GEOCAP
Geothermal Capacity Building Program Indonesia - Netherlands

Bandung Train The Trainers 16th -28th May 2016

Reservoir Geomechanics

Train The Trainers workshop , WP 1.04 WP leader Peter Fokker TNO

Auke Barnhoorn, Peter Fokker

Cooperating Companies and Universities

INAGA

IF Technology

DNVGL

Institute Teknologi Bandung

Delft University of Technology

Department of Geo-Technology

University of Twente

Faculty of ITC

Universitas Gadjah Mada

Universitas Indonesia

University of Utrecht

Faculty of Geosciences – Department of Earth Sciences

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Reservoir Geomechanics Module

- **Half a day** lecture material containing a basic introduction into reservoir geomechanics targeted to MSc student community.
- No prior knowledge of geomechanics is required to attend this course.
- Material contain powerpoint lecture (~3 x 40 min) + multiple in-class exercises (2x 10 minutes in between class and 2 exercises for the end of the day).
- At the end of the module students will have a better understanding of the basics of geomechanics and an appreciation of its importance for subsurface engineering for geothermal and petroleum reservoirs.

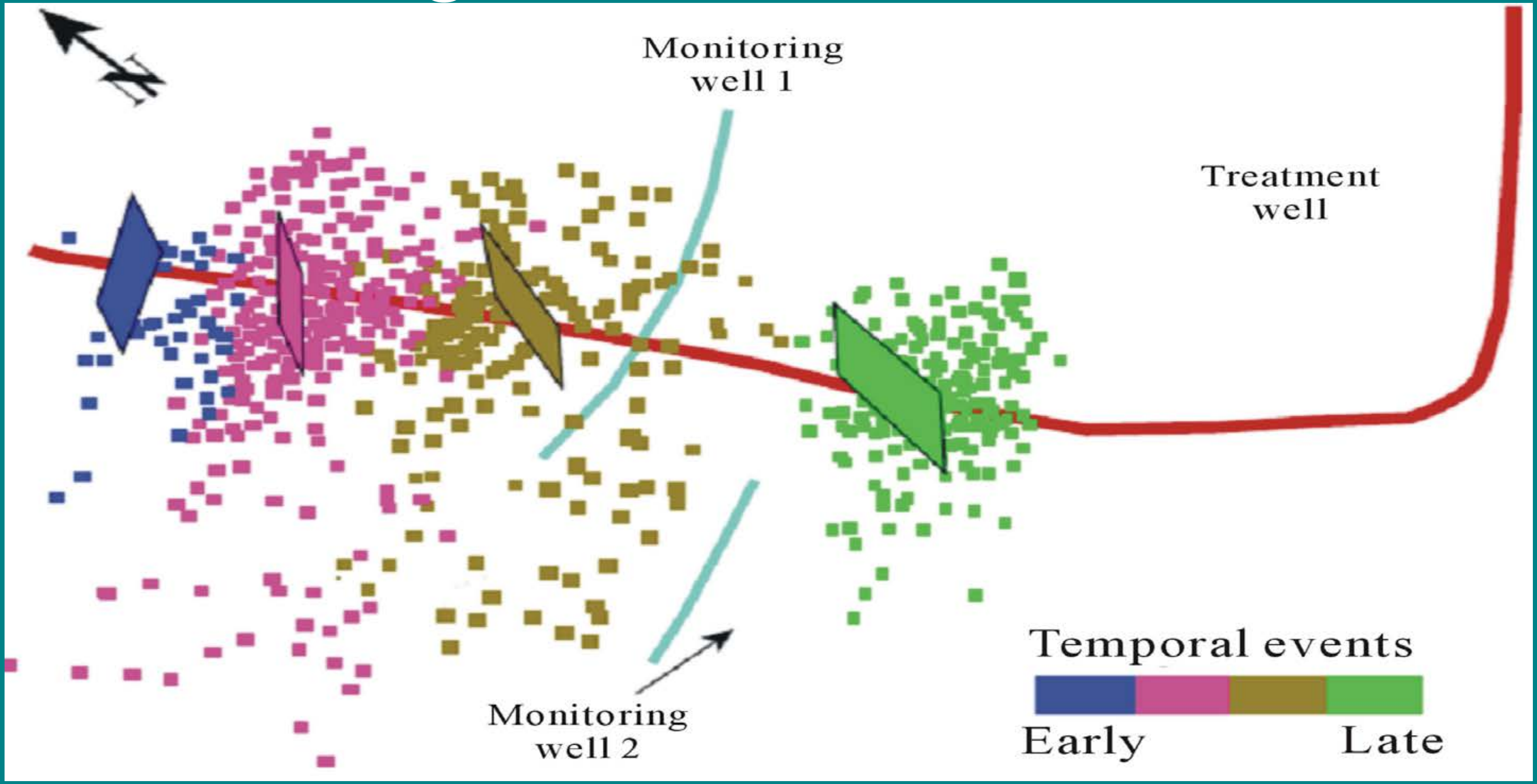
Importance of reservoir geomechanics

- Seismicity (induced and natural)
- Hydraulic fracturing
    - Borehole fluid pressures
    - Fracture orientation
- Well bore stability
- Compaction due to production
- Current stress field in the subsurface
- Geophysics – seismic exploration
- Etc.

M6.0 April 6th, 2016

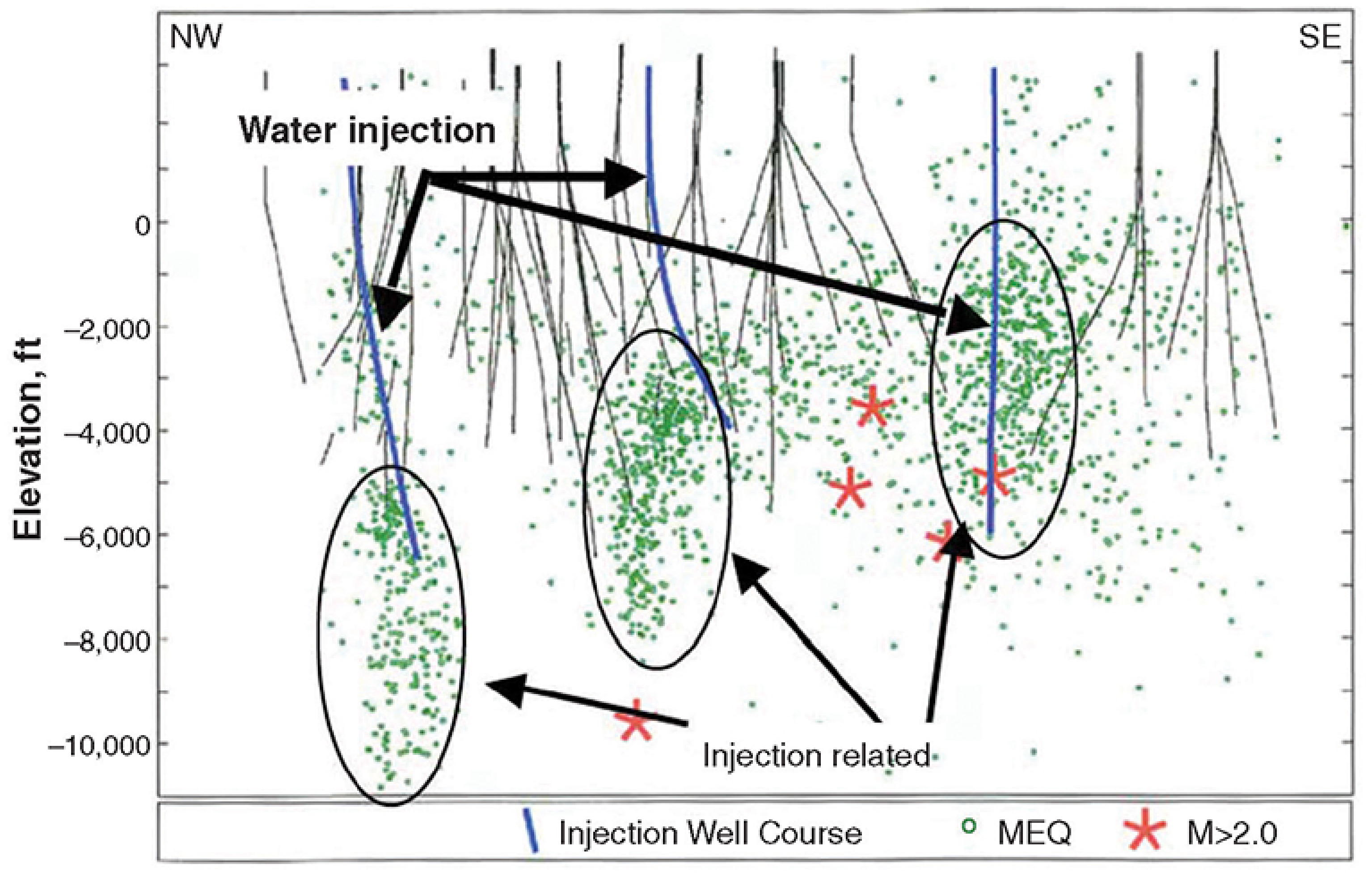
http://thewatchers.adorraeli.com/2016/04/06/strong-and-shallow-m6-0-earthquake-hit-near-the-coast-of-java-indonesia/

