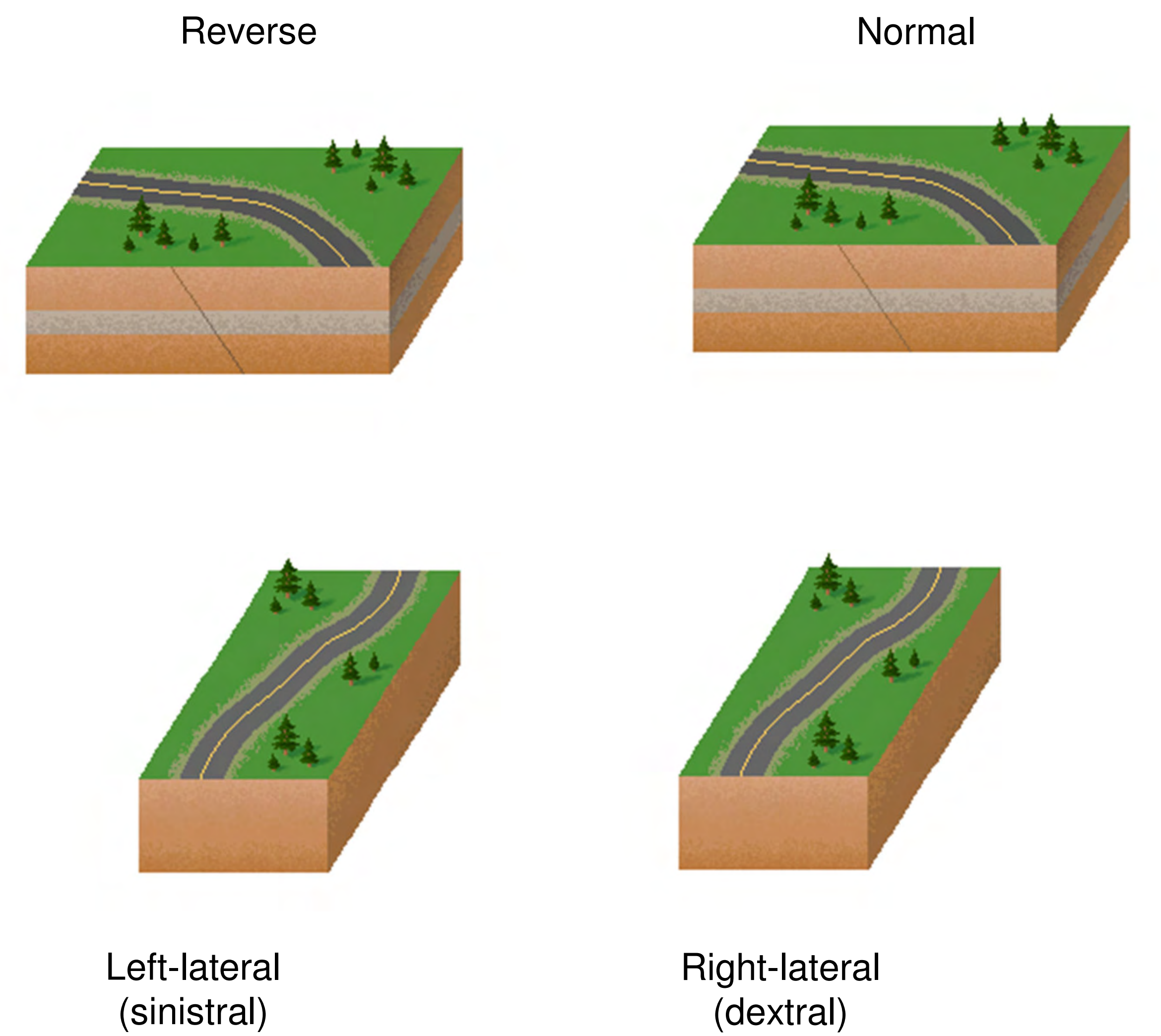


Block diagram sketch showing the net-slip vector with its strike-slip and dip-slip components, as well as the rake and rake angle.

Fault Types Fig. 8.4



Fault Types animated



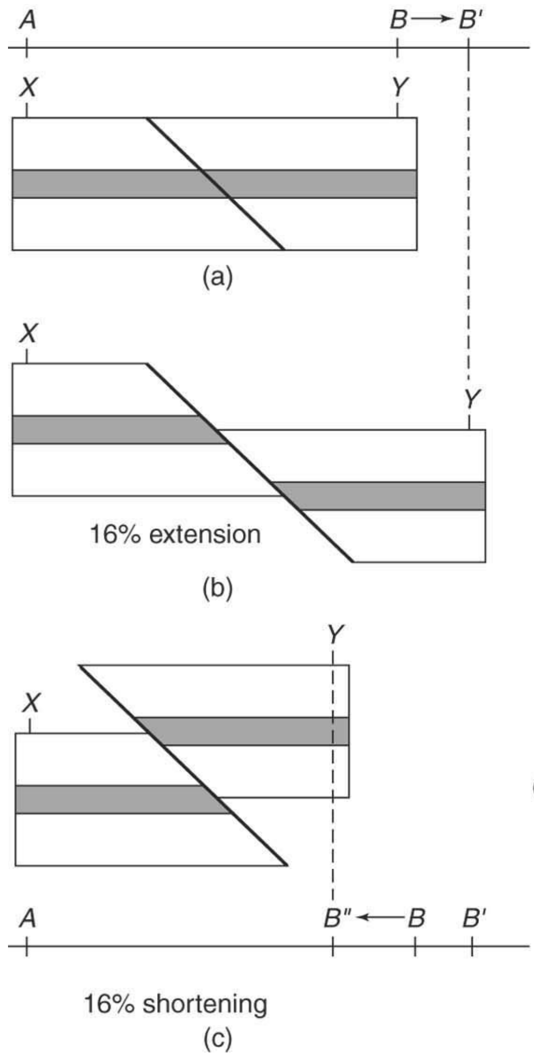
Fault Geometry and Displacement Sec. 8.2

TABLE 8.1	DESCRIPTION OF FAULT DIP
Horizontal faults	Faults with a dip of about 0°; if the fault dip is between about 10° and 0°, it is called **subhorizontal.**
Listric faults	Faults that have a steep dip close to the Earth's surface and have a shallow dip at depth. Because of the progressive decrease in dip with depth, listric faults have a curved profile that is concave up.
Moderately dipping faults	Faults with dips between about 30° and 60°.
Shallowly dipping faults	Faults with dips between about 10° and 30°; these faults are also called *low-angle faults.*
Steeply dipping faults	Faults with dips between about 60° and 80°; these faults are also called *high-angle faults.*
Vertical faults	Faults that have a dip of about 90°; if the fault dip is close to 90° (e.g., is between about 80° and 90°), the fault can be called **subvertical.**

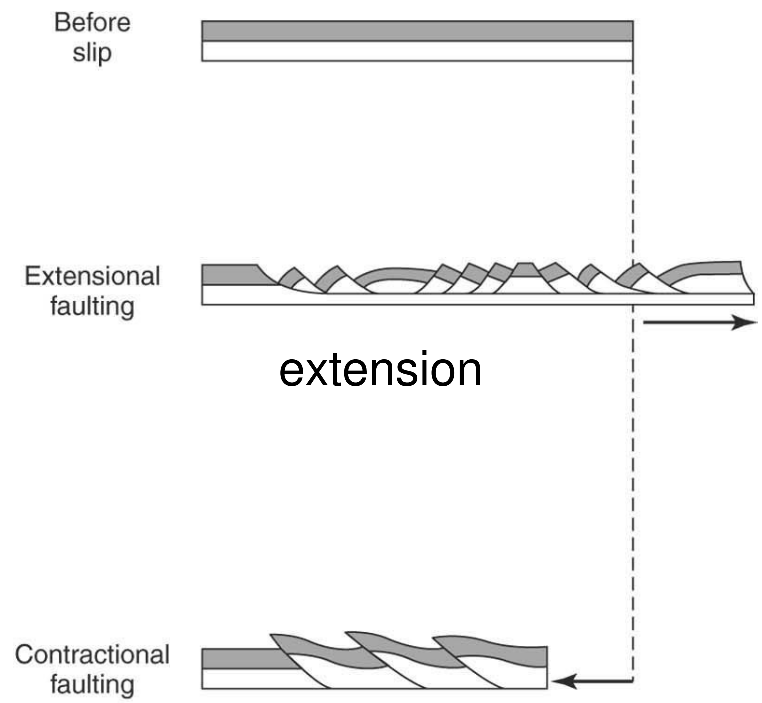
TABLE 8.2	TYPES OF FAULTS
Allochthon	The thrust sheet above a detachment is the allochthon (meaning that it is composed of *allochthonous* rock; i.e., rock that has moved substantially from its place of origin).
Autochthon	The footwall below a detachment is the autochthon; it is composed of *autochthonous* rock, or rock that is still in its place of origin.
Contractional fault	A contractional fault is one whose displacement results in shortening of the layers that the fault cuts, regardless of the orientation of the fault with respect to horizontal.
Décollement	The French word for detachment.
Detachment fault	This term is used for faults that initiate as a horizontal or subhorizontal surface along which the hanging-wall sheet of rock moved relative to the footwall. An older term "overthrust" is a regional detachment fault on which there has been a thrust sense of movement. Some detachments are listric, and on some detachments, regional normal-sense displacement occurs.
Dip-slip fault	The slip direction on a dip-slip fault is approximately parallel to the dip of the fault (i.e., has a rake between ~80° and 90°).
Extensional fault	An extensional fault is one whose displacement results in extension of the layers that the fault cuts, regardless of the orientation of the fault with respect to horizontal.
Normal fault	A normal fault is a dip-slip fault on which the hanging wall has slipped down relative to the footwall.
Oblique-slip fault	The slip direction on an oblique-slip fault has a rake that is not parallel to the strike or dip of the fault. In the field, faults with a slip direction between ~10° and ~80° are generally called oblique-slip.

Overthrust fault	This is an older term that you may find in older papers on faults, but is no longer used much today. The term is used for thrust faults of regional extent. In this context, "regional extent" means that the thrust sheet has an area measured in tens to hundreds of square km, and the amount of slip on the fault is measured in km or tens of km. Today, such faults are generally called regional detachments.
Par-autochthonous	If a fault block has only moved a small distance from its original position, the sheet is par-autochthonous (literally, relatively in place).
Reverse fault	A reverse fault is a dip-slip fault on which the hanging wall has slipped up relative to the footwall.
Scissors fault	On a scissors fault, the amount of slip changes along strike so that the hanging-wall block rotates around an axis that is perpendicular to the fault surface (Figure 8.4i).
Strike-slip fault	The slip direction on a strike-slip fault is approximately parallel to the fault strike (i.e., the line representing slip direction has a rake [pitch] in the fault plane of less than ~10°). Strike-slip faults are generally steeply dipping to vertical.
Transfer fault	A transfer fault accommodates the relative motion between blocks of rock that move because of the displacement on other faults.
Transform fault	In the preferred sense, transform faults are plate boundaries at which lithosphere is neither created nor destroyed. In a general sense, a transform fault links two other faults and accommodates the relative motion between the blocks of rock that move because of the displacement on the other two faults. However, we reserve the term *transfer fault* for this general type of displacement, independent of scale.

