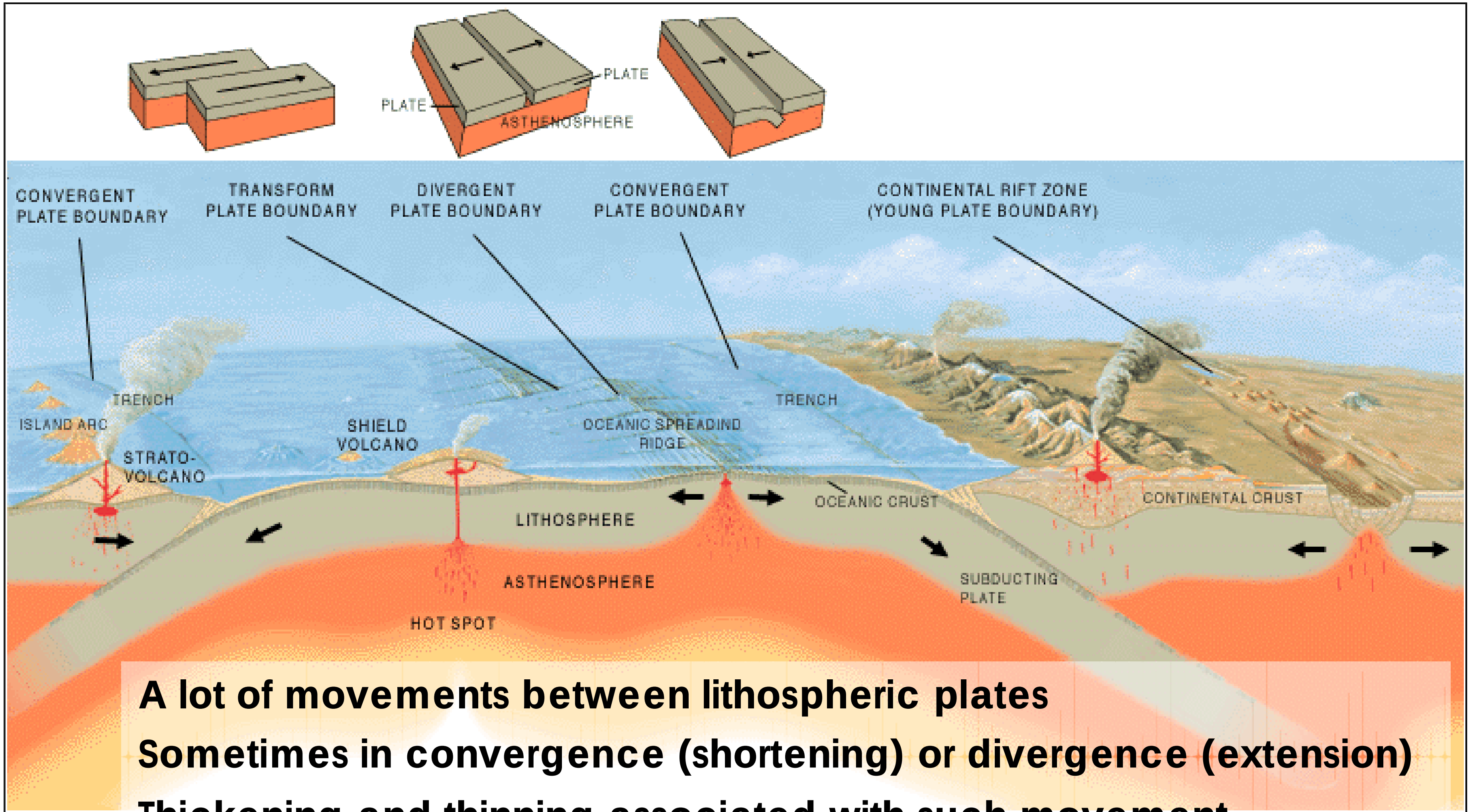
Deformation

Geology 1

G. Bertotti

TU Delft



A lot of movements between lithospheric plates

Sometimes in convergence (shortening) or divergence (extension)

Thickening and thinning associated with such movement

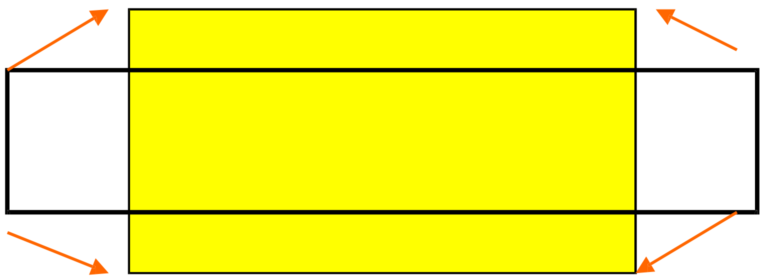
Horizontal deformations

Some terminology before we begin

- stresses are applied to bodies
- if these stresses are higher that the strength of the body, this will deform

you can extend a body

you can shorten a body



Forces and deformations are NOT the same

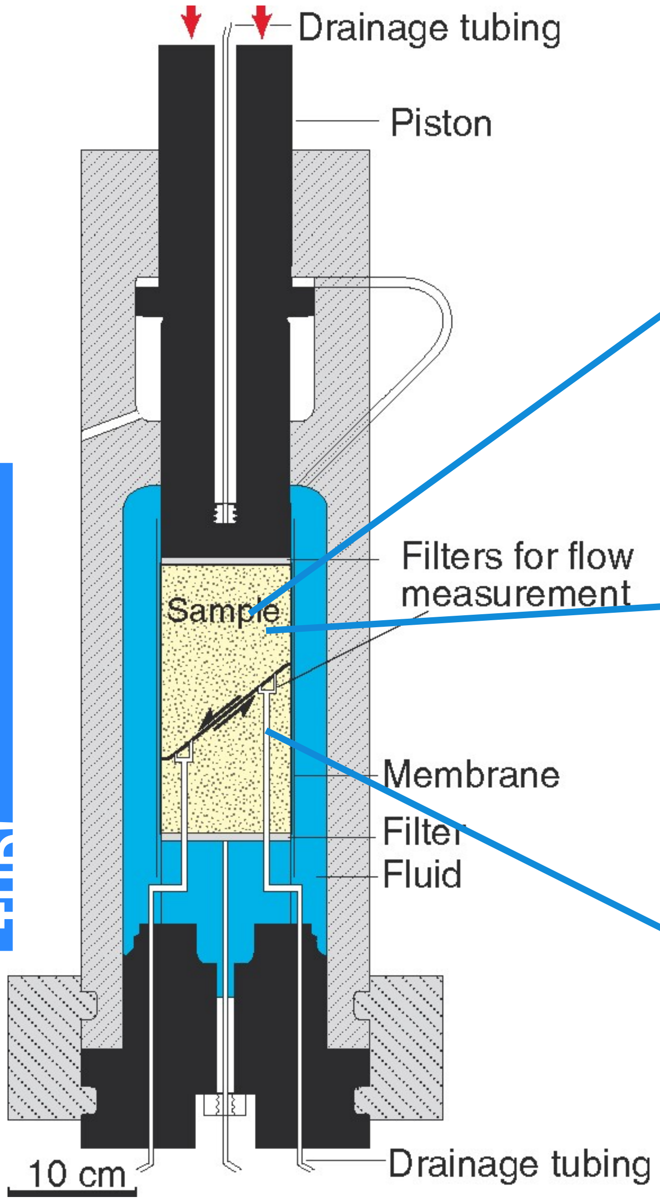
You can stress a body without having deformation

You can make a body longer within a general pressure

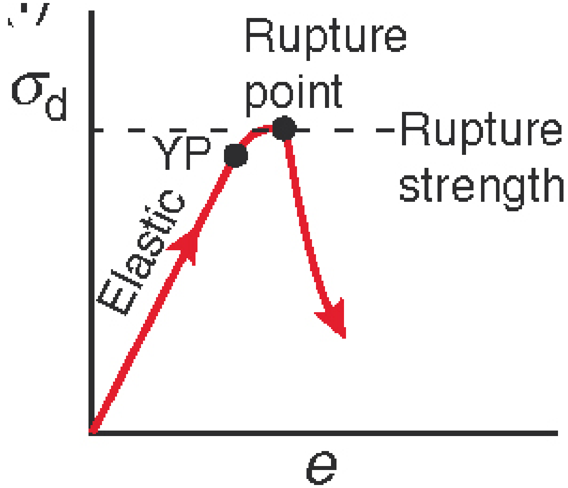
Forces/stresses	Dimension changes
Tension (*rek*)	Extension (stretching)
Compression	Shortening contraction

The rock mechanics perspective:

Also present at

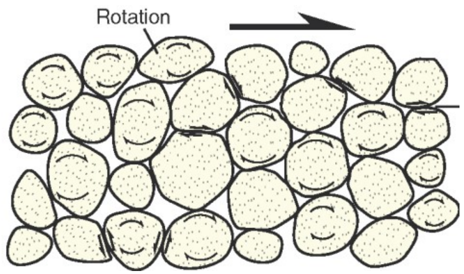


stress-strain relations

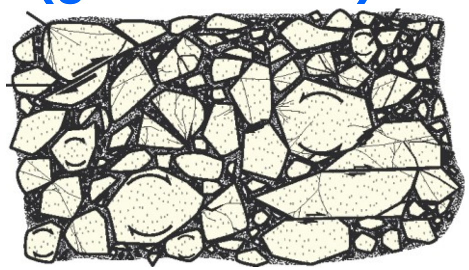


deformation mechanism

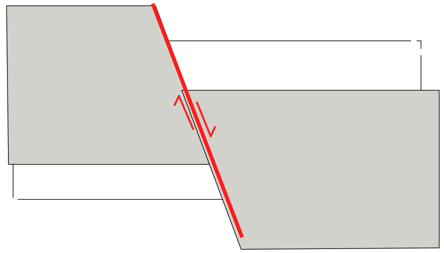
granular flow



Cataclastic flow (grains break)



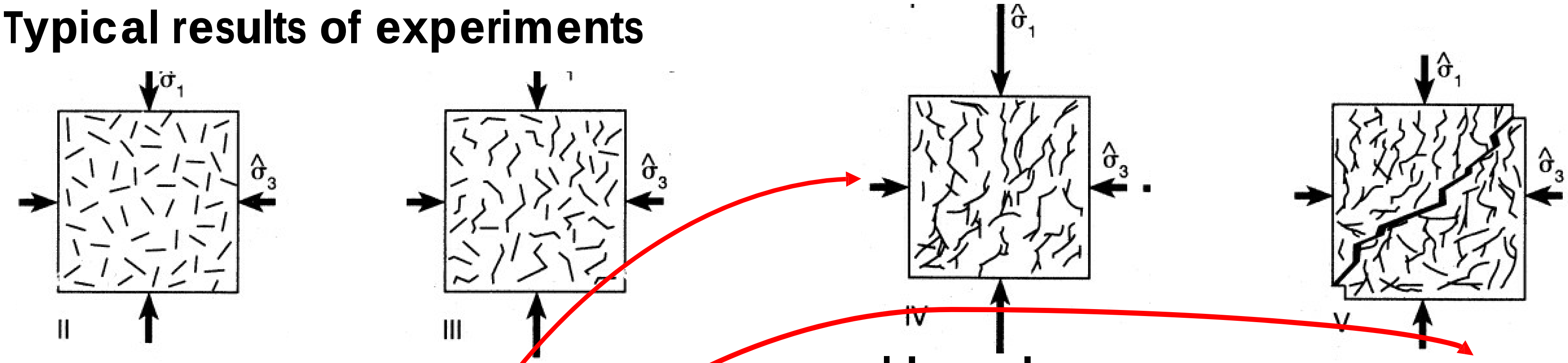
geometry of deformation



localized (discrete)

distributed

Typical results of experiments

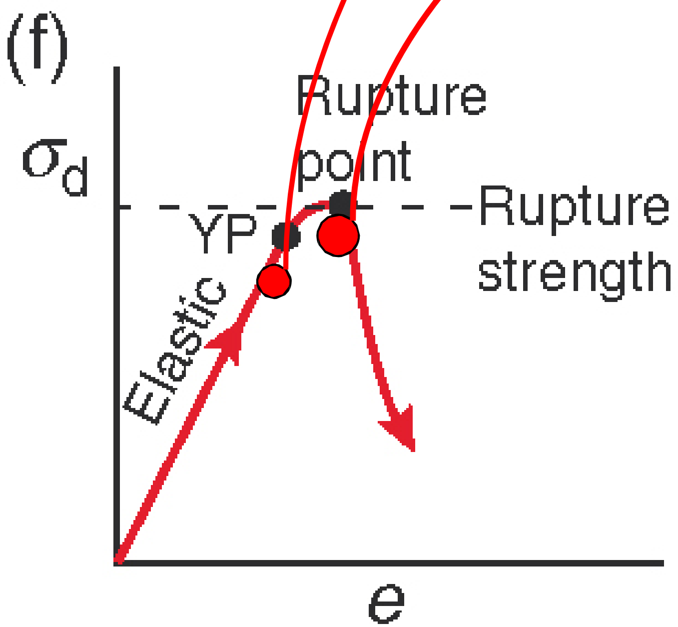


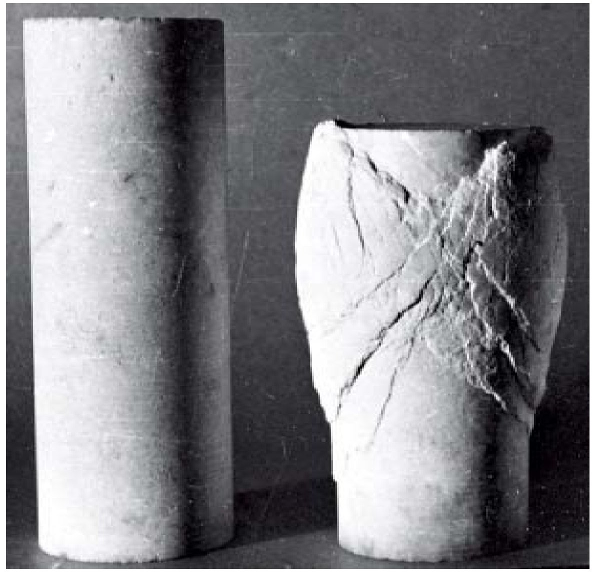
cracks are closed

old cracks propagate, new cracks form

old cracks propagate, new cracks form

a new through-going fracture is established

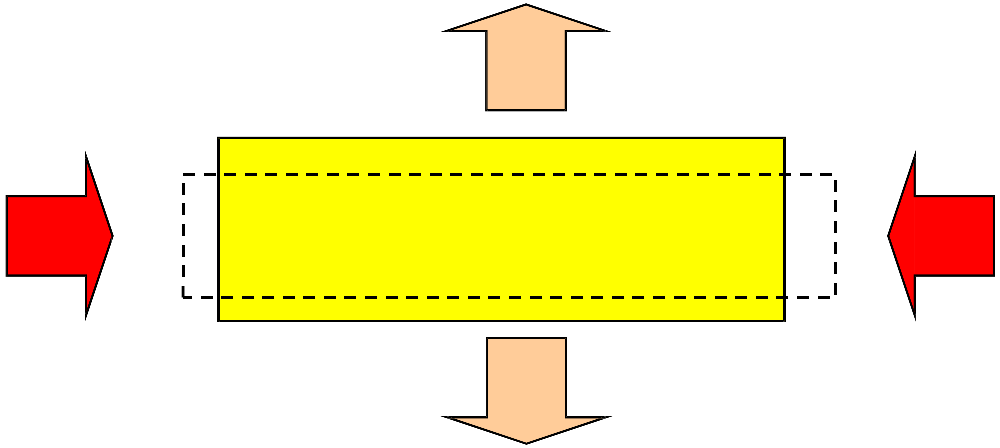




We distinguish a life before and one after the development of a mechanic instability (through-going faulting or folding)

Before through-going faulting

The body accommodates deformation in a distributed manner, i.e. without developing instabilities (folds and/or faults)



The amount of deformation which one can accommodate in this stage is limited

-<10-15% in the case of shortening. It is called Layer parallel shortening (LPS)