Induced seismicity due to hydraulic fracturing



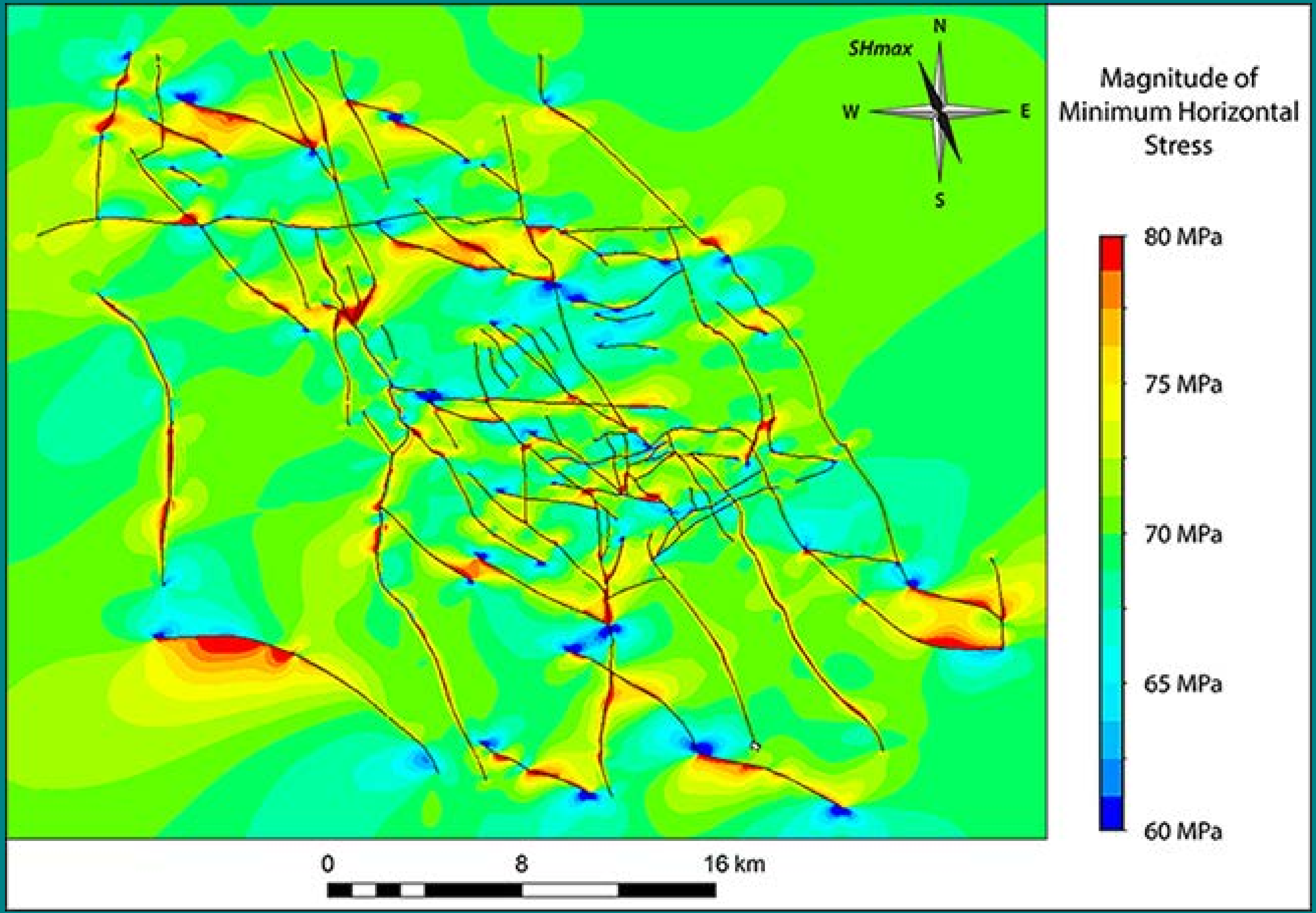
Abdulaziz, 2013

Induced seismicity due waste water injection



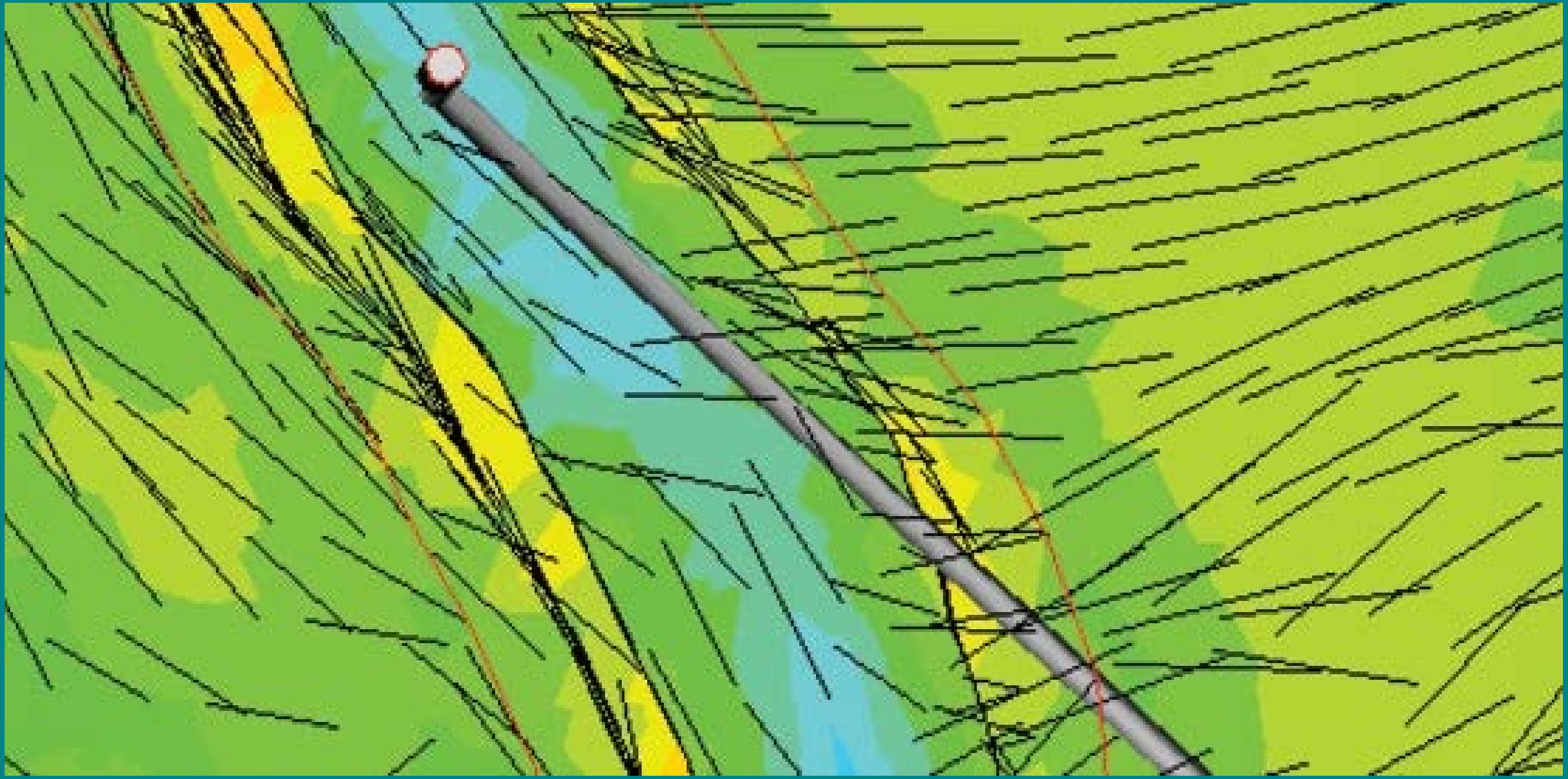
http://www.spe.org/jpt/article/7139-searching-for-solutions-to-induced-seismicity/

Stress distribution in a reservoir - magnitude



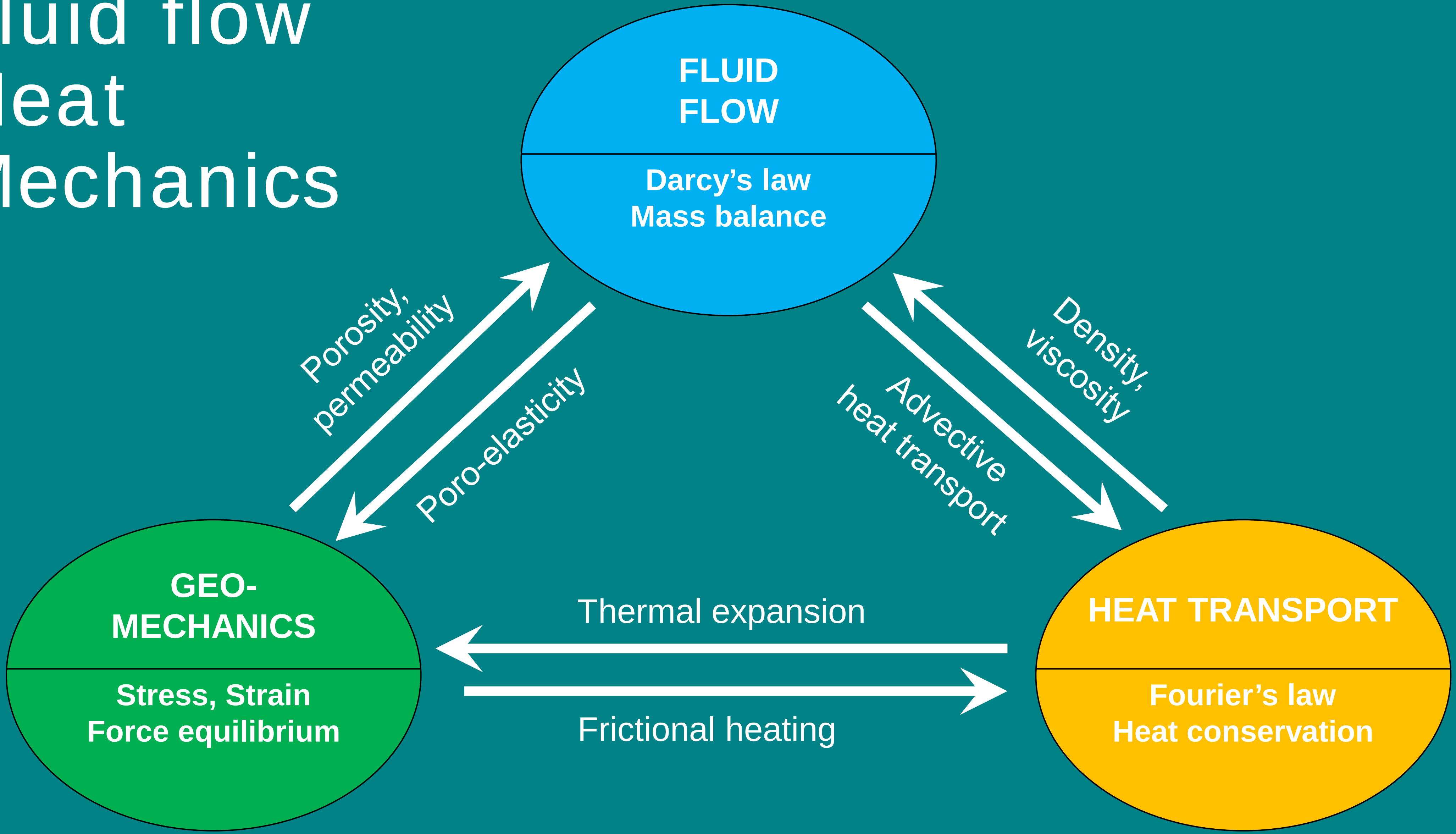
http://www.geo.tu-darmstadt.de/fg/inggeol/inggeo_forschung/dgmk_forschungsprojekt_721/dgmk_project_721.en.jsp

Stress distribution in a reservoir - orientation



http://www.golder.com/ph/modules.php?name=Newsletters&op=viewarticle&sp_id=167&page_id=1100&article_id=570

Fluid flow
Heat
Mechanics



From Peter Fokker, TNO

Use of geomechanics for geothermals

- Knowledge of the orientation of the natural faults/fractures

- Hydraulic stimulation to improve fluid path ways

- Fluid flow/production may influence PT conditions in the subsurface and/or porosity/permeability of the rocks that may result in geomechanical responses

Outline for this afternoon

- Basics of geomechanics
  - Stress
  - Strain
  - Elasticity
  - Inelasticity (fracturing, creep, ductile flow)
- Subsurface stresses & rock failure in wellbores
- Application examples of reservoir geomechanics

- Exercises

Stress

- Stress is everywhere in the Earth
- Stress varies with depth, location, locality, tectonic setting etc.

- Stress controls dynamics in the Earth
  - Movement of rocks on geological timescales
  - Rock shape and volume changes
  - Failure of rocks

Stress

- $Stress = \frac{Force}{Area} = \frac{F}{A}$

- Unit of stress?

Stress

- $Stress = \frac{Force}{Area} = \frac{F}{A}$

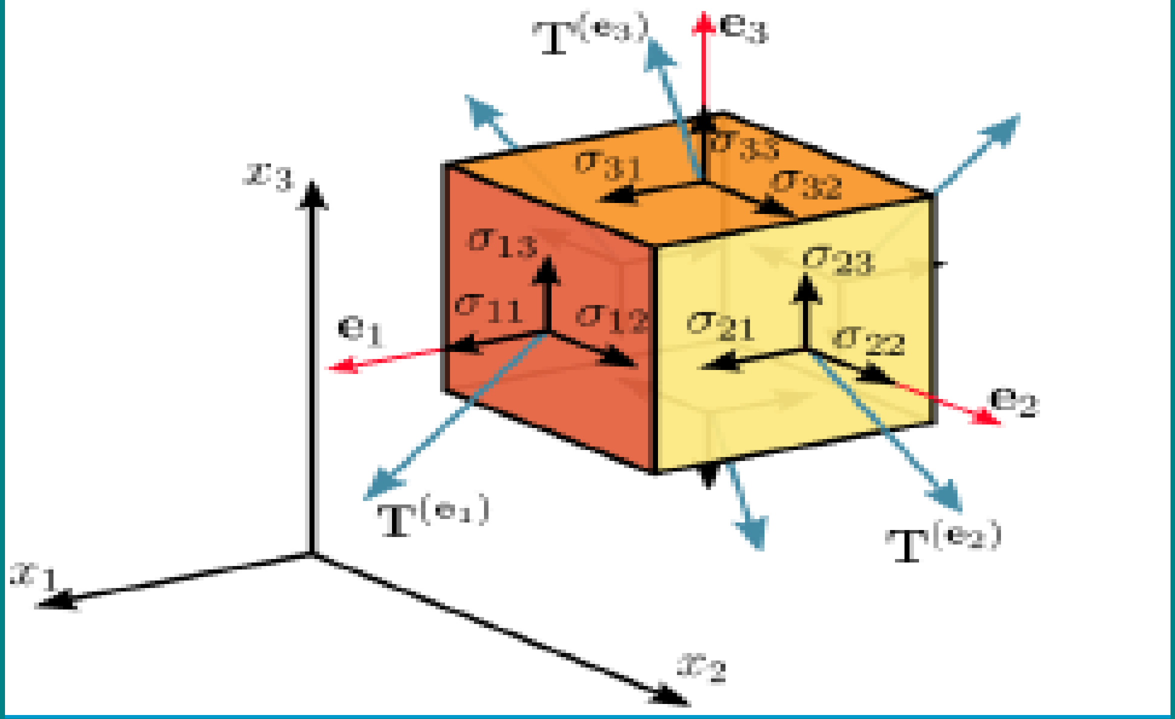
- Unit of stress is Pa (Pascal) or MPa for reservoir geomechanics

- Unit of Force is N (Newton)
- Unit of Area is m^2
- 1 Pa = 1 N/m^2

Stress tensor

$$\sigma = \begin{pmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \end{pmatrix} = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{pmatrix}$$

$$= \begin{pmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{pmatrix}$$



Stress component: Force acting in a specific direction acting on an area of a certain orientation

Stress tensor

$$\sigma = \begin{pmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \end{pmatrix} = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{pmatrix}$$

