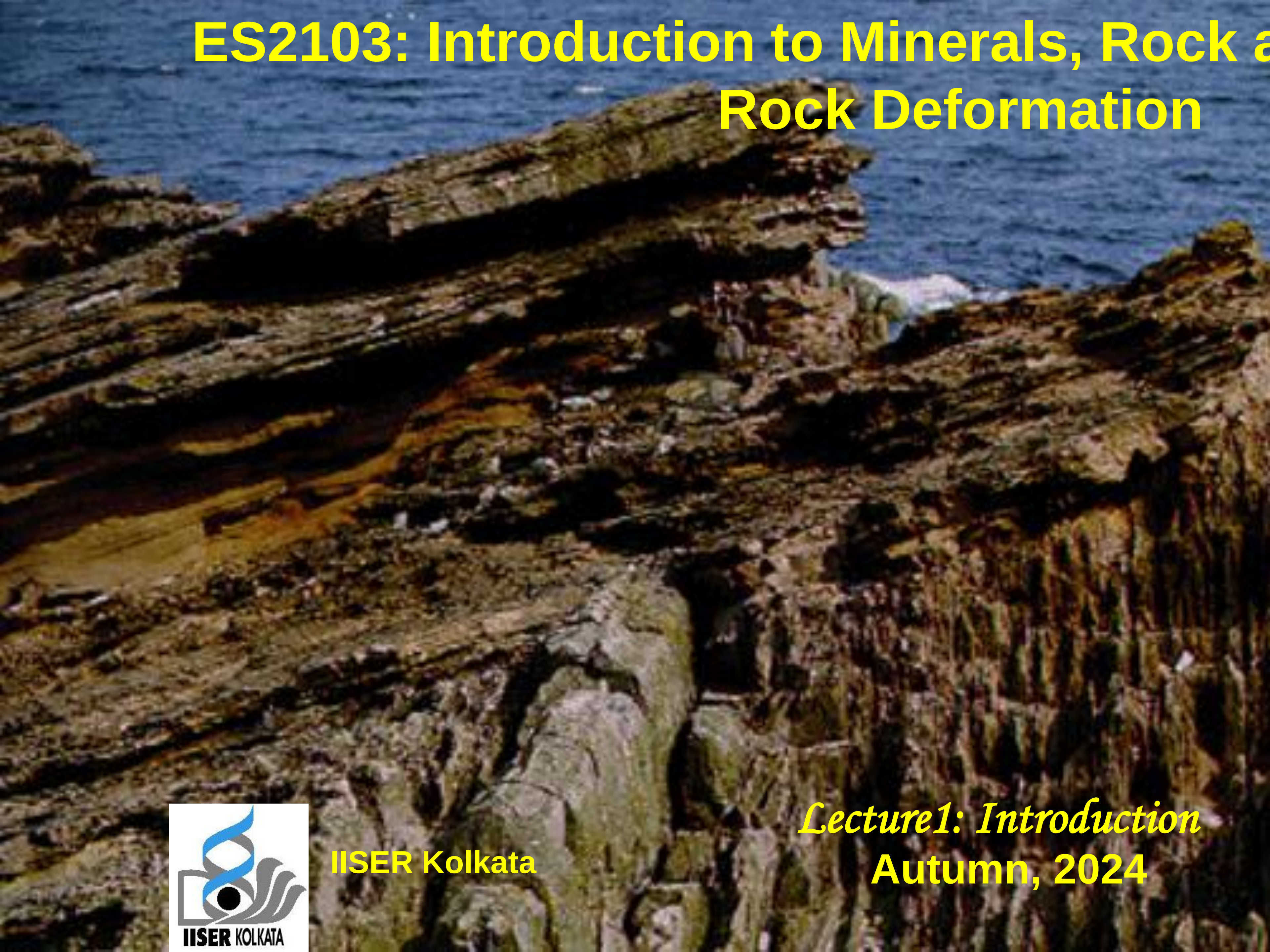
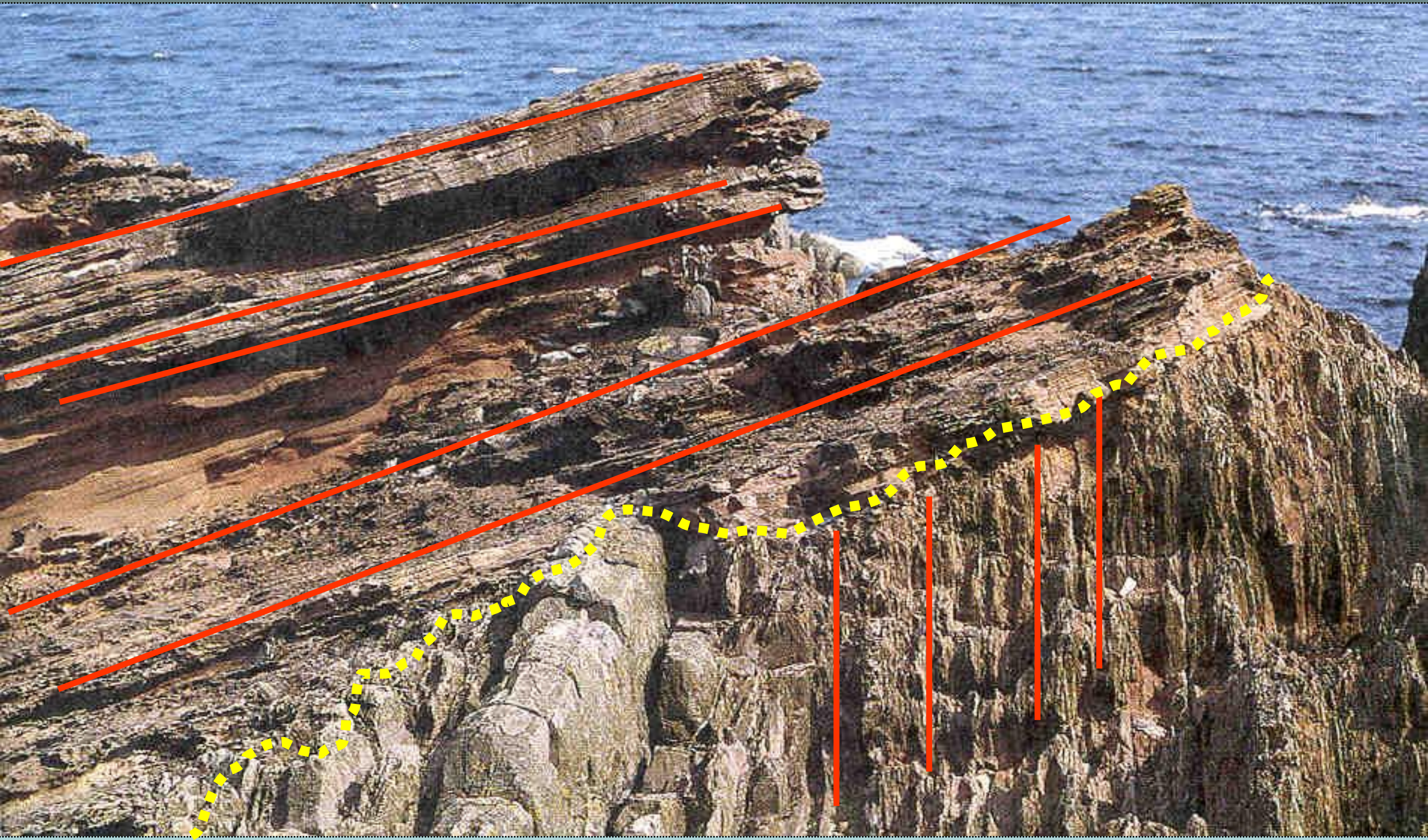


ES2103: Introduction to Minerals, Rock a Rock Deformation

IISER Kolkata

Lecture1: Introduction

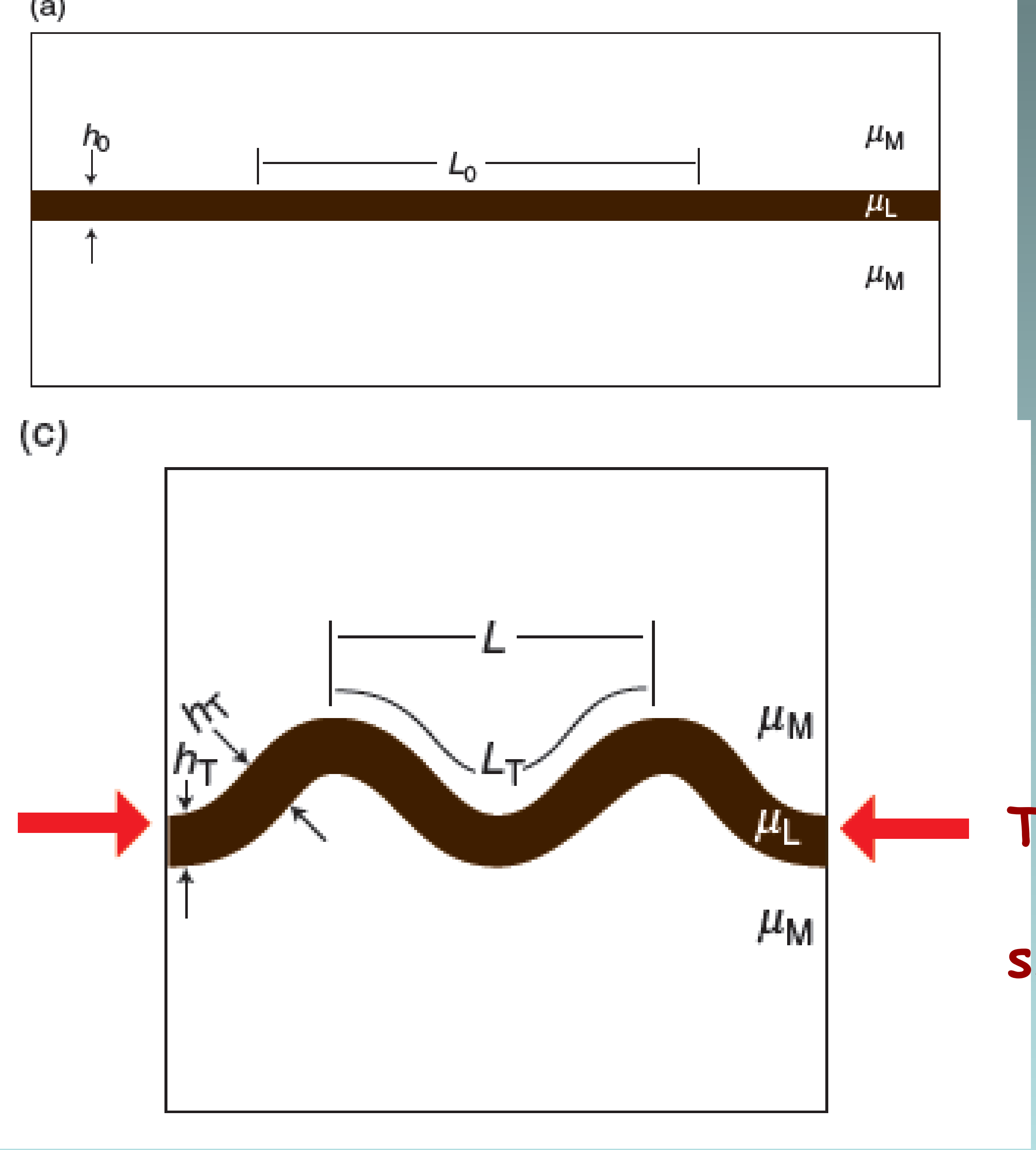
Autumn, 2024



Layers that are not presently horizontal must have been some way deformed !

Principle of Original Horizontality

Nicholas Steno (17th Century)