-<5-6% in the case of extension (rocks are weaker under tension than under compression)

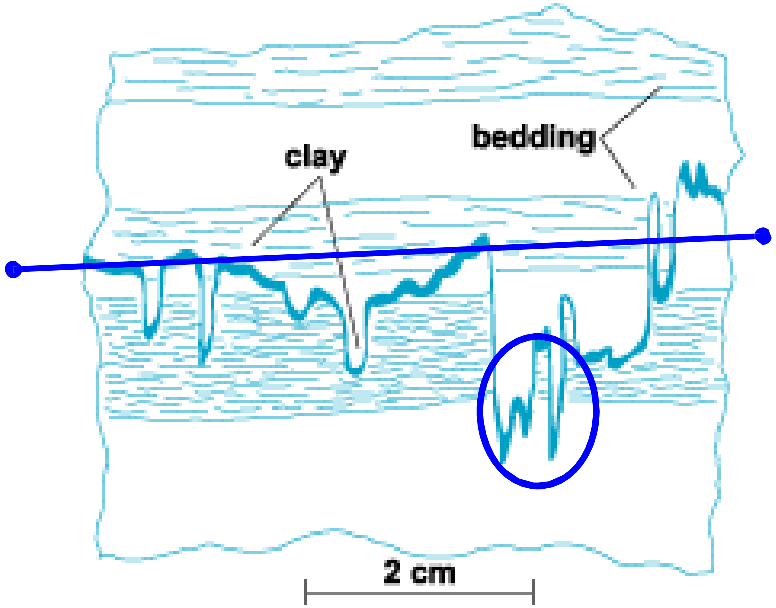
The body becomes shorter and thicker

The main structures to accomplish this are

- stylolites (to decrease volume)
- veins (increase volume)
- joints (increase volume)

LPS structures (1): Stylolites

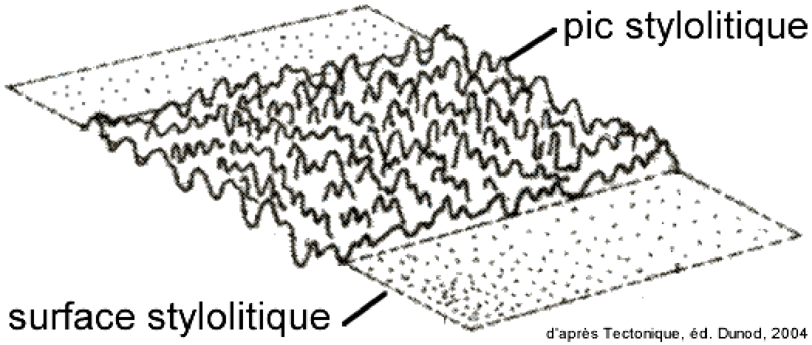
***Solution structures where shortening is mostly accommodated by volume loss*. The main driving force is pressure-driven solution.**

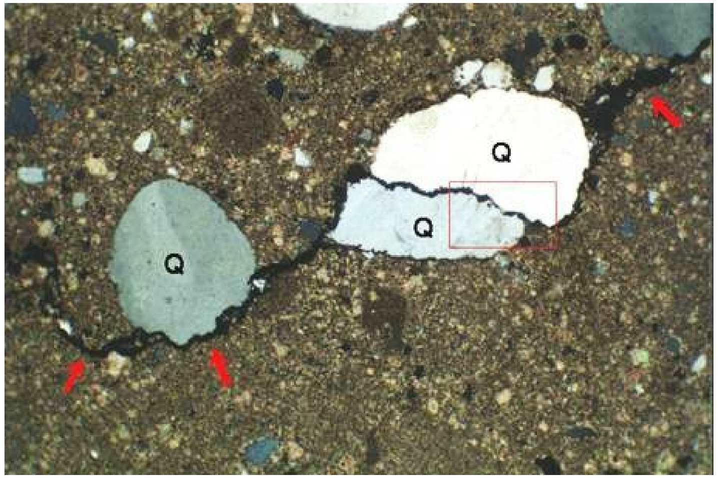


the enveloping surface
often, not always, perpendicular to the teeth

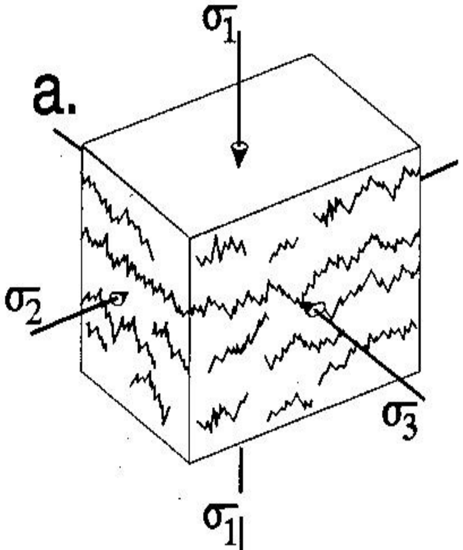
the "teeth"
always parallel to the compression direction

This is what the surface looks like if you remove one of the blocks





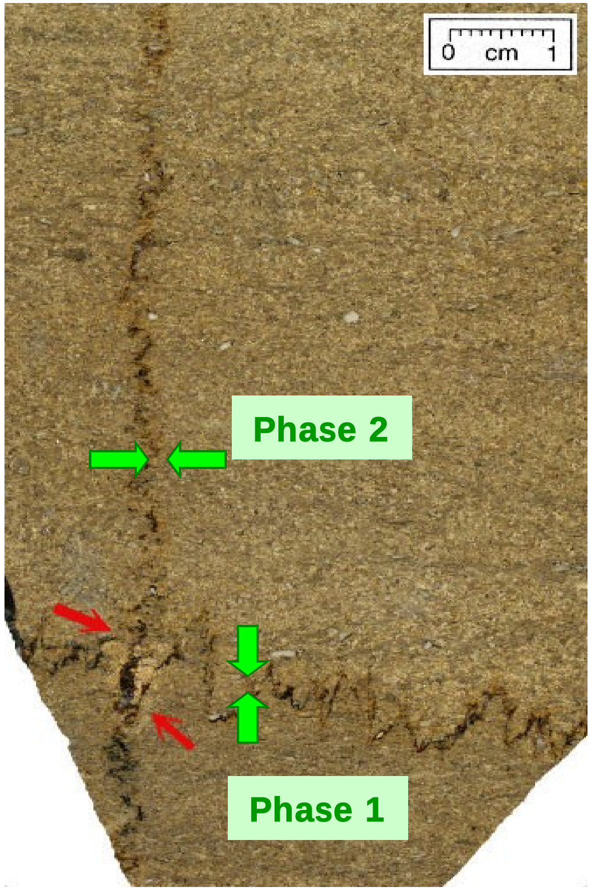
Each stylolite accommodates few % of shortening



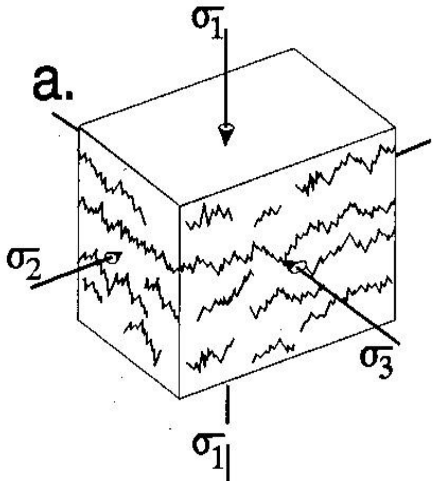
As they occur frequently in bundles, they can accommodate large shortening = produce a lot of solute which is exported

Mainly found in carbonate rocks, but present also in quartz rich sandstones

They leave behind a thin film of shale which form major permeability barriers



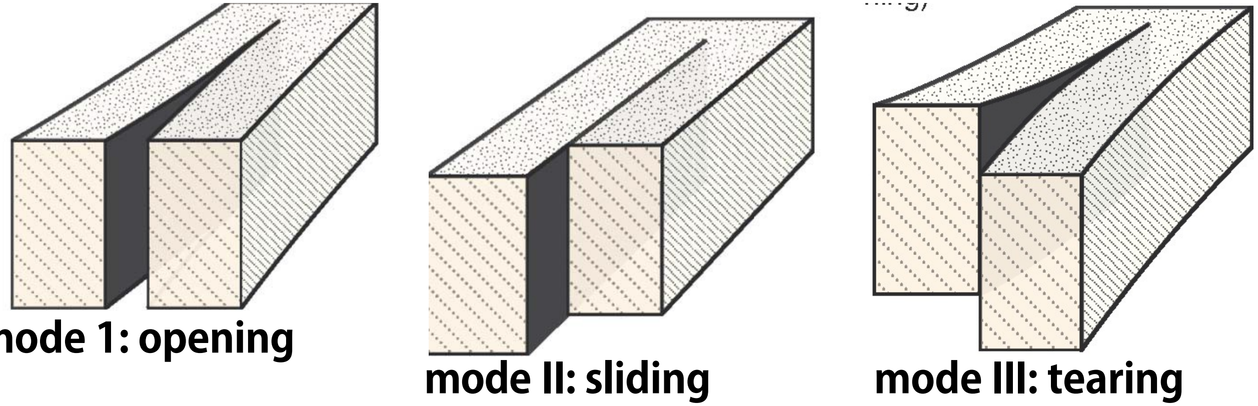
The most common stylolites are parallel to bedding (overburden)

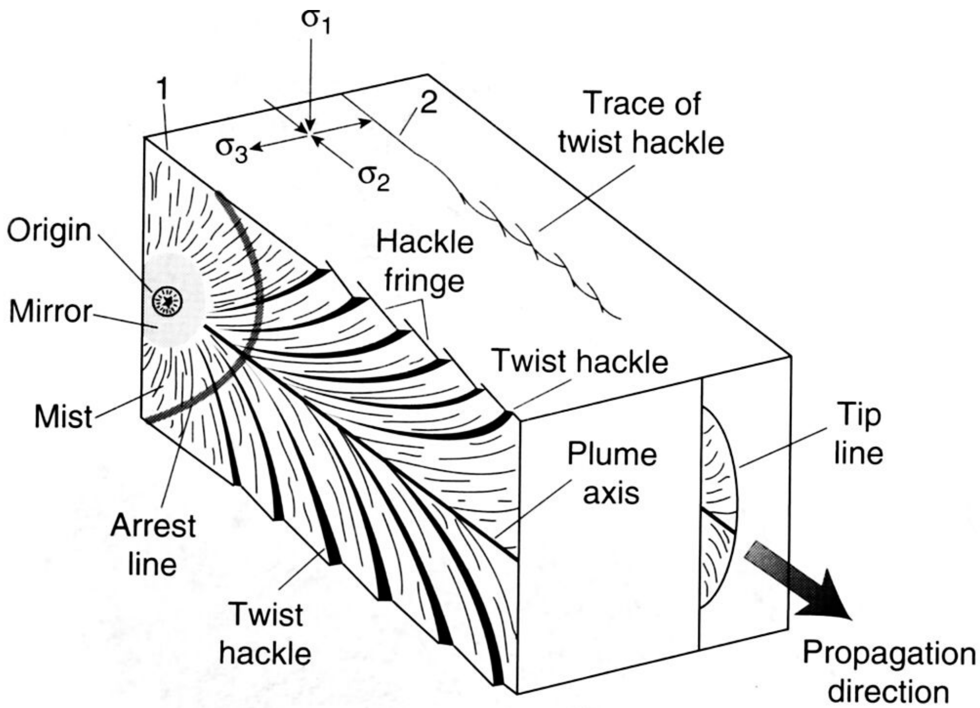


Non bedding-parallel stylolites (e.g. phase 2) are associated with tectonic stresses

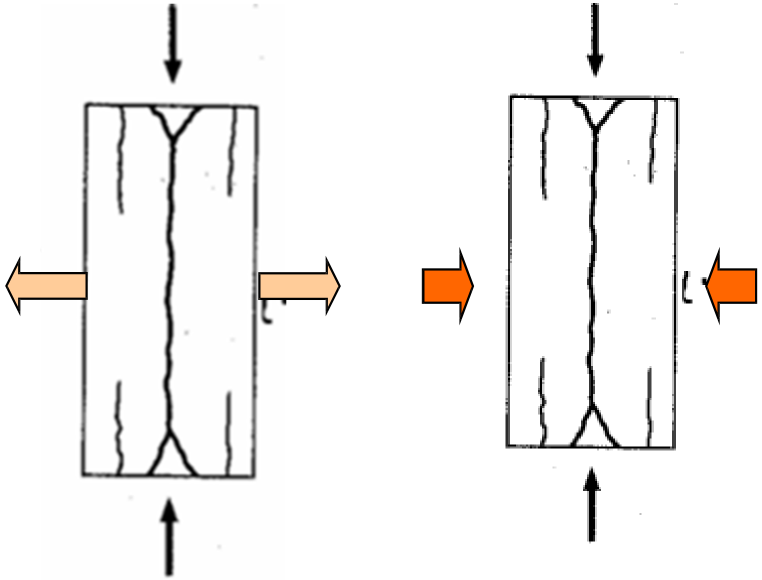
LPS structures (2): Joints

Are opening fractures (mode I) with very little displacement



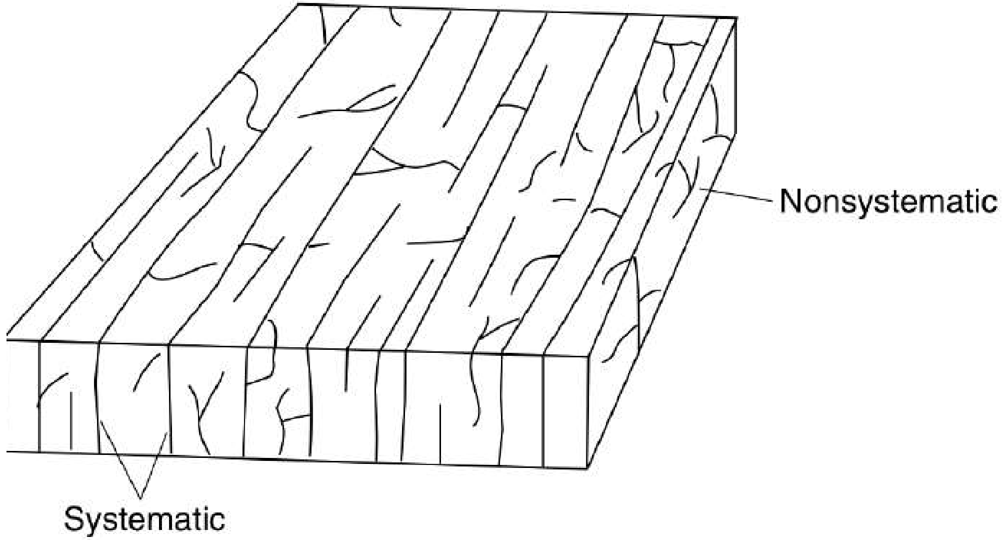


Start at irregularity points and propagate at very high rates generally along the bedding.