Extensional and contractional fault regimes Fig. 8.5



Starting condition



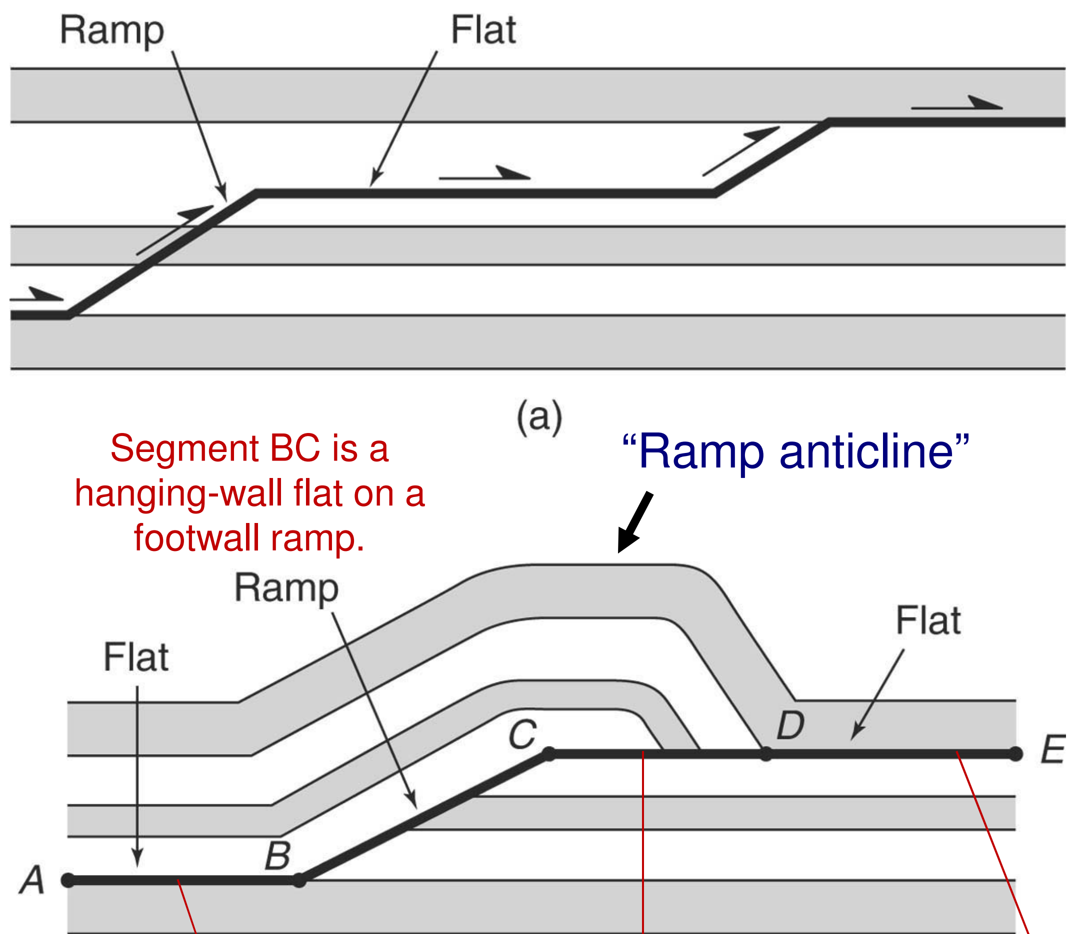
extension

contraction.

Note the respective horizontal length changes.

Alpine Thrusts

Thrust: Ramps and Flats Fig. 8.11



"Ramp anticline"

Segment BC is a hanging-wall flat on a footwall ramp.

Segment AB is a hanging-wall flat on a footwall flat.

Segment CD is a hangingwall ramp on a footwall flat, and segment

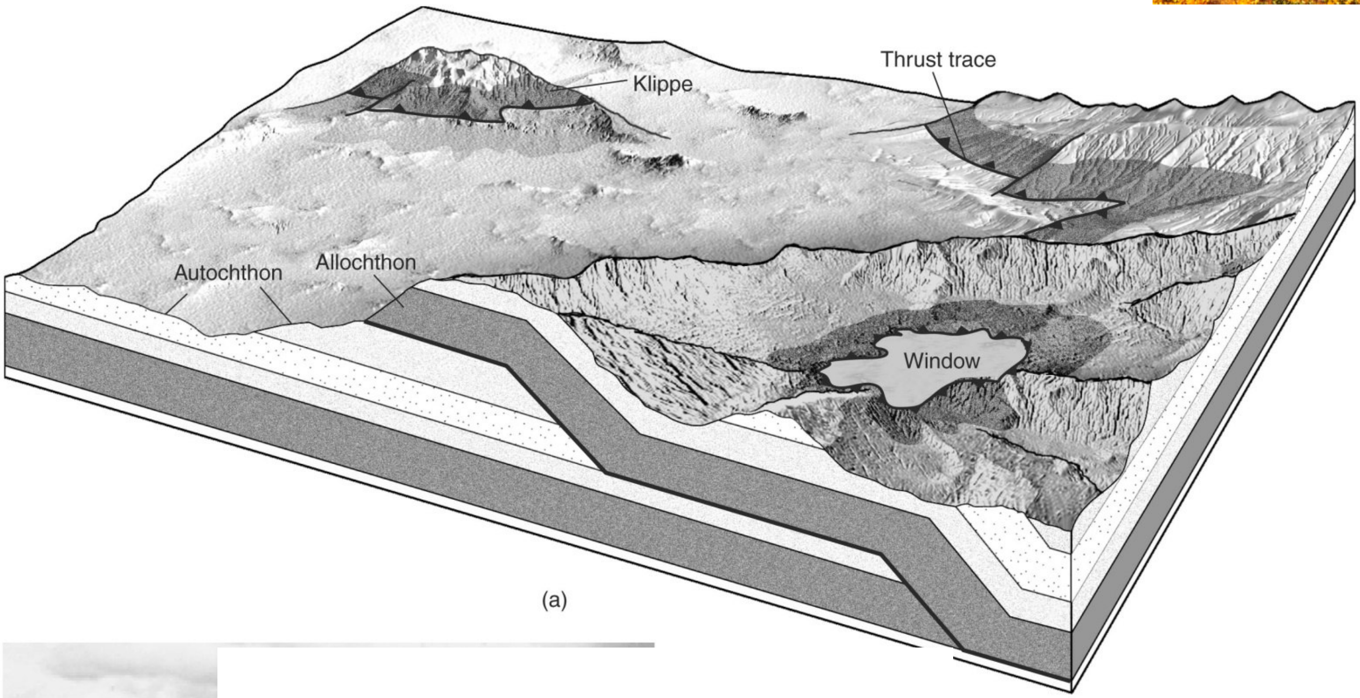
Segment DE is a hanging-wall flat on a footwall flat.

Cross section showing the geometry of ramps and flats along a thrust fault. The fault geometry is shown prior to displacement on the fault.

Cross section illustrating hanging-wall and footwall flats and ramps.

Klippe and Window Fig. 8.8

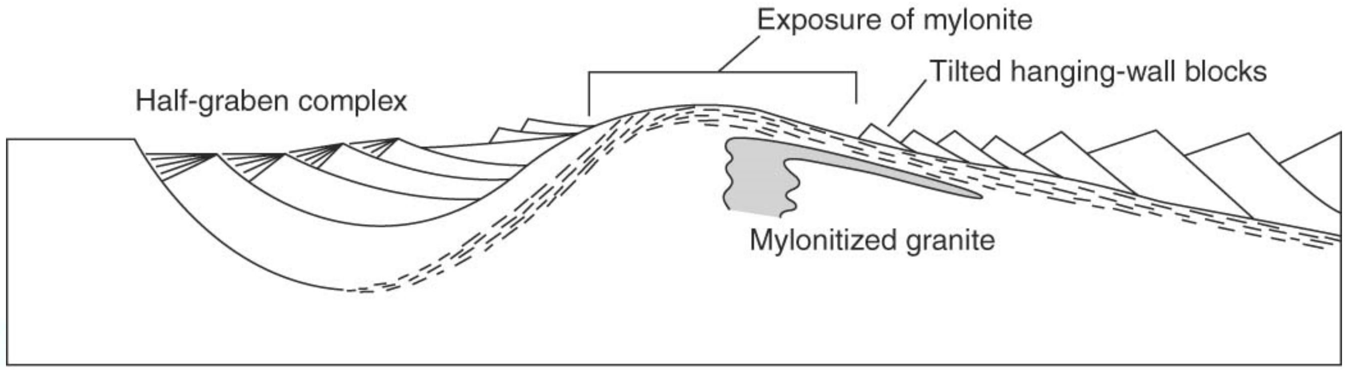
Block diagram illustrating klippe, window (or fenster), allochthon (gray), and autochthon (stippled) in a thrust-faulted region.



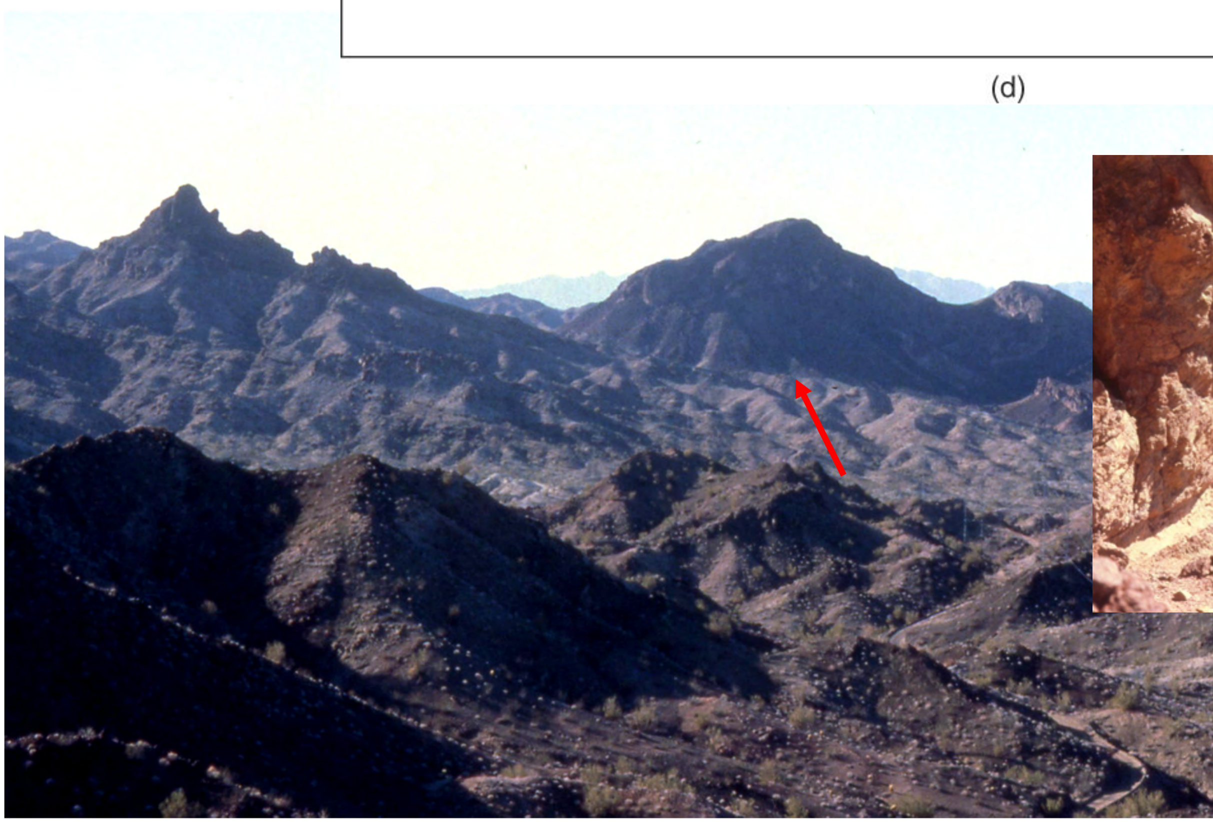
Note that the minimum fault displacement is defined by the farthest distance between thrust outcrops in klippe and window.

Normal Fault

Low-angle normal fault (detachment)