$\mu_L > \mu_M$

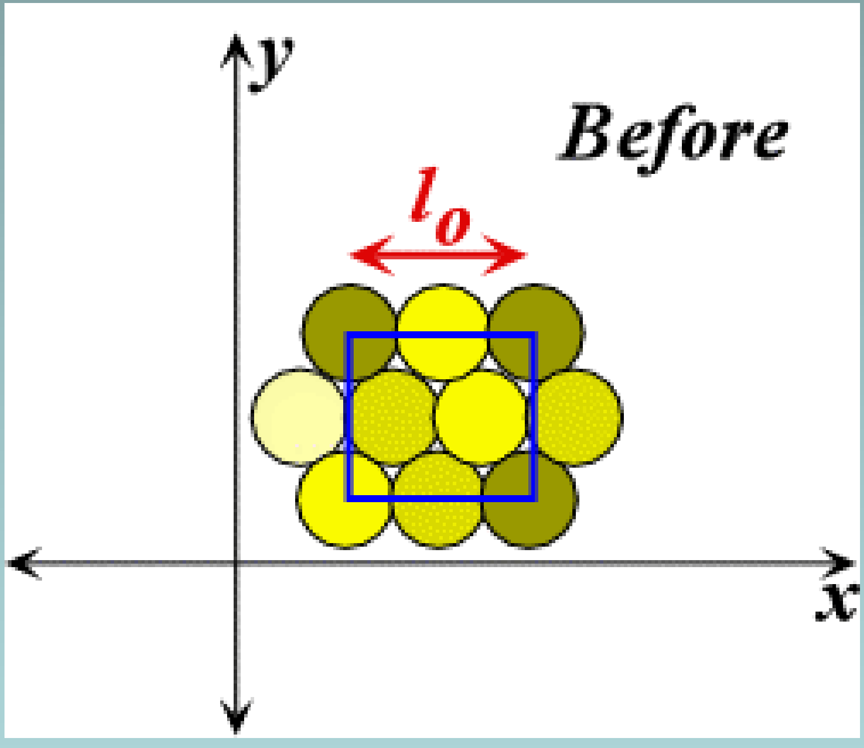
Thickening of beds

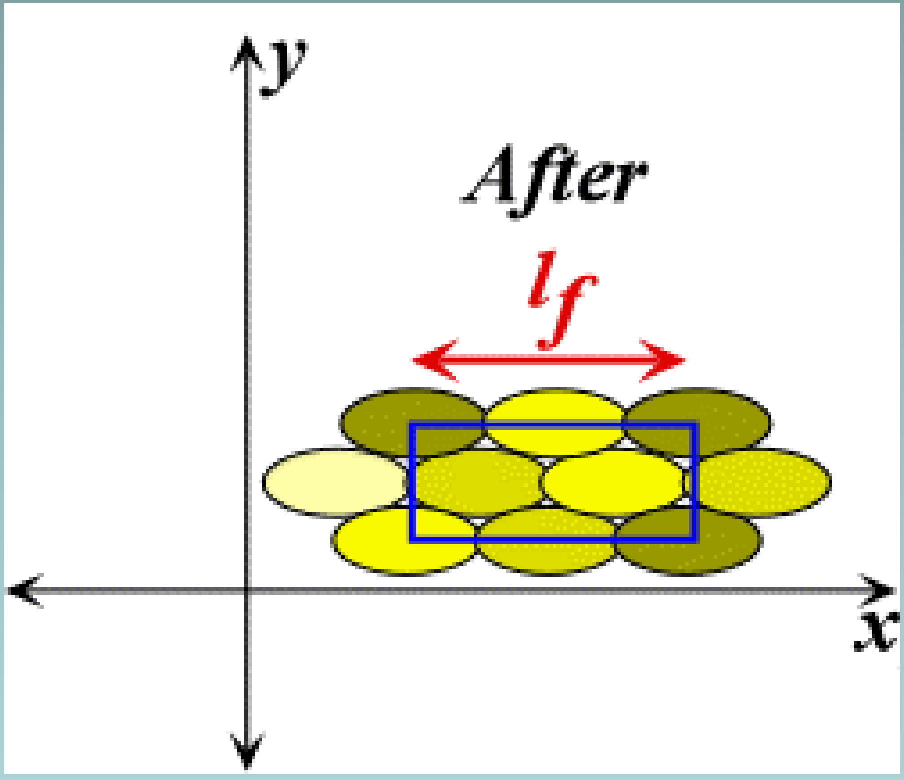
+

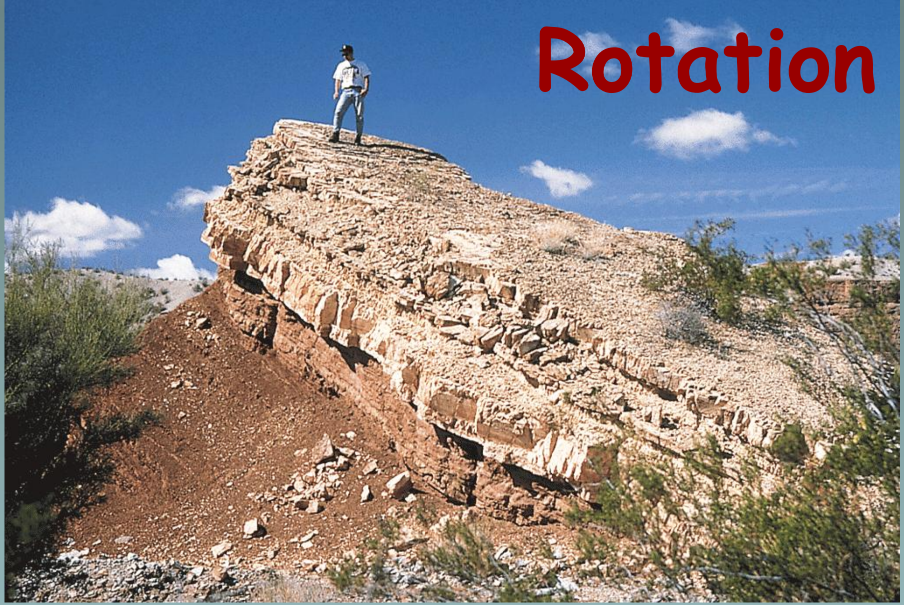
shortening of beds

1D strain

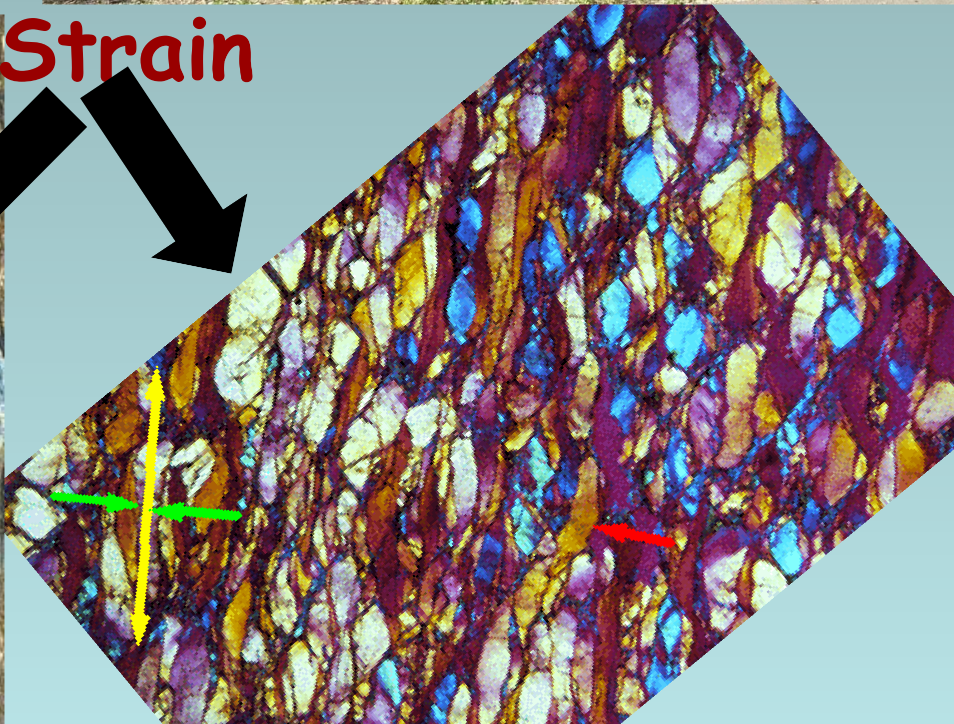
Change in Length of lines



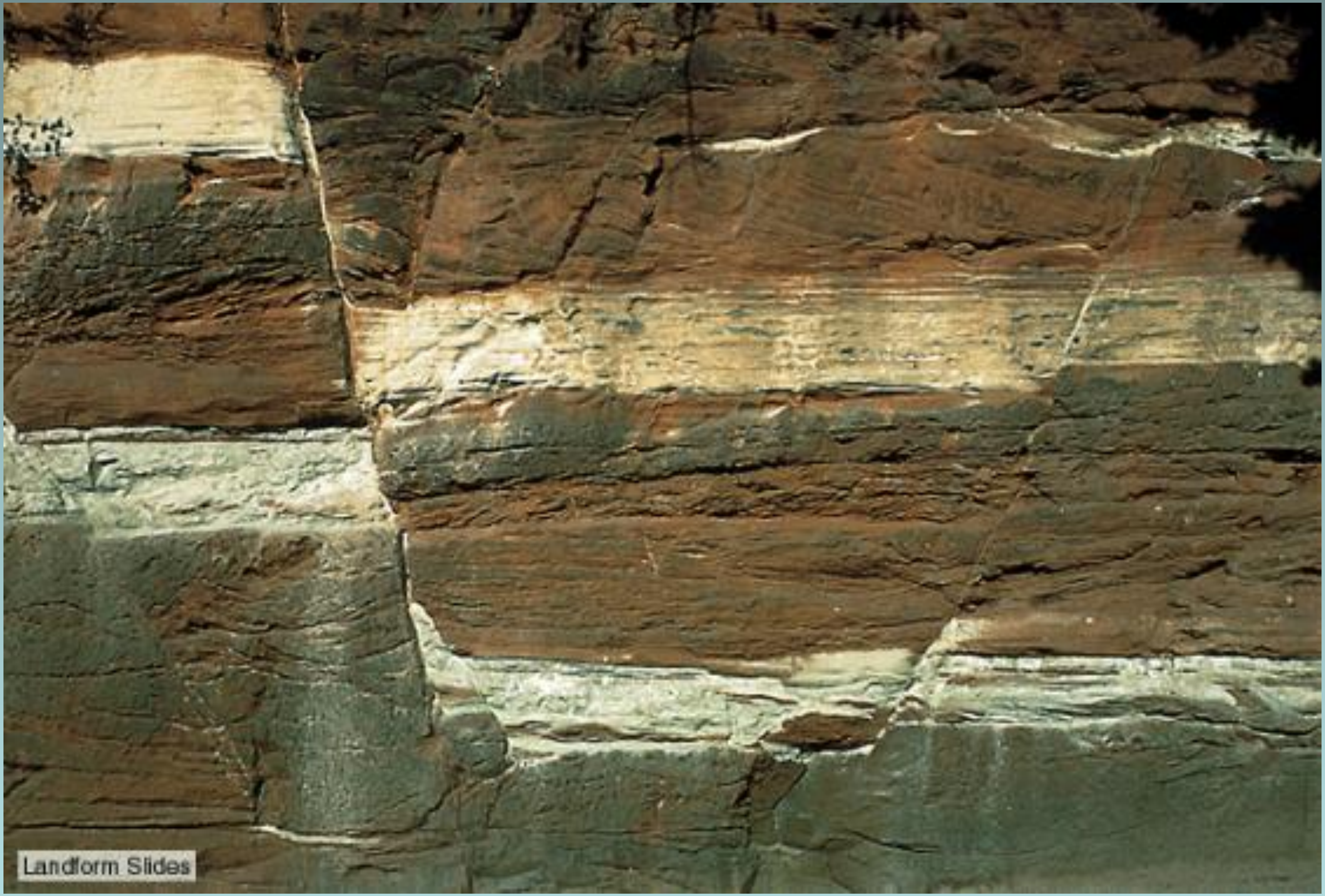


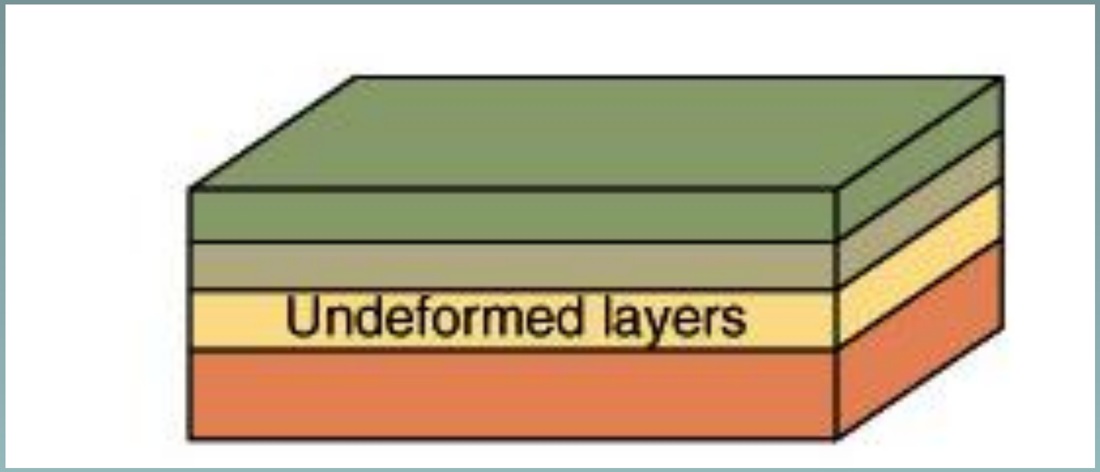


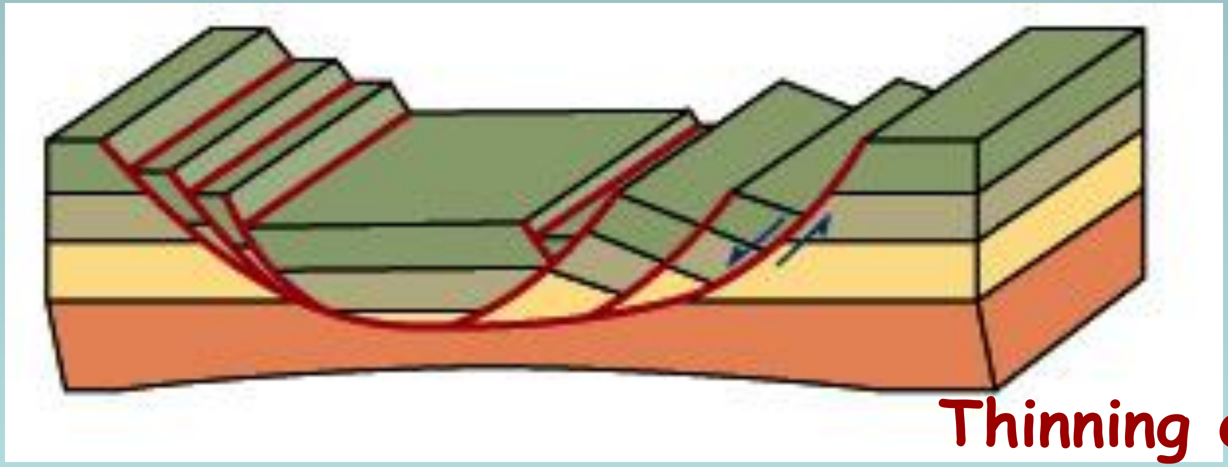
Strain



Can only shortening of rock layers?





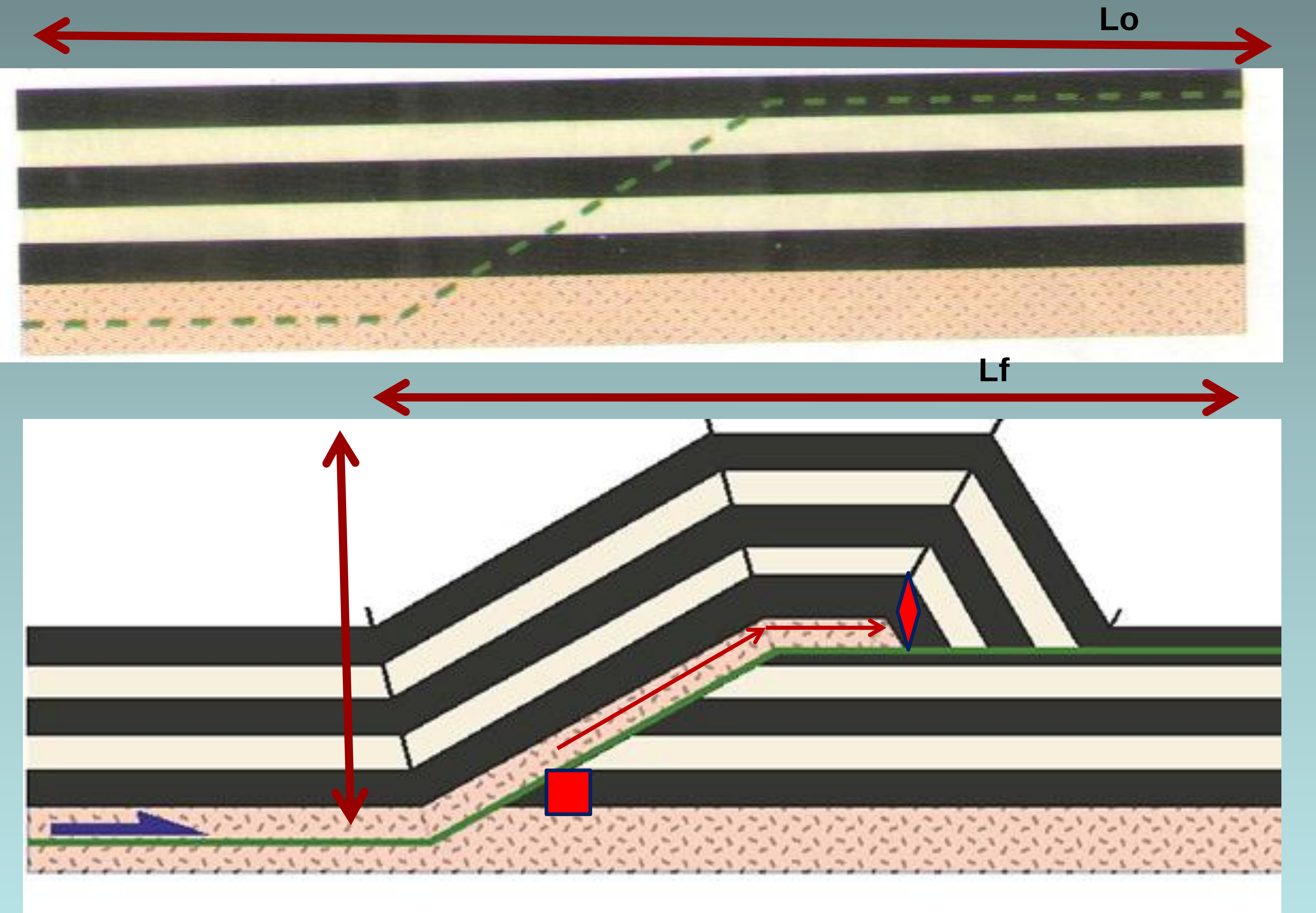


Thinning of strata

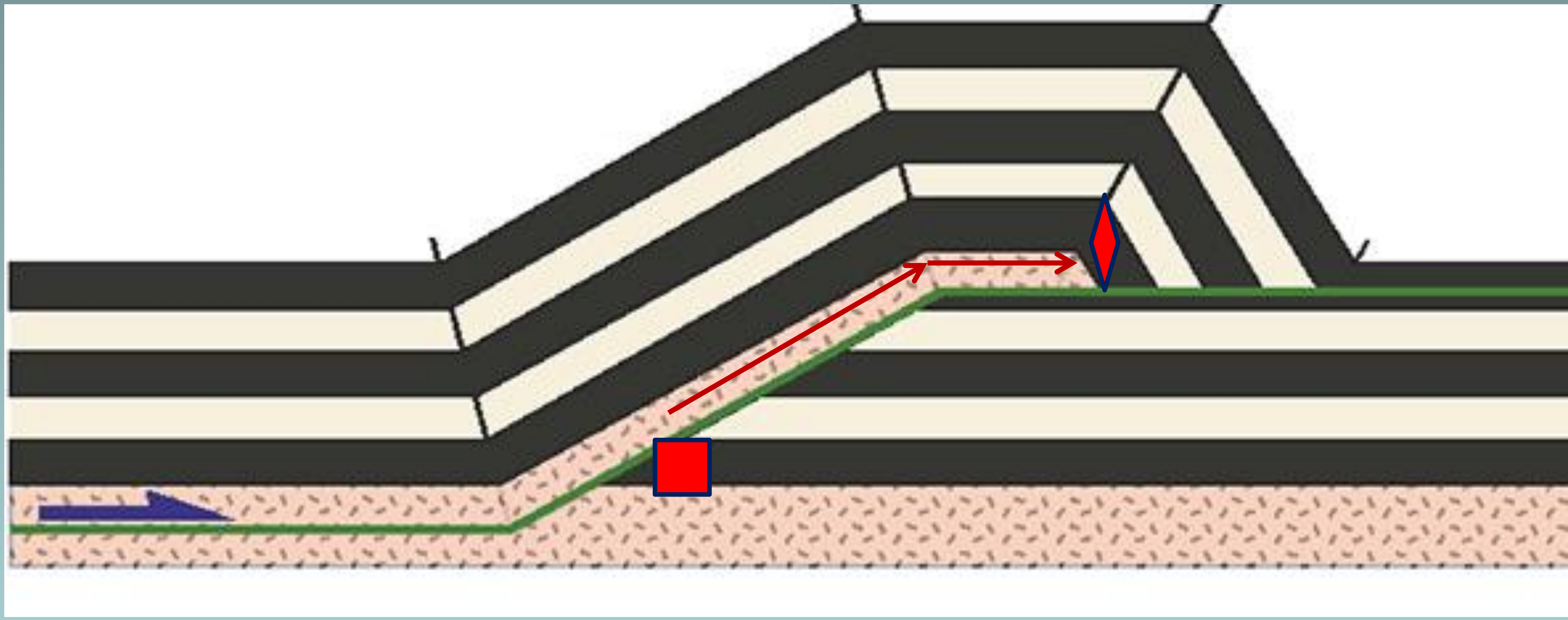
+

Lengthening of beds

Deformation?