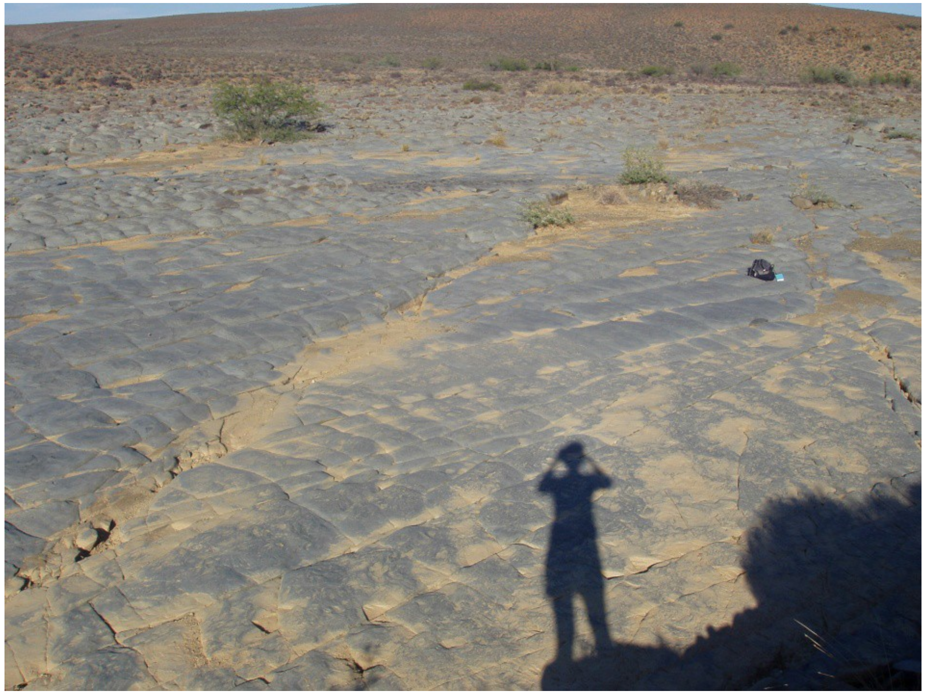


Open parallel to the maximum compression and perpendicular to the minimum stress (tensional or slightly compressional)

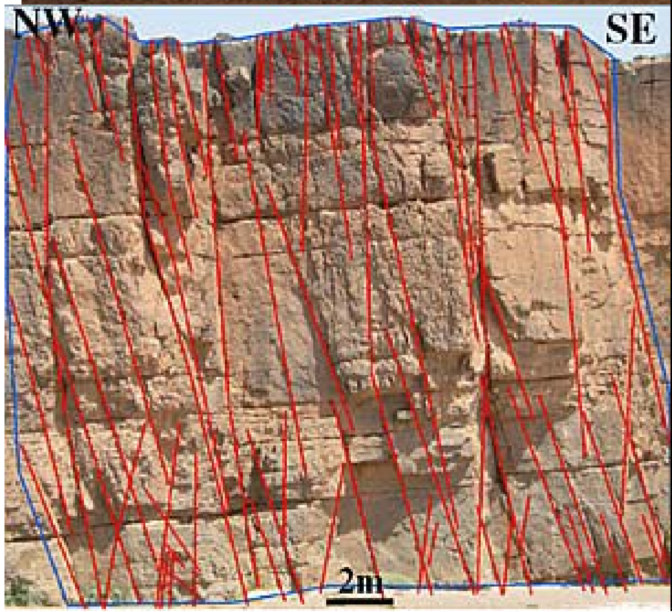
Joints become interesting when they are organized in systematic sets



Joints often affect (packages of) layers over very large regions



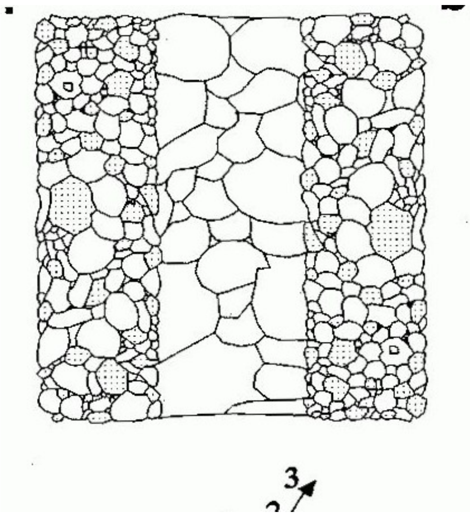
The Tata anticline:
Analog for fractured reservoirs



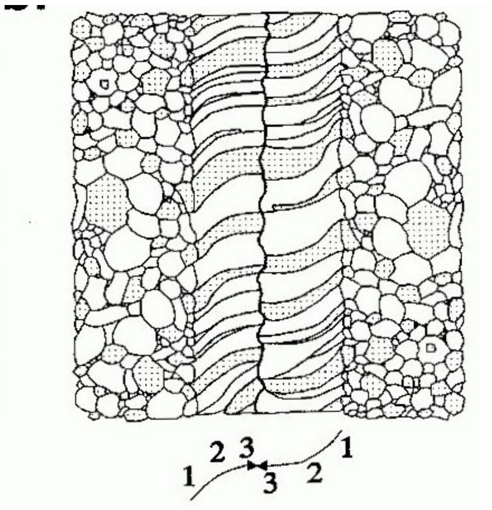
And if you have a drone….

LPS (3): veins

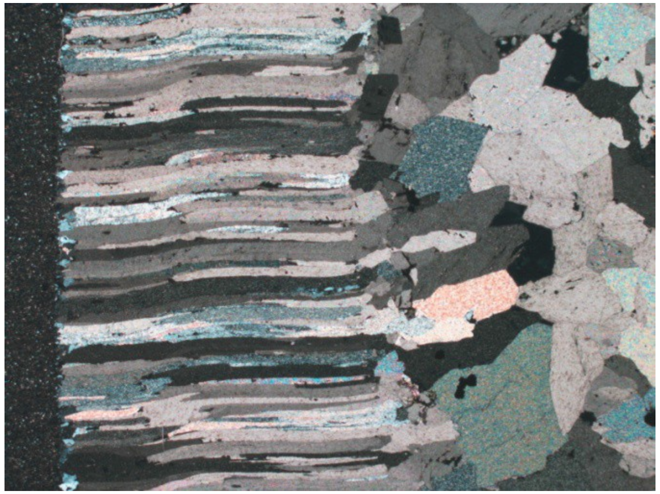
Circulating fluids can precipitate calcite, quartz or other mineral forming veins.



blocky cement

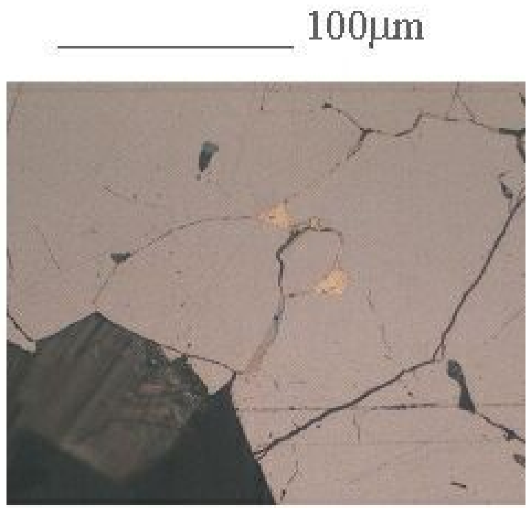


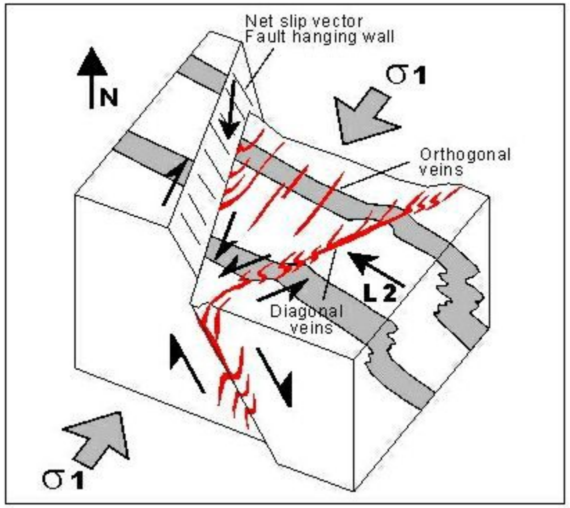
fibrous cement



Veins are fundamental systems controlling the formation of ore deposits
Millions of cubic meters of fluids must pass through a rock to leave significant quantities of cements and/or ores

GOLD!!

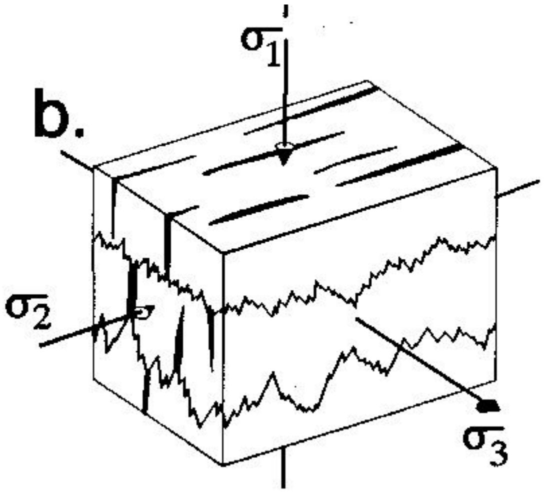


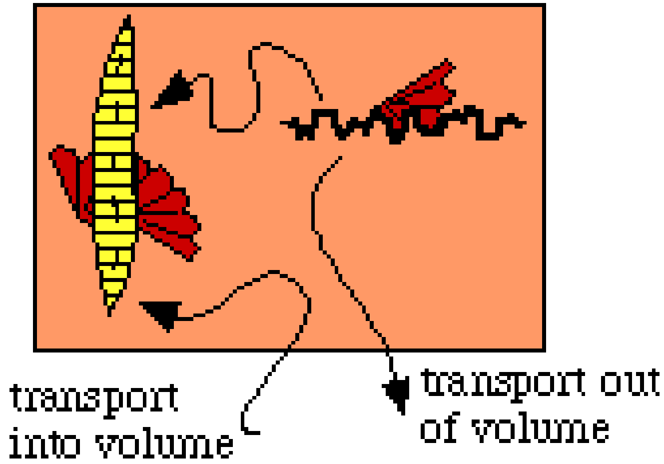


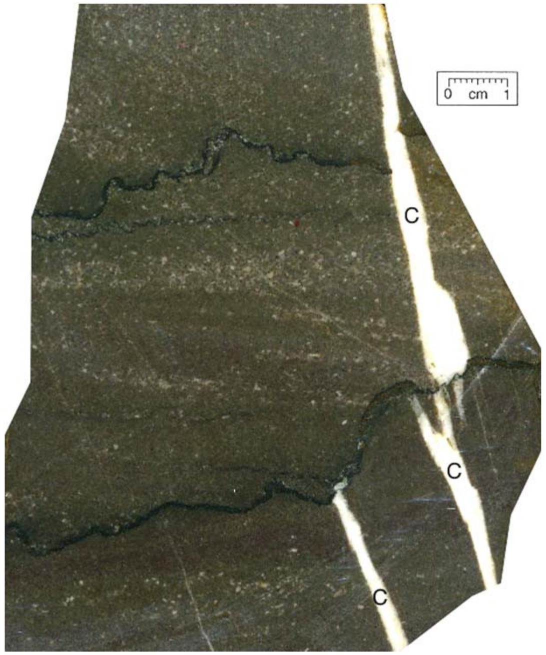
The position, distribution and orientation of veins is controlled by larger scale structures (faults, folds etc).

Structural geology is crucial in mining!

When the body needs to become shorter and thicker, veins and stylolites can develop at the same time

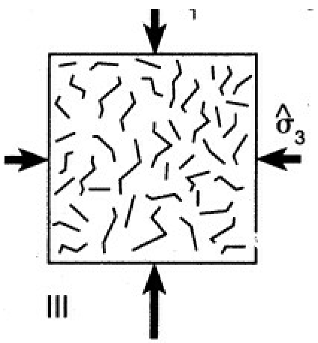




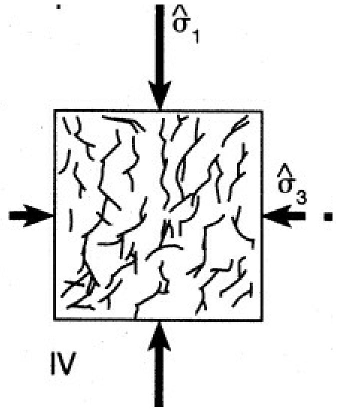


A story of this rock?

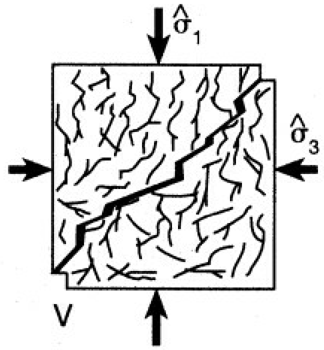
But then…too much is too much and instabilities develop



old cracks propagate, new cracks form



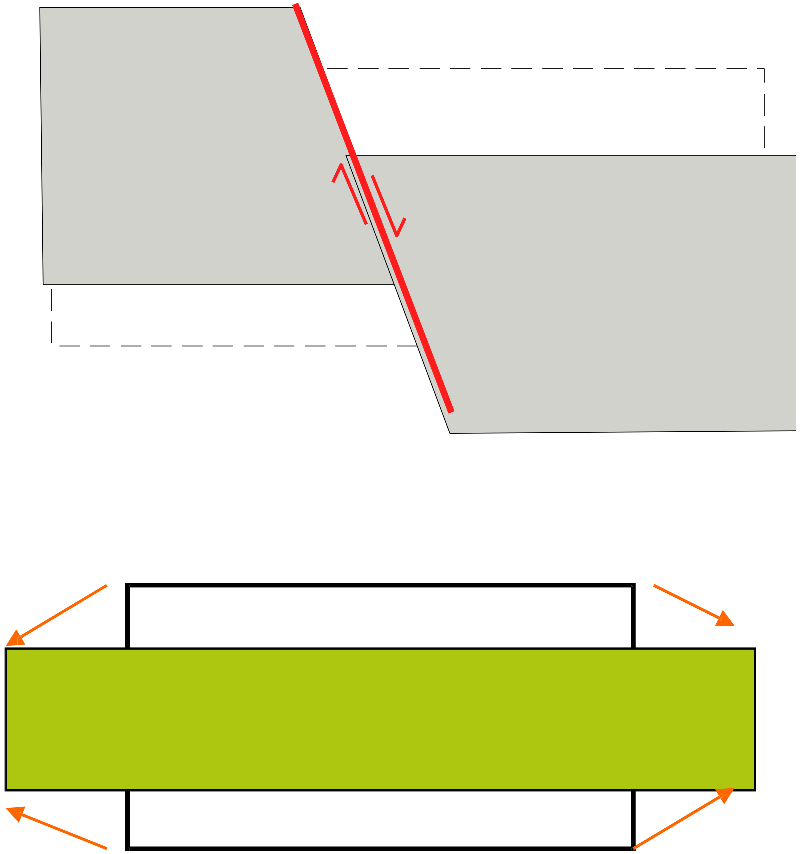
old cracks propagate, new cracks form



a new through-going fracture is established

Fault : a zone of localized deformation = it separates blocks with little deformation