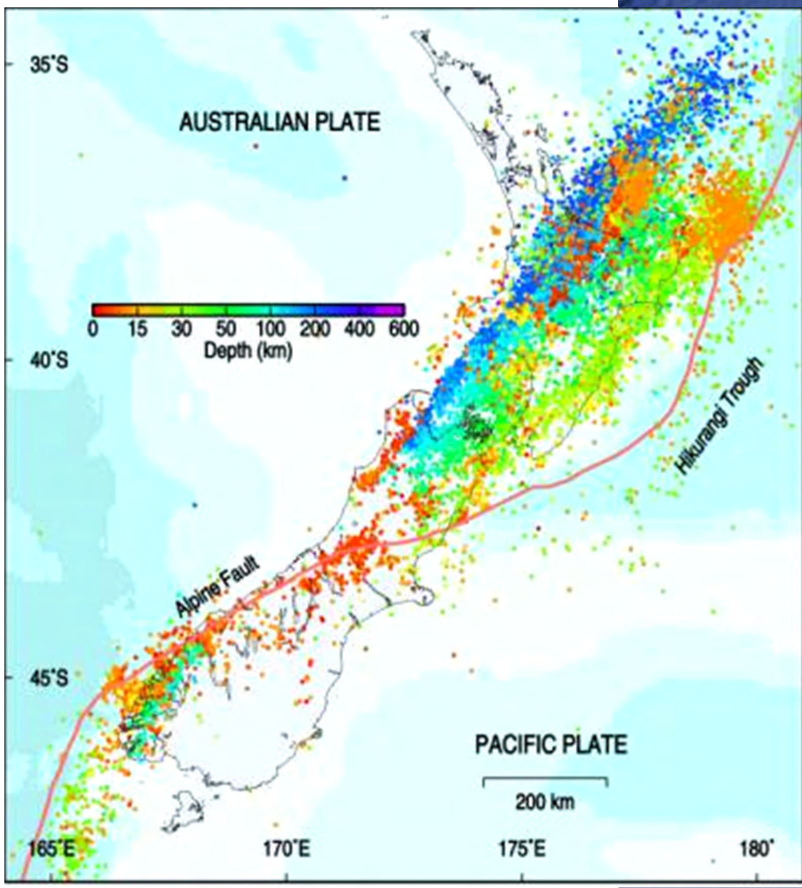


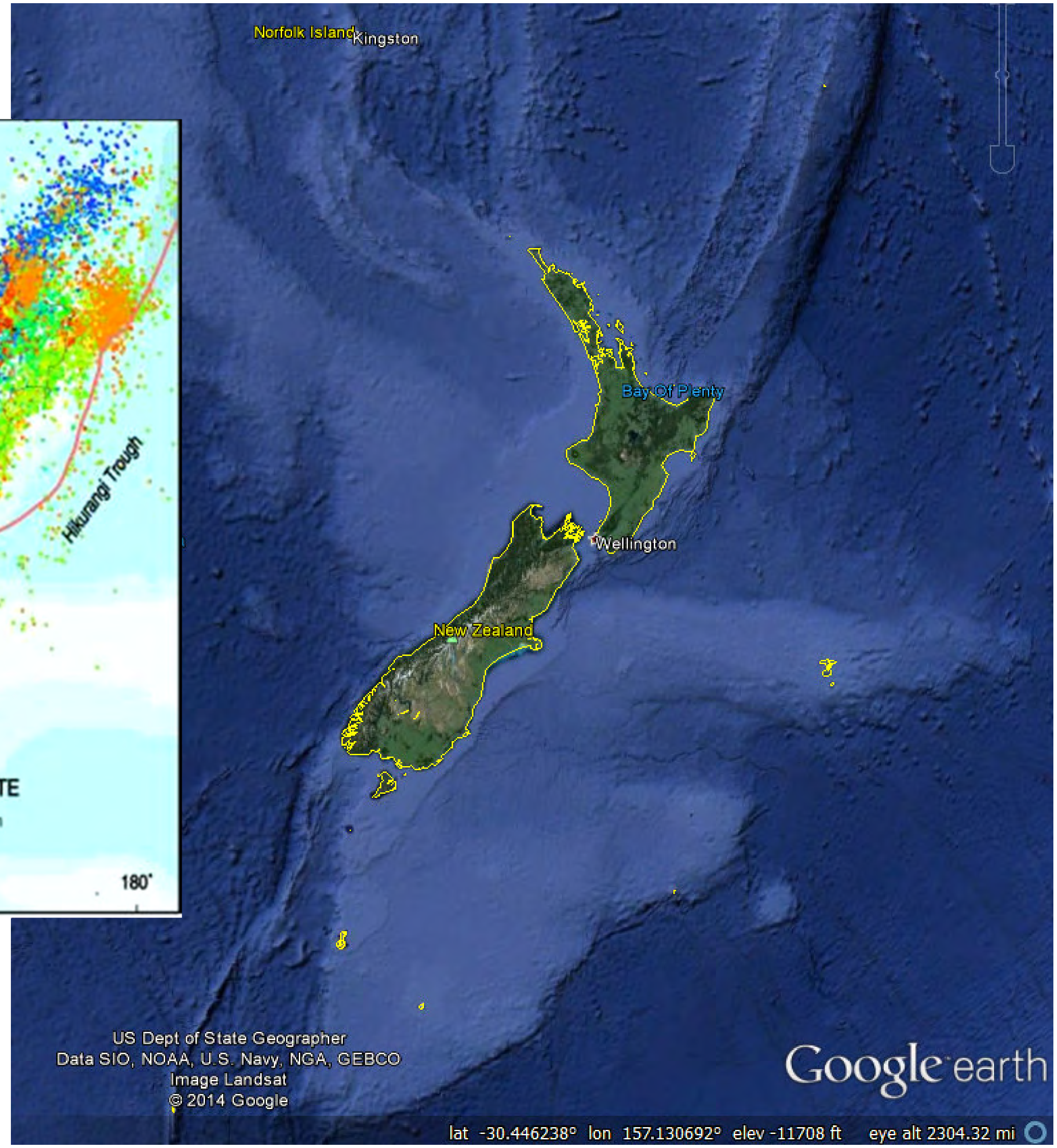
(d)



Whipple Mountains
hyperlink to DePaor

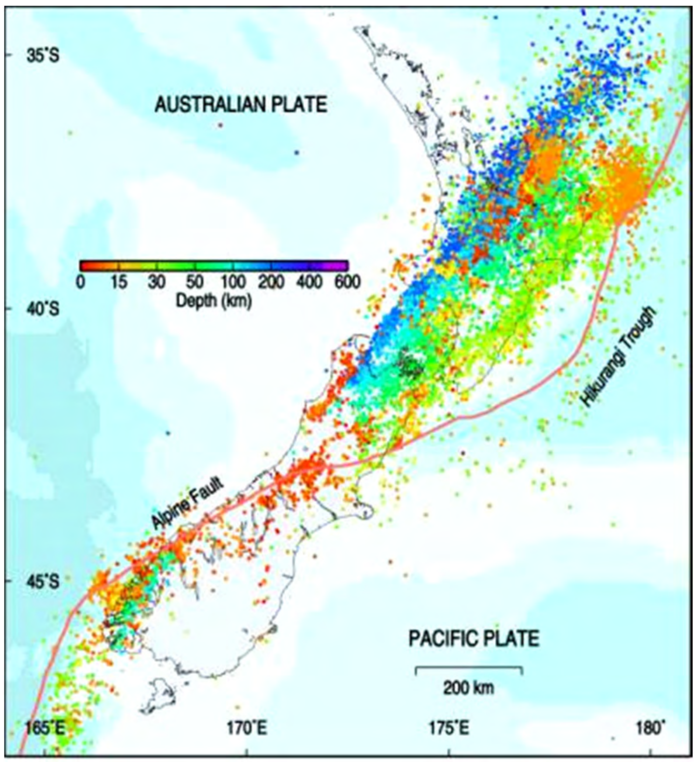
Strike-slip Fault

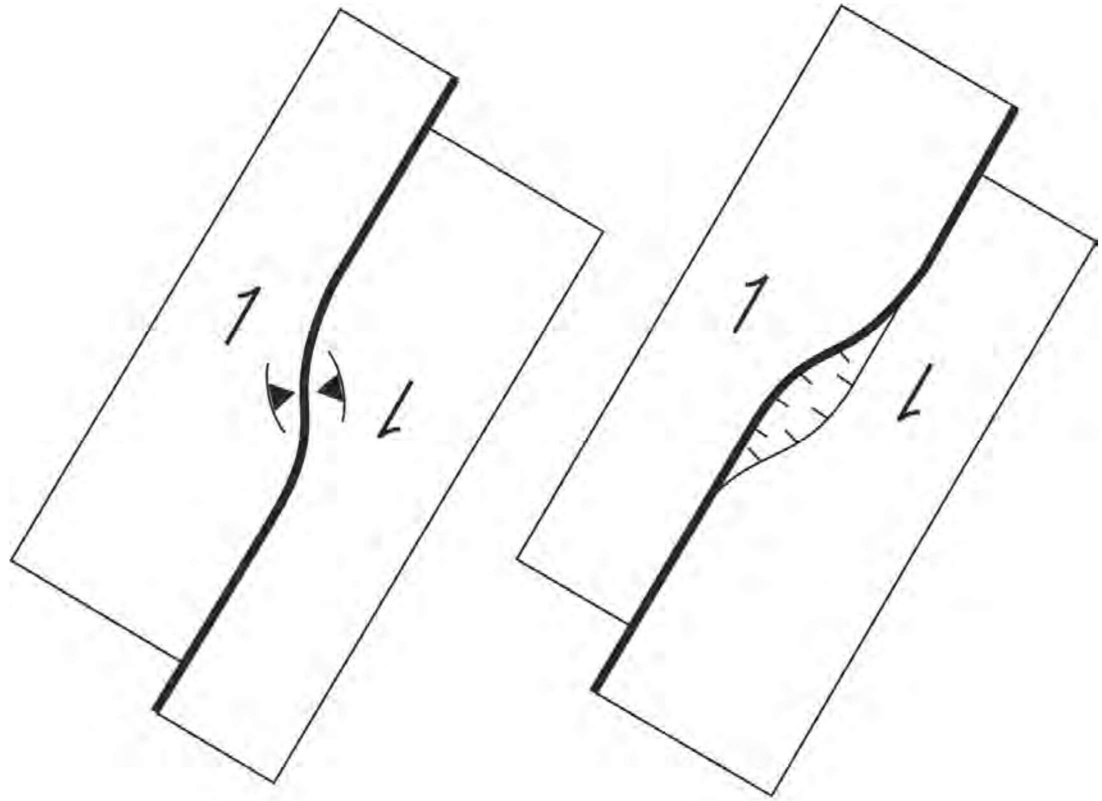




Fault bends Fig. 8.12

Map-view illustrations of a right-lateral strike slip fault.





restraining bend

releasing bend

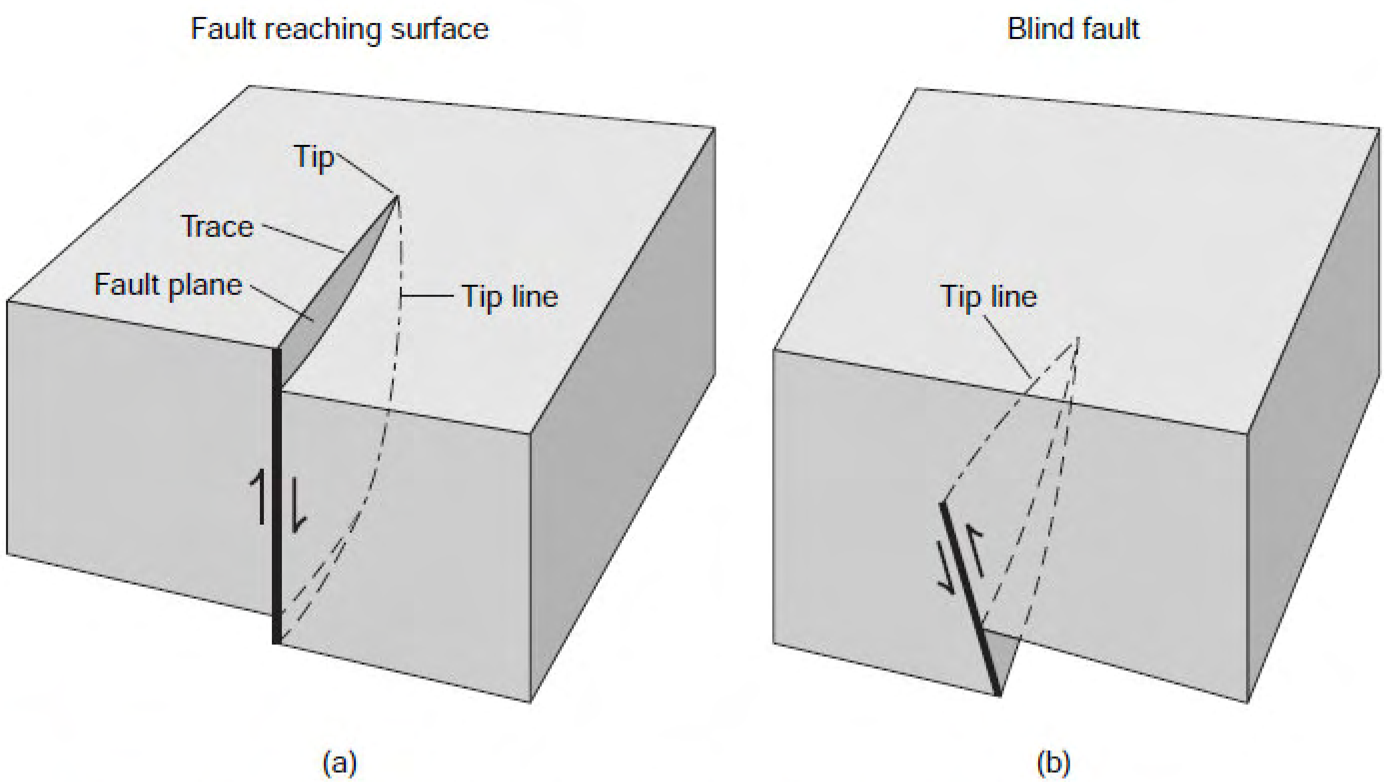


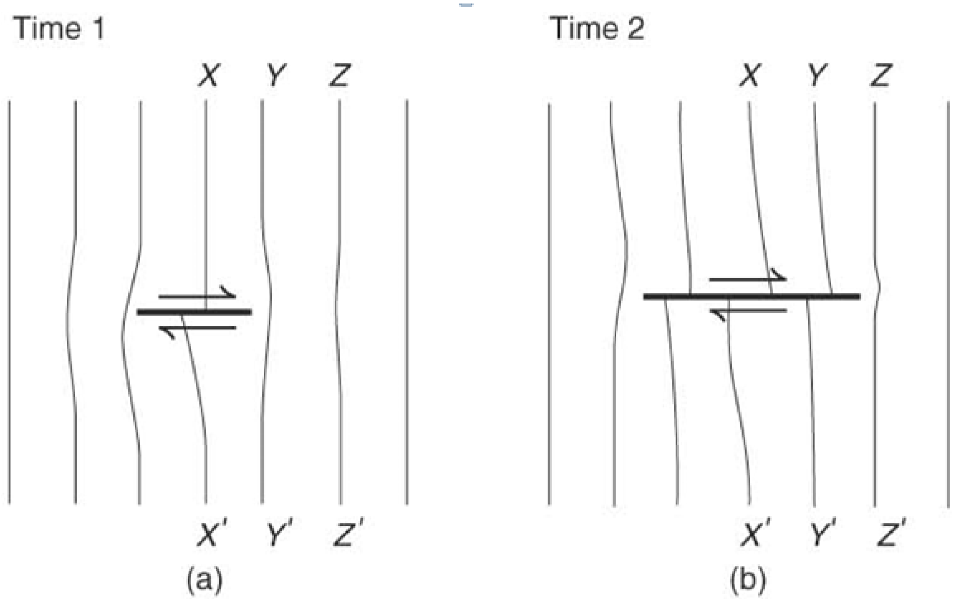
FIGURE 8.14 Tip lines for (a) an emergent fault and (b) a blind fault.