Deformation?



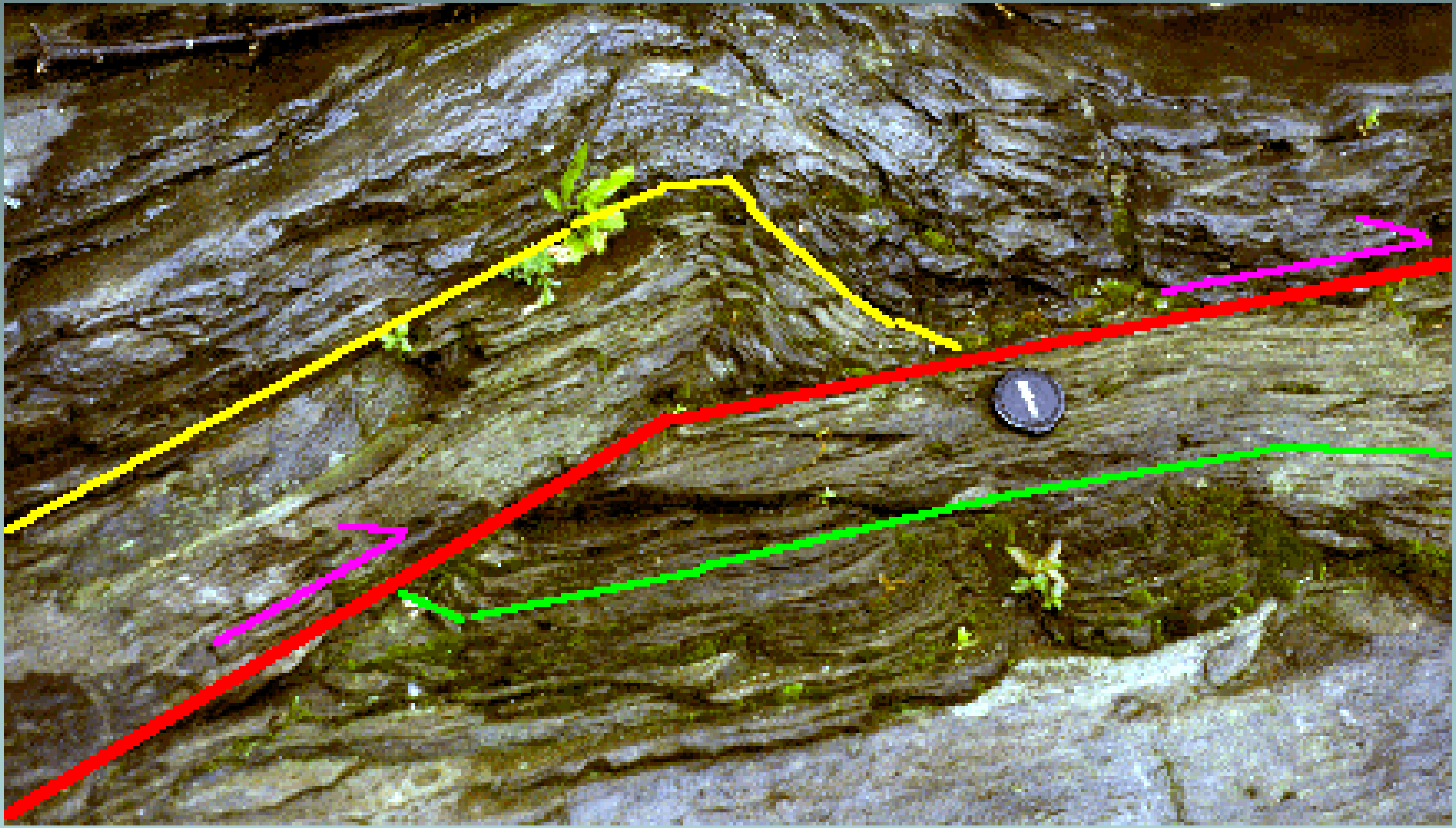
Total Displacement field: 1. Bulk Translation

2. General Deformation

Rigid Body Rotation

Strain

All of these quantities are independent of each other



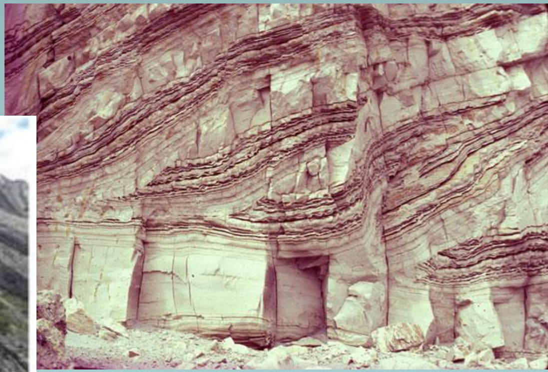
Various types of structures in same outcrop

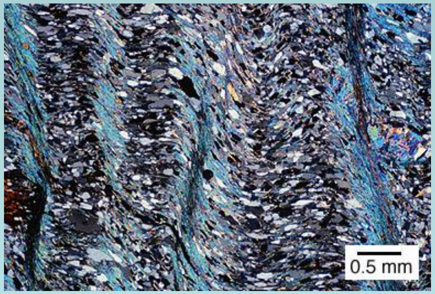
Deformation in rocks: Structural Geology

What?
How?
Why?

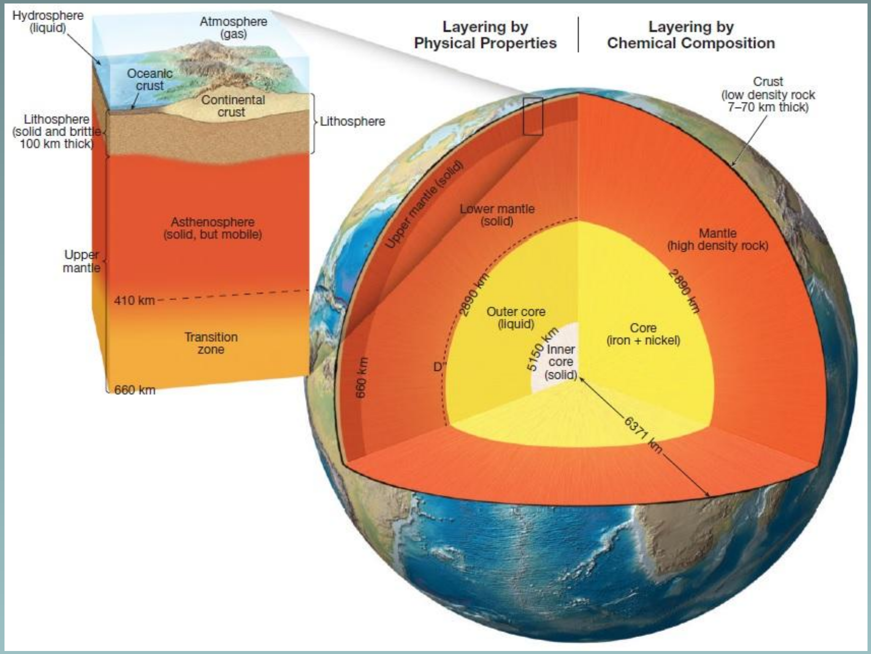
"The study of the architecture of rocks from submicroscopic to regional scales, resulting from deformation."

https://blogger.googleusercontent.com/img/bua4JI0zRXOofseaKx8DLTg/s1440/recumbent-fold.jpg

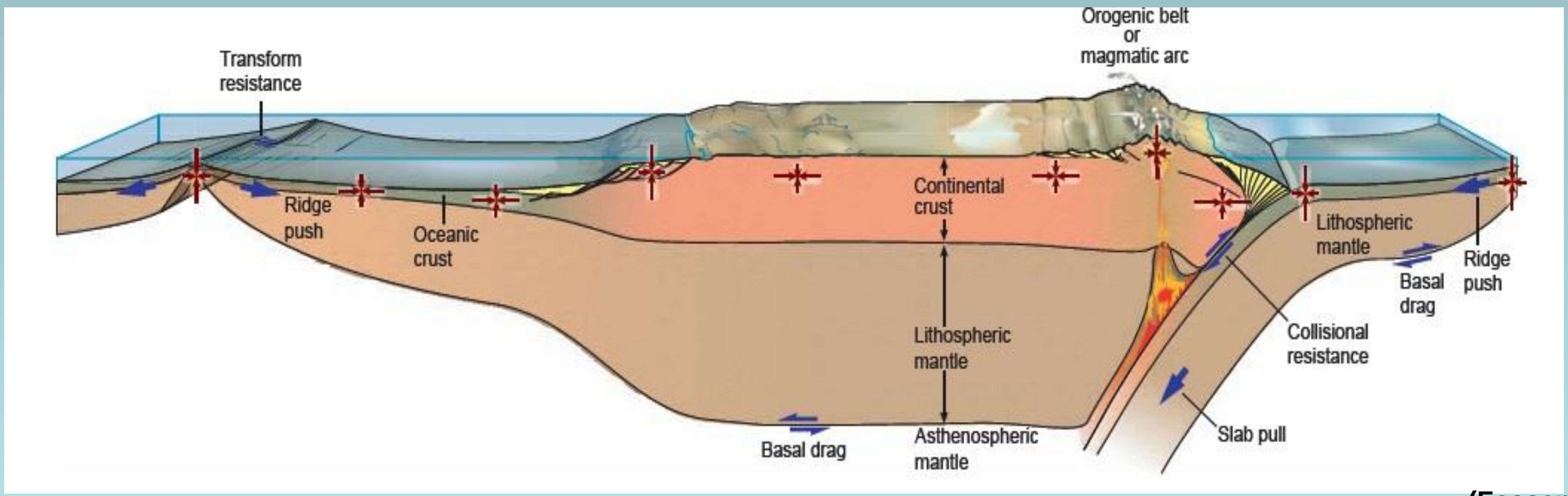




What caused the deformation in these rocks?!

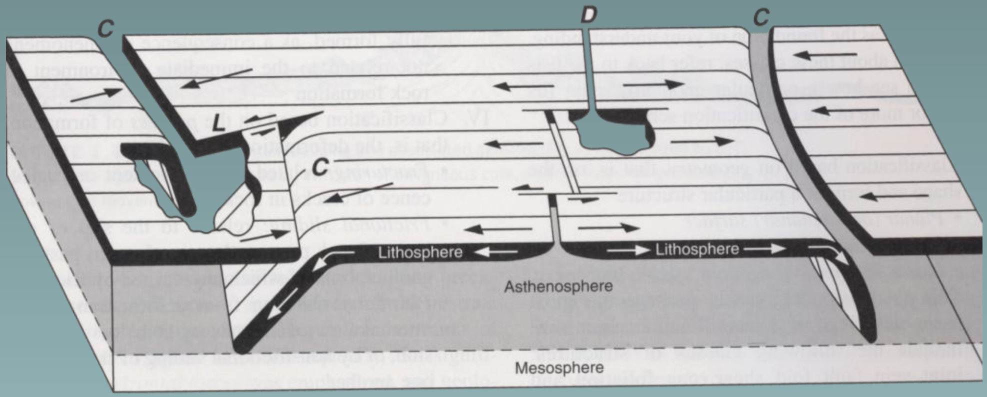


Tectonic Forces?!



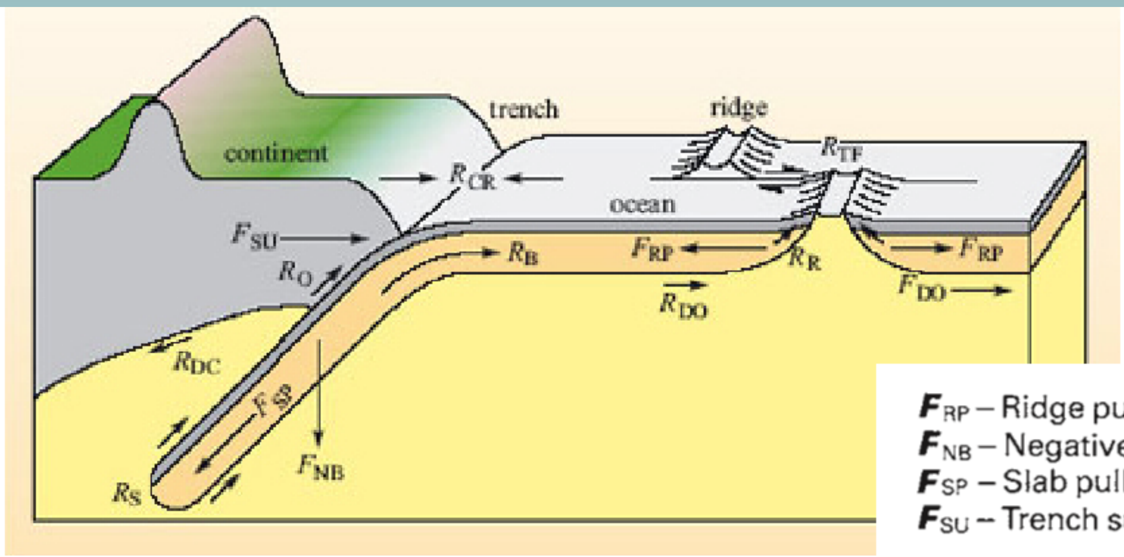
(Fossen, 2010)

What caused the deformation in these rocks?!