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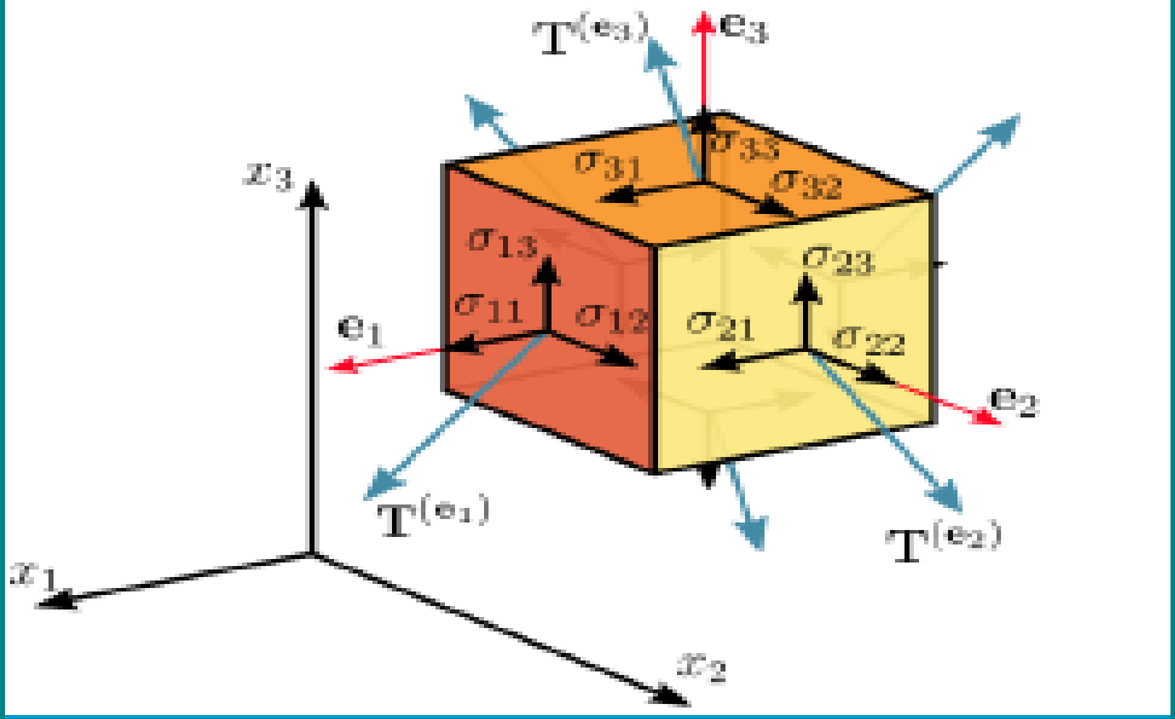
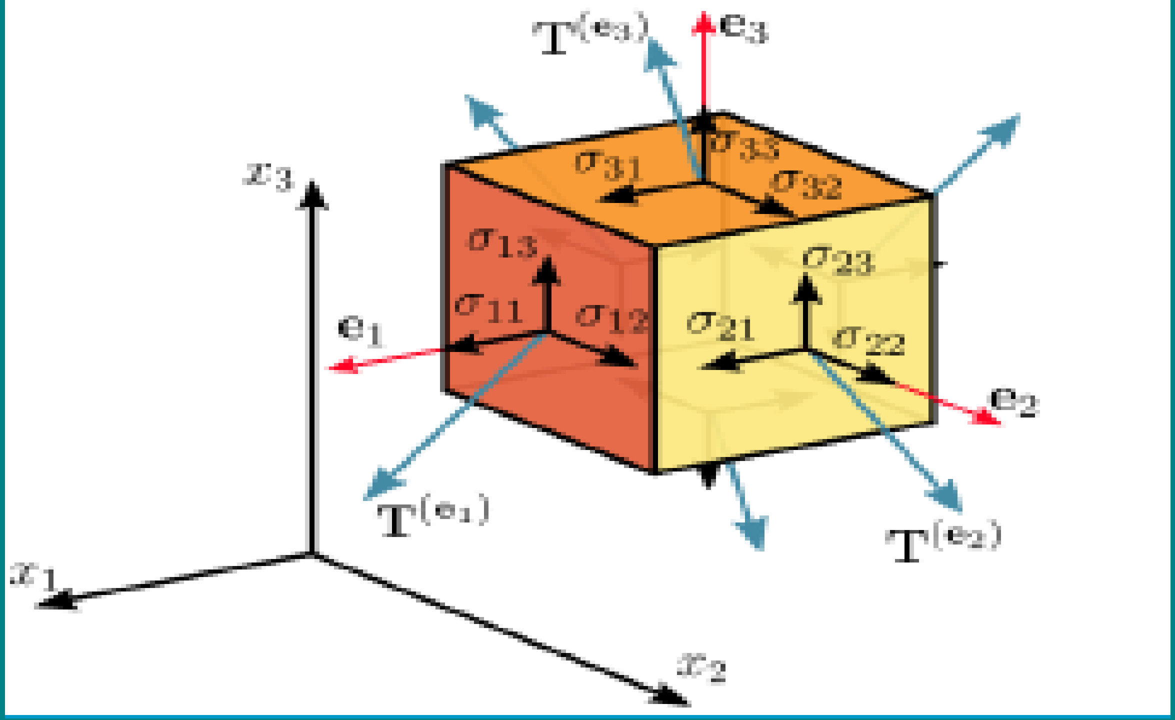


Six individual components of the stress tensor

Stress tensor

$$\sigma = \begin{pmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \end{pmatrix} = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{pmatrix}$$

$$= \begin{pmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{pmatrix}$$

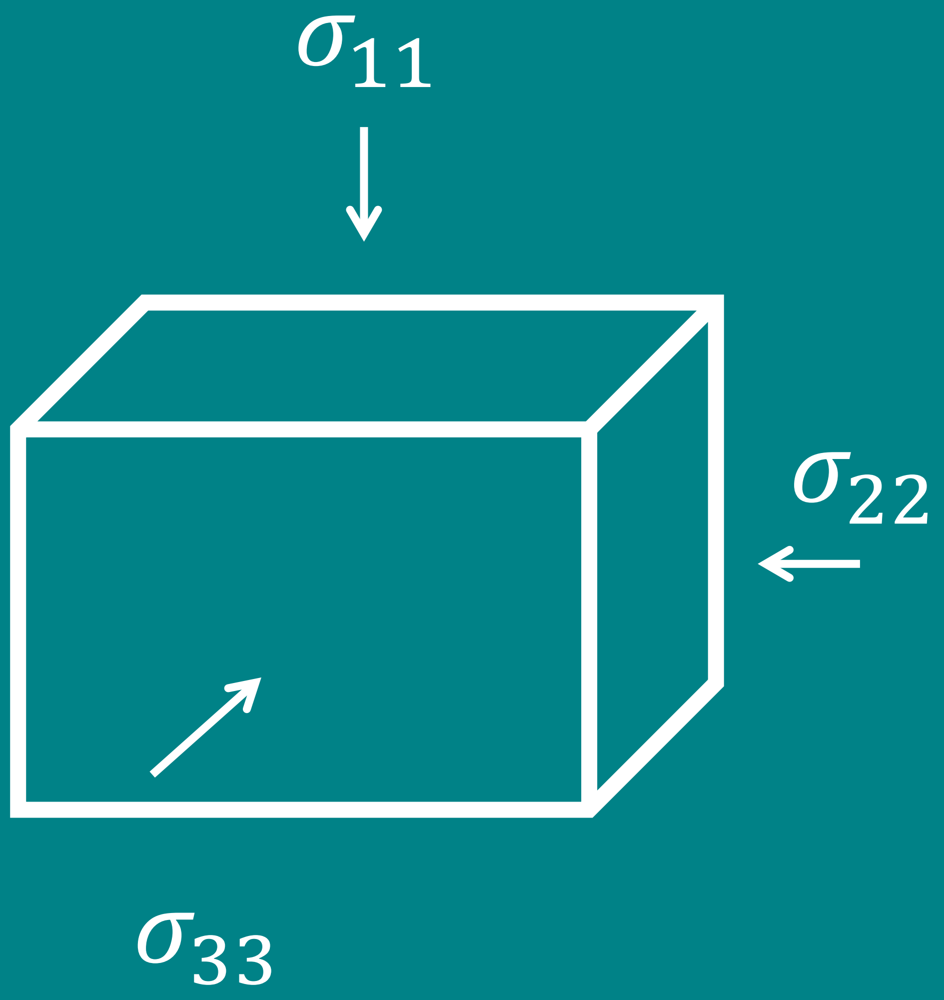


Shear stress components

Stress tensor

$$\sigma = \begin{pmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \end{pmatrix} = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{pmatrix}$$

$$= \begin{pmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{pmatrix}$$

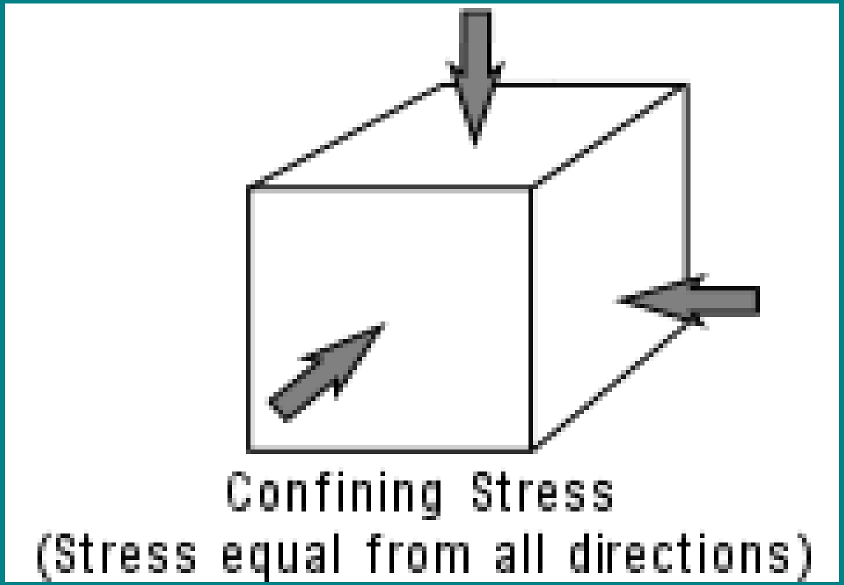


Principal / normal stress components

Uniform normal stress

The components on the diagonal of the stress tensor, σ_{xx}, σ_{yy}, σ_{zz}, are the normal stresses and cause compression and tension of the material, since the forces are parallel with the normal of the plane on which they work.

Uniform normal stress ($\sigma_{xx} = \sigma_{yy} = \sigma_{zz}$) in an isotropic material causes a change in volume, not in shape.

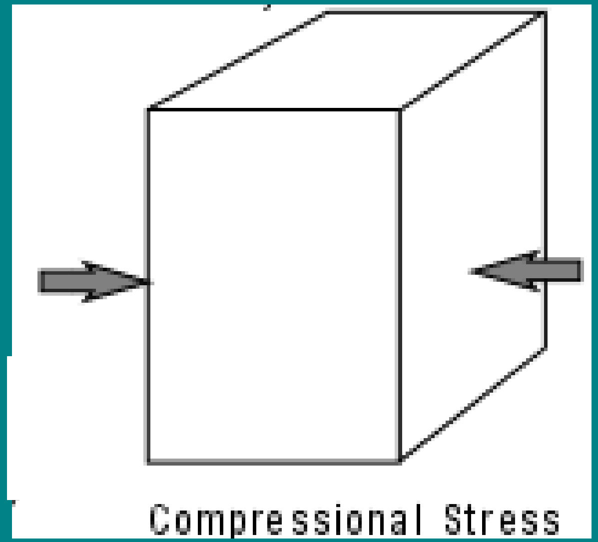


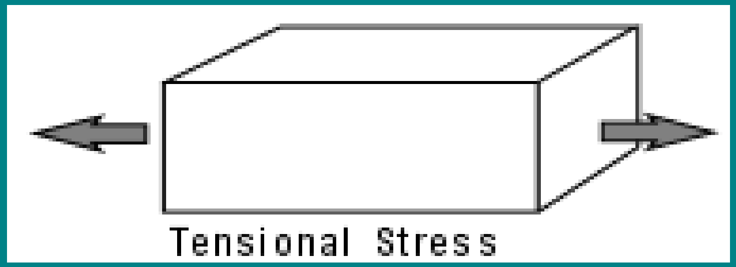
Uniform uniaxial stress

Non-uniform normal stress ($\sigma_{xx} \neq \sigma_{yy} \neq \sigma_{zz}$) cause a change in volume and shape also in isotropic materials.

Normal forces directed toward each other on the same plane (compressive stresses) cause uniaxial compression.

Normal forces in opposite direction on the same plane (tensional stresses) cause uniaxial tension.



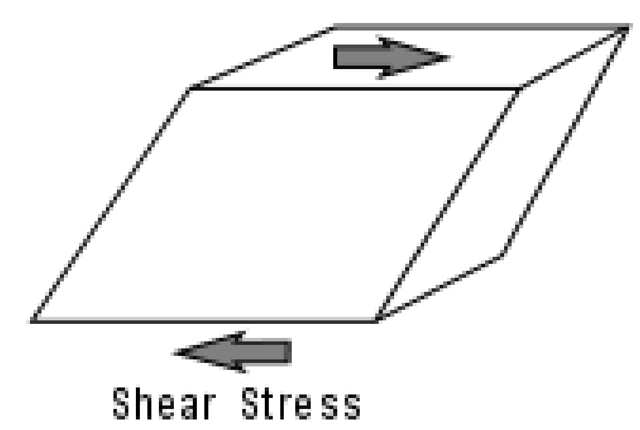


Shear stress

The components that are not on the diagonal of the stress tensor, σ_{xy}, σ_{zx}, σ_{yz}, etc., are shear stresses and cause shear or couple in the material. The forces are perpendicular to the normal of the plane on which they work.

For pure shear the forces are parallel but in opposite directions on the opposite planes.

An isotropic material changes shape without changing volume.