Fault Scaling and Self-similarity Fig. 8.15

Map view illustrating that displacement on a fault grows as the fault length increases.

At time 1, the short fault only offsets marker line XX′ by a small amount.

At time 2, the fault has grown in length, and marker line XX′ has been offset by a greater amount.



Note that the displacement decreases toward the end (tip) of the fault and is greatest in the center

Fault Scaling and Self-similarity Fig. 8.15

Log–log plot showing the apparent relationship between fault length (L) and fault displacement (D): $D = c * L^n$.

The exponent, n, is called the fractal dimension. Various fits are possible, but a general relationship is $D = 0.03 * L^{1.06}$, suggesting an approximate displacement–length ratio of about 0.03.

D is 3% of L

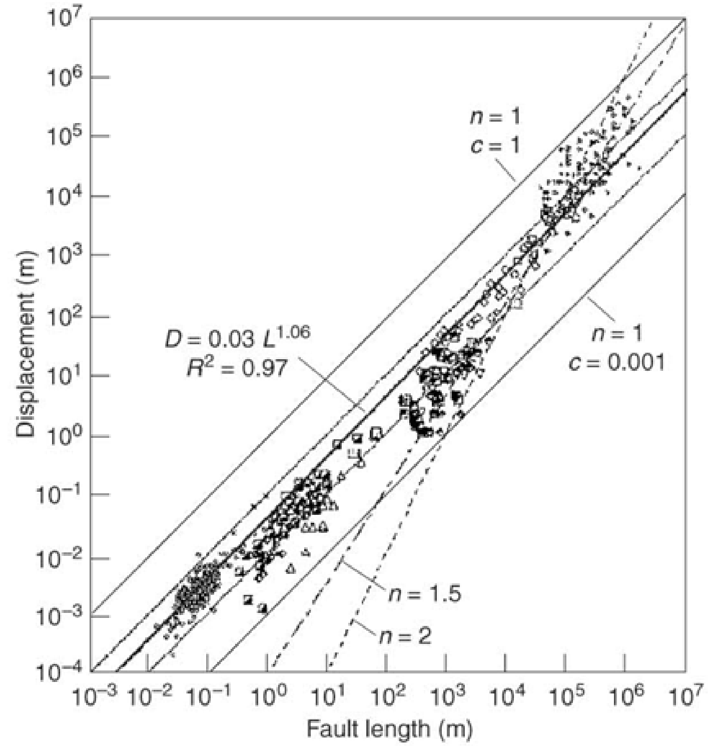


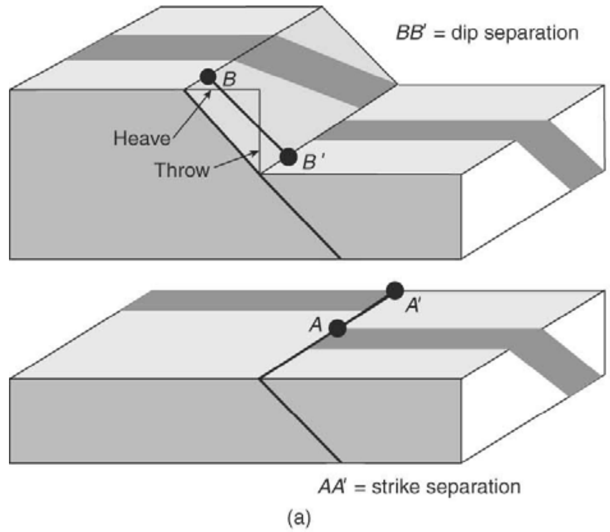
TABLE 8.4 FIRST-ORDER RELATIONSHIPS BETWEEN FAULT PARAMETERS

	Length	Displacement	Fault Zone Width
Length	—	10^2	10^4
Displacement	10^{-2}	—	10^2
Fault Zone Width	10^{-4}	10^{-2}	—

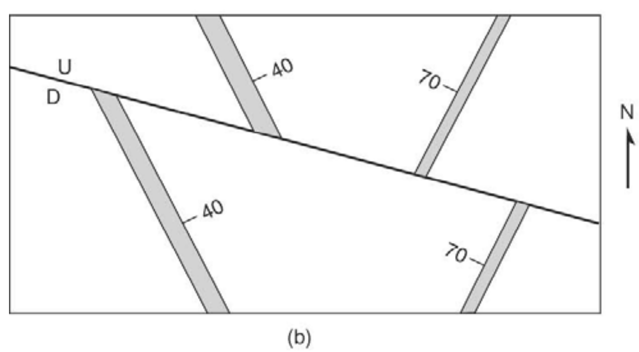
Row fault property equals value times column property; for example, width = 0.01 × displacement ($W = 0.01 \times D$). *(From Scholz, 2002)*

Offset terminology Fig. 8.10

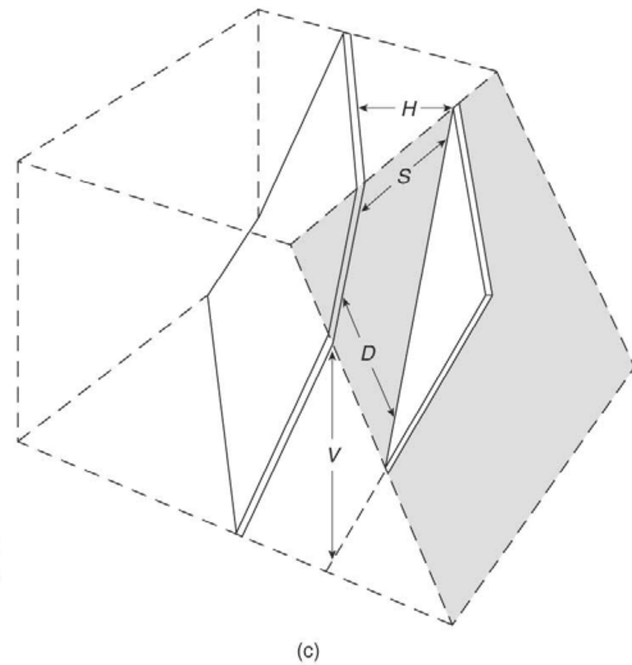
Block diagrams showing dip separation, strike separation, heave, and throw.



Map view showing how separation depends on the orientation of the offset layer.



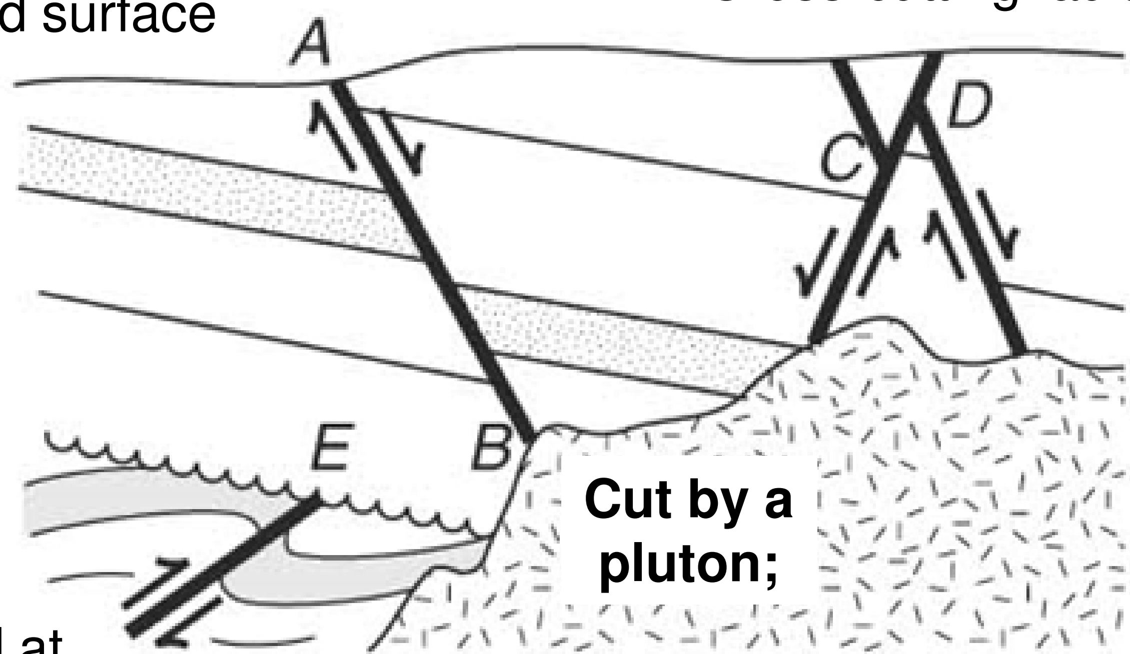
The two dikes shown here dip in different directions and have, therefore, different strike separations.



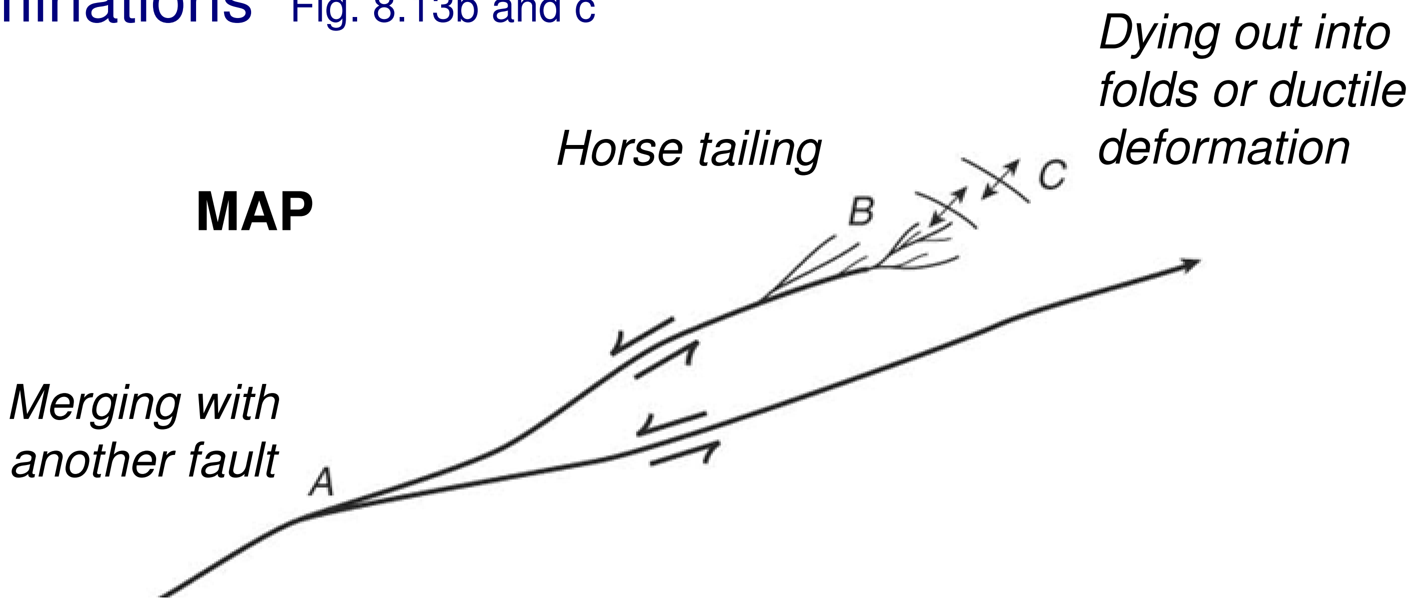
Block diagram illustrating horizontal (H) and vertical (V) separation, as well as dip (D) and strike (S) separation