Relative movement of lithospheric plates:

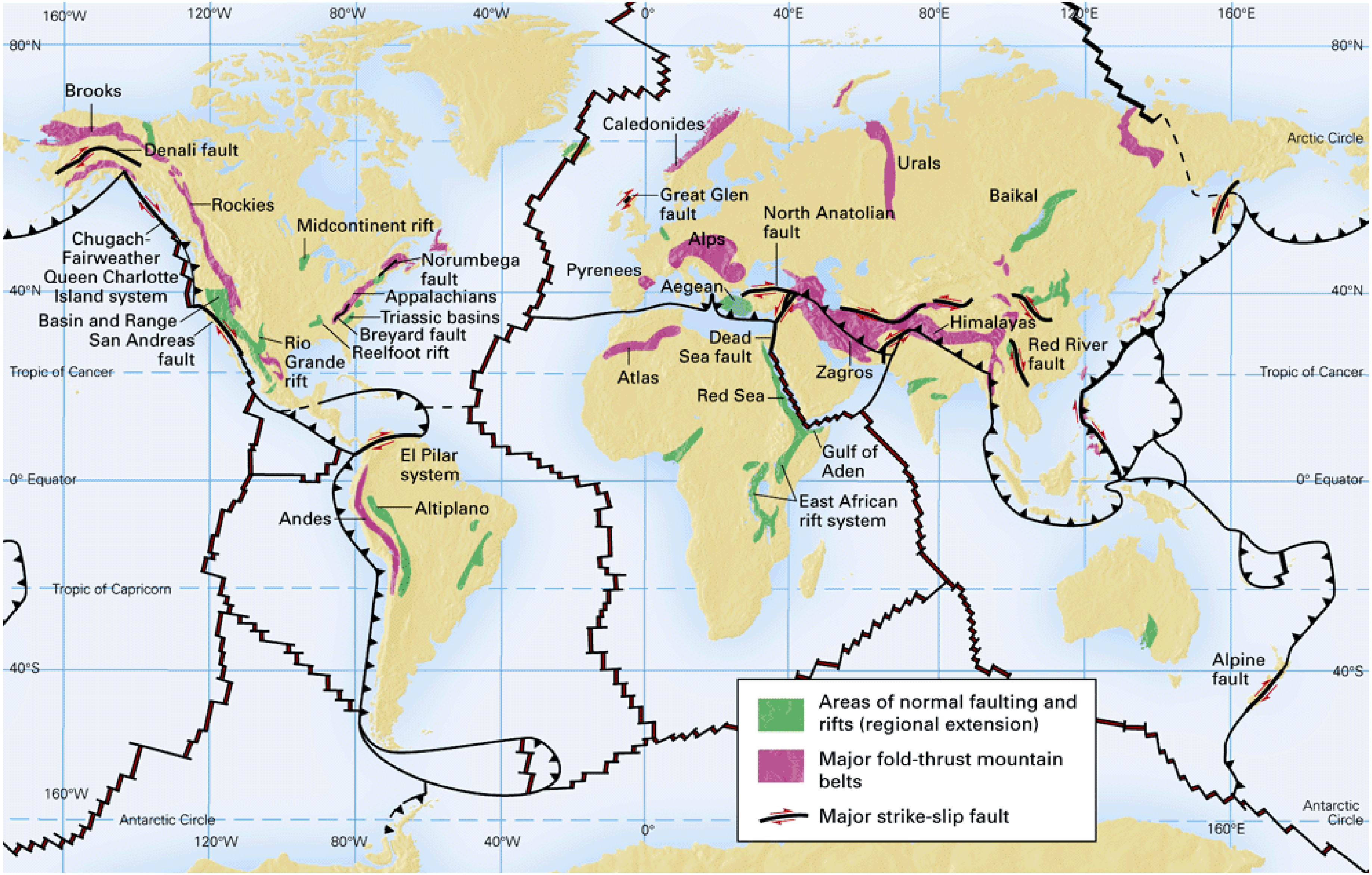
- **Convergent boundary (C)**
- **Divergent Boundary (D)**
- **Transform boundary (L)**



F_{RP} – Ridge push
F_{NB} – Negative buoyancy
F_{SP} – Slab pull
F_{SU} – Trench suction

R_R – Ridge resistance
R_B – Bending resistance
R_S – Slab resistance
R_O – Overriding plate resistance
R_{DO} – Mantle drag under ocean
R_{DC} – Mantle drag under continent

(after Forsyth and Uyeda, 1975)



160°W
120°W
80°W
40°W
0°
40°E
80°E
120°E
160°E
80°N
40°N
Tropic of Cancer
0° Equator
Tropic of Capricorn
40°S
Antarctic Circle
Arctic Circle
Brooks
Denali fault
Rockies
Chugach-Fairweather
Queen Charlotte Island system
Basin and Range
San Andreas fault
Rio Grande rift
Midcontinent rift
Norumbega fault
Appalachians
Triassic basins
Breyard fault
Reelfoot rift
El Pilar system
Altiplano
Andes
Caledonides
Great Glen fault
Alps
Pyrenees
Aegean
Atlas
Dead Sea fault
Red Sea
North Anatolian fault
Urals
Baikal
Himalayas
Zagros
Red River fault
Gulf of Aden
East African rift system
Alpine fault
Areas of normal faulting and rifts (regional extension)
Major fold-thrust mountain belts
Major strike-slip fault

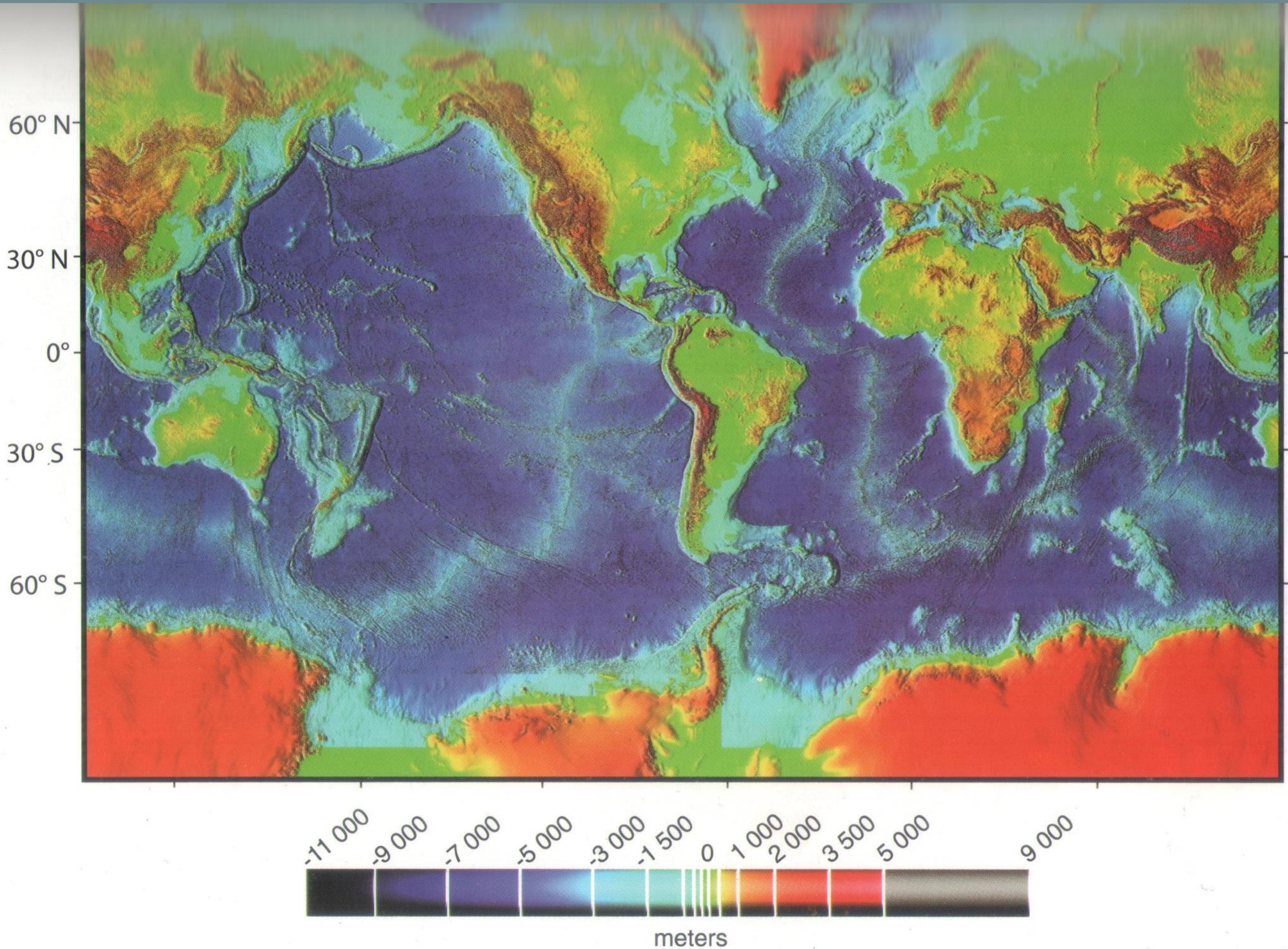


Plate 1.1 *Global relief map (reproduced courtesy of the National Geophysical Data Center of the US National Oceanic and Atmospheric Administration).*

Geologic Structure: Any definable shape/fabric in a rock body

(a) Primary structures

- **Form during or shortly after deposition of sediments/formation of rocks**

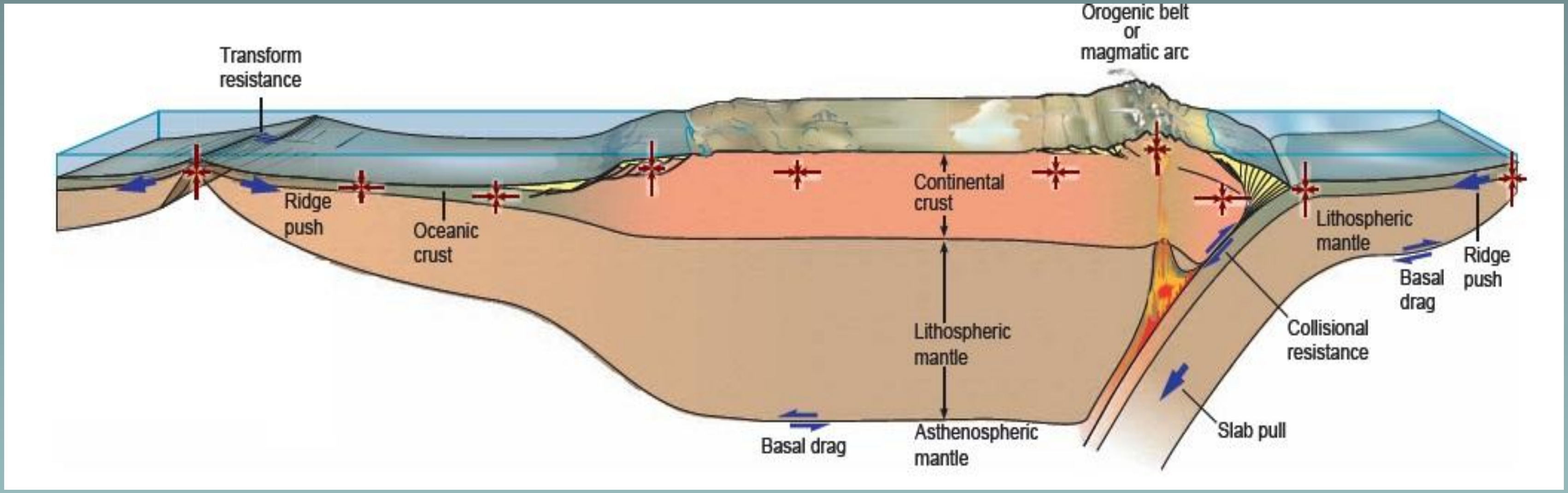
(b) Secondary structures

- **Tectonic structures: Form in response to forces generated by plate interactions.**

Quiz: Can you distinguish?

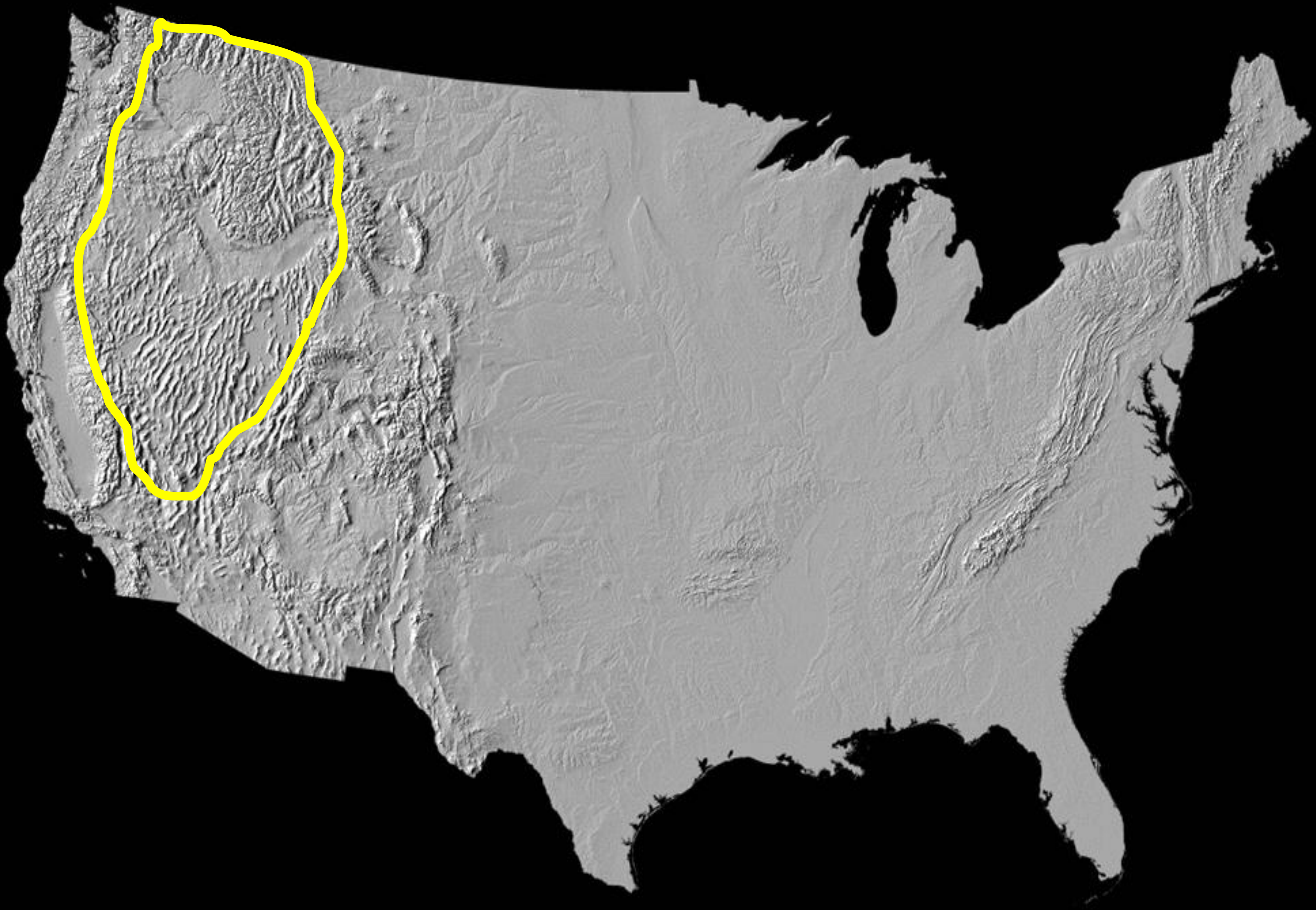
https://en.wikipedia.org/wiki/Cross-bedding#/media/File:Trough_xbed_mcr1.JPG

Why Structural Geology?