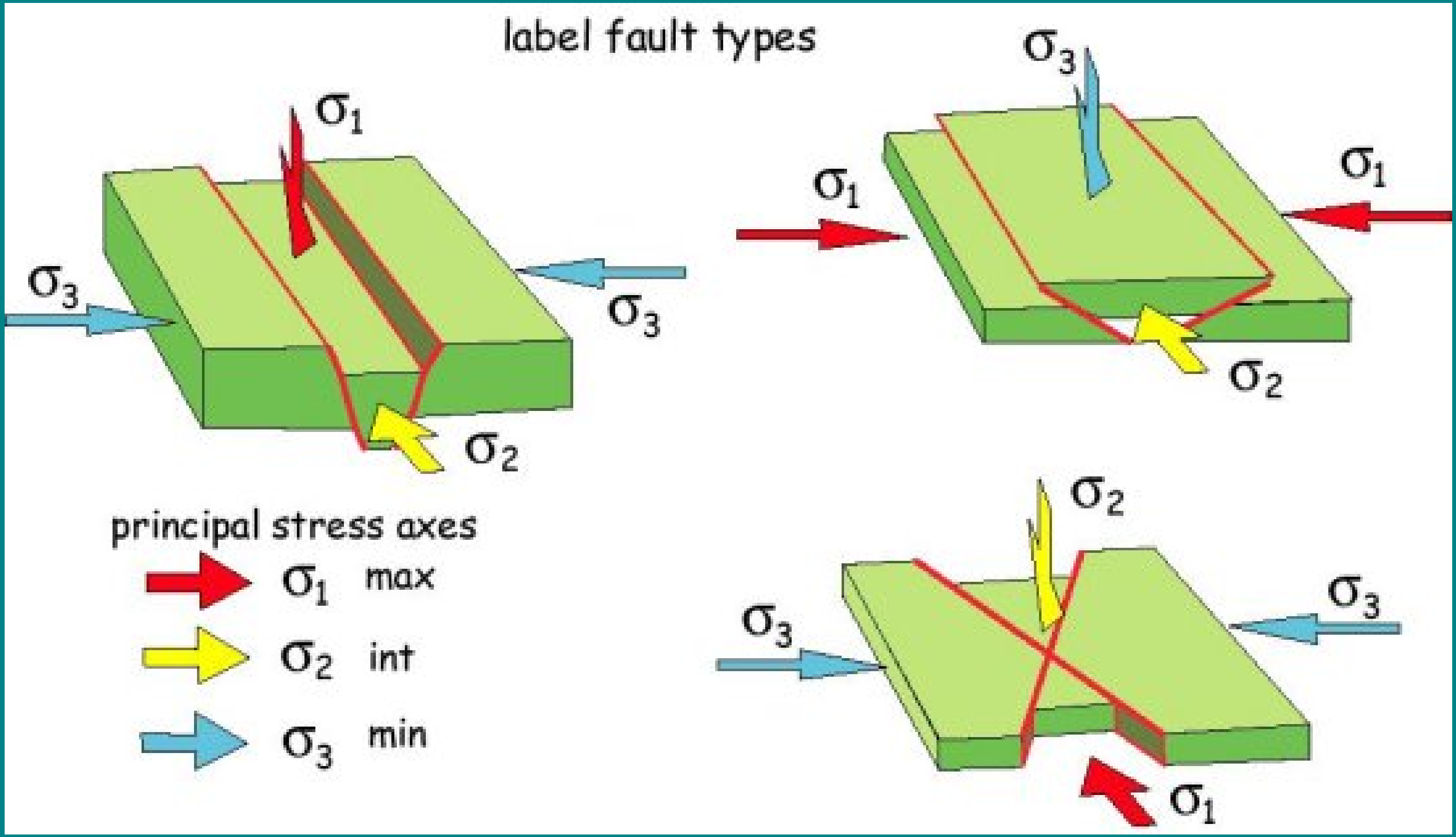


Stress conditions in the Earth

- Difference in magnitude between the three principal stress conditions controls favourable orientation of growth of faults and fractures

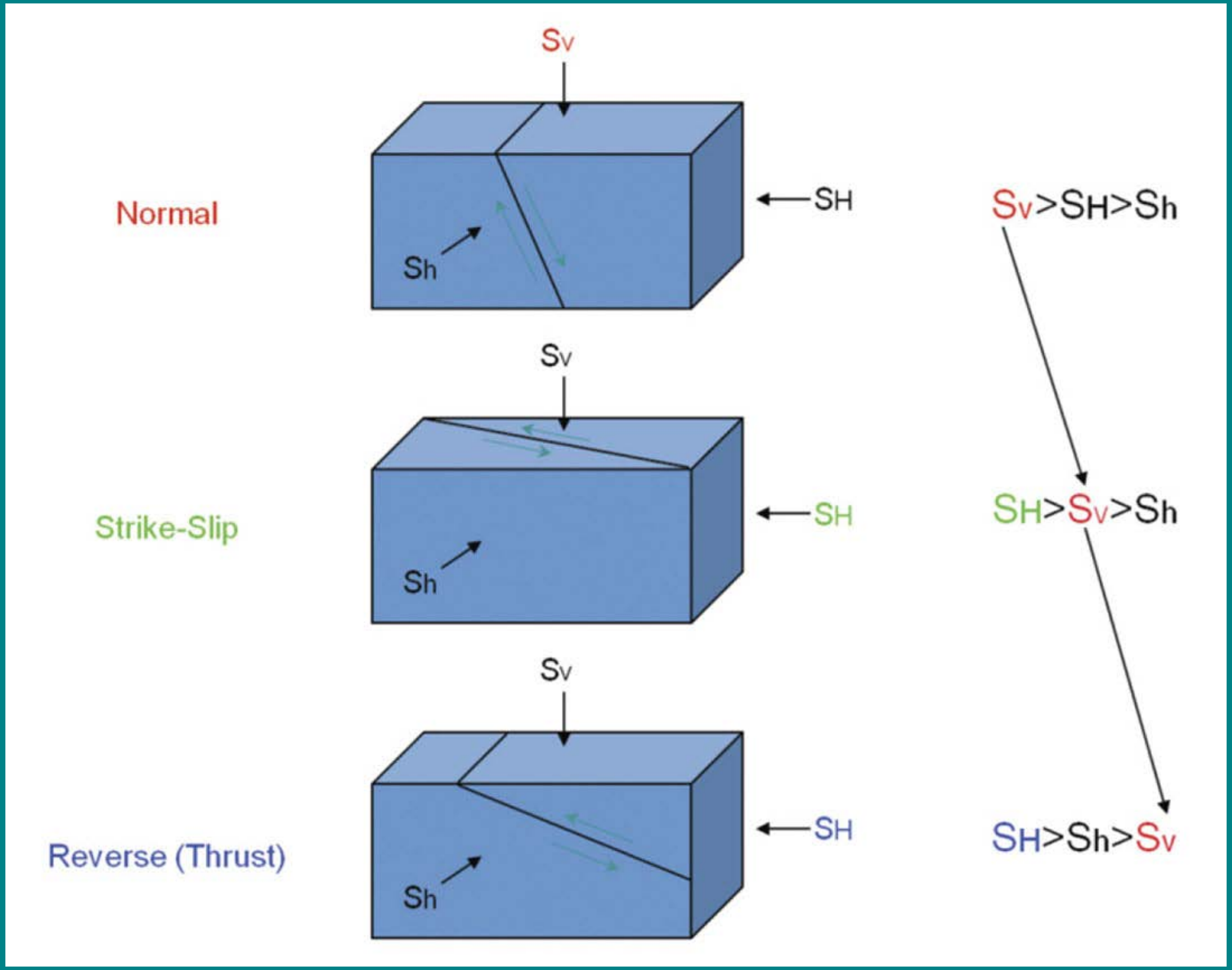
- Direction of the 3 principal stresses controls fracture growth direction in an Earth reference frame AND have control current fracture opening.

Stress conditions in the Earth



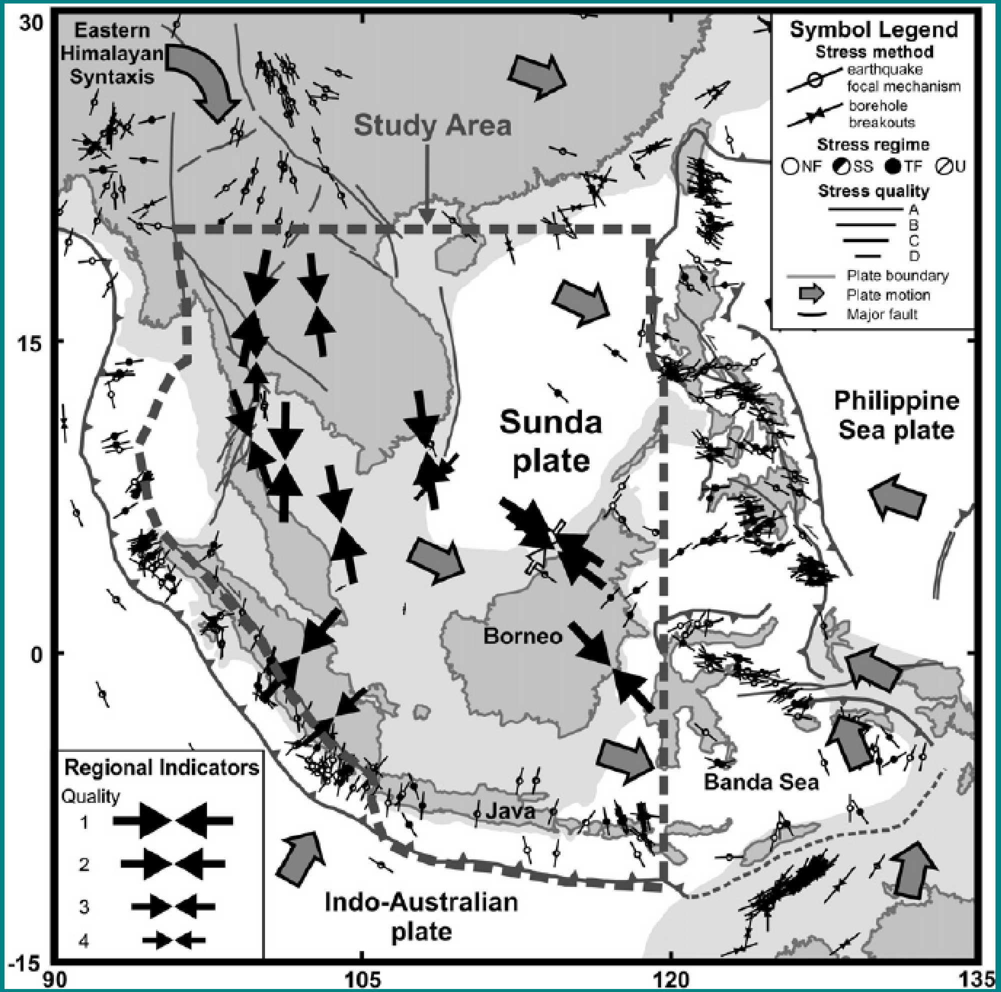
http://earth.leeds.ac.uk/ugpublic/ears1053/2003/lecture03/notes3.htm

Stress conditions in the Earth



http://csegrecorder.com/articles/view/geomechanics-bridging-the-gap-from-geophysics-to-engineering

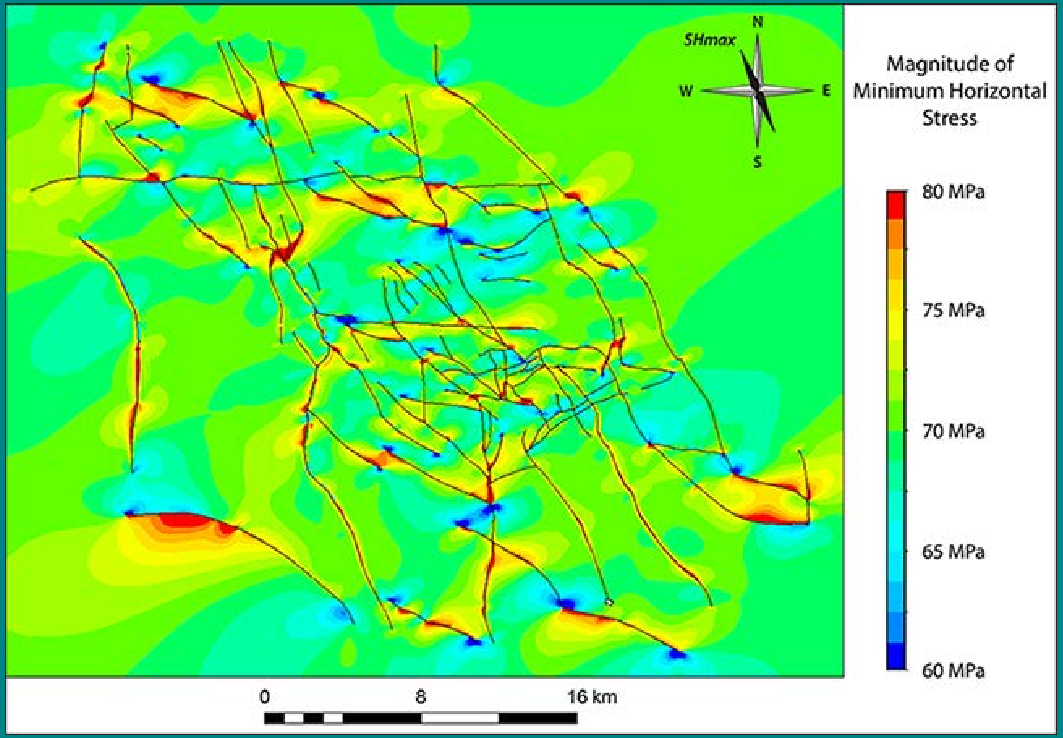
Horizontal stresses in Indonesia



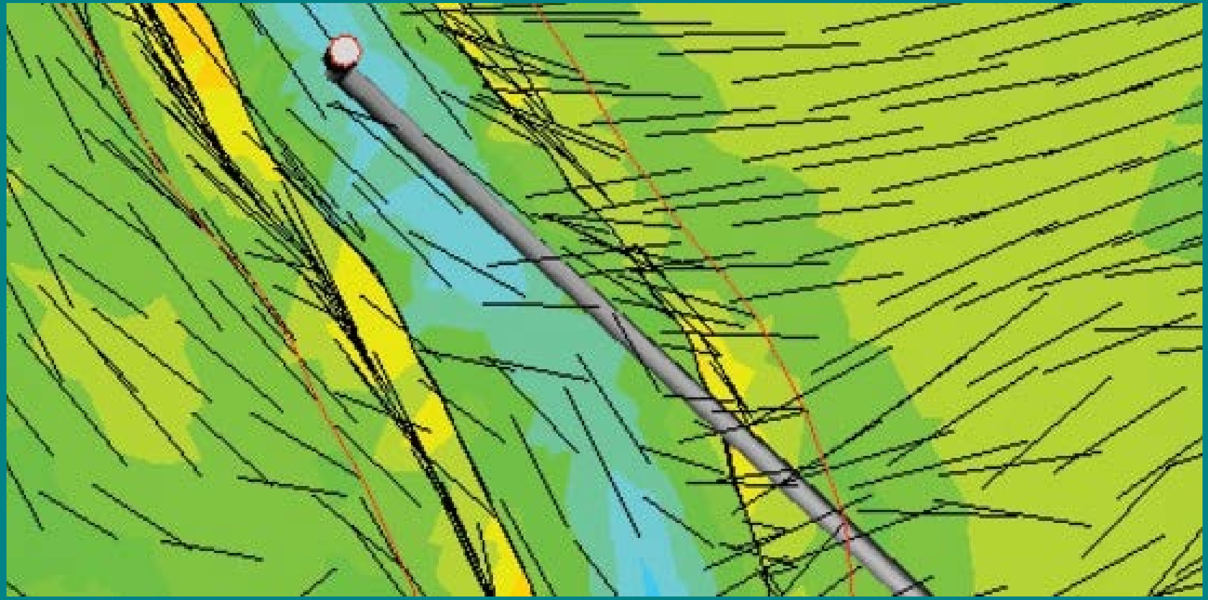
Tingay et al.:
‘NE–SW in Sumatra, and NNE–SSW in Java, with the NE–SW stress direction in Sumatra confirmed from borehole breakouts and hydraulic fracture tests (Fig. 7, Mount and Suppe, 1992)’

Tingay et al., 2010.