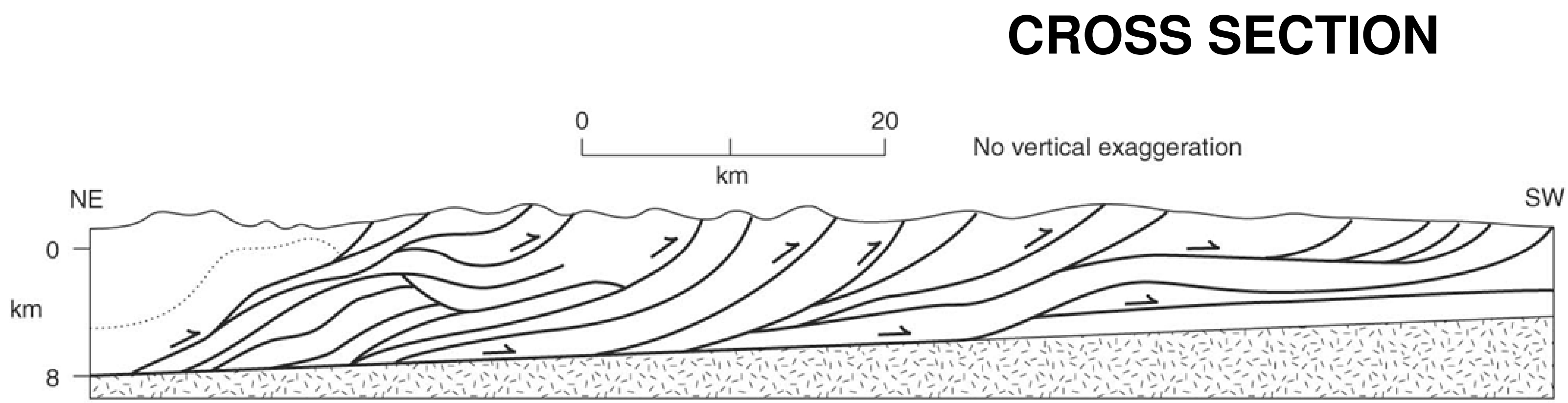
Fault terminations Fig. 8.13a

Cross-sectional sketch showing various types of fault terminations.



Fault terminations Fig. 8.13b and c



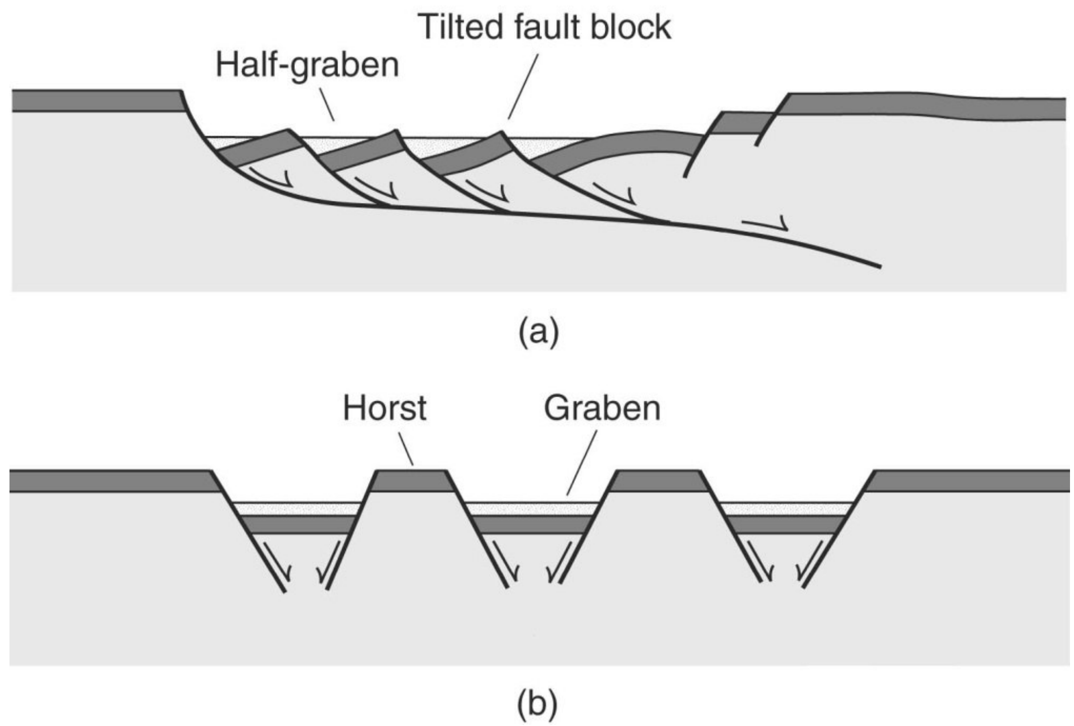


A series of ramps merging at depth with a basal detachment.

Normal fault systems Fig. 8.32

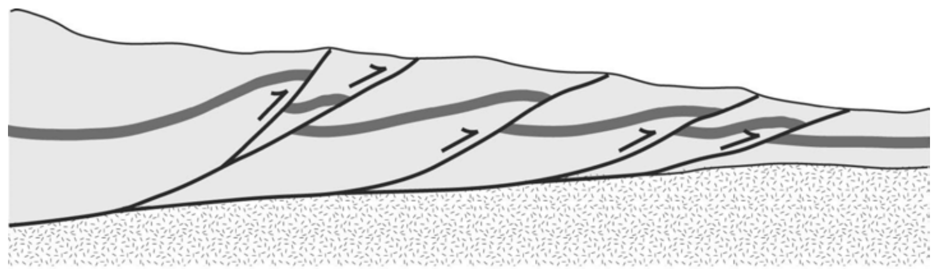
Half-graben

Horst-and-graben system



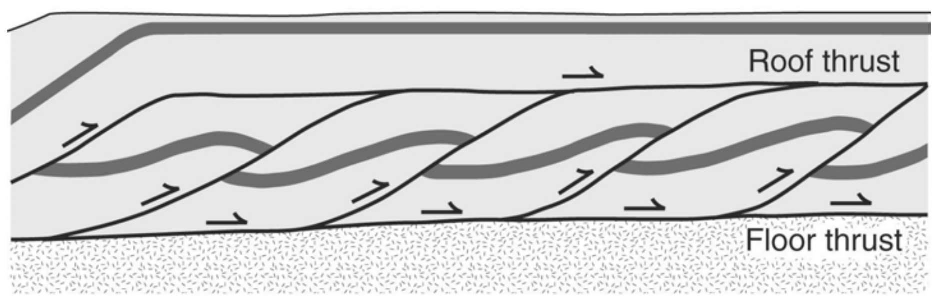
Reverse fault systems Fig. 8.33

Imbricate fan



(a)

Duplex system with horses in between the floor and roof thrusts

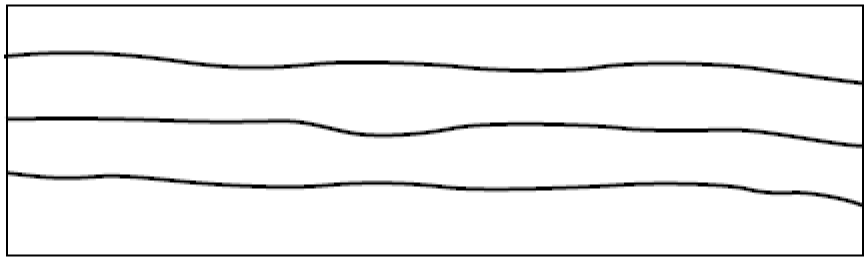


(b)

TABLE 8.7	GEOMETRIC CLASSIFICATION OF FAULT ARRAYS
Parallel fault array	As the name suggests, a parallel fault array includes a number of fault surfaces that roughly parallel one another.
Anastomosing array	A group of wavy faults that merge and diverge along strike, thereby creating a braided pattern in map view or cross section.
***En echelon* array**	A group of parallel fault segments that lie between two enveloping surfaces and are inclined at an angle to the enveloping surfaces.
Relay array	In map view, a relay array is a group of parallel or subparallel non-coplanar faults that are spaced at a distance from one another across strike, but whose traces overlap with one another along strike. As displacement dies out along the strike of one fault in the array, displacement increases along an adjacent fault. Thus, displacement is effectively "relayed" (transferred) from fault to fault. In a thrust belt containing a relay array of faults, regional shortening can be constant along the strike of the belt, even though the magnitude of displacement along individual faults dies out along strike.
Conjugate fault array	An array composed of two sets of faults that are inclined to one another at an angle of about 60°. Conjugate fault arrays can consist of dip-slip faults or strike-slip faults. If the faults in the array are strike-slip, then one set must be dextral and the other sinistral.
Nonsystematic fault array	In some locations, faulting occurs on preexisting fractures. If the fracture array initially had a wide range of orientations, then slip on the fractures will yield faults in a wide range of orientations. Such an array is called a nonsystematic array.

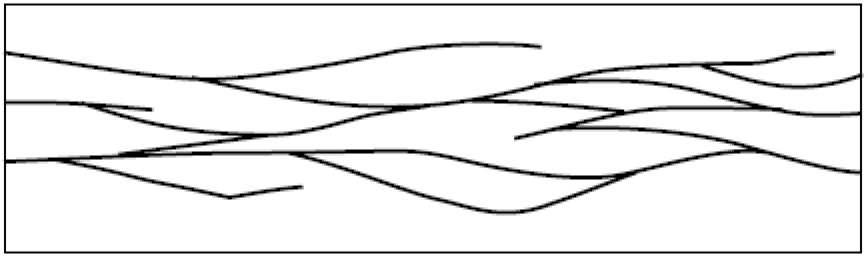
Geometry of fault arrays Sec. 8.6.1

(a)



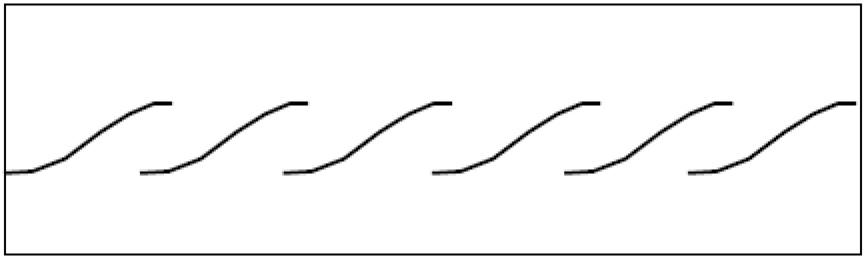
Parallel fault array includes a number of fault surfaces that roughly parallel one another.

(b)



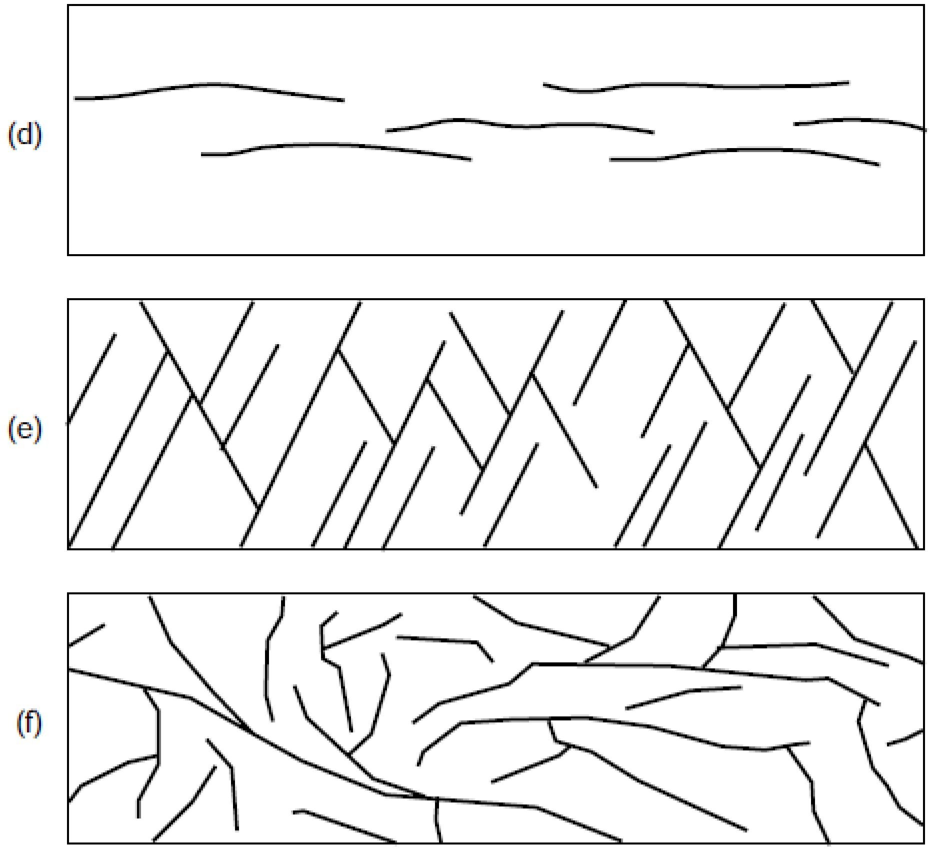
Anastomosing array A group of wavy faults that merge and diverge along strike, thereby creating a braided pattern in map view or cross section.