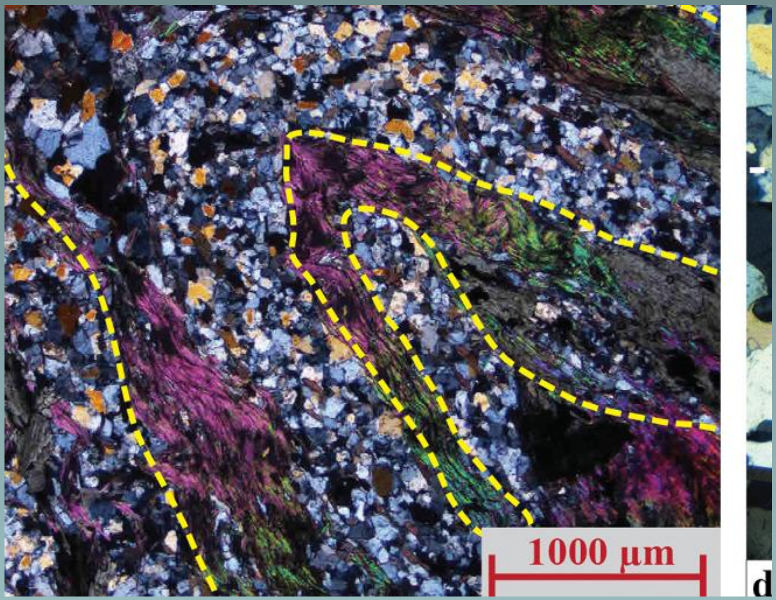


(Fossen, 2010)

- How rocks accommodate deformation?
- Manifestation & Quantification
- Mechanics & Kinematics
- Formation of Mountain Belts,Basins, Climate, Erosion
- Evolution of Crust through space and time



https://link.springer.com/article/10.1007/s00531-017-1486-5



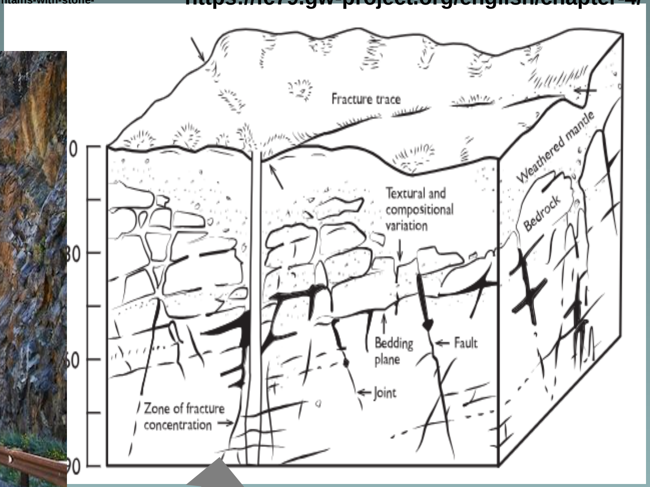
(Ghosh et al., 2020)

Engineering Geology

https://www.freepik.com/premium-photo/image-view-center-road-tunnel-through-mountains-with-stone-wall_21634376.htm

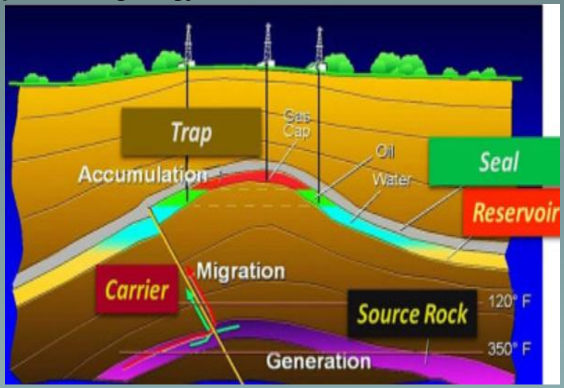
Groundwater studies

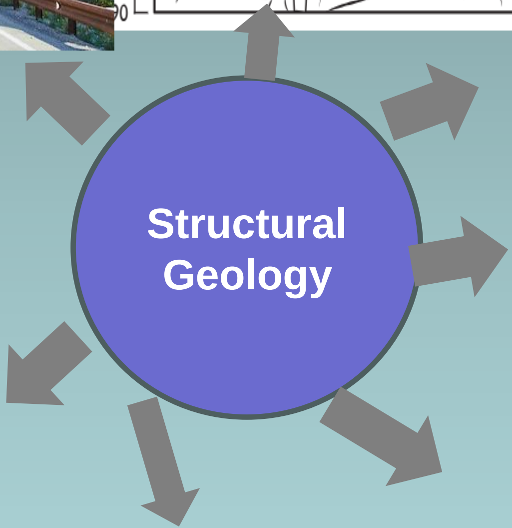
https://fc79.gw-project.org/english/chapter-4/



Oil & Gas Exploration

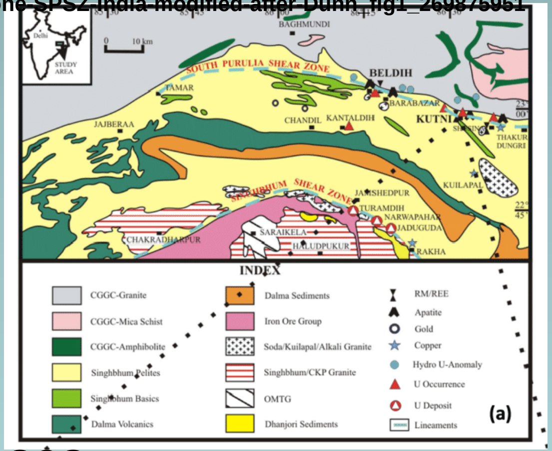
https://www.sciencedirect.com/topics/earth-and-planetary-sciences/petroleum-geology

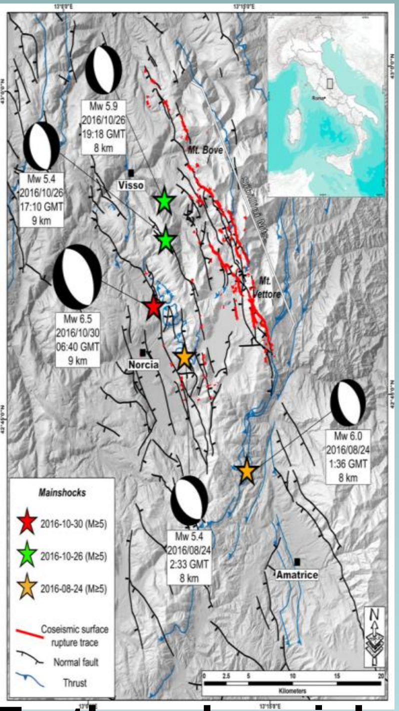




Mineral Exploration

https://www.researchgate.net/figure/a-General-geological-map-of-South-Purulia-Shear-Zone-SPSZ-India-modified-after-Dunn_fig1_269875951



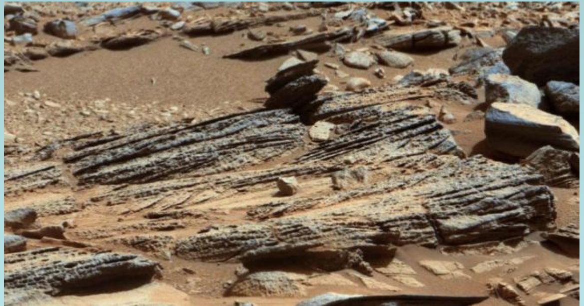


Earthquakes risk assessment

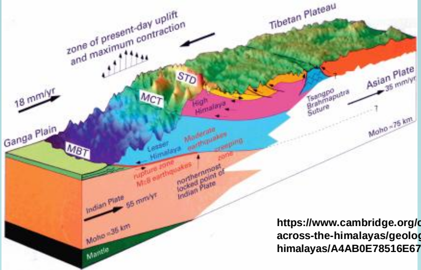
DOI:10.1038/sdata.2018.49

Extraterrestrial processes

https://geology.com/stories/13/rocks-on-mars/cross-bedding-outcrop-lg.jpg



Climate Sciences

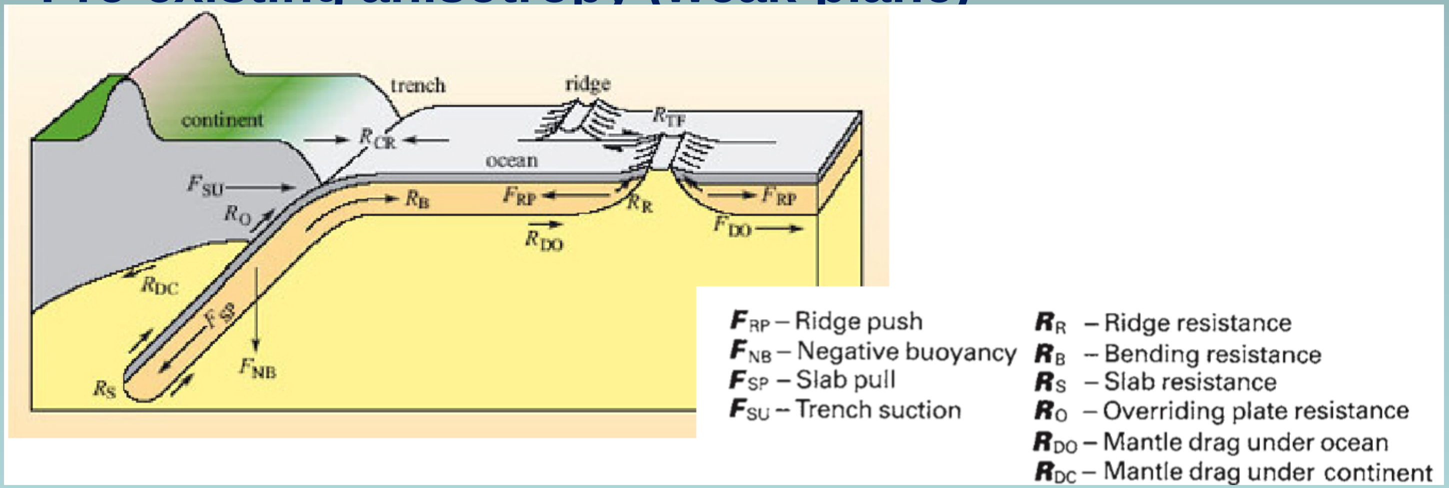


https://www.cambridge.org/core/books/abs/bird-migration-across-the-himalayas/geological-origin-and-evolution-of-the-himalayas/A4AB0E78516E6761F52EDDE9B5D2125B

Mechanics of Structures

How Rocks Deform Depend on:

- Force applied
- Temperature
- Pressure (rock or lithostatic pressure)
- Pore fluid pressure
- Composition of rocks
- Rate of deformation
- Grain size
- Pre-existing anisotropy (weak-plane)

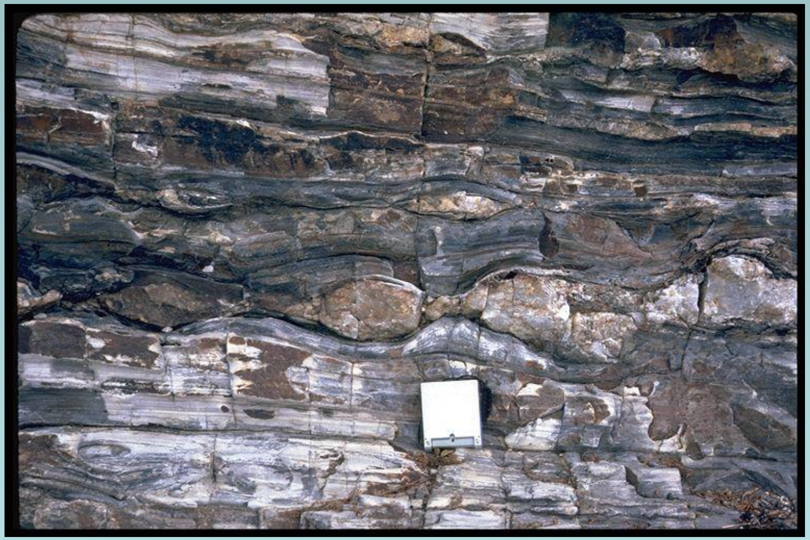


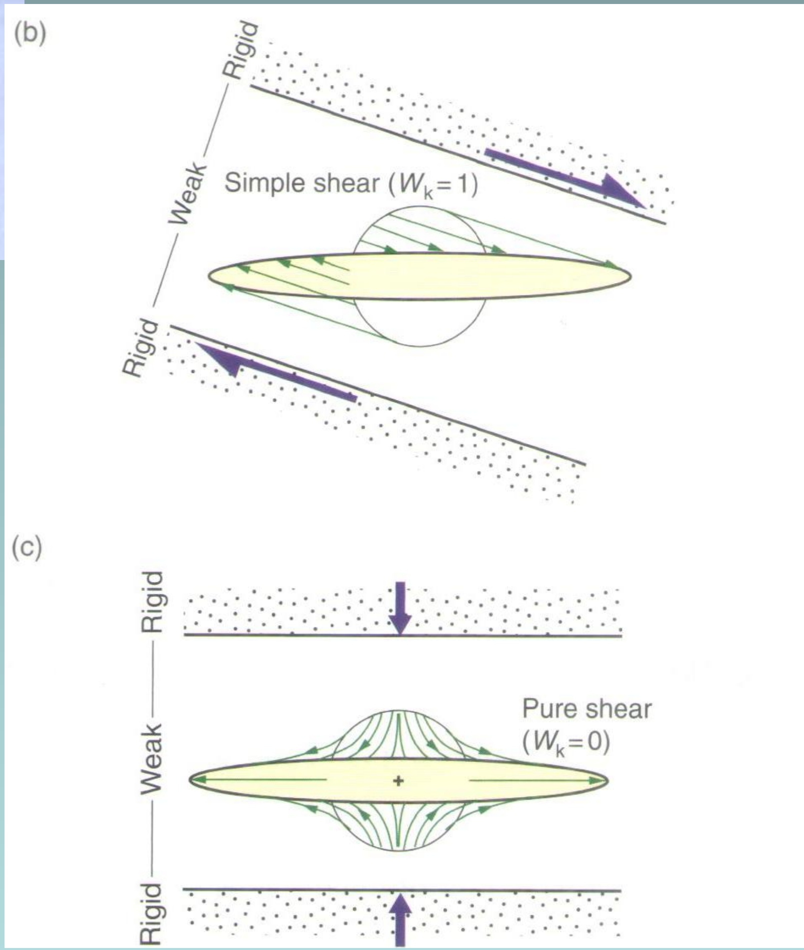
Forces: Push or Pull.