In the extensional domain

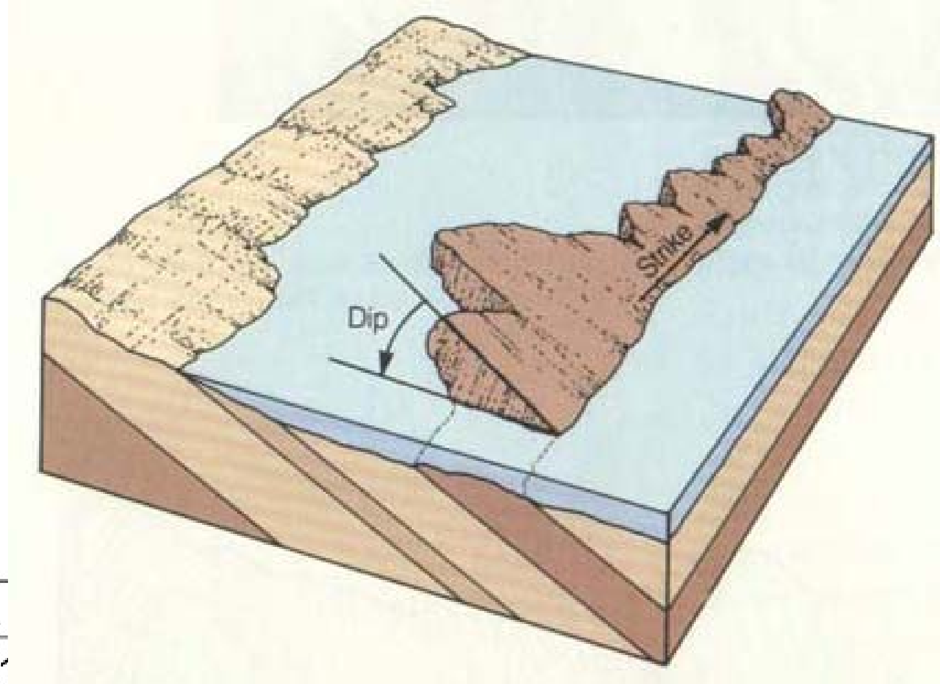


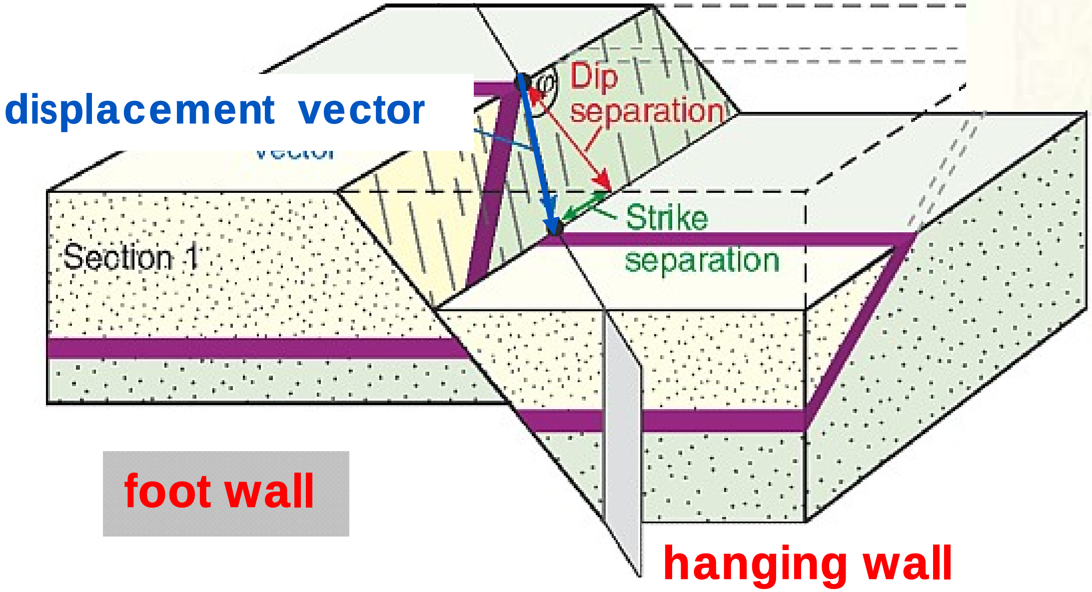
Distributed deformation is the opposite end member of localized deformation

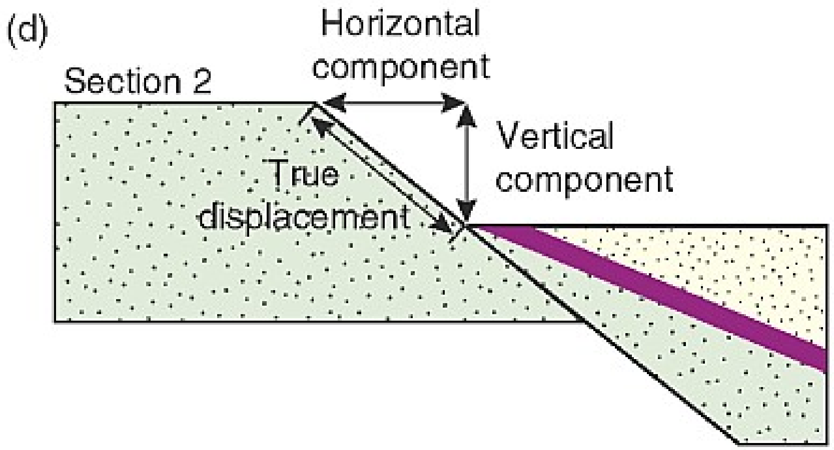
Geometric elements of faults

fault plane and the displacement vector and other features

The position in space of faults, and other planar features, is defined by a direction (strike or dip direction) and a dip angle





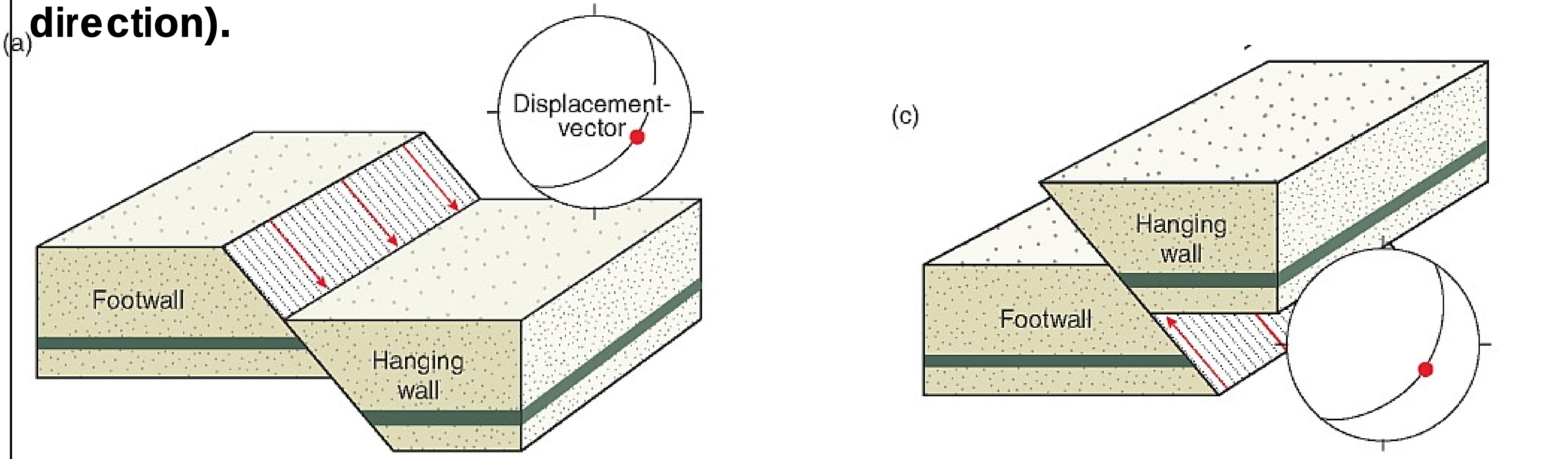


Fossen 2010

Faults are classified on the basis of the relative movements of the blocks

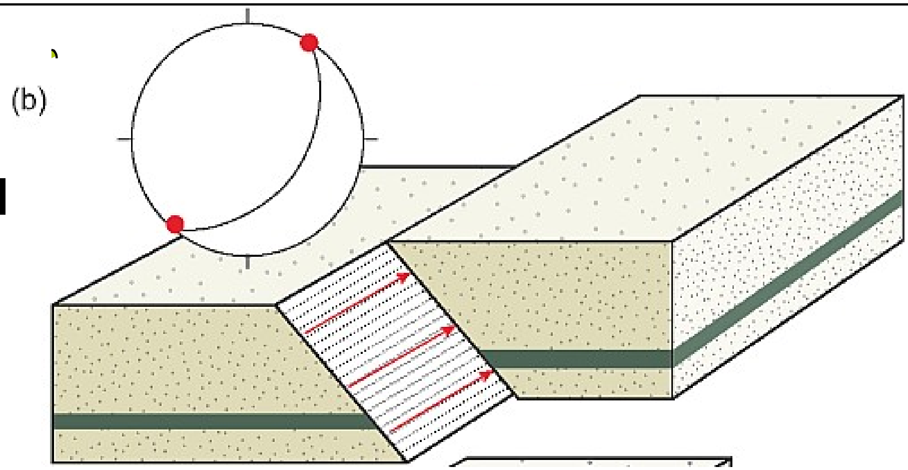
Dip slip faults:

Slip (displacement vector) is parallel to the dip of the fault plane (the steepest direction).



strike slip faults:

Slip (displacement vector) is parallel to the strike of the fault plane (the horizontal line belonging to the fault plane)

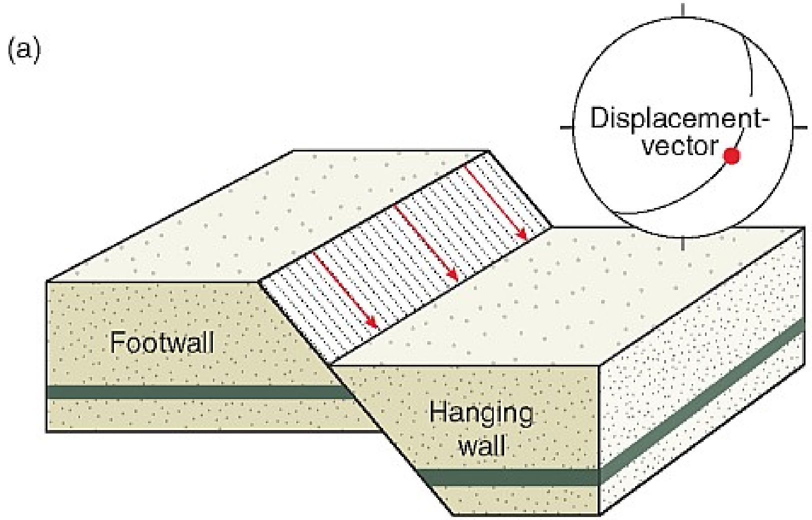


dip -slip

Normal faults

The hanging wall moves downward with respect to the footwall

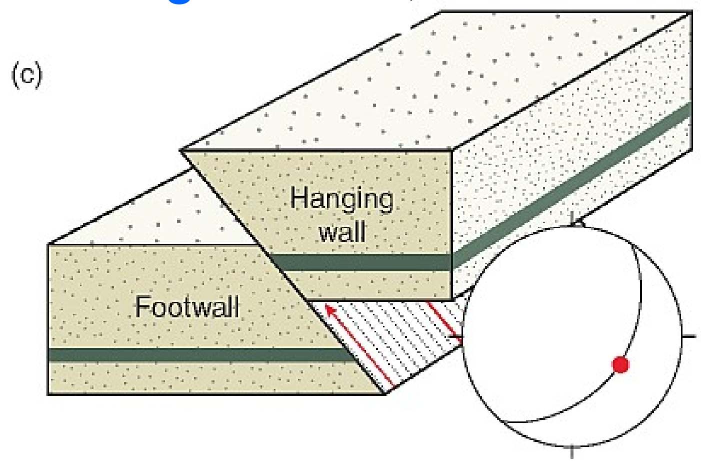
Create horizontal extension



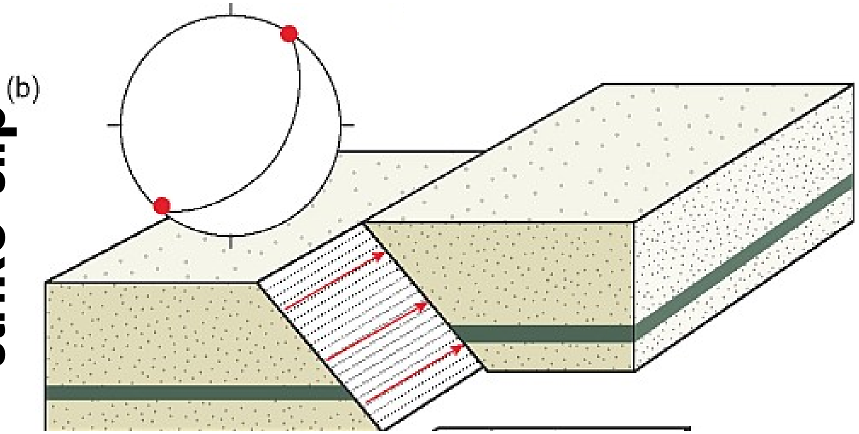
Reverse faults

The hanging wall moves upward with respect to the footwall

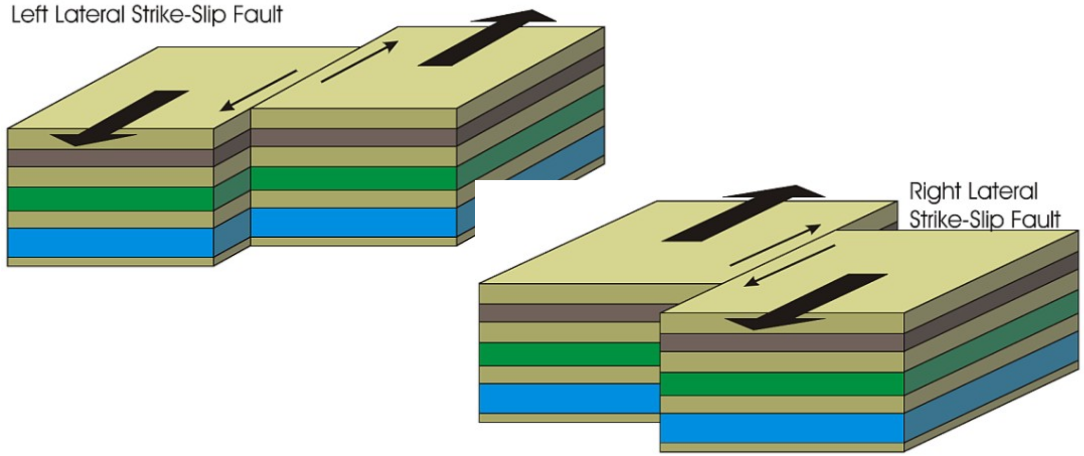
Accommodate horizontal shortening



strike-slip



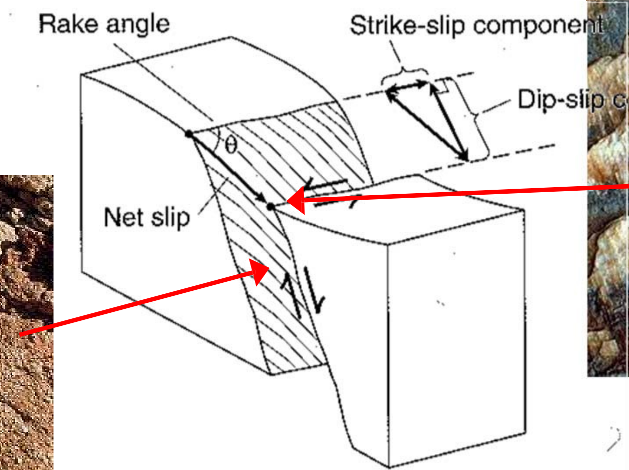
Strike-slip faults: Can be sinistral or dextral