Local stress magnitude and direction



http://www.geo.tu-darmstadt.de/fg/inggeol/inggeo_forschung/dgmk_forschungsprojekt_721/dgmk_project_721.en.jsp



http://www.golder.com/ph/modules.php?name=Newsletters&op=viewarticle&sp_id=167&page_id=1100&article_id=570

Local stresses can vary significantly from tectonic stresses

Strain

- Deformation is the transformation of a body from a *reference* configuration to a *new* configuration

- Strain is a description of deformation in terms of *relative* displacement of particles.

Strain

Strain

- Strain is a description of deformation in terms of *relative* displacement of particles.

- Strain is the length change of a body with respect to its original length

$$\varepsilon = \frac{\Delta L}{L} \qquad \varepsilon = \frac{L_{new} - L}{L}$$

- Unit of strain?

Strain

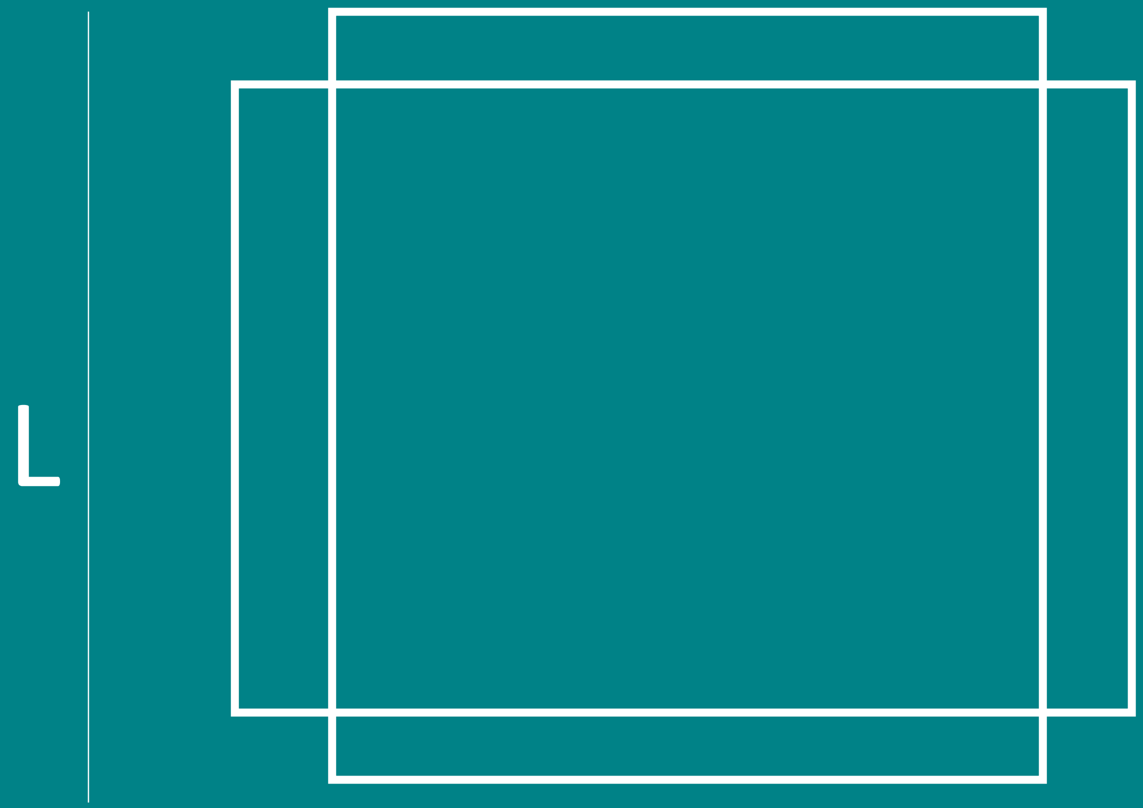
$$\varepsilon = \frac{\Delta L}{L}$$

$$\varepsilon = \frac{L_{new} - L}{L}$$

Strain

$$\varepsilon = \frac{\Delta L}{L}$$

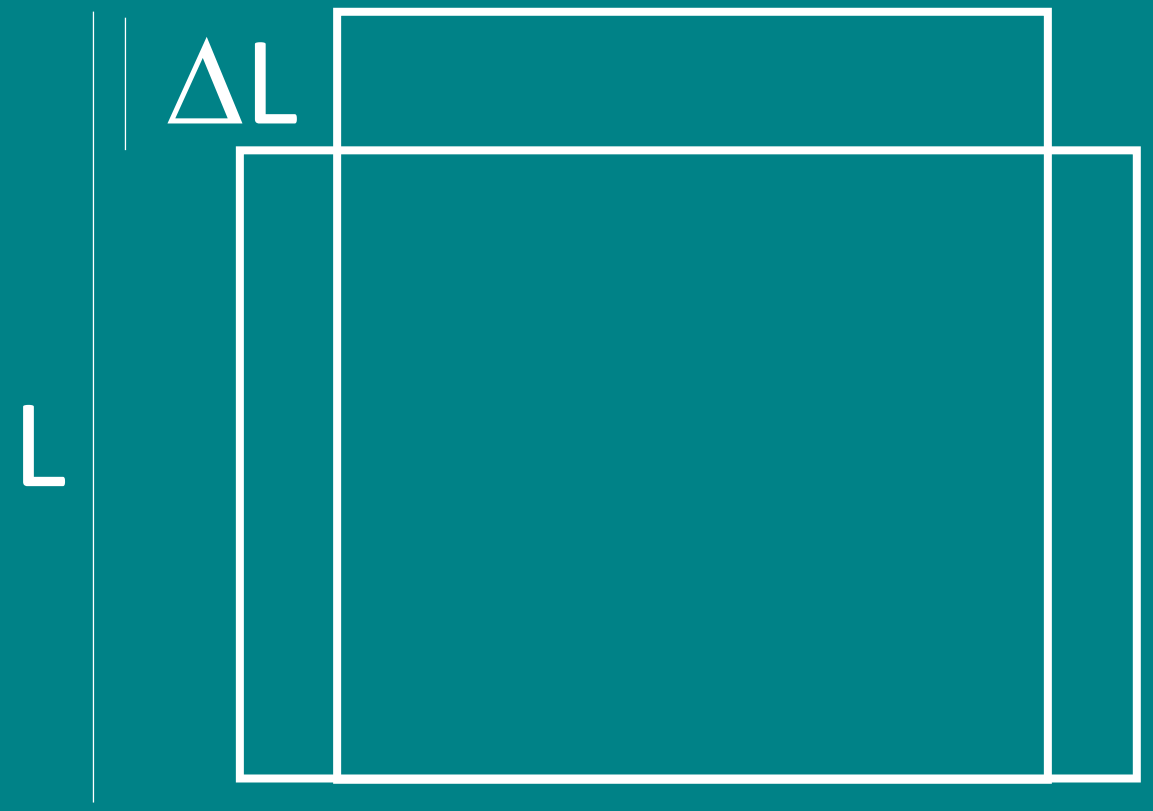