Vector quantity (SI Unit = Newton = $kg \cdot m/s^2$)

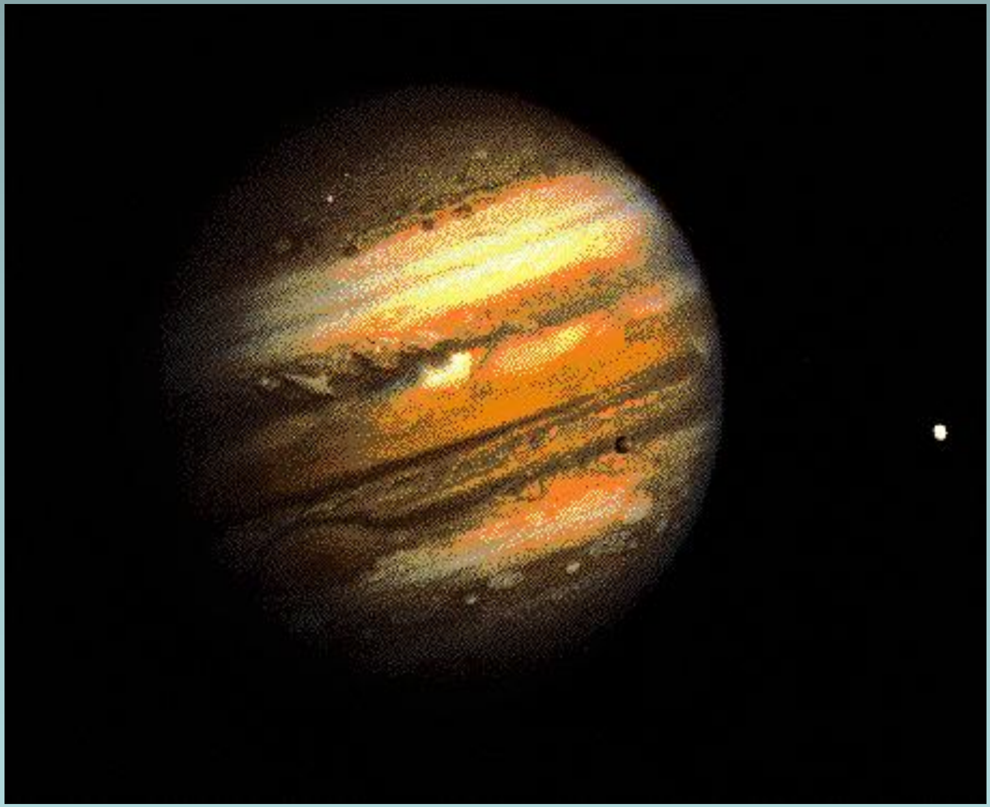
- Body force
- Surface force

https://www.stockfood.com/images/13180975-Flowing-honey





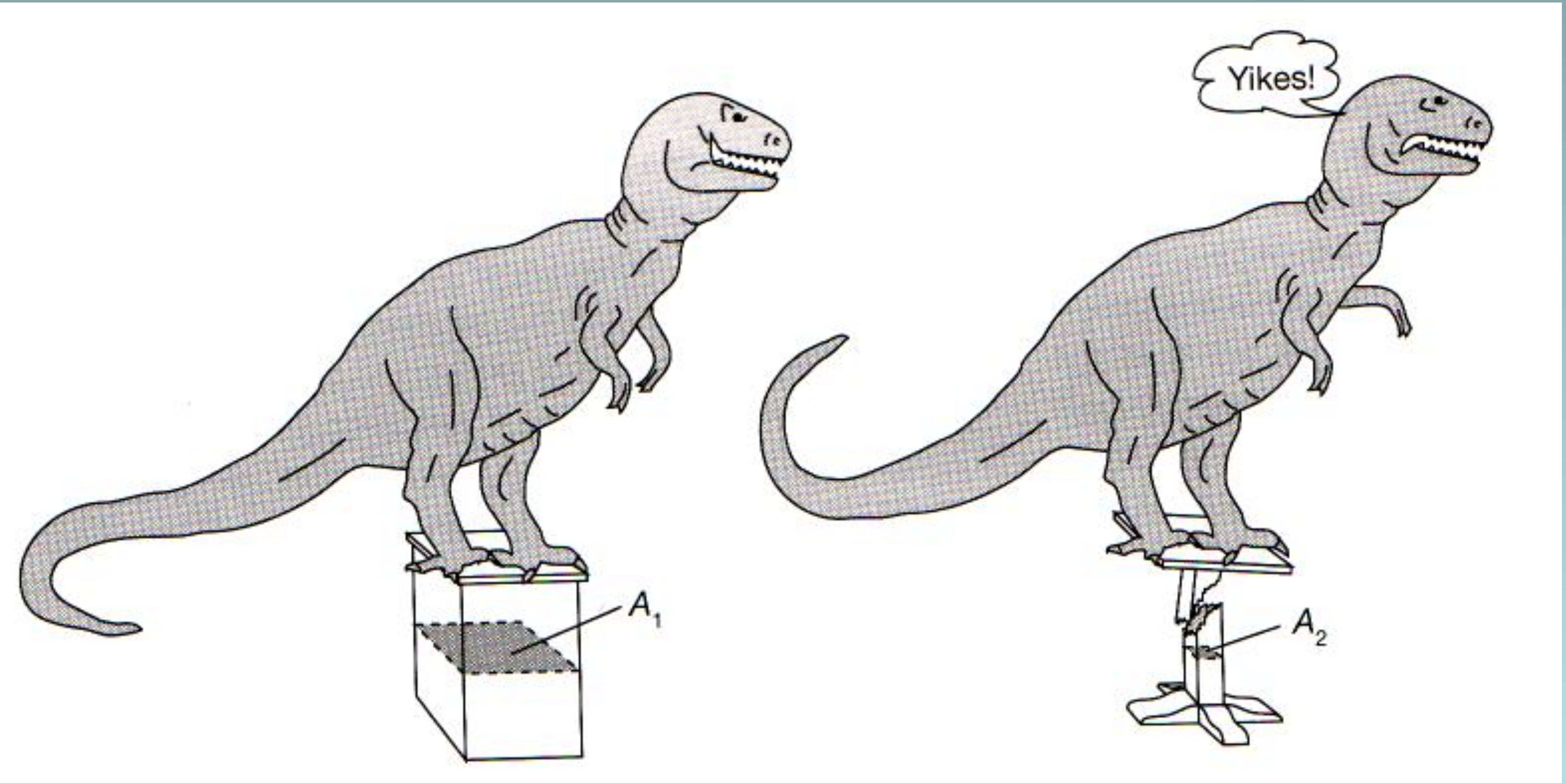
Body Force: **They act on each particle of rock in a volume, and its magnitude is proportional to the mass within that volume.**



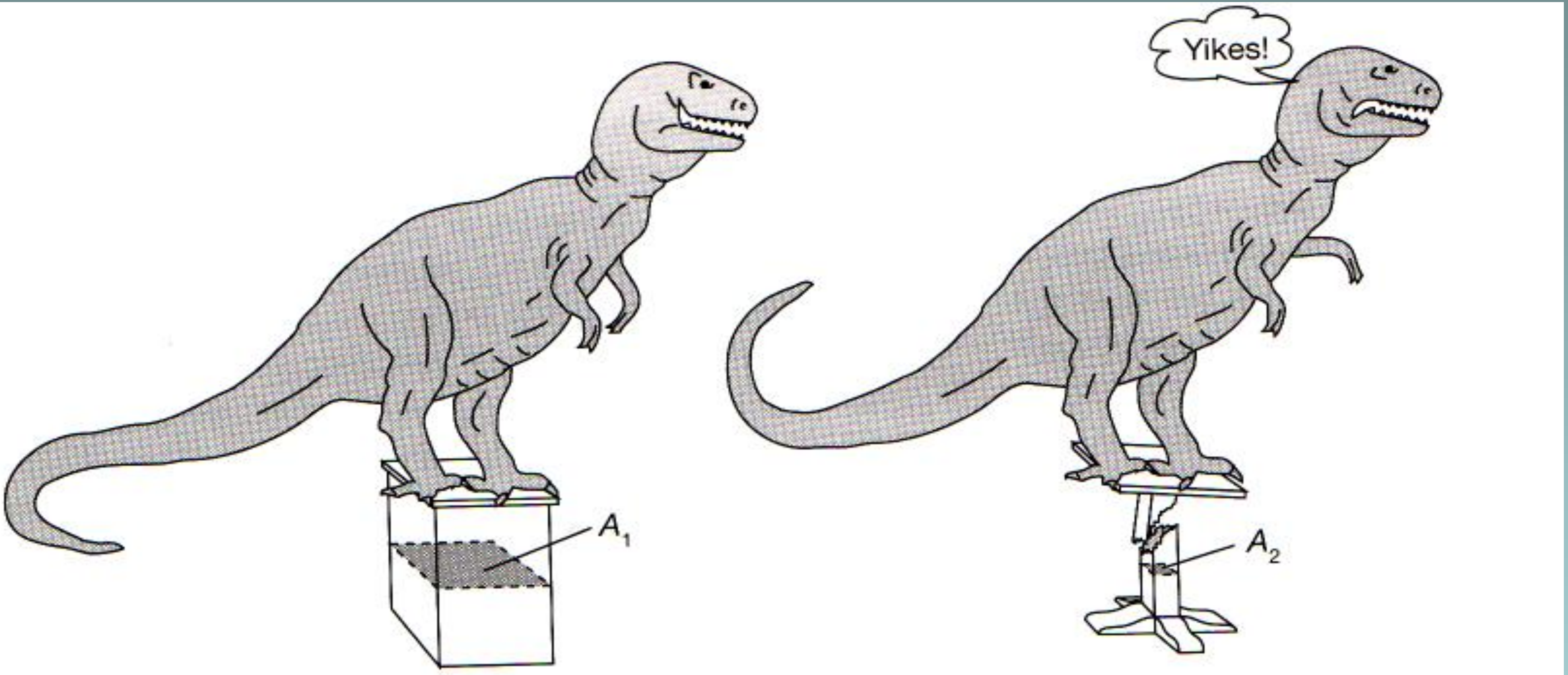
Gravitational Forces

Electromagnetic Forces

Surface Force: **Forces that result from the action of one body / part of a body on another across a shared surface. They act on a specific surface of a body.**

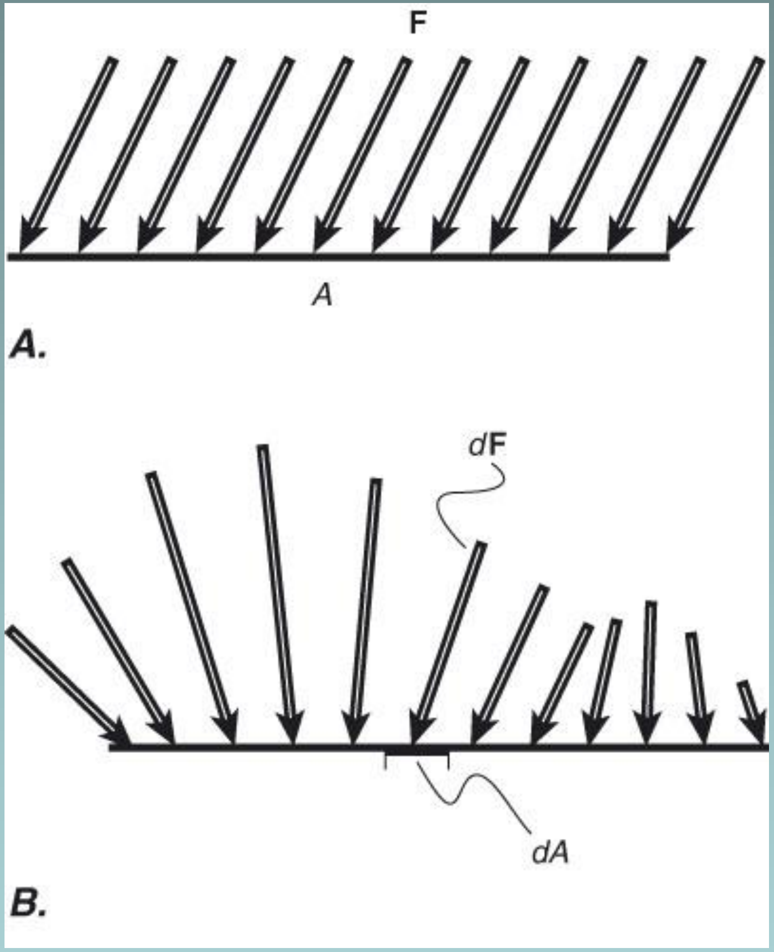


Traction: Intensity of Force



Σ = F/A

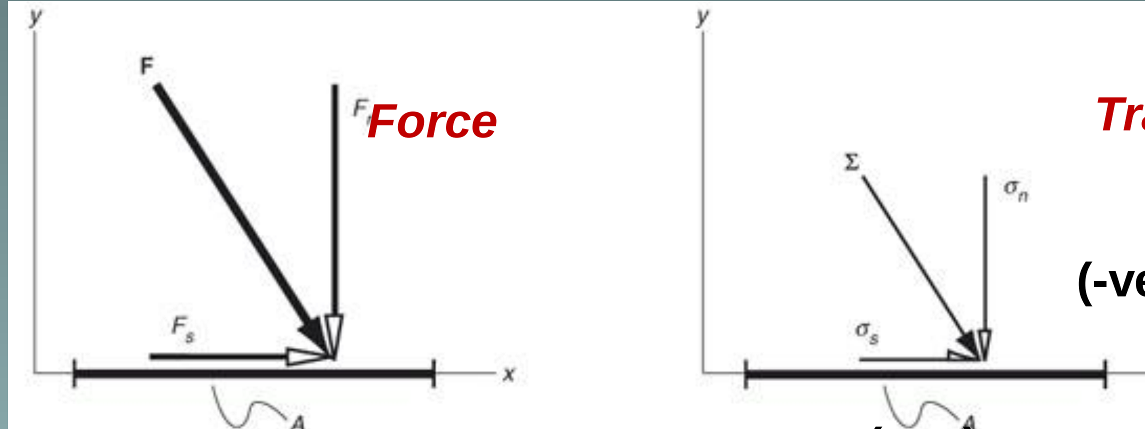
But…



Traction at a point,

$$\Sigma = dF/dA$$

Magnitude & direction of traction can vary from point to point across a surface.

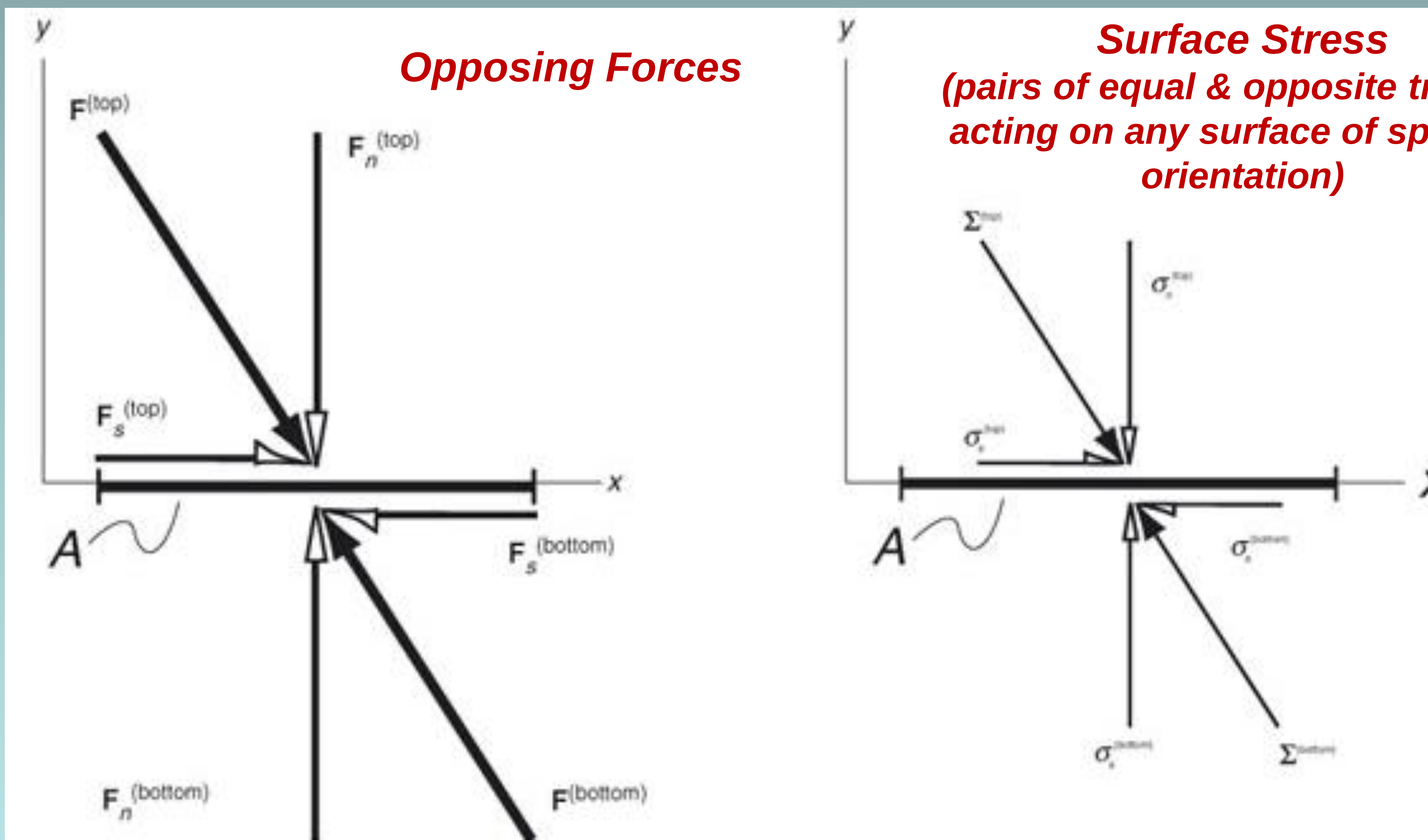


Force

Traction

(-ve)