Displacement vectors are often expressed as scratches and striations on the fault plane

growth of new mineral

mechanical scratches

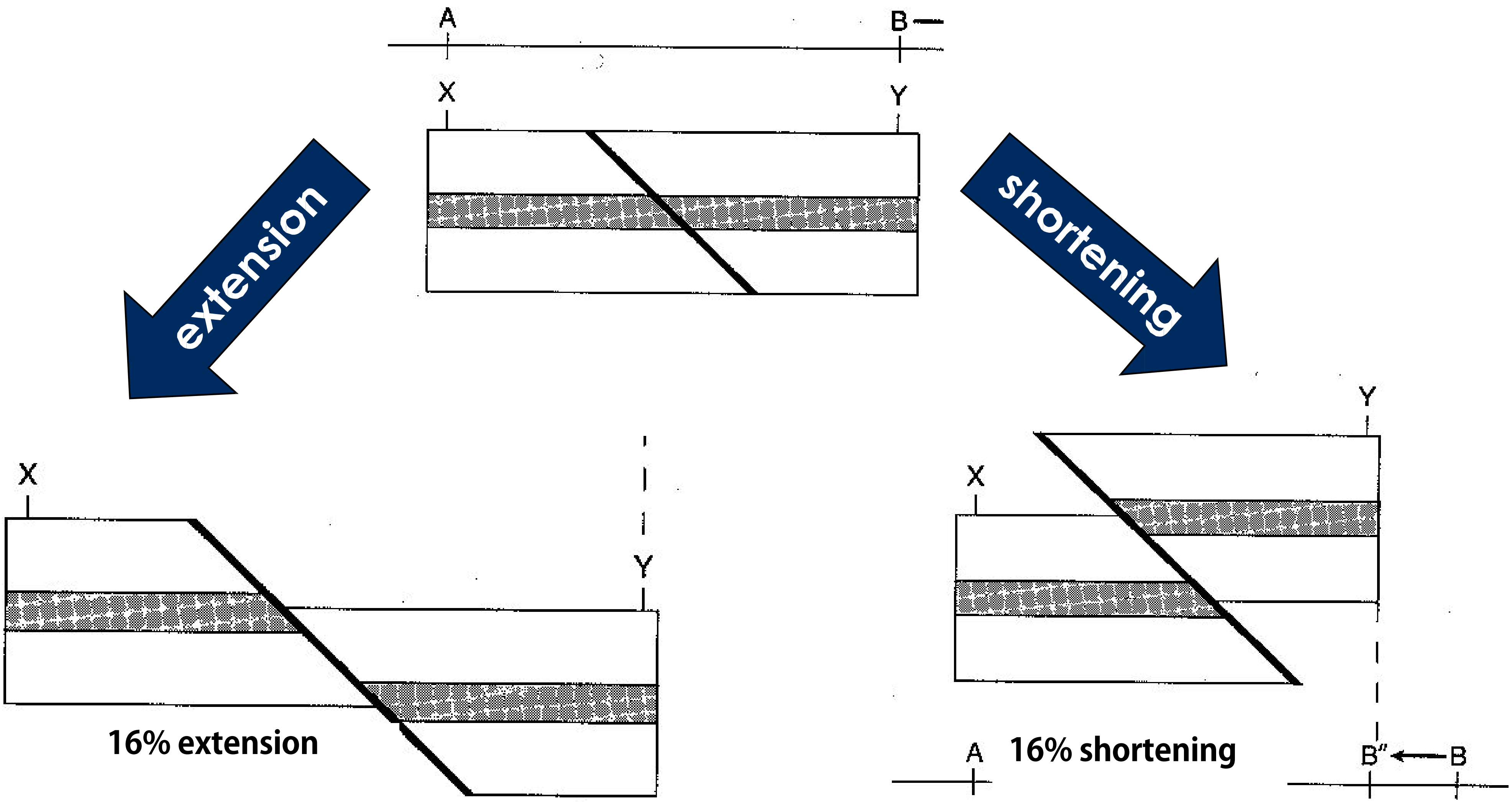


Quantifying fault displacements

extension or contraction = $L_f - L_i$

strain = $\varepsilon = (L_f - L_i)/L_i$

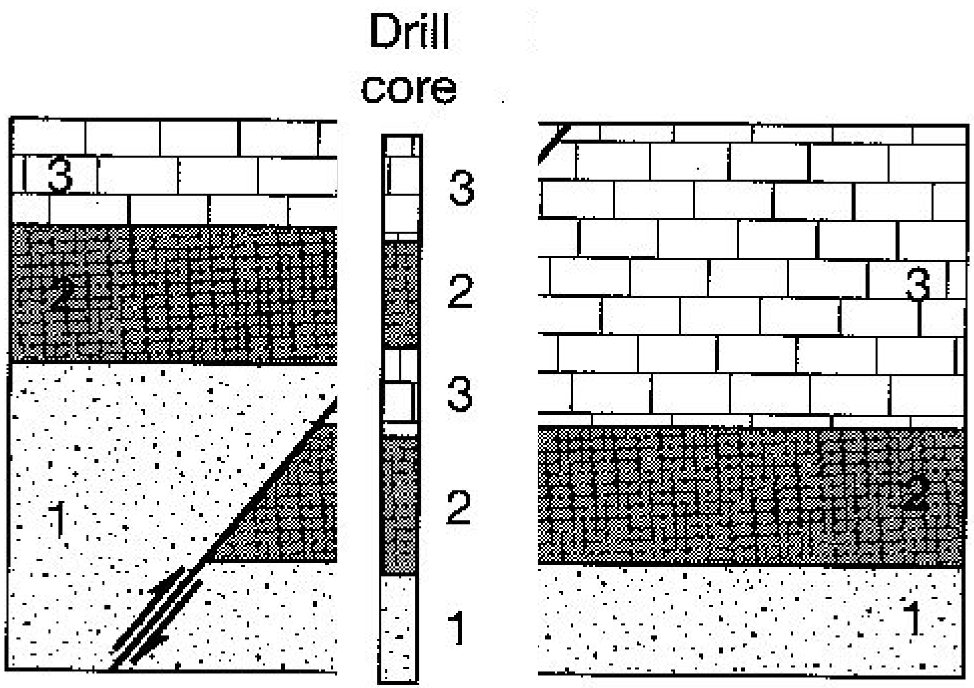
strain (%) = (Lf-Li)/Li * 100



How to identify the kind of fault?

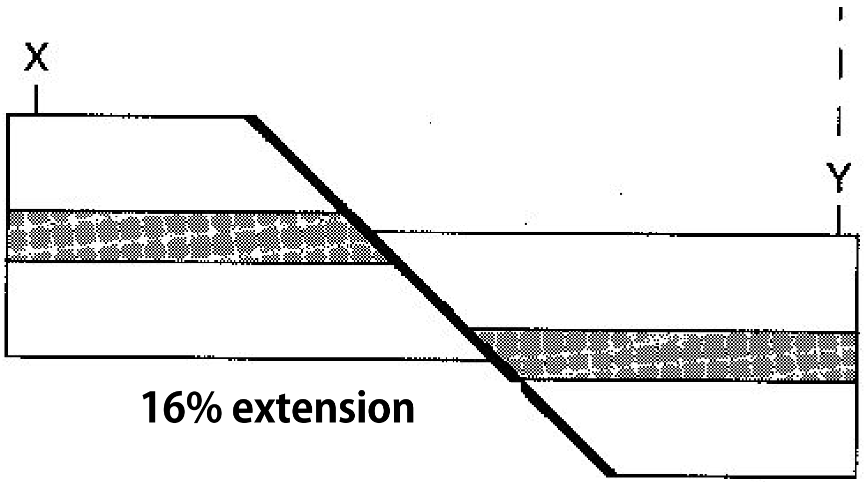
1) Trace the same stratigraphic horizon on the two sides of the fault: has the body in consideration become longer or shorter?

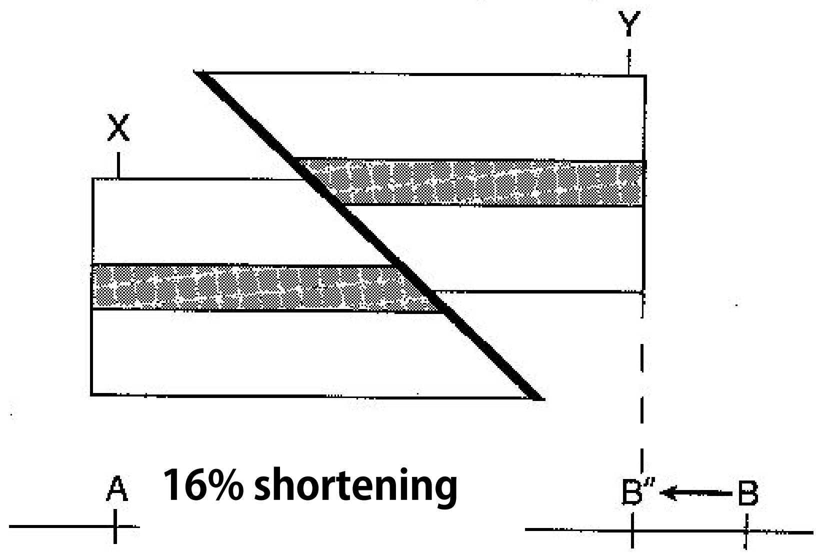
2) Look at the succession of rocks across the fault: In a reverse fault one has a repetition, in a normal fault, some of the rocks are missing (stratigraphic cut off)



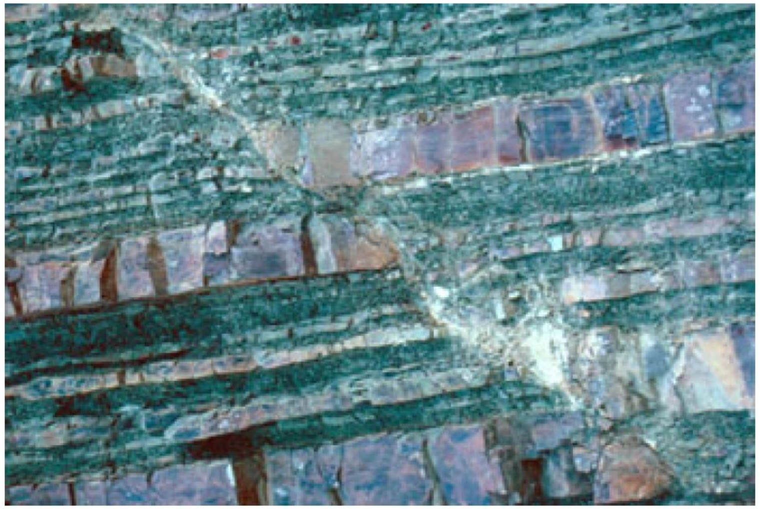
Remember

- names such as normal, reverse... only define relative movements of the two blocks; they say nothing on absolute movements (for instance with respect to sea level)
- these definitions refer to the present position! Pay attention when layers are tilted
- stretching and shortening refer to the horizontal dimension; they are always associated with shortening and extension (respectively) in another direction (vertical or horizontal)





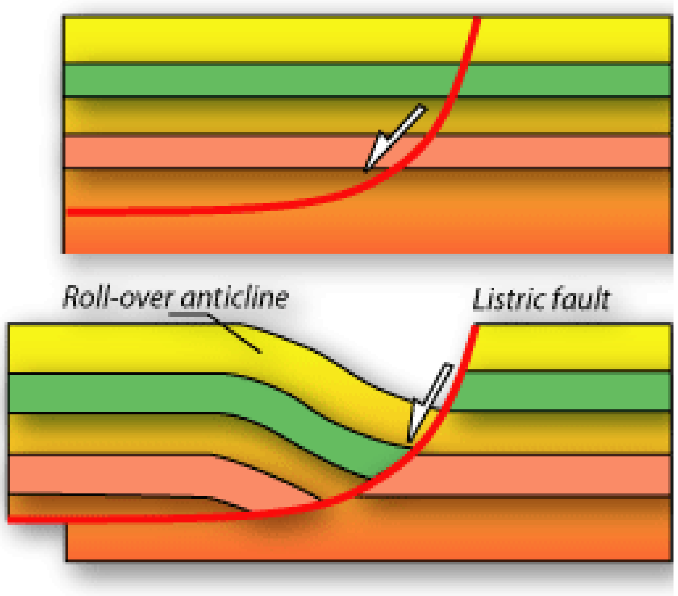
Faults can be planar

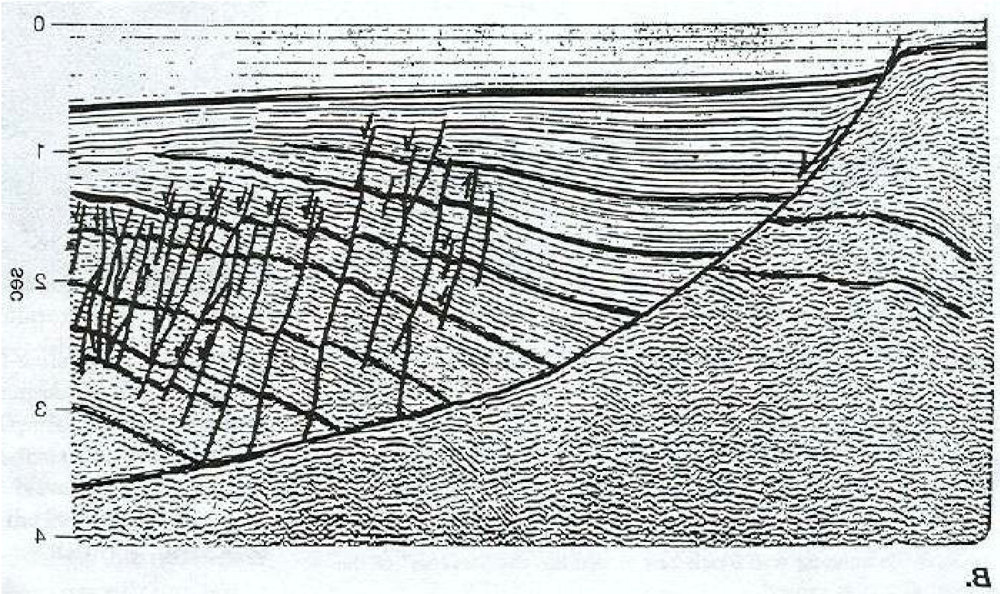


Faults can be curved.

in the extensional domain:

Listric faults: The fault surface is curved and flattens at depth (in a detachment horizon)





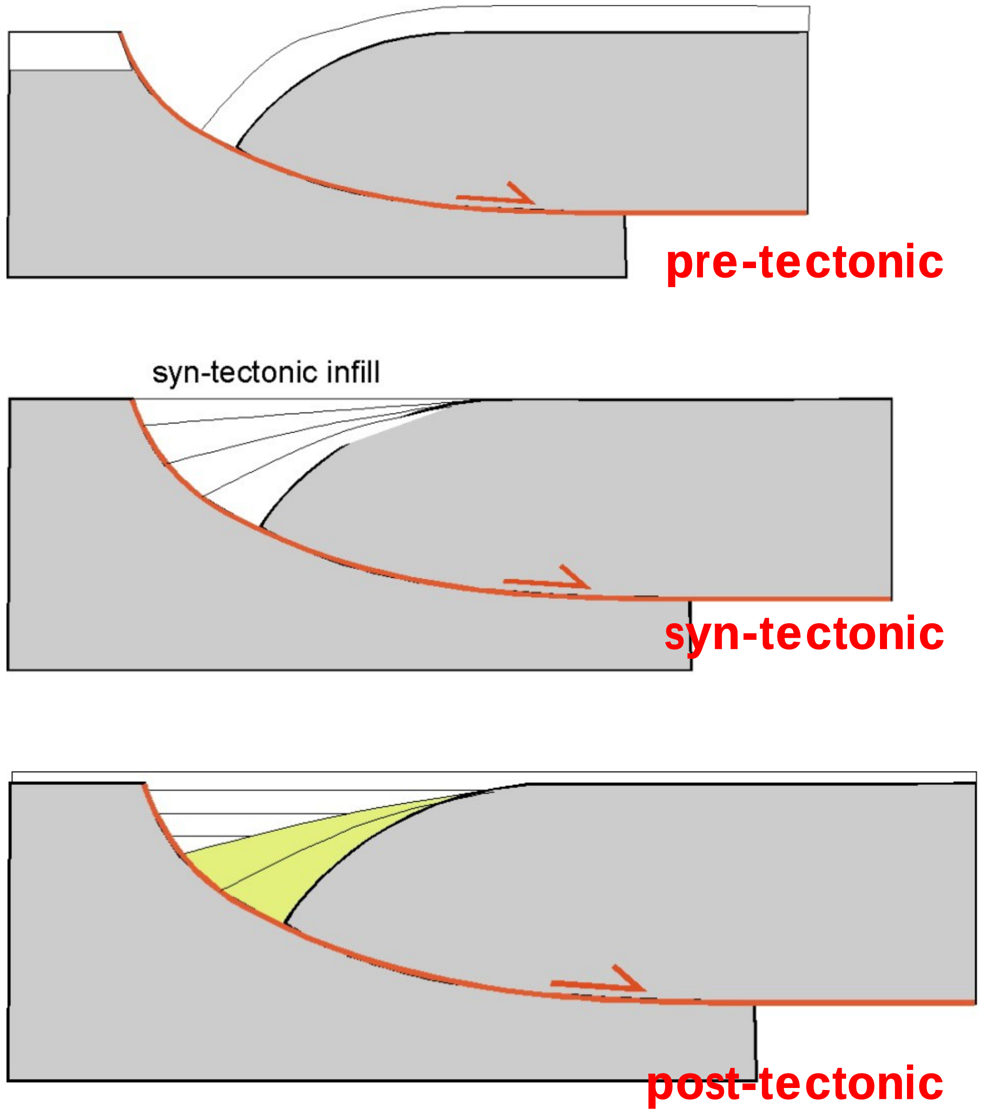
With increasing displacement, the hanging wall descends with respect to the footwall, rotates and forms a fold, the roll-over anticline.