$$\varepsilon = \frac{L_{new} - L}{L}$$



Strain

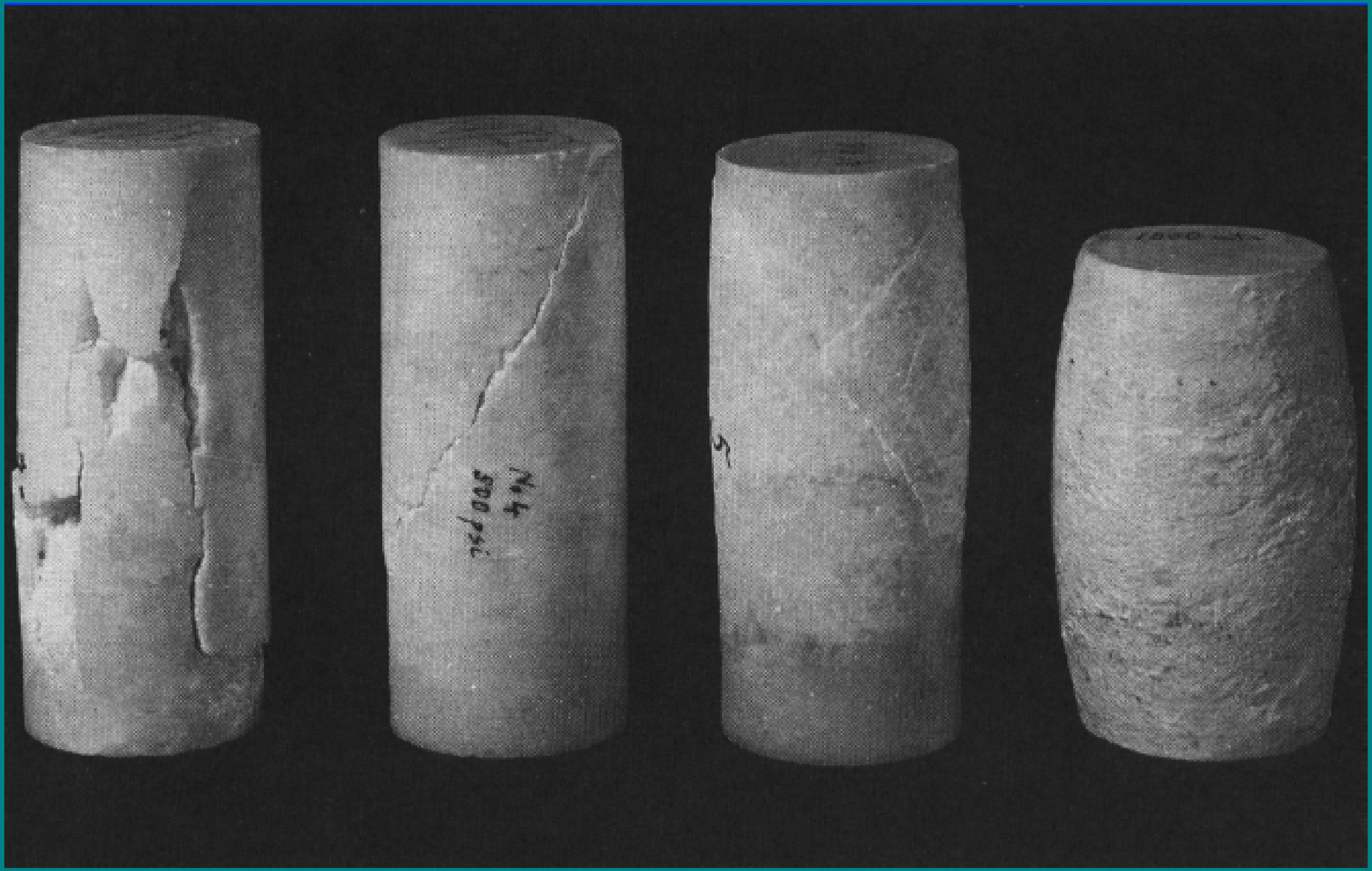
$$\varepsilon = \frac{\Delta L}{L}$$

$$\varepsilon = \frac{L_{new} - L}{L}$$



Assumption: No volume change of the body

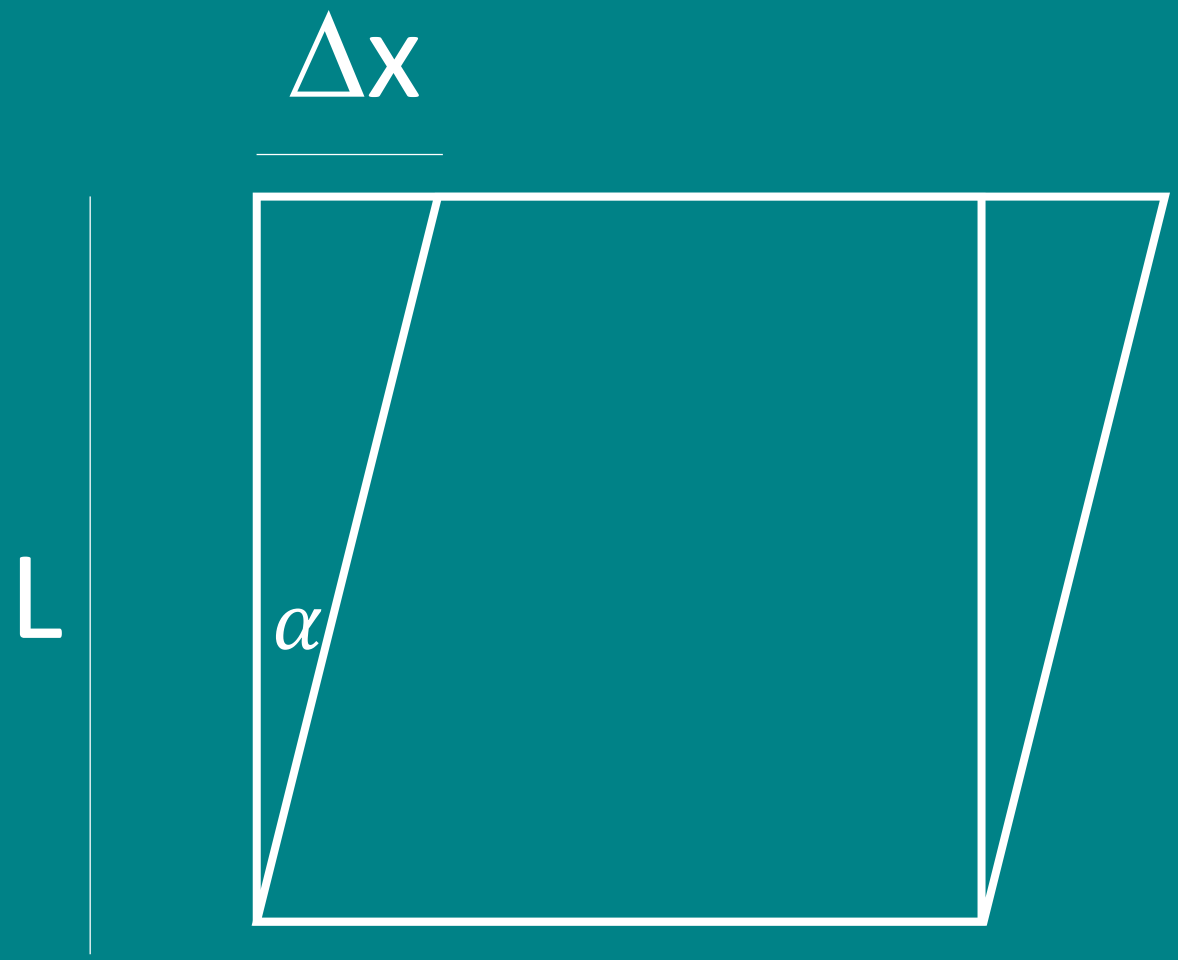
Strain in lab experiments



geode.colorado.edu

Shear strain

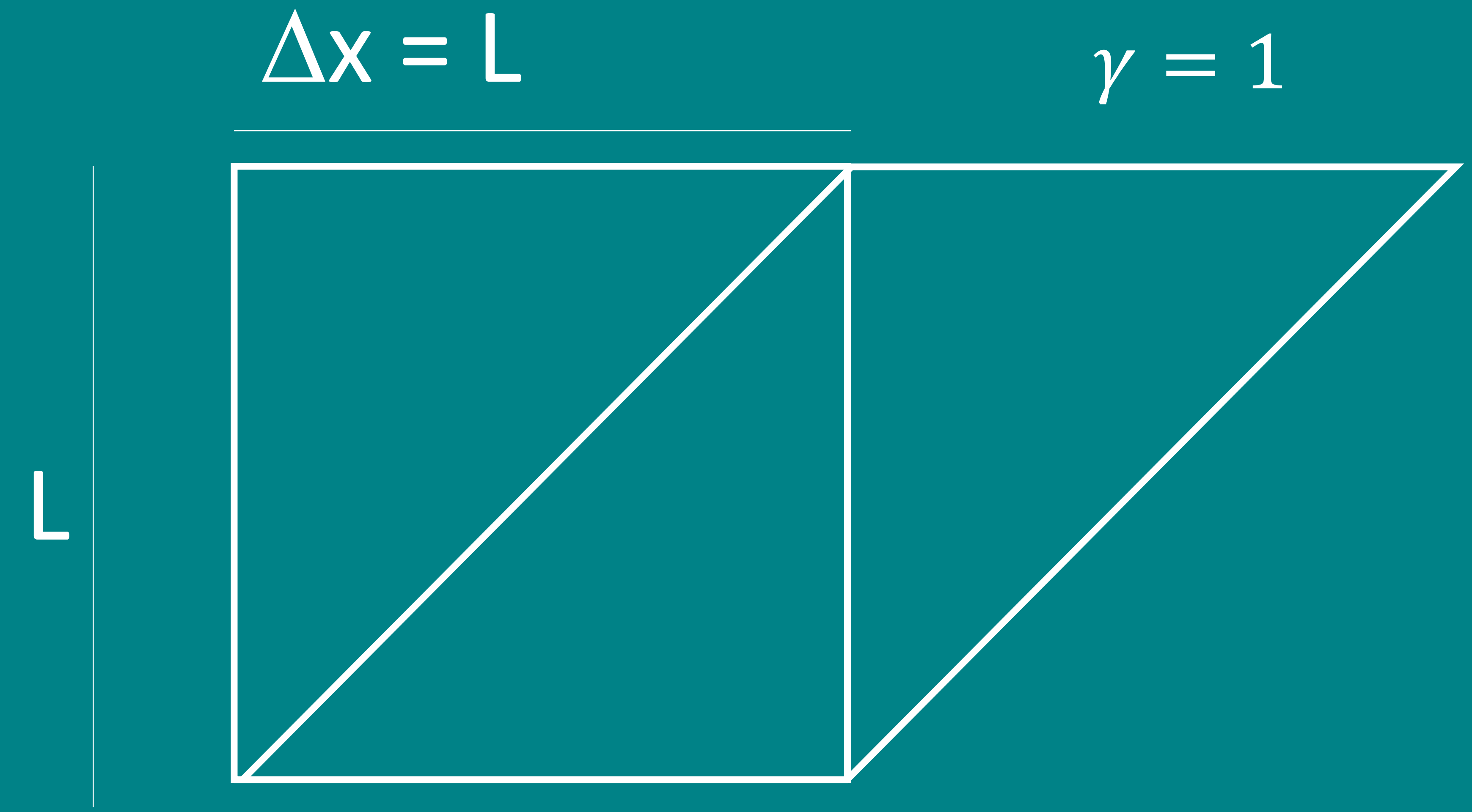
Shear strain



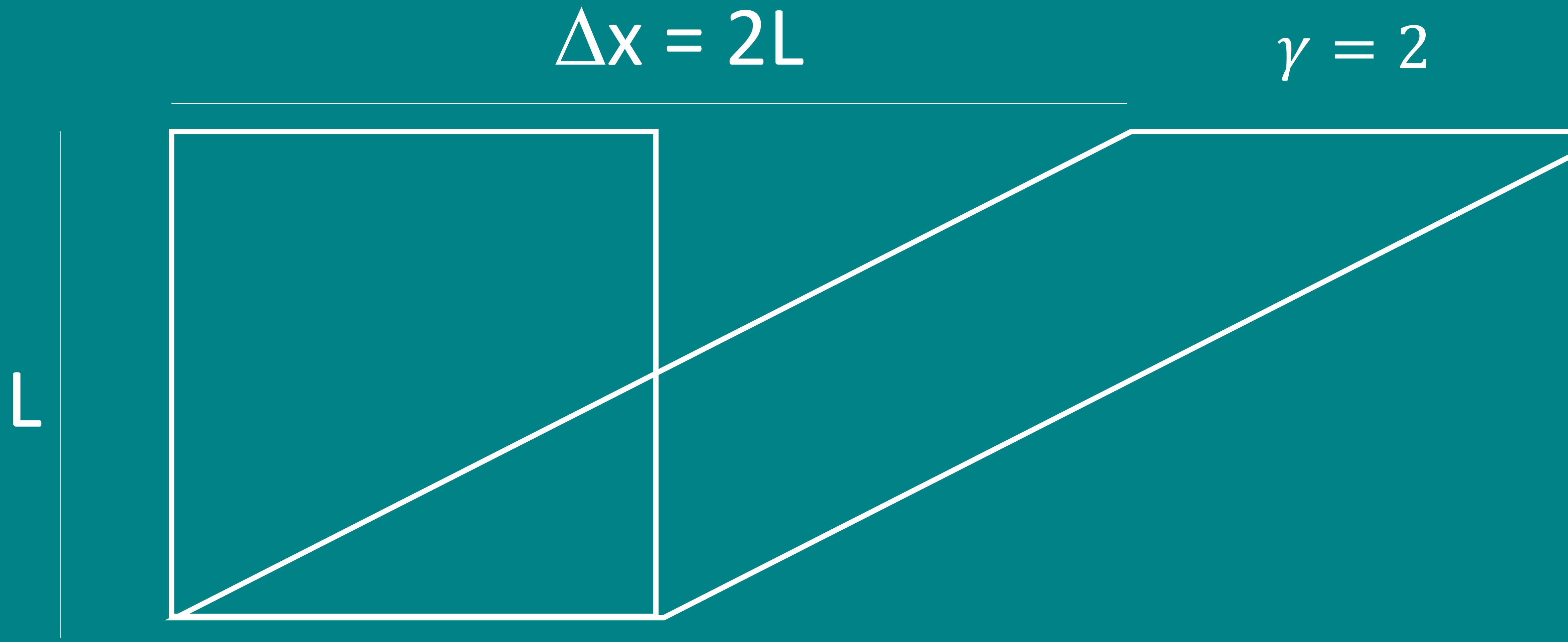
$$\gamma = \frac{\Delta x}{L} = \tan\alpha$$

Δx = Displacement / Deformation
L = Original Length
γ = Shear strain

Shear strain



Shear strain

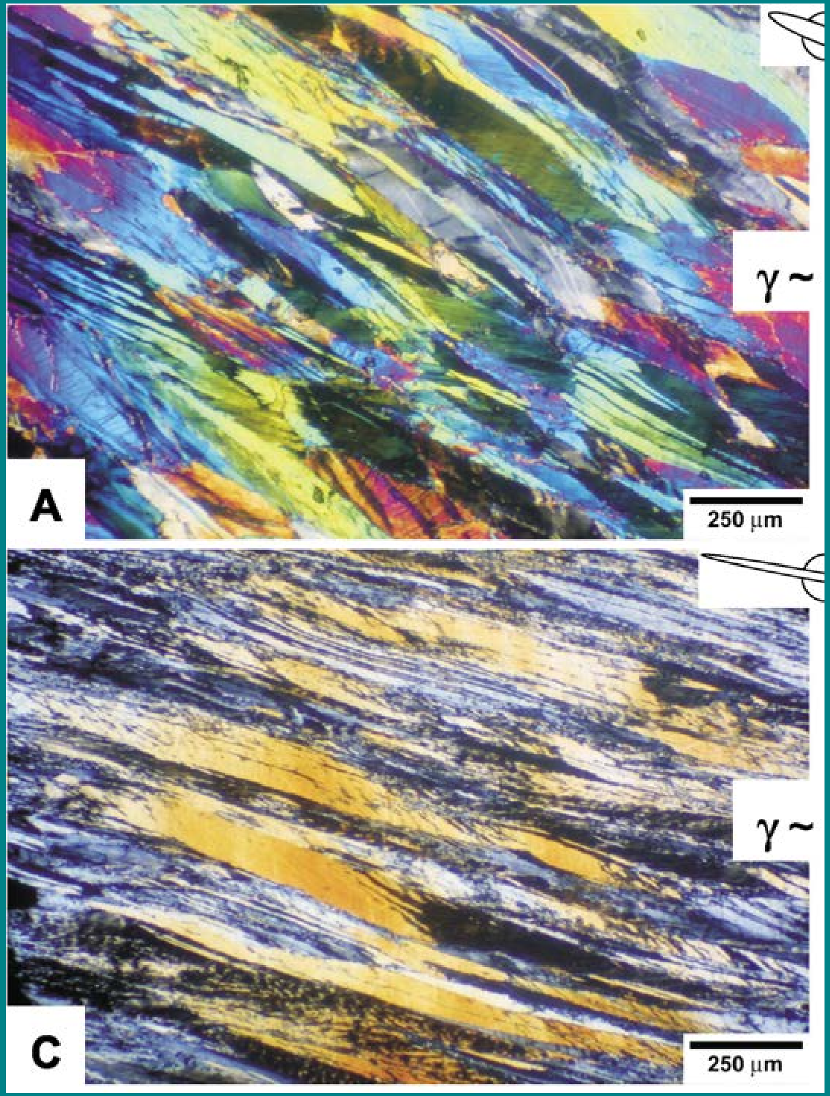


In-class stress-strain exercise - 1
10 min

Lavallee et al., 2008

- Calculate the vertical and horizontal strain for each of these samples. The sample at the left is the original undeformed sample.

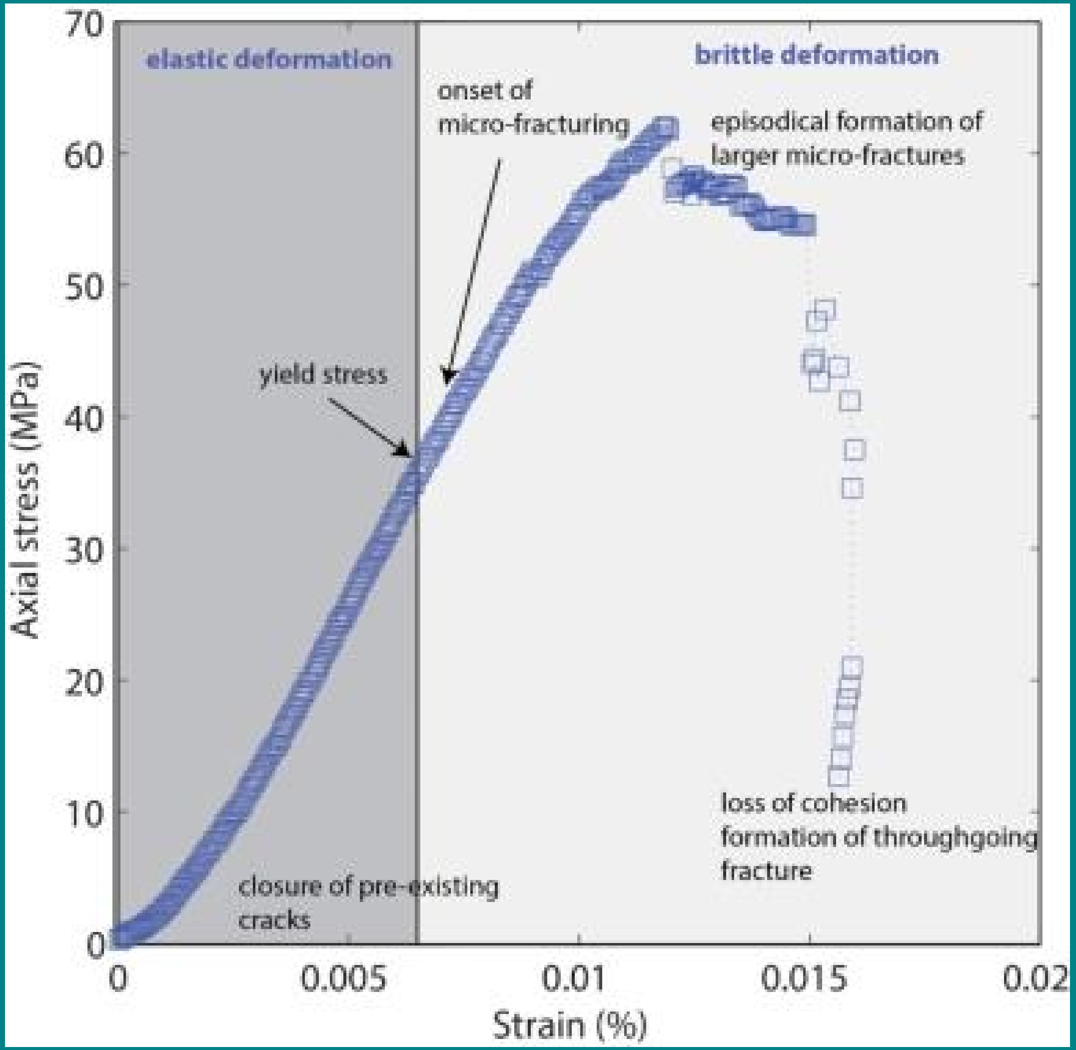
In-class stress-strain exercise - 2



- What is the shear strain of these 2 samples? The lineations in the images indicate the long axes of the parallelogram.