(+ve)

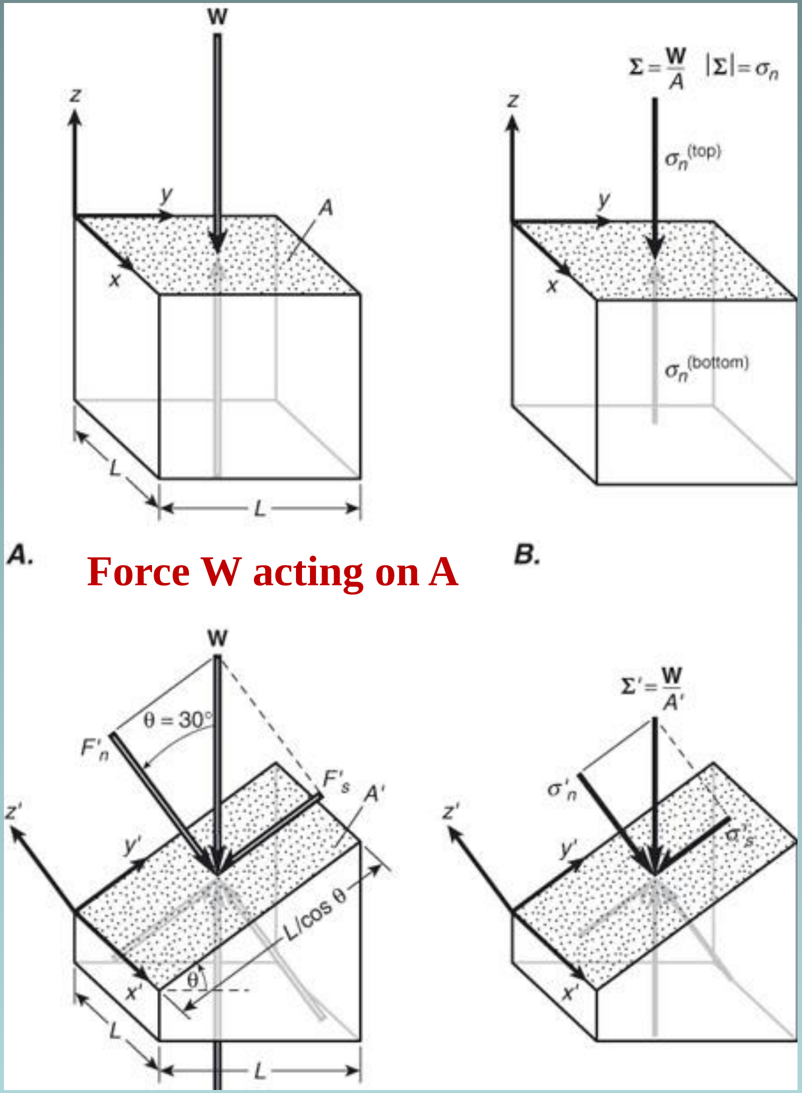


Opposing Forces

Surface Stress

(pairs of equal & opposite tractio
acting on any surface of specific
orientation)

Stress across planes of different orientations



Force W acting on A

Force W acting on inclined A'

$\sigma_n = W/A$

$\sigma_s = 0$

$F'_n = W \cos\Theta$

$F'_s = W \sin\Theta$

$F = \sigma * A$

$\sigma'_n = W \cos\Theta / L.L' = W\cos\Theta / L.(L/\cos\Theta) = W \cos\Theta/[A/\cos\Theta] = \sigma_n \cos^2\Theta$

$\sigma'_s = W \sin\Theta / [A/\cos\Theta] = \sigma_n \cos\Theta \sin\Theta = (\sigma_n/2)\sin 2\Theta$

Transformation eqn for stress

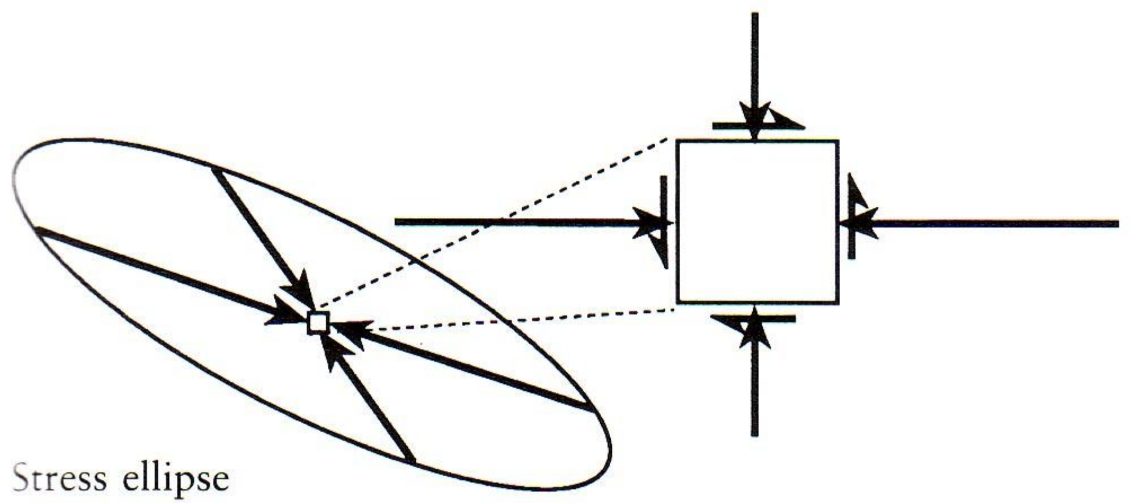
Stress ellipse:

State of Stress at a point (σ) :

Defined by $\sigma_{n,}$ σ_s that act on planes of all possible orientations passing through the point.

Plotting surface stresses on all possible orientations through a point –ends of all arrows fall on an ellipse (2D; arrows are radii of ellipse) – *stress ellipse → state of stress at that point*

shape & orientation of ellipse→complete state of stress at that point

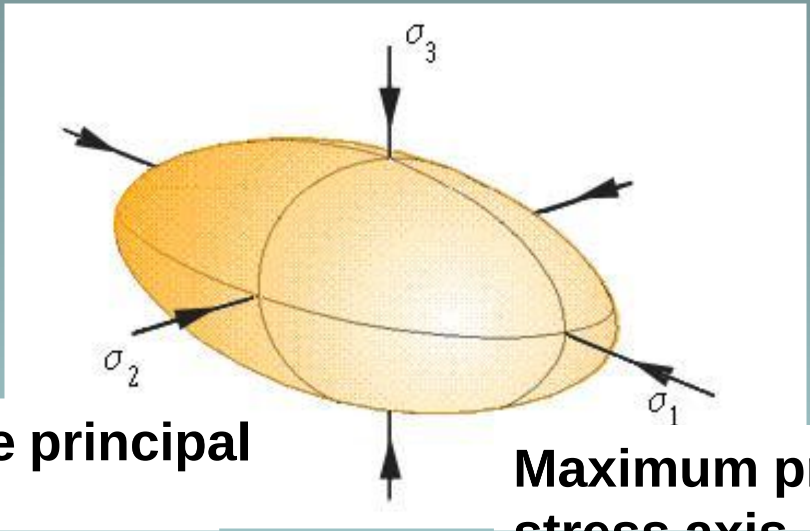


Stress ellipse

1Pa = 1N/m^2= 1kg/(ms^2)
1MPa = 10 bar=10.197kg/cm^2
100 MPa= 1kbar

Stress Ellipsoid

Minimum principal stress axis



Intermediate principal stress axis

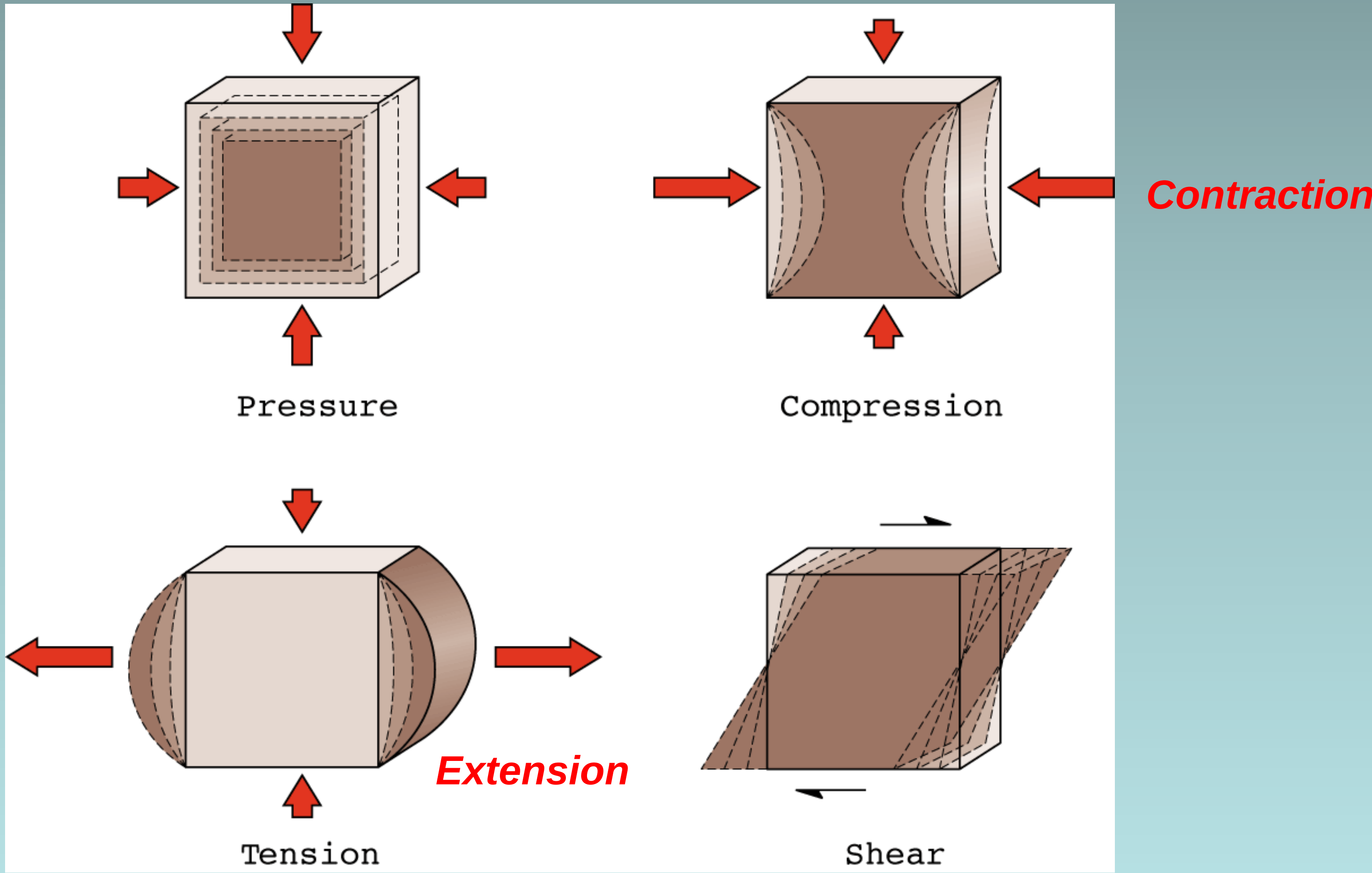
Maximum principal stress axis

$\sigma_1 \geq \sigma_2 \geq \sigma_3$

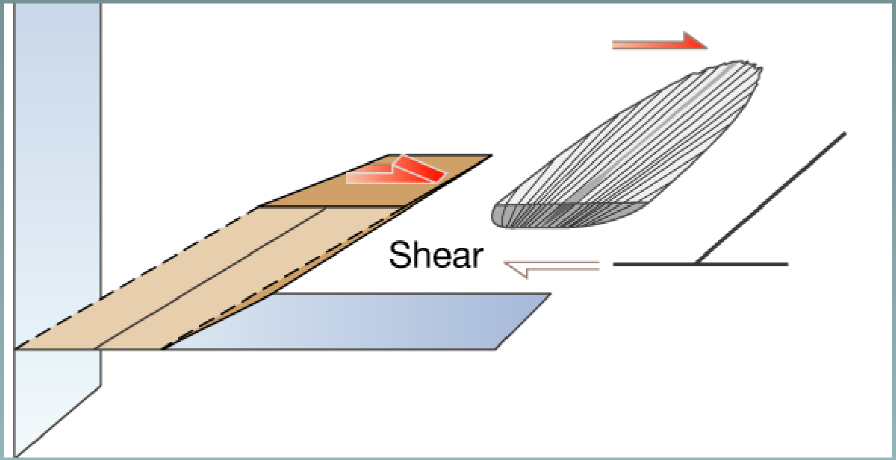
Stress ellipsoid

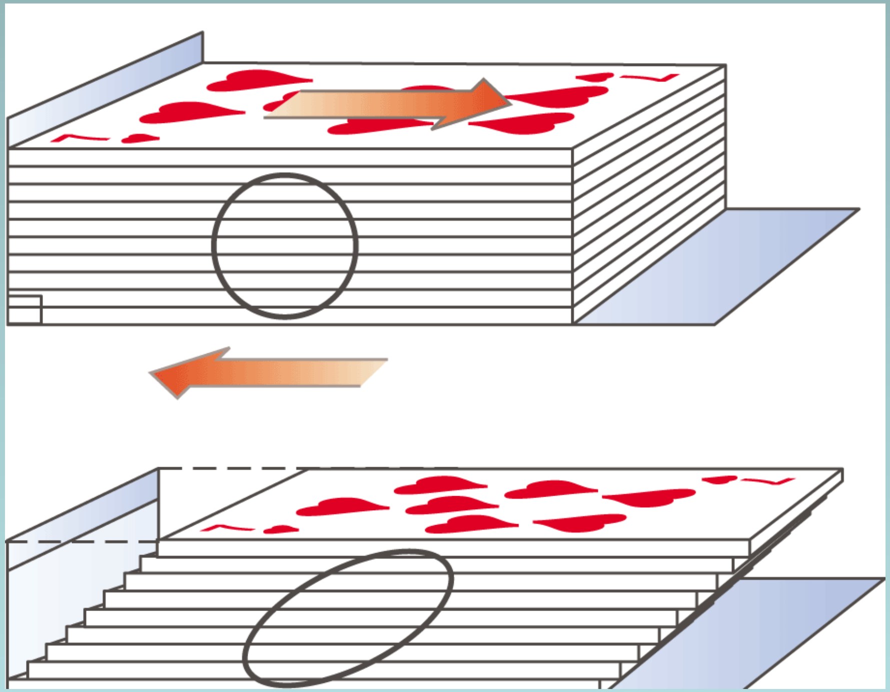
Stress causes Strain

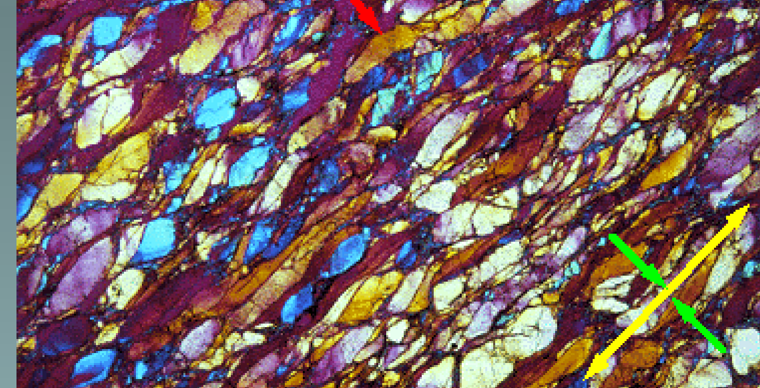
Strain – A shape change or volume loss (size change) that is a response to an applied stress



Shear







Tracks XY/
shortening
plane

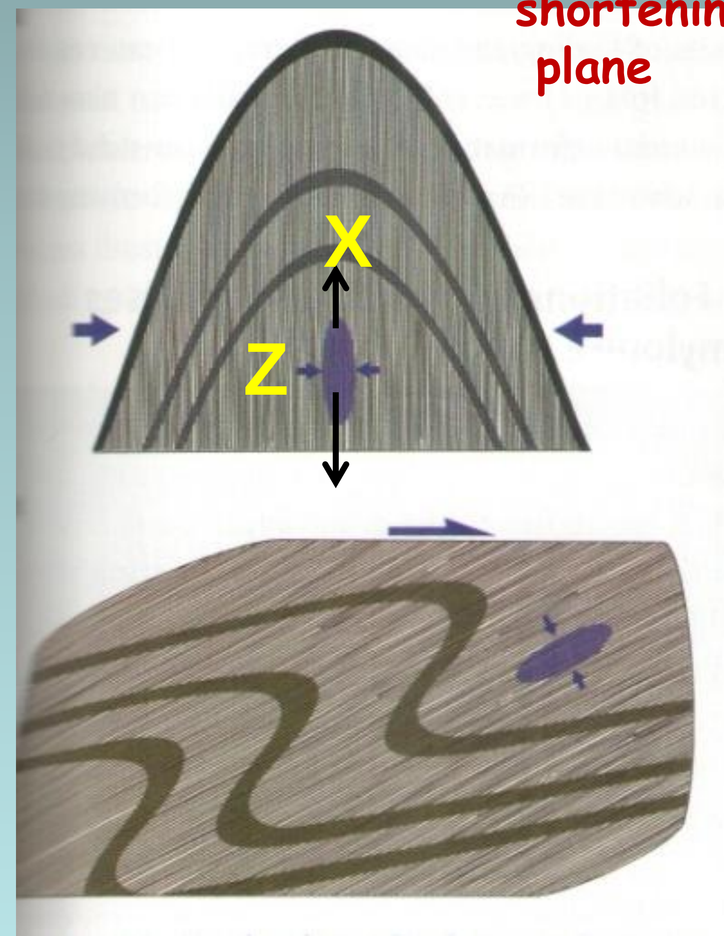


Figure 12.17 Simple relationship between shortening direction (arrows), strain ellipse and cleavage for (a) upright folds, for instance in slate belts, and (b) shear zones.