Accommodation space is created!
If sediments are available in the area, they can be dumped there!

Sediment geometries in listric faults provide information on the timing of fault movement

Assuming that sediments are deposited in a horizontal position then:

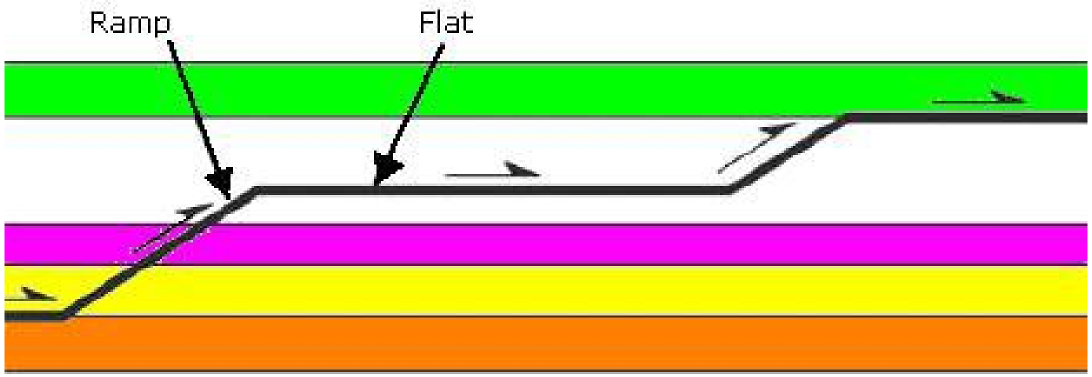
- sediments deposited before the onset of faulting will have parallel layering
- sediments deposited during faulting will
    - o diverge (=thicken) towards the fault
    - o older sediments steeper than young ones (these will be sub-horizontal)
- sediments deposited following rifting will be flat lying and not cut by the fault



Non-planar faults in the contractional domain

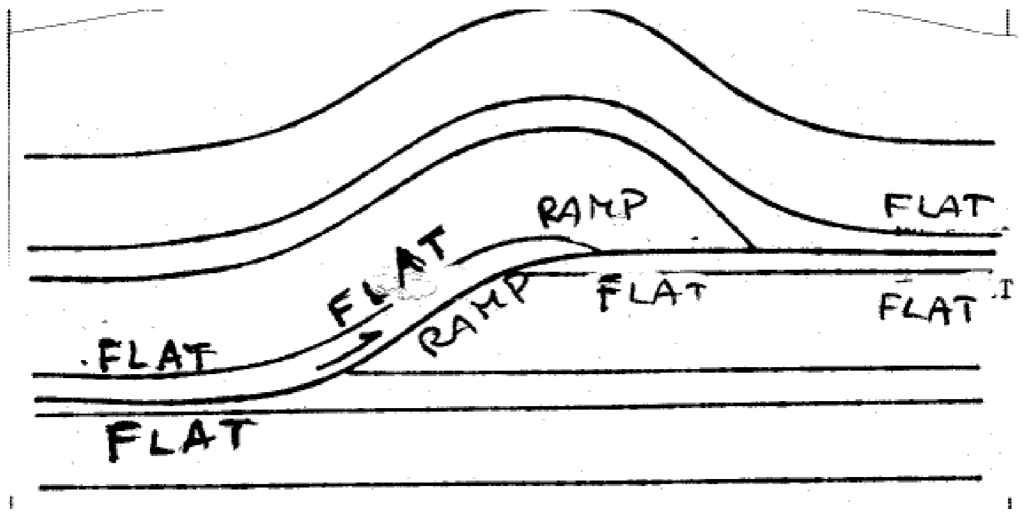
Because rocks in the outer part of the Earth are generally stratified, contractional faults often develop a staircase geometry remaining parallel to soft layers (flats) and cutting hard ones (ramps)

ramps and flats



With proceeding shortening,

- the hanging wall moves, climbs on top of the foot wall ramp and forms a fold
- Ramps become separated from each other and might be juxtaposed to flats of the other block
- (see later)

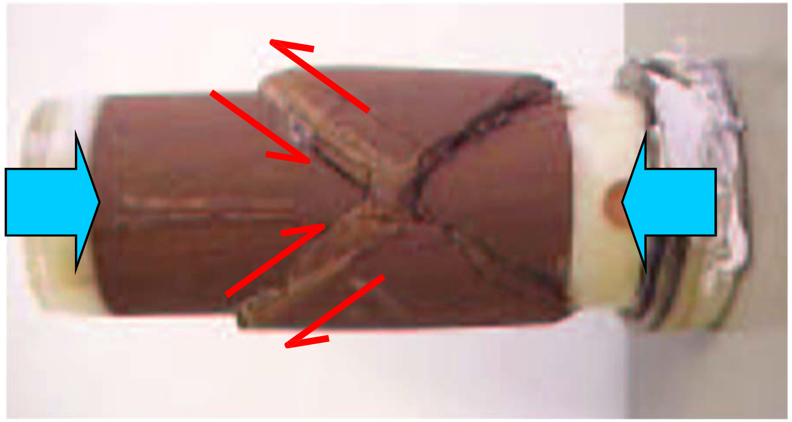


Fault systems: faults are (±) never alone

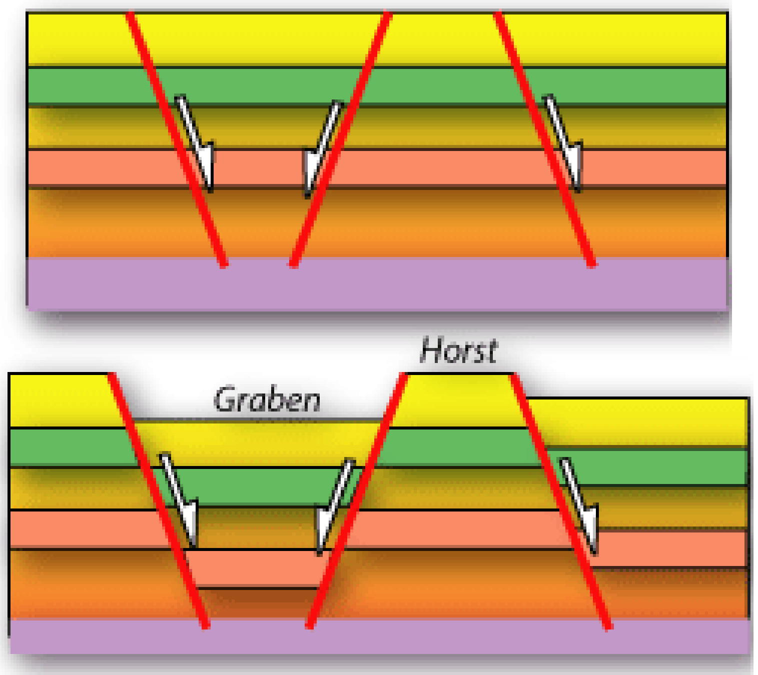
Conjugate faults: two faults develop in experiments, with an angle of ~60° between them.

In extension

In contraction



Fault systems



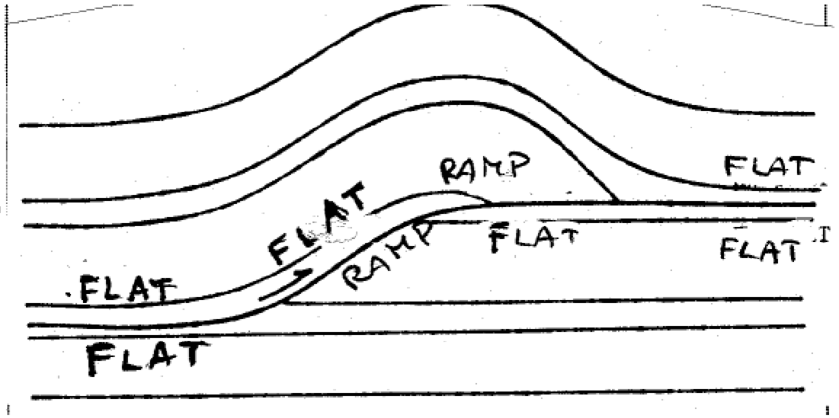
Horst and graben

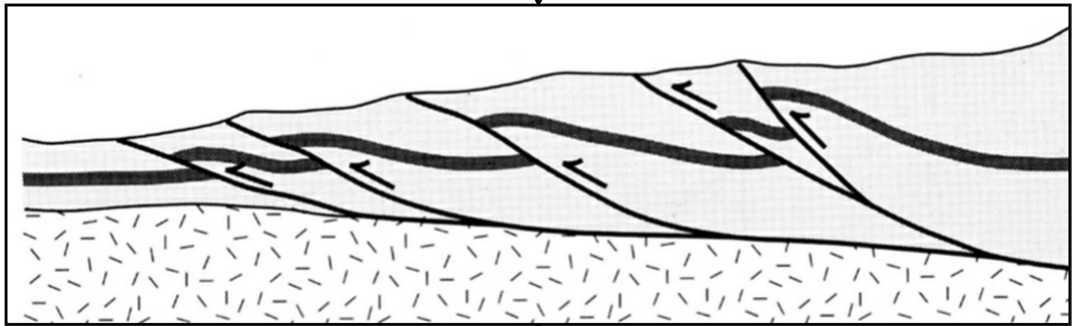
Sets of planar faults with opposite dips

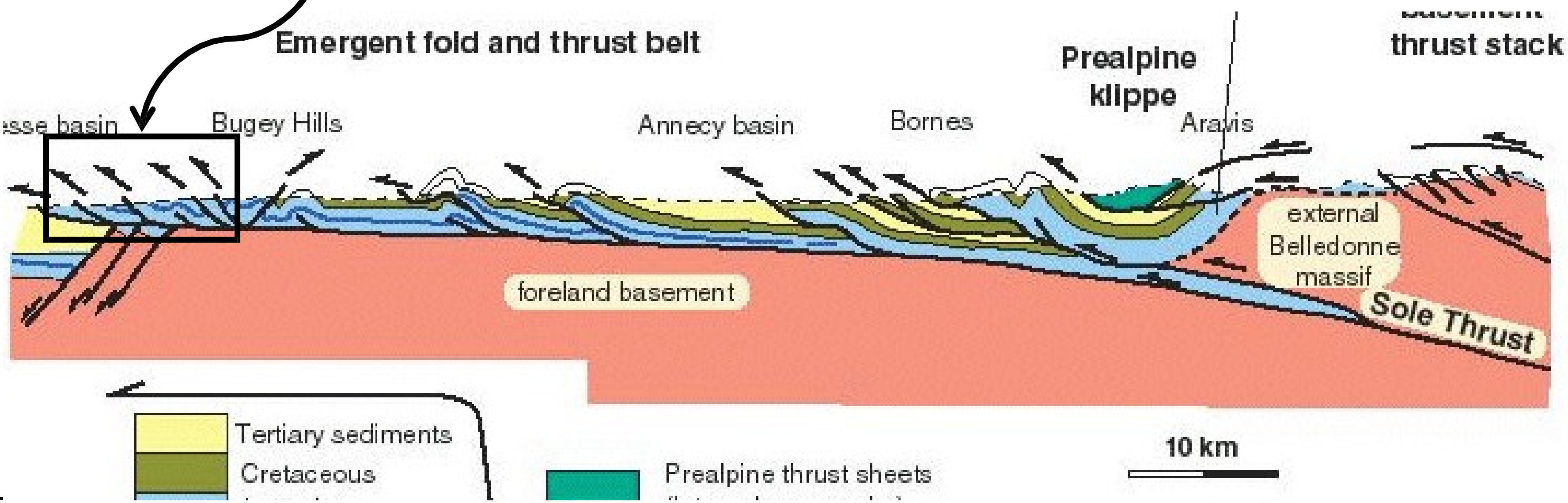
Domino faults

Sets of planar faults dipping in the same direction

Fault systems: Thrust belts



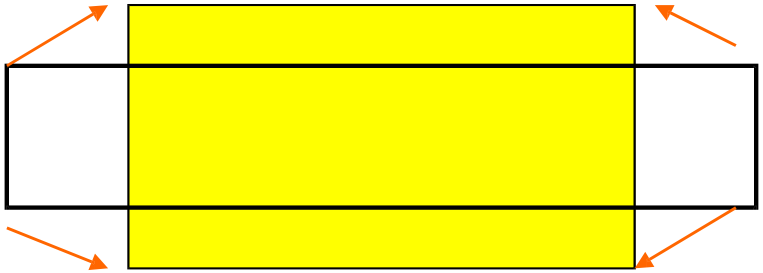




more will follow

Folds

A typical mechanic instability to accommodate shortening after the LPS stage



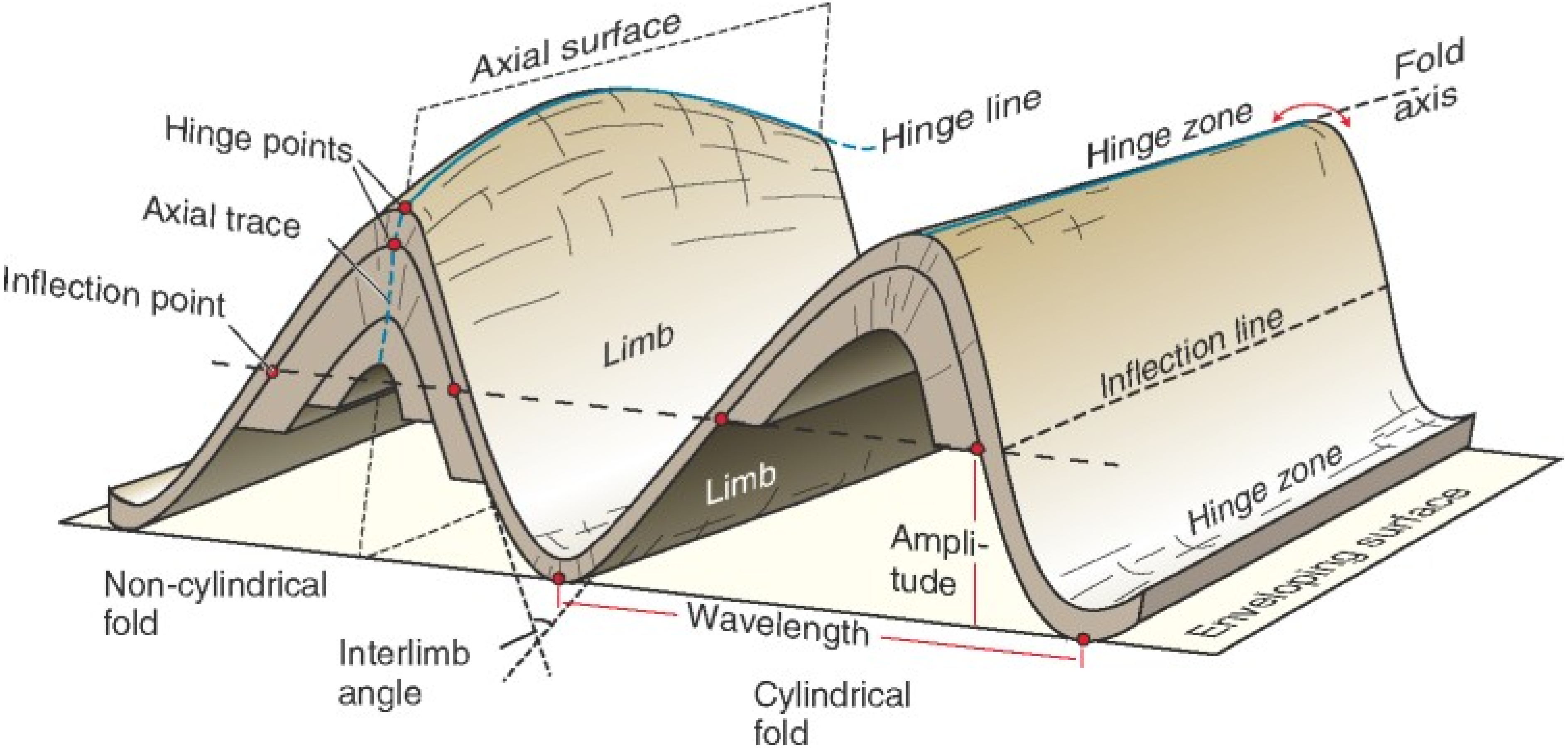
Rocks are pervasively deformed

The geometry of folds

Hinge area: the area of max curvature between limbs

The fold axis is the direction of the hinge line. It is not located in a specific point

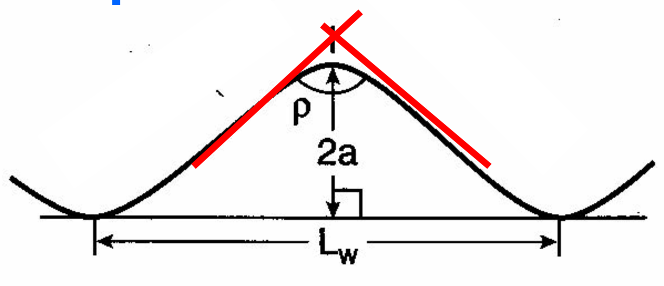
The surface containing the hinge lines is the axial plane.