Barnhoorn et al, 2004

In-class stress-strain exercise - 3

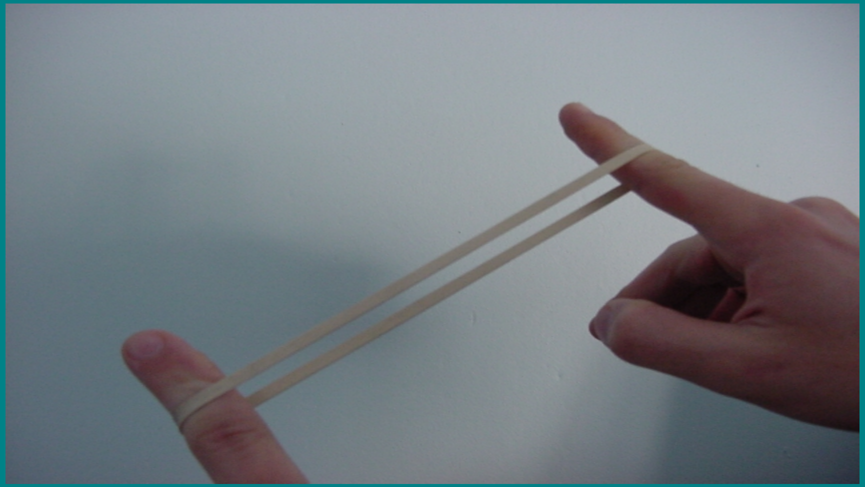


- What is the stress-strain ratio ($^{\Delta\sigma}/_{\Delta\varepsilon}$) of this experimentally deformed shale sample? Determine the stress-strain ratio only in the gray part of the diagram. The unit of the stress-strain ratio is in GPa.

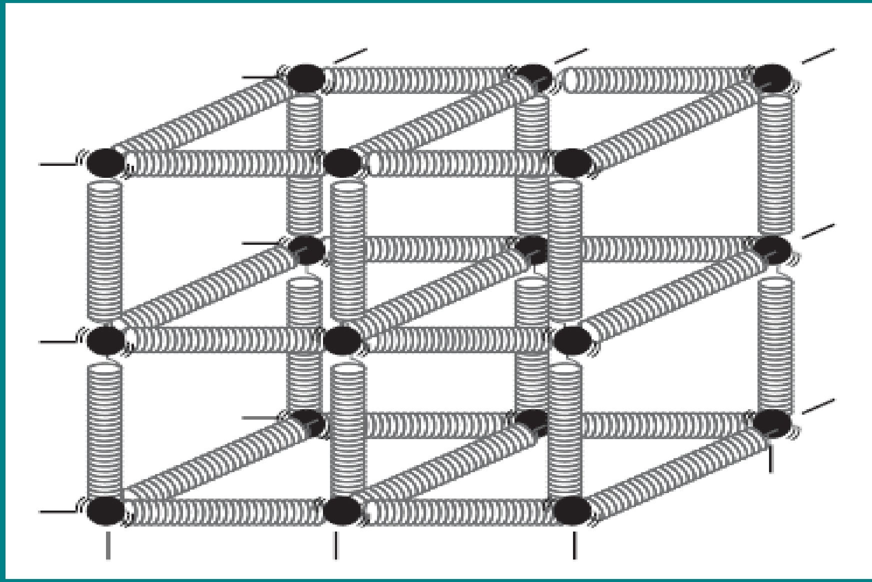
15 minute break

Elastic behaviour

- Definition of elasticity
  - In physics, **elasticity** is a physical property of materials which return to their original shape after the stress that caused their deformation is no longer applied.



http://en.wikipedia.org/wiki/Elasticity_%28physics%29



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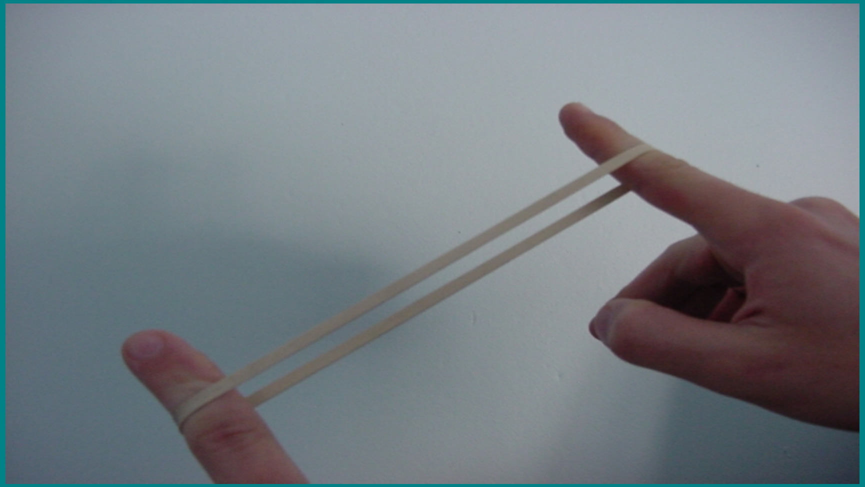

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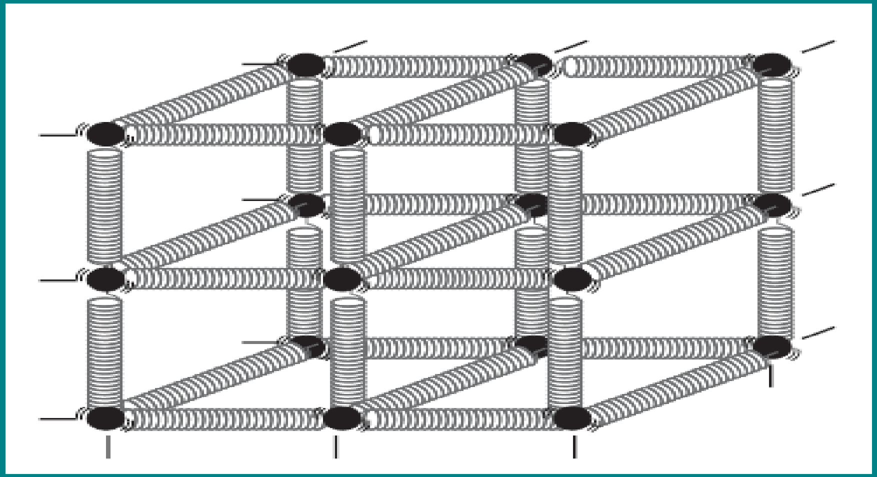

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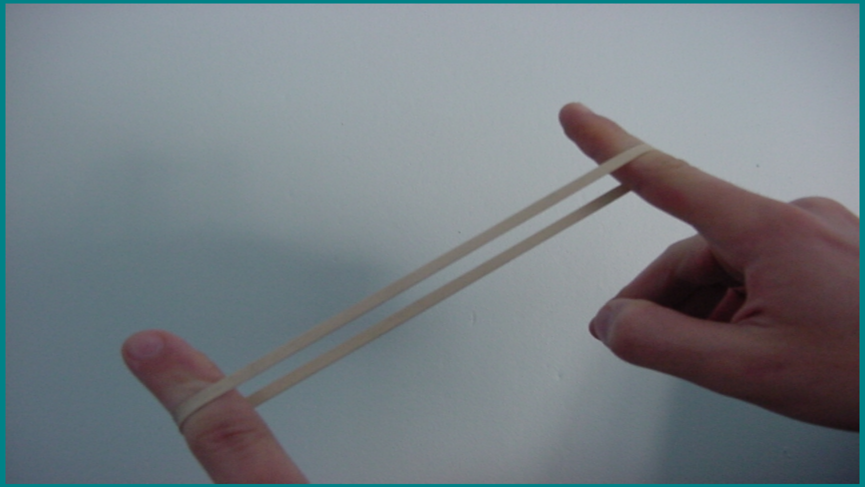

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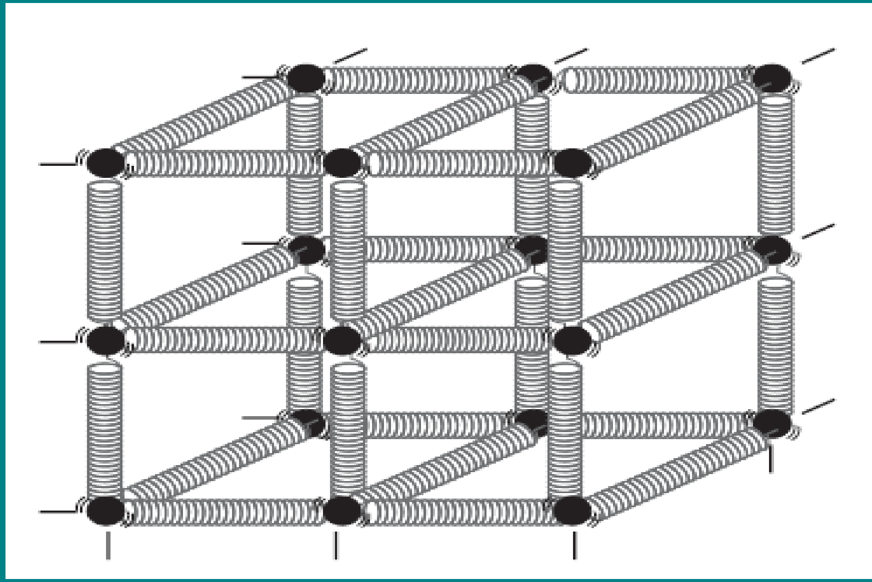
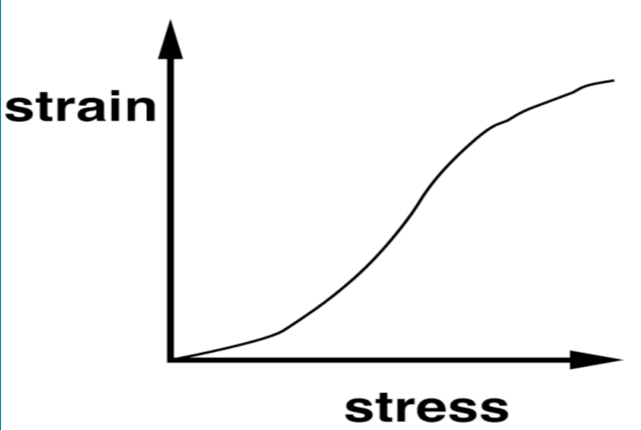


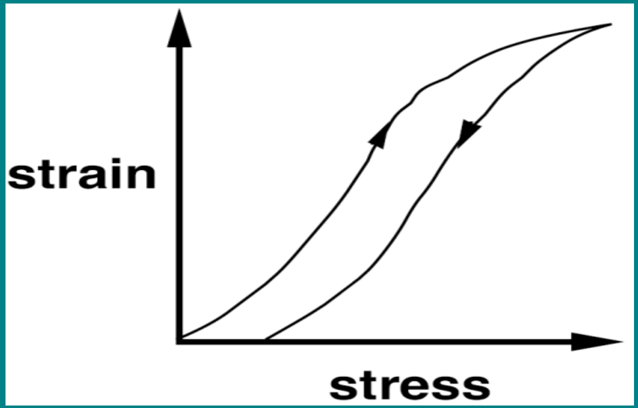
Elastic vs. inelastic behaviour

A material is elastic if:

- The material returns to its unique relaxed state after the applied loads are removed.
- The displacement and strain are independent of the loading history (i.e. no hysteresis).