Quantification of Strain

Length Change

Dimensionless Number

Elongation (engineer's extension) $= e = (l_f - l_o)/l_o$

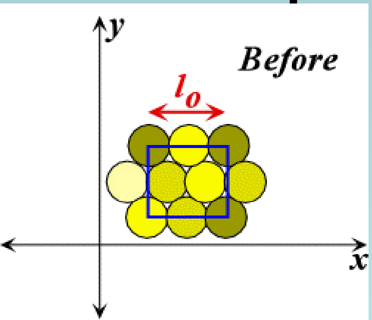
Useful for small strains

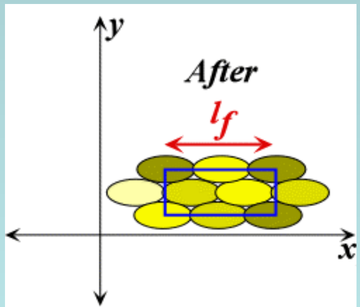
e (-) = shortening

e (+) = extension

Stretch $= T$ (or S) $= l_f/l_o = 1 + e$

Used in expressing axial ratios





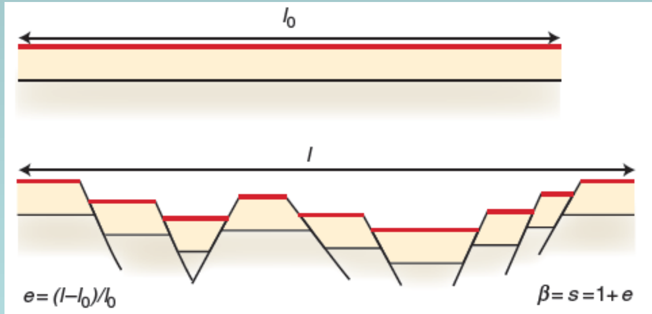


Figure 2.7 Extension of layers by faulting. The red layer has an original (l_0) and a new length, and the extension e is found by comparing the two. The beta-factor (β) is commonly used to quantify extension across extensional basins.

Strain ellipsoid

Deformed shape of imaginary sphere with unit radius that is deformed along with rock volume under consideration

X>Y>Z

Magnitudes of axes → Principal stretches (or, $s_1>s_2>$ $\sqrt{\lambda_1}, \sqrt{\lambda_2}, \sqrt{\lambda_3}$; or, $1+e_1>1+e_2>1+e$

Ellipticity = R= X/Y

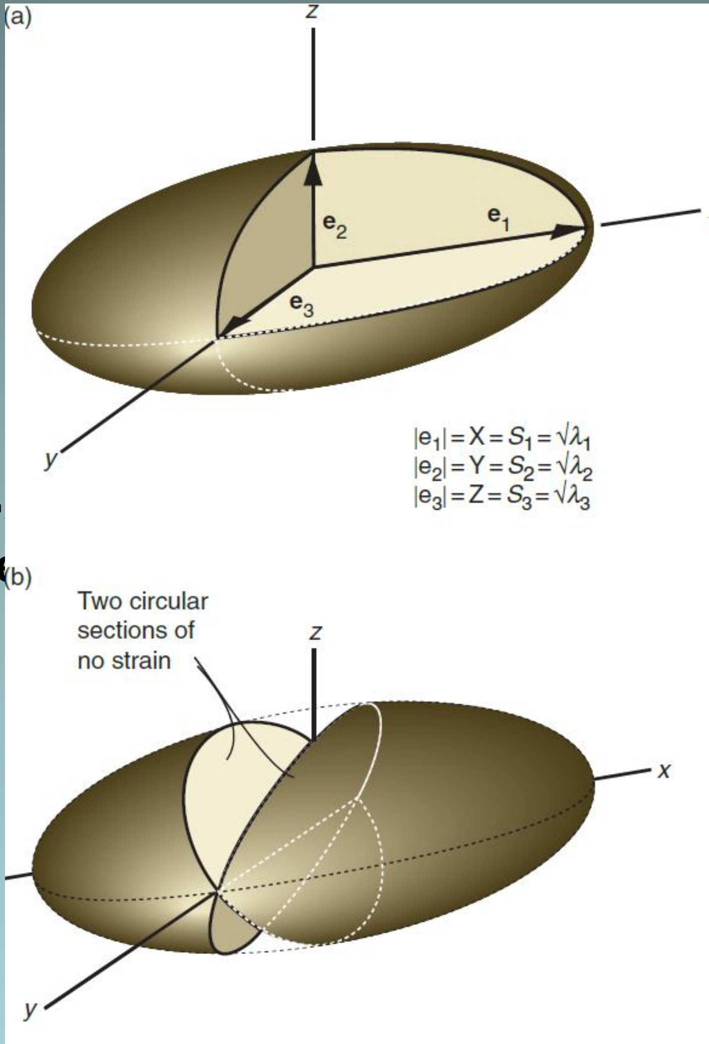
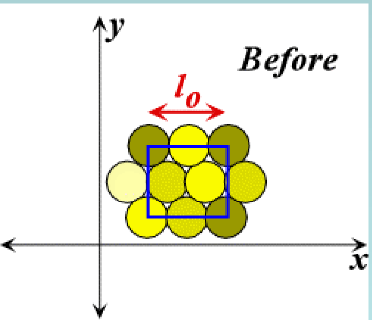
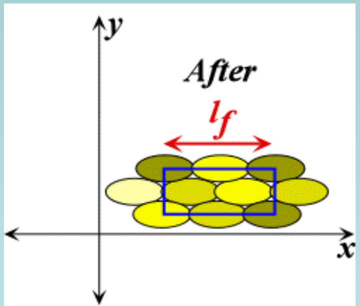
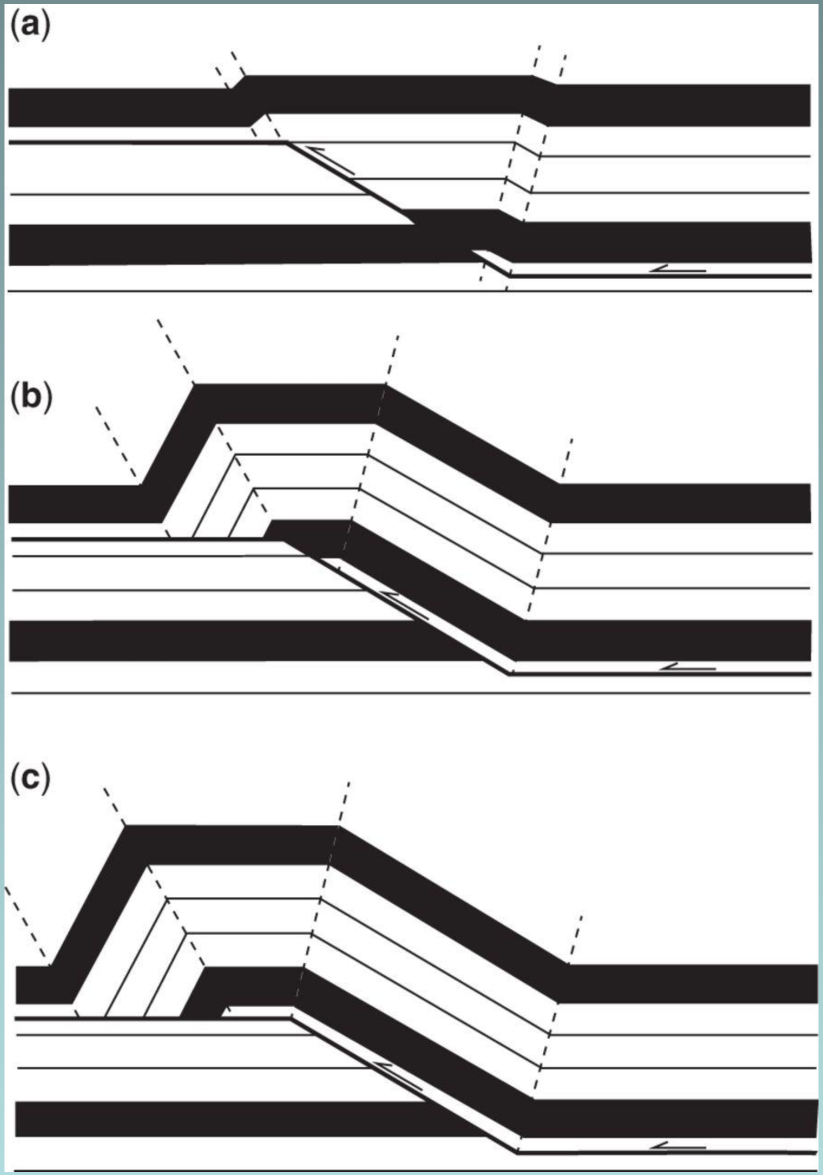


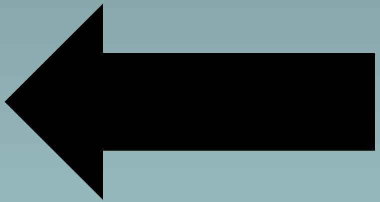
Figure 2.13 (a) The strain ellipsoid is an imaginary sphere that has been deformed along with the rock. It depends on homogeneous deformation and is described by three vectors $\mathbf{e}_1$, $\mathbf{e}_2$ and $\mathbf{e}_3$, defining the principal axes of strain (*X*, *Y* and and the orientation of the ellipsoid. The length of the vector thus describes the shape of the ellipsoid, which is independe of choice of coordinate system. (b) The ellipsoid for plane strain, showing the two sections through the ellipsoid that display no strain.





Compression (stress) ⇨ Contraction/Shortening (strain)

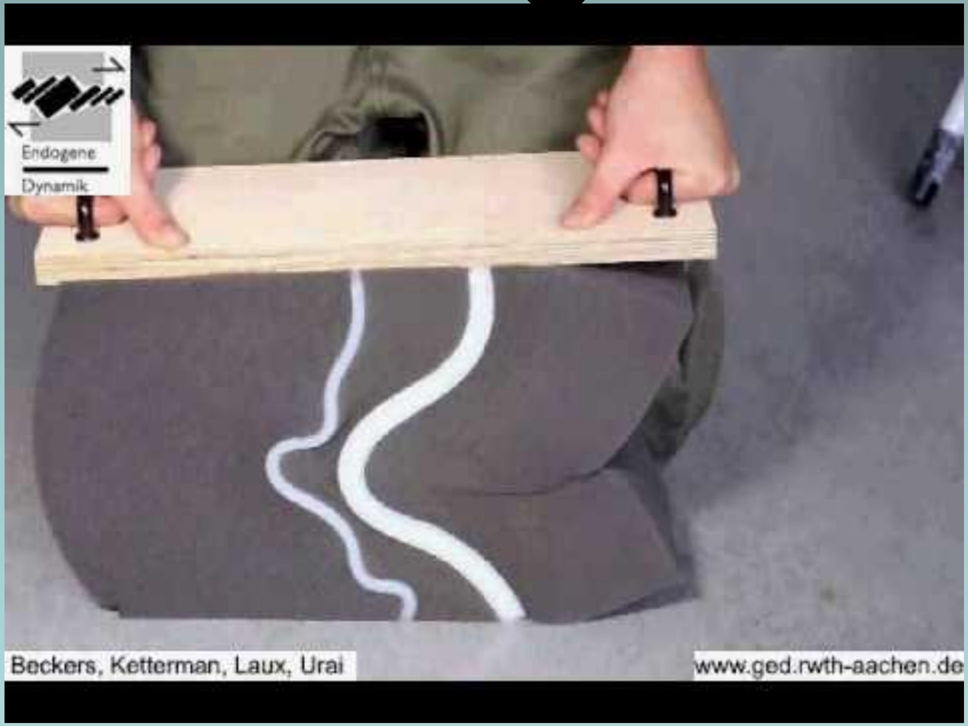




Change in Length (thickening)

Is this the only possibility?

Compression (stress) ⇨ Contraction/Shortening (strain)



Change in Length (thickening)

Stress & Strain
Not correlatable

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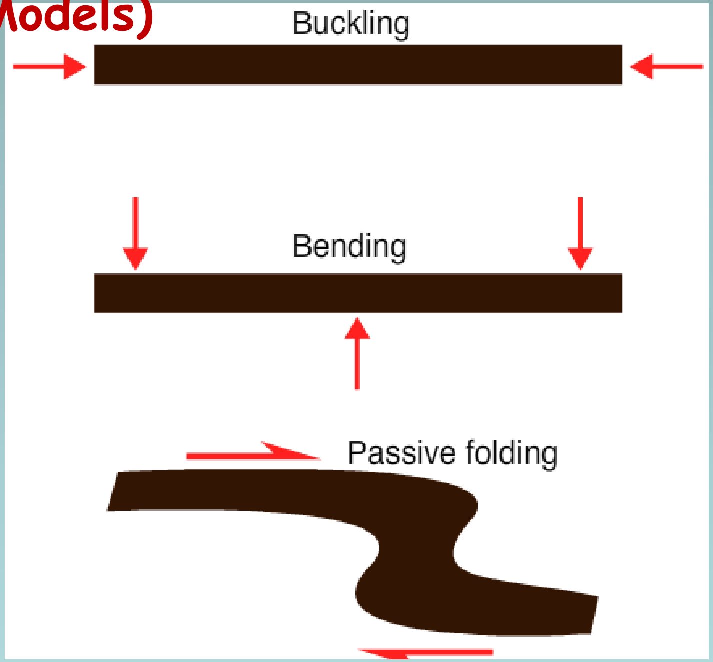
How stress acts on layered rocks (Mechanical Models)



Kinematic models of Folding

Motion of the deforming body , but generally, do not relate the motion to the mechanical properties of the folded layer &/ to the stress

Ref: 11.2; Fossen

Whether the beds respond actively/passively to the imposed strain field