(c)



En echelon array A group of parallel fault segments that lie between two enveloping surfaces and are inclined at an angle to the enveloping surfaces.

Geometry of fault arrays Sec. 8.6.1



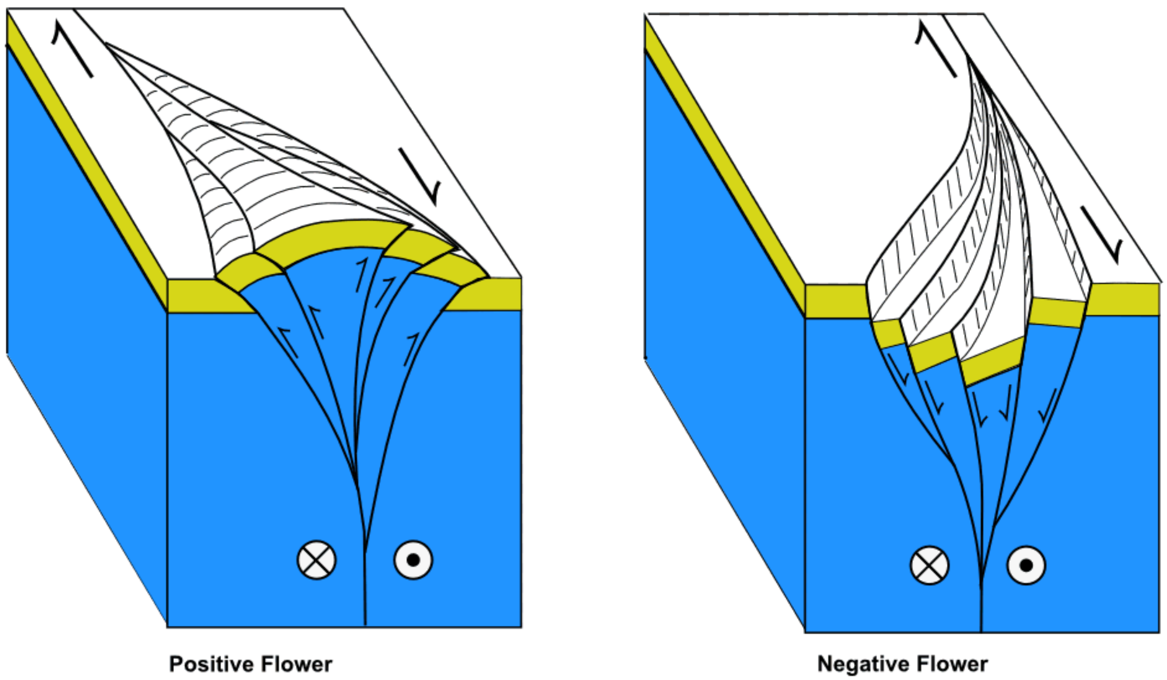
Relay array in map view is a group of subparallel non-coplanar faults that are spaced but whose traces overlap with one another along strike. As displacement dies out along the strike of one fault in the array, displacement increases along an adjacent fault.

Conjugate fault array is composed of two sets of faults that are inclined to one another at an angle of about 60° and can be dip-slip or strike-slip faults. If the faults in the array are strike-slip, then one set must be dextral and the other sinistral.

Nonsystematic fault array In some locations, faulting occurs on preexisting fractures. If the fracture array initially had a wide range of orientations, then slip on the fractures will yield faults in a wide range of orientations. Such an array is called a nonsystematic array.

Strike-slip fault systems Fig. 8.34 replaced

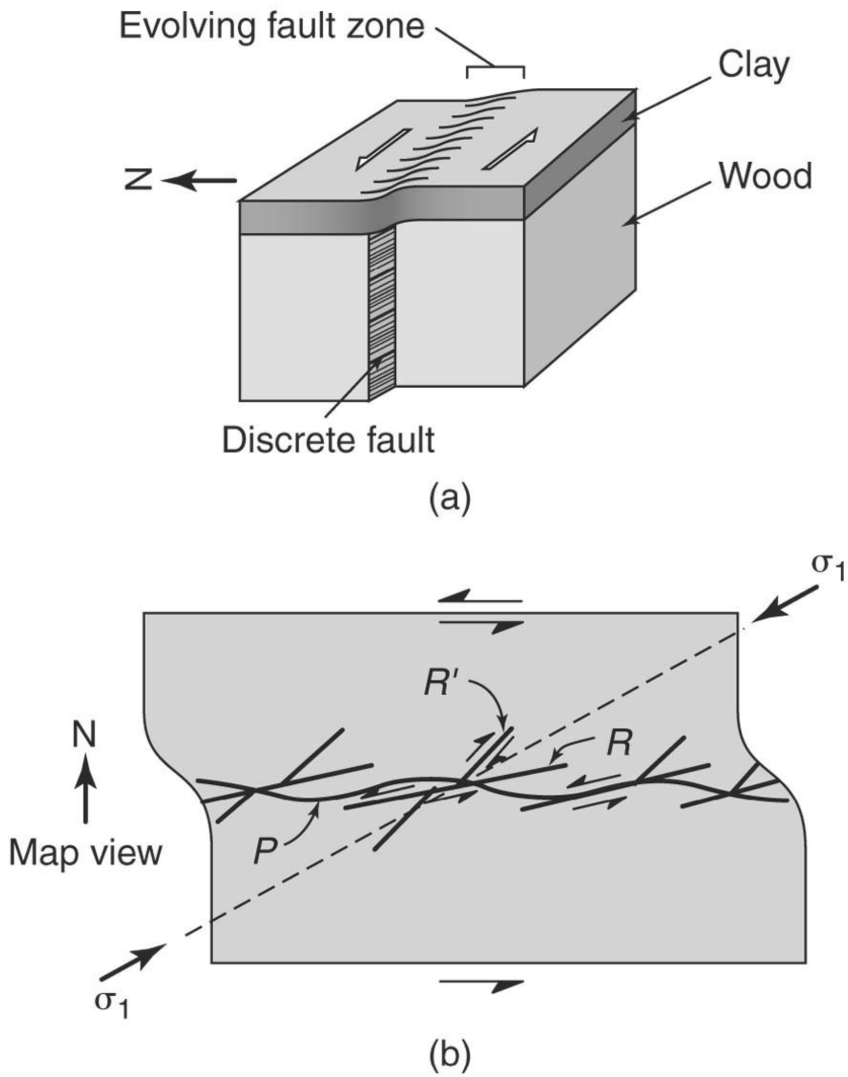
Positive and negative flower structure from strike-slip faulting accompanying transpression or transtention.



en.wikipedia.org/wiki/Strike-slip_tectonics#mediaviewer/File:Flowerstructure1.png

*The symbols **x** and **o** indicate motion **away** and **toward** an observer, respectively.*

Subsidiary Faults Fig. 8.20



Growth of R-, R′-, and P-shears.

Schematic diagram illustrating a layer of clay that deforms when underlying blocks of wood slide past one another.

Map view of the top surface of the clay layer, illustrating the orientation of **Riedel (R)**, **conjugate Riedel (R′), and P-shears**.

Note that the acute bisector of the R- and R'-shears is parallel to the remote σ_1 direction.

Fault Surfaces: Striations and Polish Fig. 8.18a plus

Fault surfaces that have been polished by the process of frictional sliding are called **slickensides**

- If slip on a fault takes place by frictional sliding, asperities on the walls of the fault break off and/or plow into the opposing surface and wear down.
- As a result, the two walls of the fault may become smoother and, in some cases, attain a high polish.

Fault surfaces: fibers Figs. 8.18 and 8.19

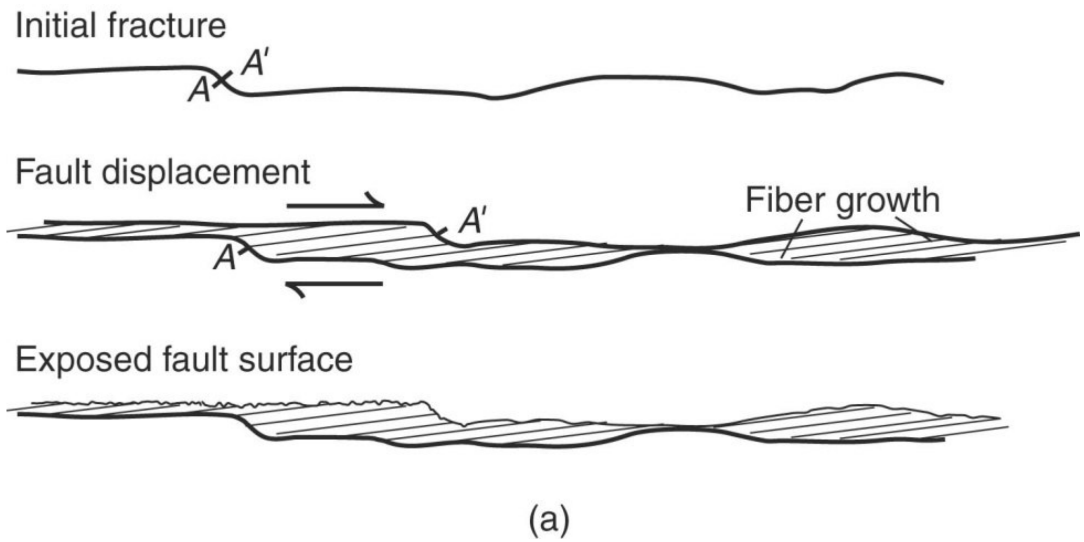


Illustration of the growth of slip fibers on a fault plane

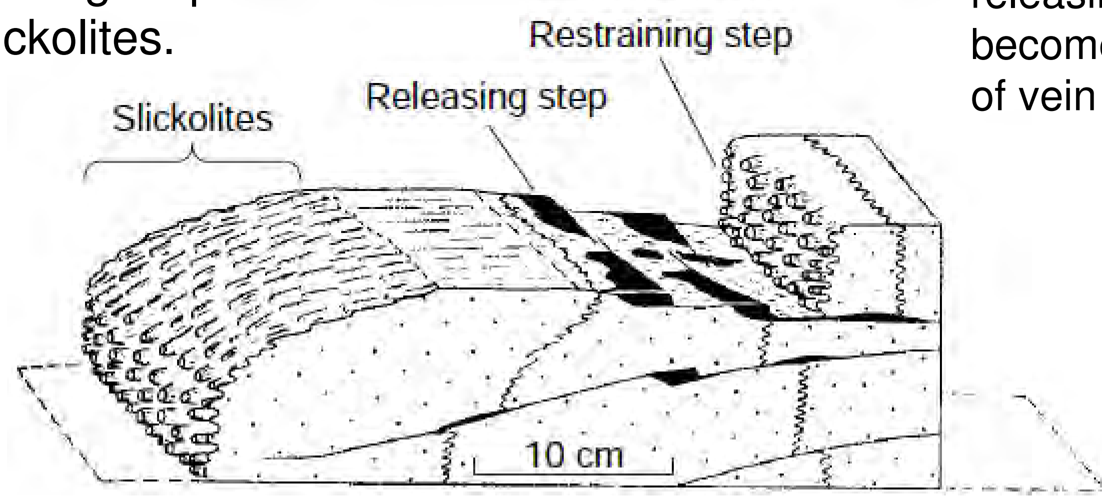
TABLE 8.6 | SHEAR-SENSE INDICATORS FOR BRITTLE FAULTS AND FAULT ZONES

Offset markers	You can define shear sense if you are able to define the relative displacement of two piercing points on opposite walls of the fault, or can calculate the net-slip vector based on field study of the separation of marker horizons.
Fault-related folds	The sense of asymmetry of fault-related folds defines the shear sense. Typically, fault-inception folds verge in the direction of shear (see Chapter 11 for a definition of fold vergence). If the hinges of folds in a fault zone occur in a range of orientations, you may need to use the Hanson slip-line method to determine shear sense. Note that the asymmetry of rollover folds relative to shear sense is opposite to that of other fault-related folds.
Fiber-sheet imbrication	The imbrication of slip-fiber sheets on a fault provides a clear indication of shear sense. Fiber sheets tilt away from the direction of shear.
Steps on slickensides	Microscopic steps develop along slickensided surfaces. Typically the face of the step is rougher than the flat surface. However, slickenside steps may be confused with the intersection between pinnate fractures and the fault, giving an opposite shear sense.
En echelon veins	*En echelon* veins tilt toward the direction of shear. If the veins are sigmoidal, the sense of rotation defines the shear sense.
Carrot-shaped grooves	Grooves on slickensides tend to be deeper and wider at one end and taper to a point at the other, thus resembling half a carrot. The direction in which that "carrot" points defines the direction of shear.
Chatter marks	As one fault block moves past another, small wedge-shaped blocks may be plucked out of the opposing surface. The resulting indentations on the fault surface are known as chatter marks.
Pinnate fractures	The inclination of pinnate fractures with respect to the fault surface defines the shear sense.