Other important terms: wavelength, amplitude...

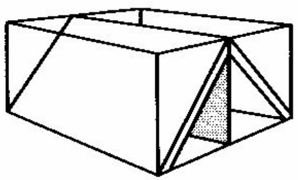
Names for different fold shapes

On the basis of the interlimb angle

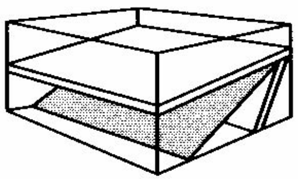


interlimb angles	
0-10º	Isoclinal
10-60 º	Tight
60-120 º	Open
120-180 º	gentle

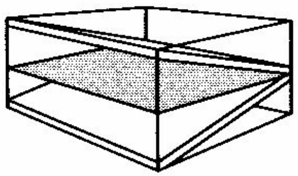
on the basis of orientation of hinge line and axial surface



Upright horizontal

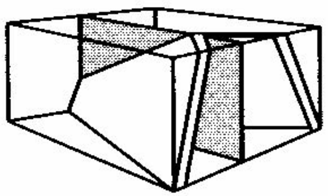


Inclined horizontal

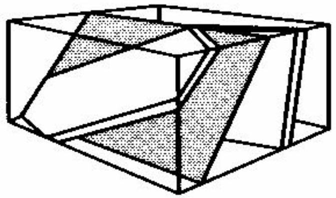


Recumbent

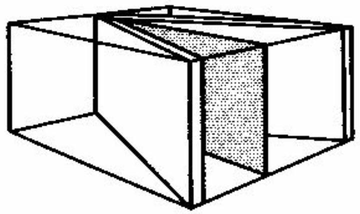
Plunge of hinge line		Dip of axial surface	
0-10º	Horizontal	0-10 º	Recumbent
10-30 º	Shallow	10-70 º	Inclined
30-60 º	Intermediate	70-90 º	upright
60-80 º	steep		
80-80 º	Vertical		



Upright plunging



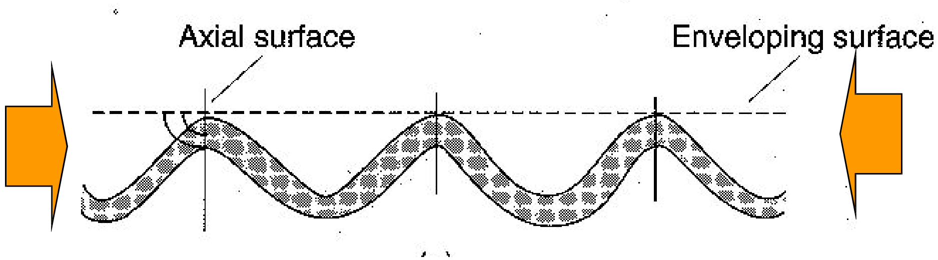
Inclined plunging

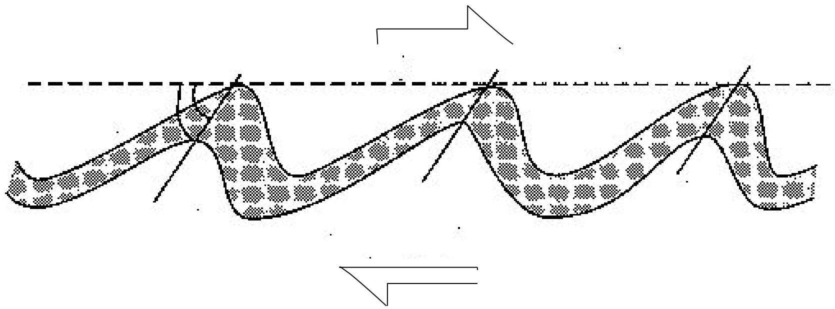


Vertical

The (a)symmetry of folds

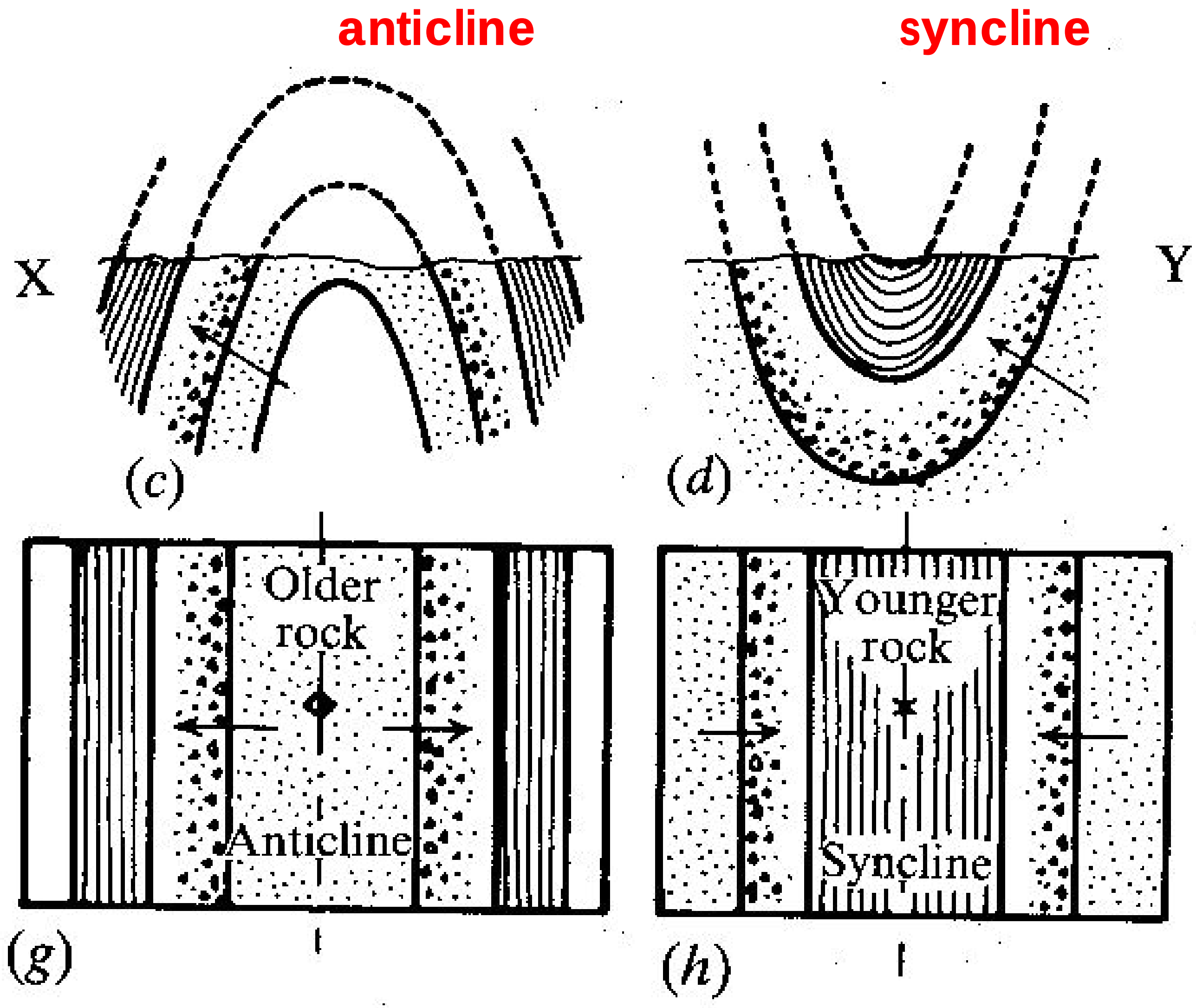
Symmetric folds have axial planes which are perpendicular to the *enveloping surface*. Symmetric folds result from *pure shear shortening*





In asymmetric folds the axial plain is oblique to the enveloping surface. Relative movement between "upper" and "lower" block is required. This is called simple shear

Geometry is not all: geological layers have a bottom (old) and a top (young)!



Anticlines have old rocks in the core and close upward

Synclines have young rocks in the core and close downward

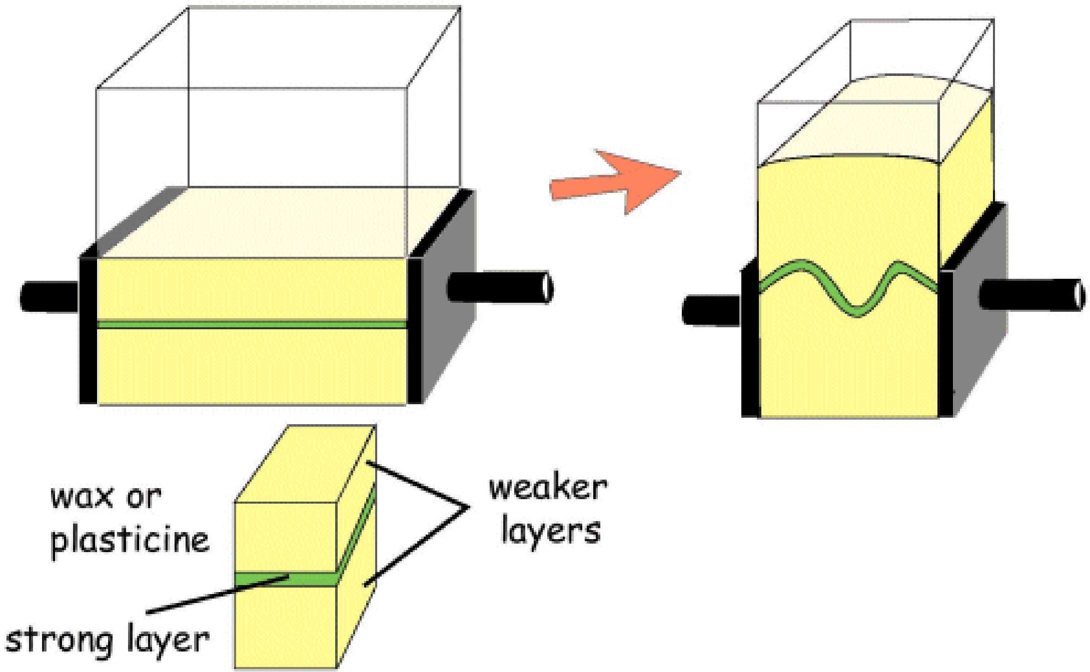
TWO FUNDAMENTALLY DIFFERENT MECHANISMS OF FOLDING:

- **Buckling (active folding)**
- **Fault-related folding (passive folding)**

BUCKLE FOLDS

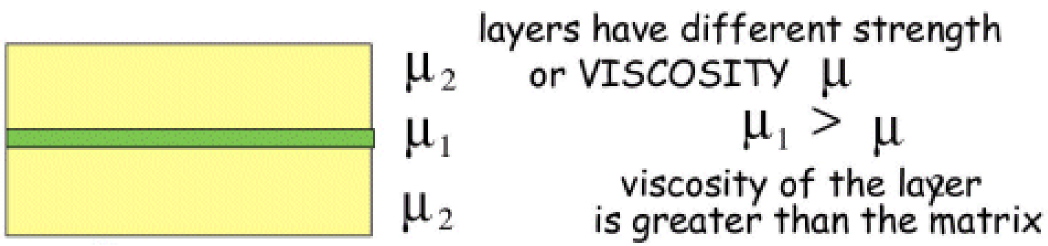
Folding of layer or series of layers by a compressive stress directed along the layer

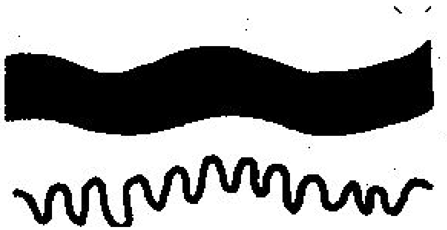
The shape and dimensions of the fold are controlled by the mechanics of the layer (or multilayer)



In a single layer, wave length and amplitude depend on:

- **the thickness of the layer**
- **the strength contrast between layers**





$$\lambda = 2\pi t \sqrt[3]{\frac{\mu_1}{6\mu_2}}$$

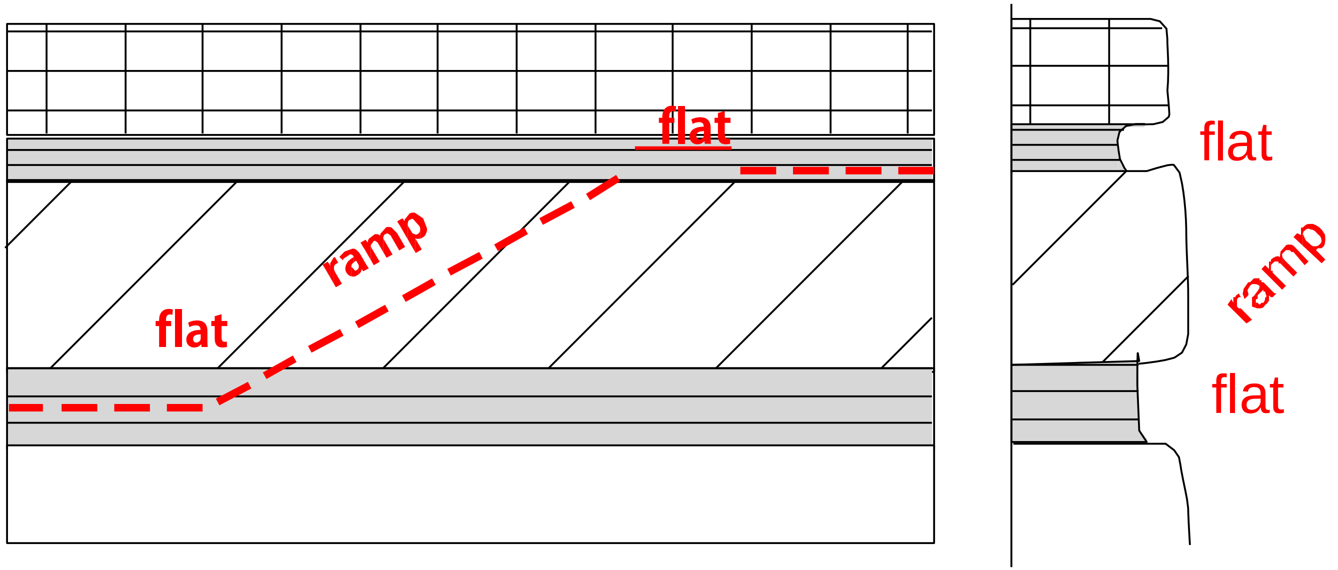
λ= wavelength
t = thickness of competent layer
μ = viscosity

PASSIVE FOLDS

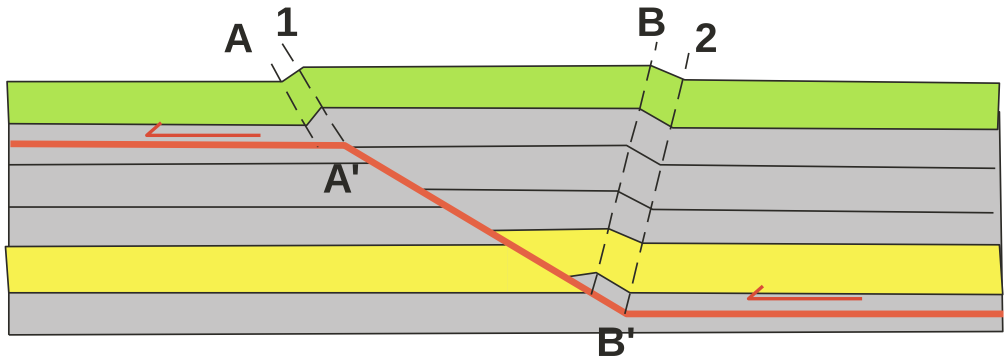
The shape and dimensions of the fold are controlled by the geometry of fault surfaces underneath the folded body

In layered bodies (typical for sediments) the thrust surface will tend to follow soft horizons (flats) and cut through hard formations (ramps).

Ramps are those segments of the fault which cut the layers. Ramp angle are typically <20º.



Evolution of fault-bend folds (the most common passive fold)

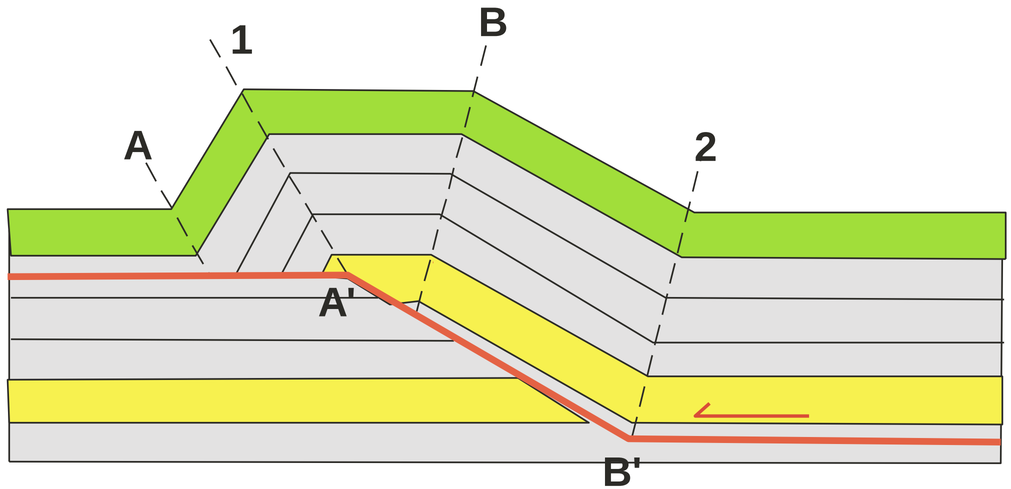


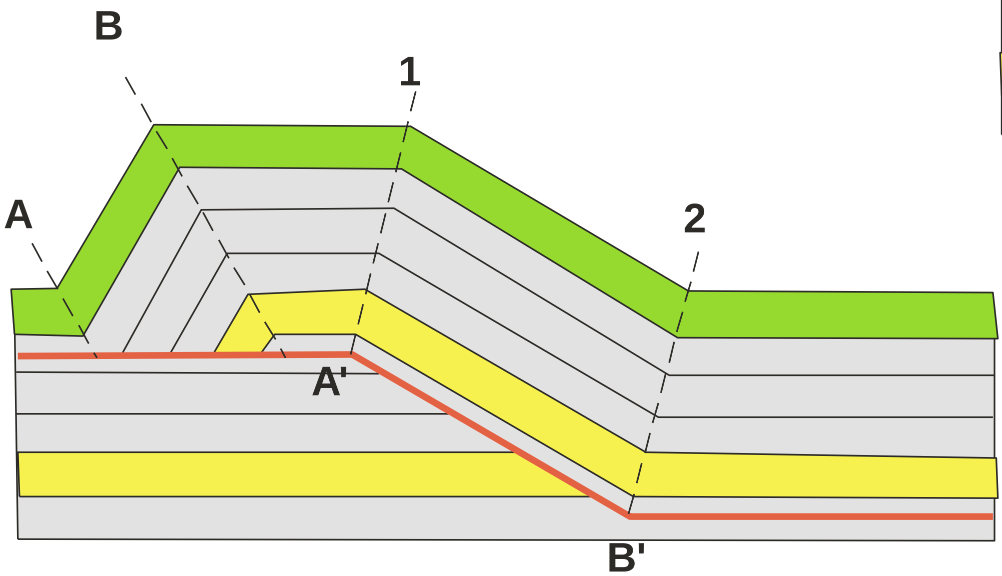
Onset of movement:

The upper block starts climbing on top of the foot-wall ramp

The hanging-wall ramp reaches the top of the foot-wall ramp

Folds grow especially in height





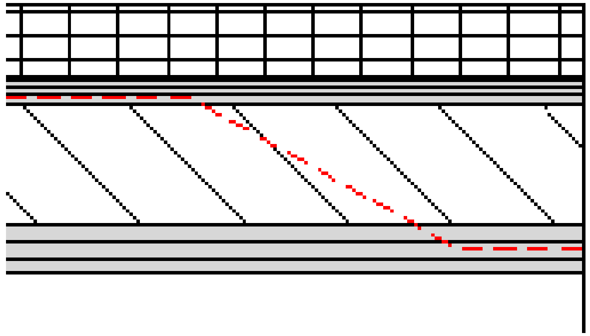
The hanging-wall ramp moves on top of the foot-wall flat

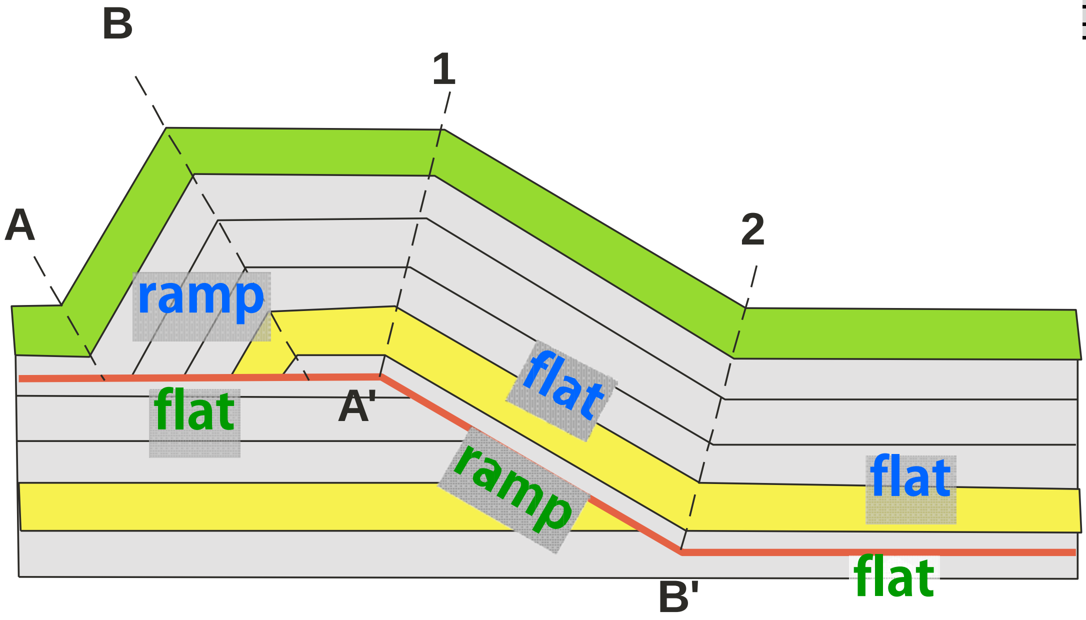
Folds do not grow in height and expand laterally (increase distance)

Position of ramps and flats after deformation

ramps and flats of the hanging-wall

ramps and flats of the foot-wall





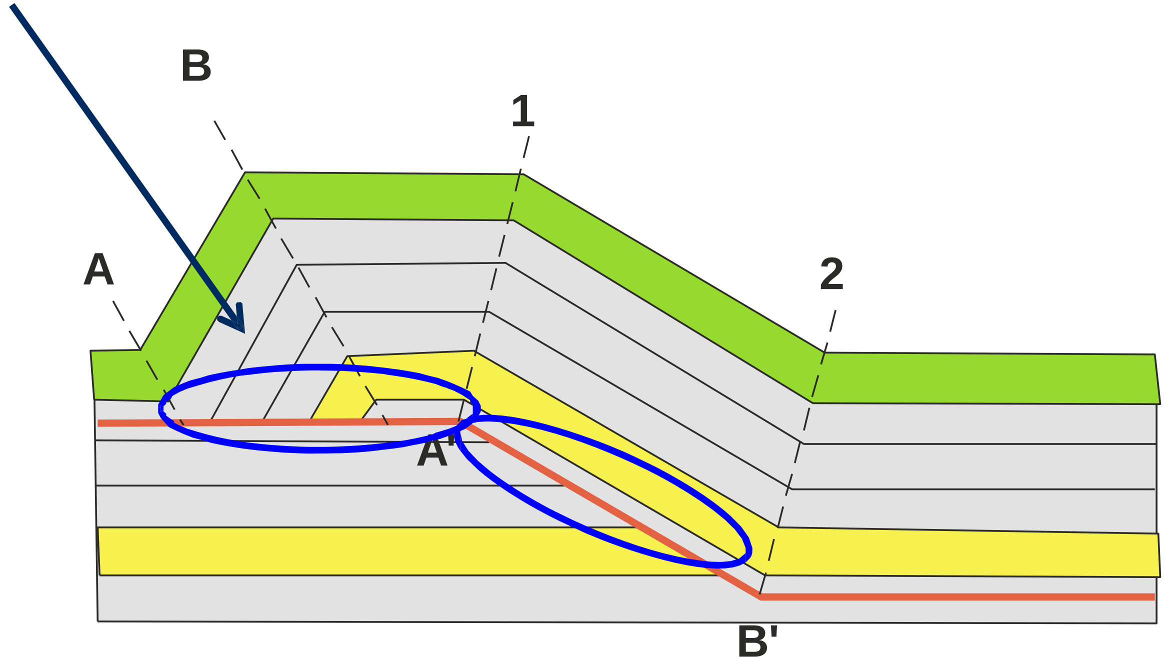
At the onset of deformation, the HW ramp is juxtaposed to the FW ramp.

With proceeding deformation, they will be displaced and a HW ramp may come to lay on top of a FW flat or viceversa.

When talking about ramps and flats, you must always specify the fault block you are referring to

Geometric characteristics

In these areas layers in the hanging-wall and foot-wall have different positions

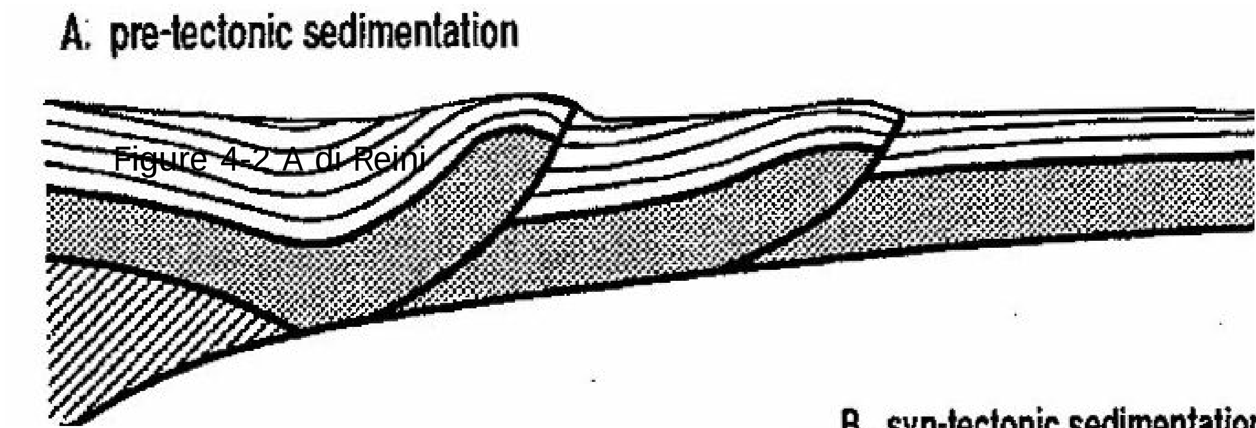


In the same areas older rocks overly younger rocks (inverted stratigraphy)

In the other areas this is not the case!

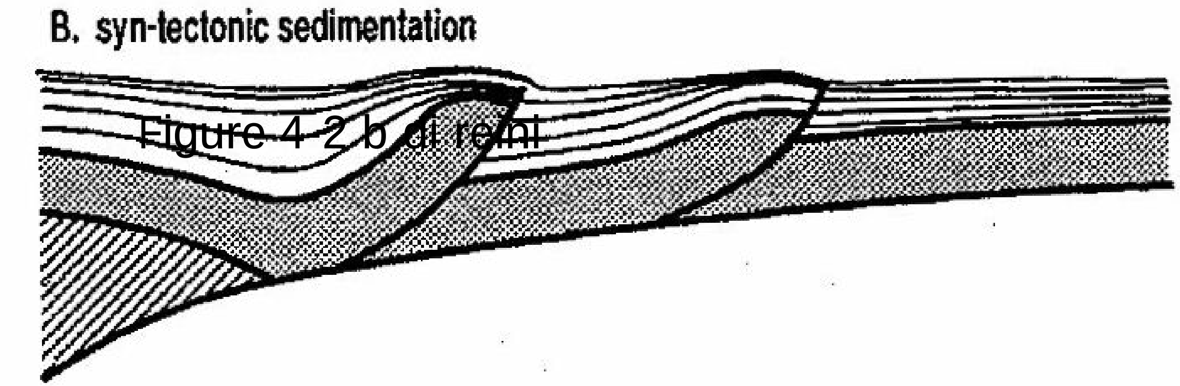
Ramp-folds can accommodate very large deformations!

Dating the activity of (passive) folds with sediment

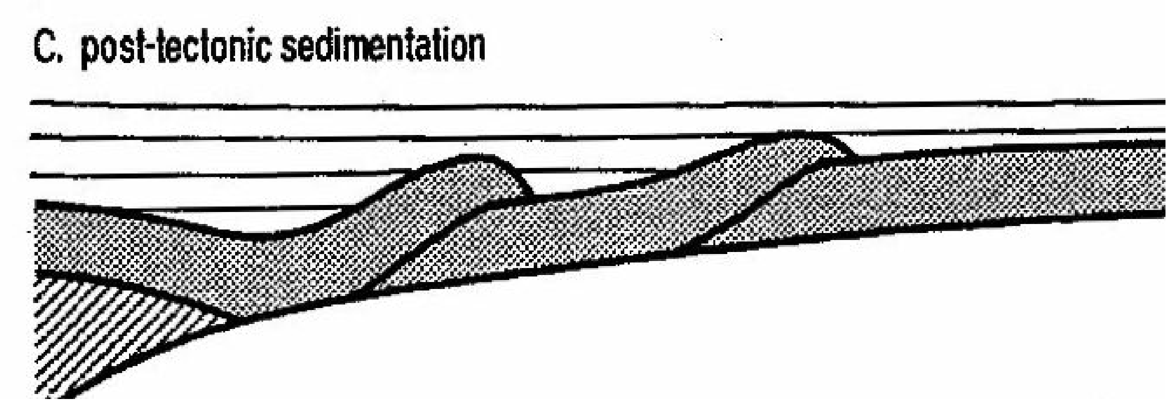


Pre-tectonic sediments are

- **cut by faults**
- **have constant thickness**
- **deformed by fold**



SYN-TECTONIC layers are cut by the fault and "feel" the activity of the fault (thickness and/or geometry and/or facies)



POST-TECTONIC layers are flat

They adapt to the morphology existing at the end of deformation: they seal the faults if everything is flat

Sources of figures

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