Fault surfaces: fibers Fig. 8.19b

Block diagram illustrating steps along a fiber-coated fault surface.

Oblique restraining steps become slickolites.

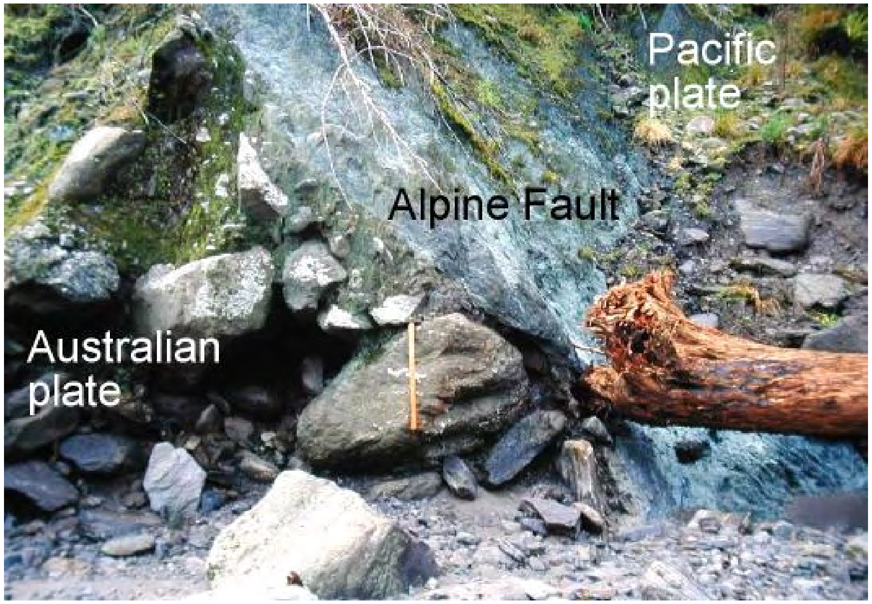


Restraining steps become pitted by pressure solution, releasing steps become the locus of vein growth

TABLE 8.5	CLASSIFICATION OF BRITTLE FAULT ROCK
Noncohesive Brittle Fault Rocks	
Fault gouge	Rock composed of material whose grain size has been mechanically reduced by pulverization. Grains in fault gouge are less than about 1 mm in diameter. Like breccia, gouge is noncohesive. Shearing of gouge along a fault surface during progressive movement may create foliation within the gouge. Clay formed by alteration of silicate minerals in fault zones may be difficult to distinguish from true gouge.
Indurated gouge	Fault gouge that has been cemented together by minerals precipitated from circulating groundwater.
Fault breccia	Rock composed of angular fragments of rock greater than about 1 mm, and as much as several m across; fault breccia is noncohesive.
Vein-filled breccia	Fault-breccia blocks that are cemented together by vein material. Another term, *indurated breccia*, is synonymous.
Cohesive Brittle Fault Rocks	
Pseudotachylyte	A glass or microcrystalline material that forms when frictional heating melts rock during slip on a fault. Pseudotachylyte commonly flows into cracks between breccia fragments or into cracks penetrating the walls of the fault. In special cases, pseudotachylyte may be several m thick (e.g., impact sites), but generally it is mm to cm in thickness.
Argille scagliose	A fault rock that forms in very fine-grained clay- or mica-rich rock (e.g., shale or slate) and is characterized by the presence of a very strong wavy anastamosing foliation. As a consequence, the rock breaks into little scales or platy flakes.
Cataclasite	A cohesive fault rock composed of broken, crushed, or rolled grains. Unlike breccia, it is a solid rock that does not disintegrate when struck with a hammer.

Also: Foliated vs. Non-foliated

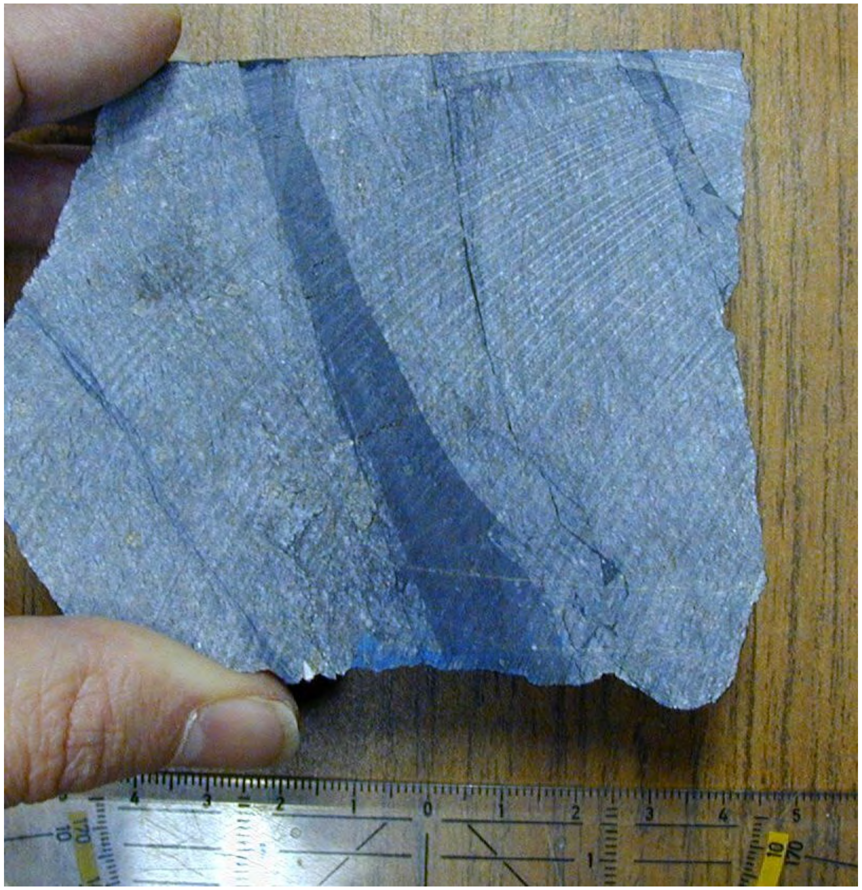
Fault Rocks: Gouge and Cataclasite



Mylonites/Shear Zones

Pseudotachylytes

A glass or microcrystalline material that forms when frictional heating melts rock during slip on a fault.



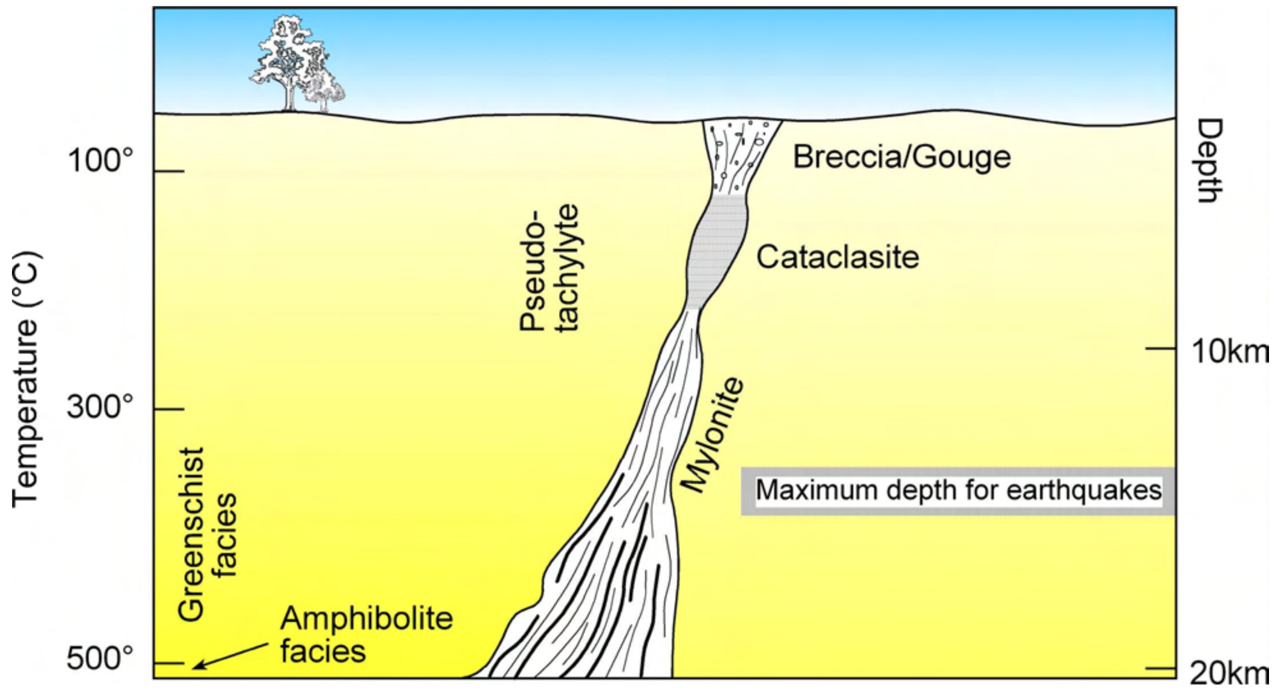
Fault habit with depth Fig. 8.26

Rocks become progressively more ductile with depth in the crust, because of the increase in temperature and pressure that occurs with depth.

Consequently, at depths between ~5 km and 10–15 km, faulting tends to yield a fault zone composed of **cataclasite.**

The **brittle-plastic transition** for typical crustal rocks lies at a depth of 10–15 km in the crust, varying as a result of rocks consisting of different minerals that behave plastically under different conditions, and because the depth of transition depends on the local geothermal gradient.

Note the change in fault zone width and types of structures with depth.



The activity of plastic deformation mechanisms below this brittle-plastic transition yields a fine-grained and foliated fault-zone rock, called **mylonite.**

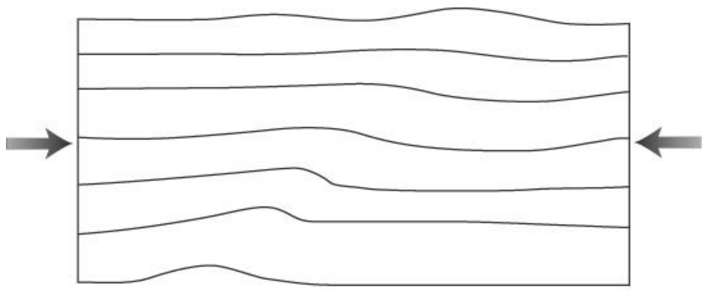
Changes in Fault Character with Depth Sec. 8.4.2

Whereas cataclasite forms by brittle deformation on a grain scale, movement in the fault zone resembles viscous flow and strain is distributed across the zone (i.e., ductile behavior).

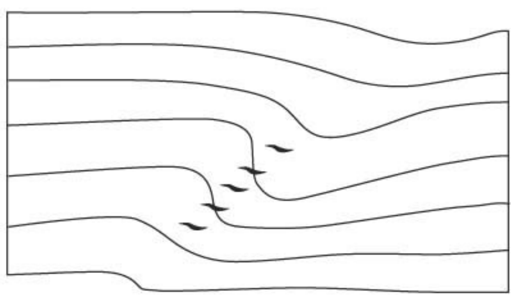
Temperature conditions at a depth of around 10–15 km are in the range of 250℃ to 350℃ (i.e., lower greenschist facies of metamorphism), where plastic deformation mechanisms become the dominant contributor to strain in (quartz-rich) crustal rocks.

Fault-related folding Fig. 8.21

A small flexure develops during shortening of the layers, and a pronounced anticline-syncline pair develops.



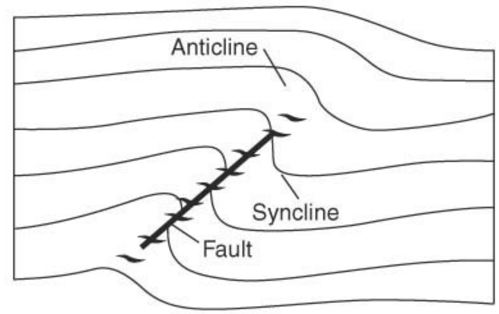
(a)



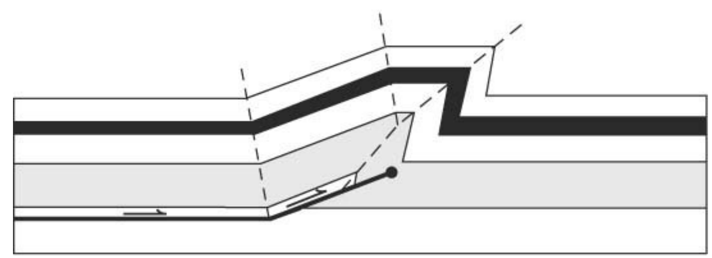
(b)

A fault breaks through the fold, cutting through a gentle flexure

En echelon (or stepped) gashes form in the fold.



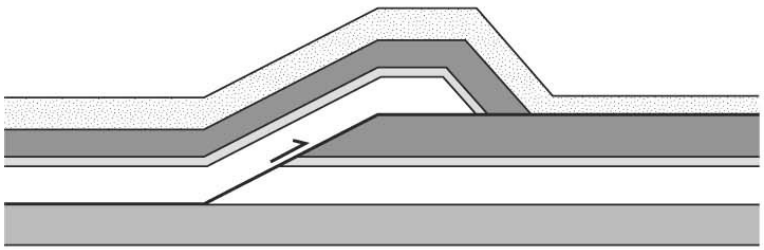
(c)

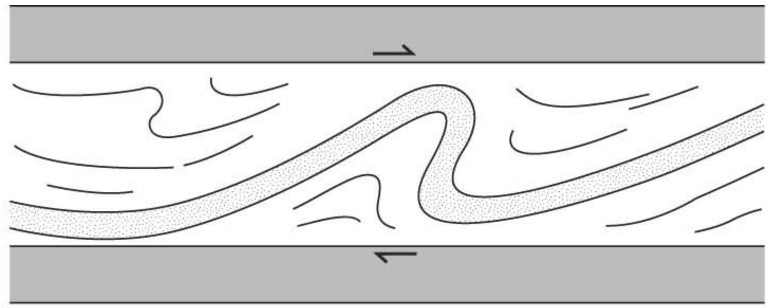


(d)

Geometry of a fault-propagation fold.

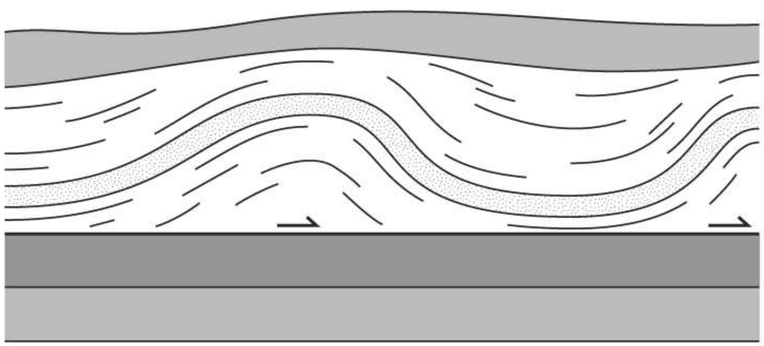
Fault-related folds Fig. 8.22

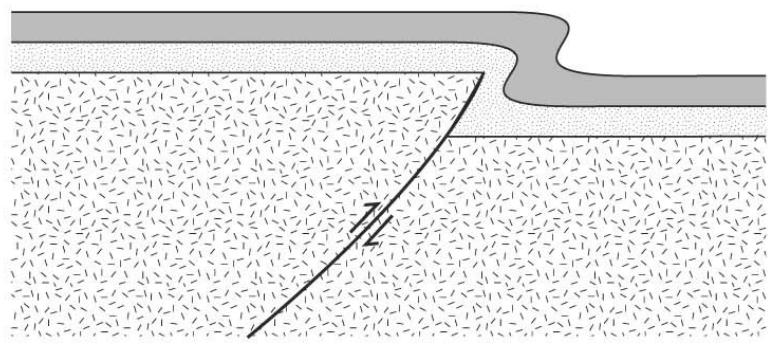

(a)


(b)

Fault-bend fold on a thrust.

Folding in a fault zone

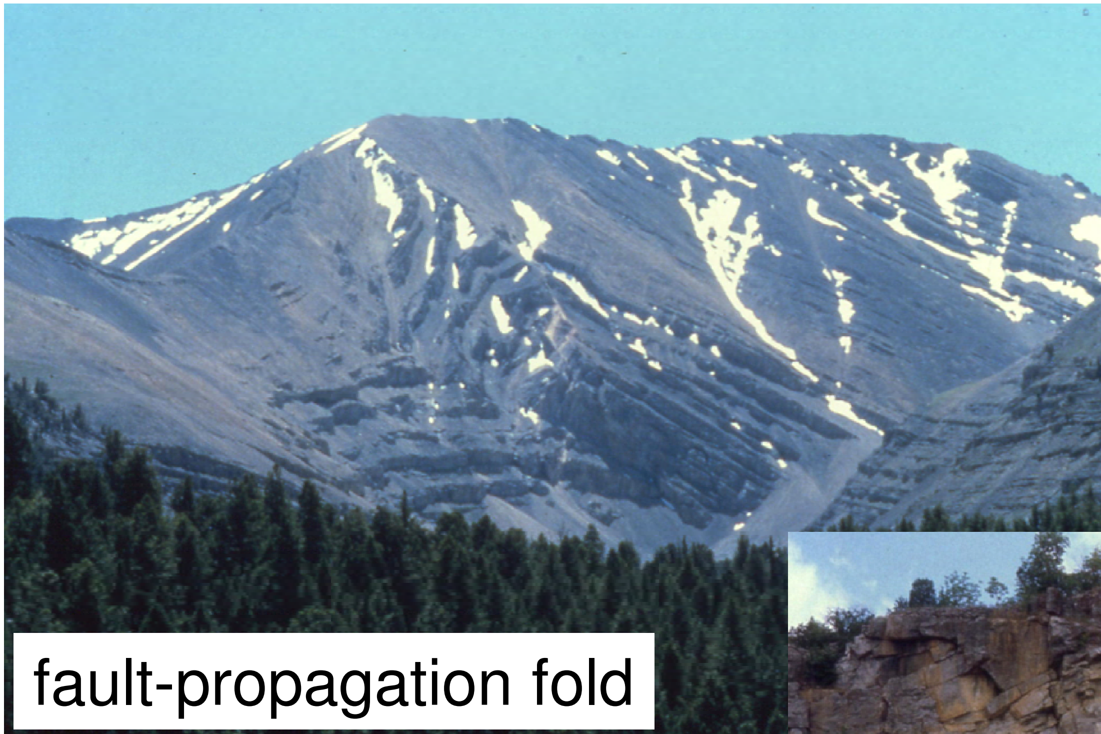

(c)


(d)

Detachment fold.

Drape fold over faulted basement.

Fault-related folds

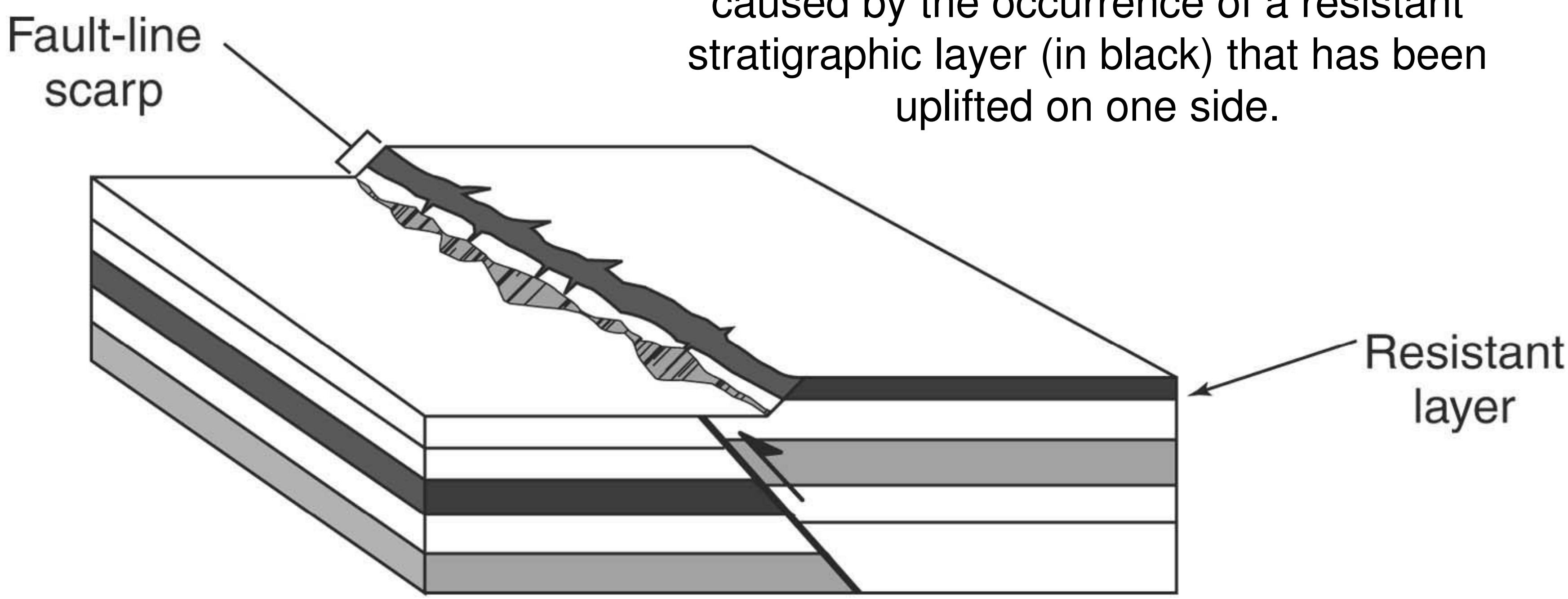


fault-propagation fold

fault-bend fold

Fault scarp Fig. 8.25

Block diagram illustrating a fault-line scarp caused by the occurrence of a resistant stratigraphic layer (in black) that has been uplifted on one side.



- Alternatively, if the fault becomes ***indurated***, it may become more resistant to erosion than the surrounding region and will stand out in relief.

- Second, if the fault juxtaposes two rock units with different resistance to erosion, then a topographic scarp develops along the trace of the fault because the weaker unit erodes more rapidly, and the land surface underlain by the weaker unit becomes topographically lower). Such a **fault-line scarp** differs from a **fault scarp**, in that it is not the plane of the fault itself.

Fault scarp in the Basin and Range Province (Nevada, USA). Note the normal sense of offset, with person for scale

Fluids and faulting Sec. 8.5.2

The fracturing that accompanies fault displacement creates open space within the fault zone for fluid to enter.

- Because of the increase in open space, fluid pressure in the fault zone temporarily drops relative to the surrounding rock.
- The resulting fluid-pressure gradient can actually drive groundwater into the fault zone until a new equilibrium is established.
- Such faulting-triggered fluid motion is known as **fault valving** or **seismic pumping.**

Fluids and faulting Sec. 8.5.2

The presence of water in fault zones affects the stress at which faulting occurs in three ways.

- First, alteration minerals formed by reaction with water in the fault zone tend to have lower shear strength than minerals in the unaltered rock, and thus their presence may permit the fault to slip at a lower frictional stress than it would otherwise.
- Second, the presence of water in a rock may cause hydrolytic weakening of silicate minerals, and therefore allow deformation to occur at lower stresses.
- Third, the pore pressure of water in the fault zone decreases the effective normal stress in a rock body, and thus decreases the magnitude of the shear stress necessary to initiate a shear rupture in intact rock or initiate frictional sliding on a preexisting surface.