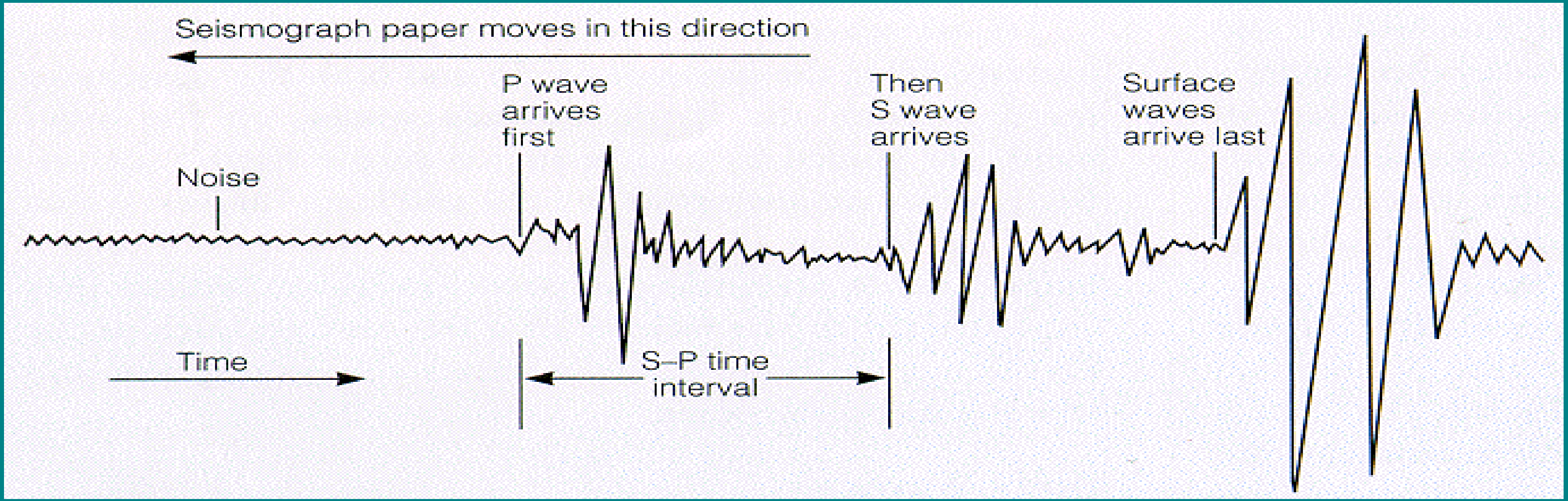
Unique stress-strain relation

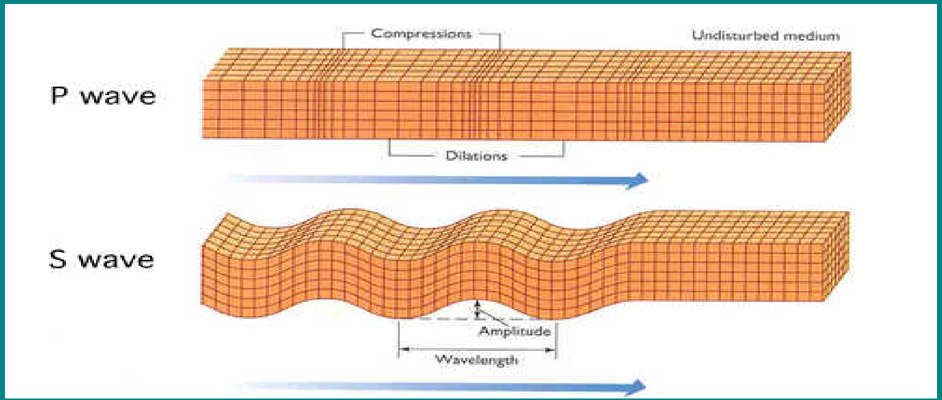


Mavko, 2003

Non-unique stress-strain relation

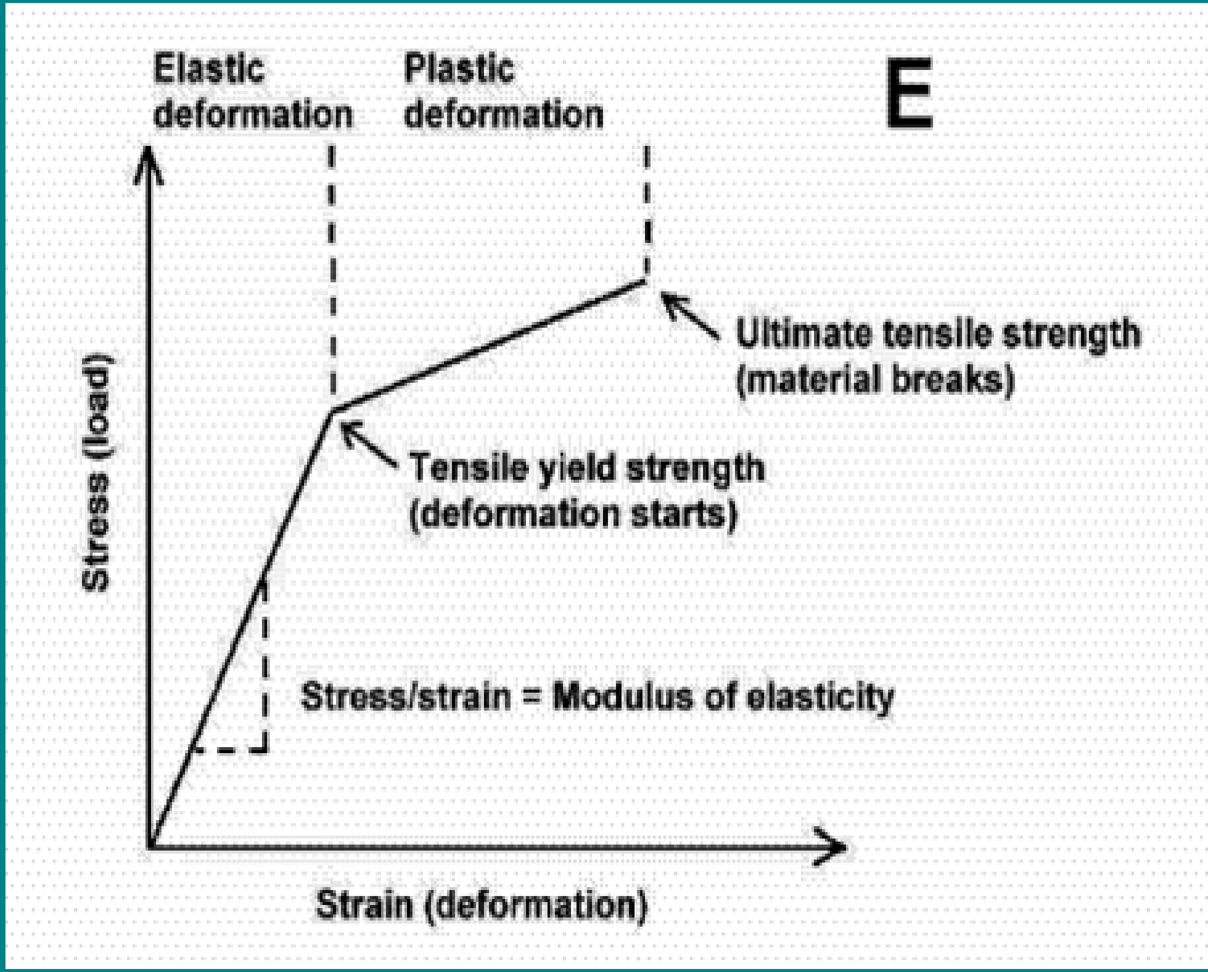
Seismic waves



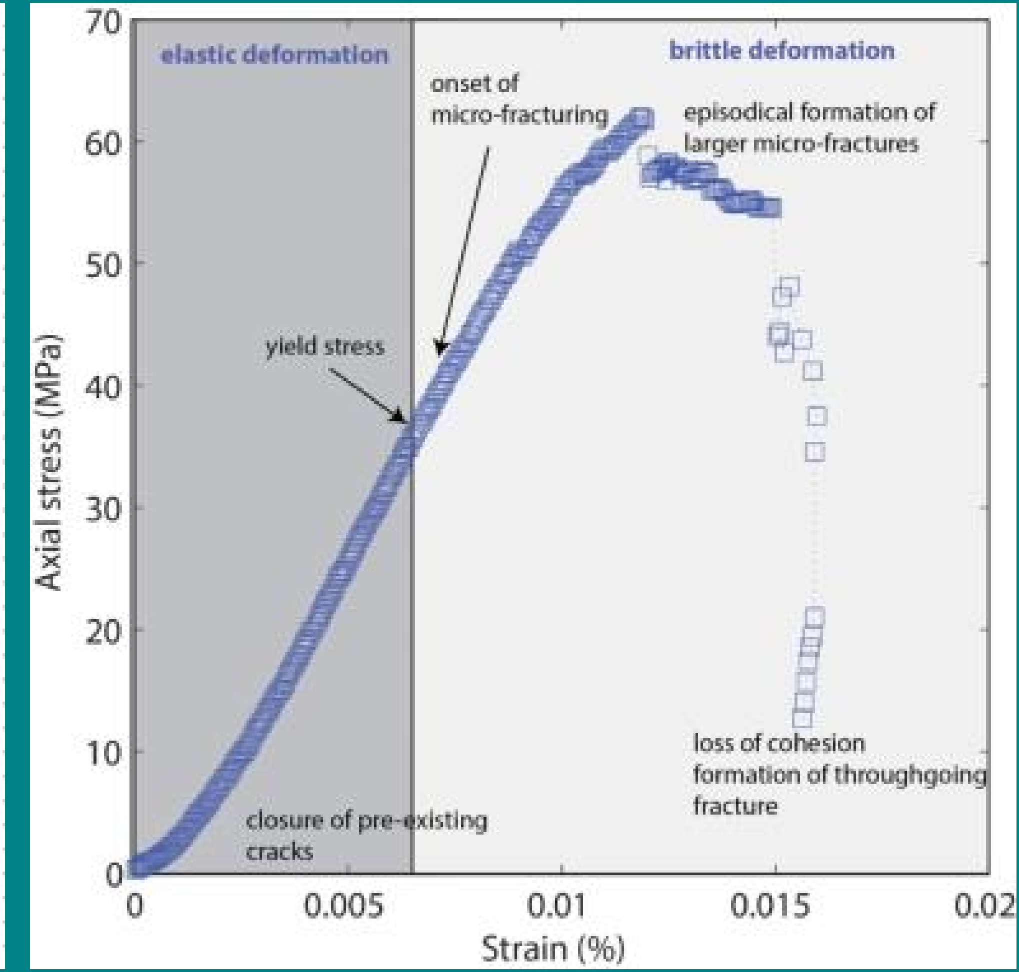


http://www.tjhsst.edu/~jlafever/wanimate/Wave_Properties2.html

Elasticity



Elastic deformation
Plastic deformation
E
Ultimate tensile strength (material breaks)
Tensile yield strength (deformation starts)
Stress/strain = Modulus of elasticity
Stress (load)
Strain (deformation)



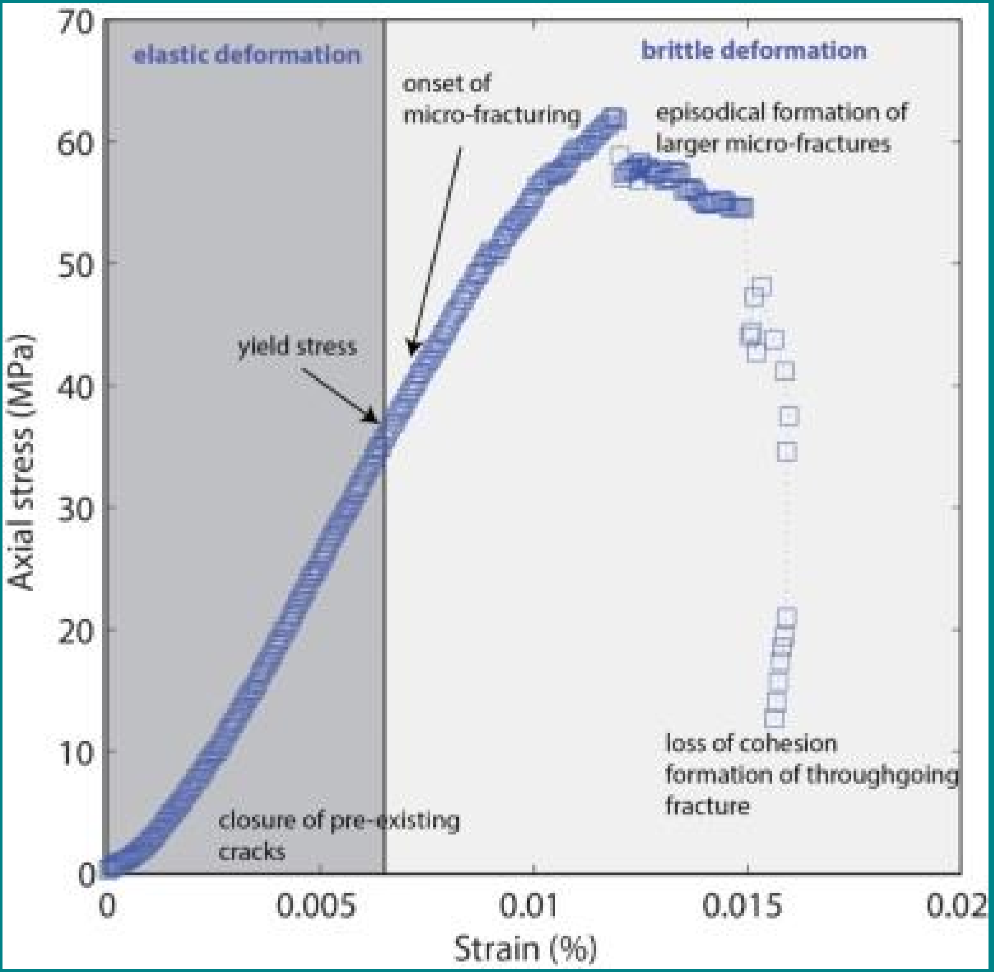
elastic deformation
brittle deformation
onset of micro-fracturing
episodical formation of larger micro-fractures
yield stress
loss of cohesion formation of throughgoing fracture
closure of pre-existing cracks
Axial stress (MPa)
Strain (%)
0
10
20
30
40
50
60
70
0
0.005
0.01
0.015
0.02

Inelastic behaviour

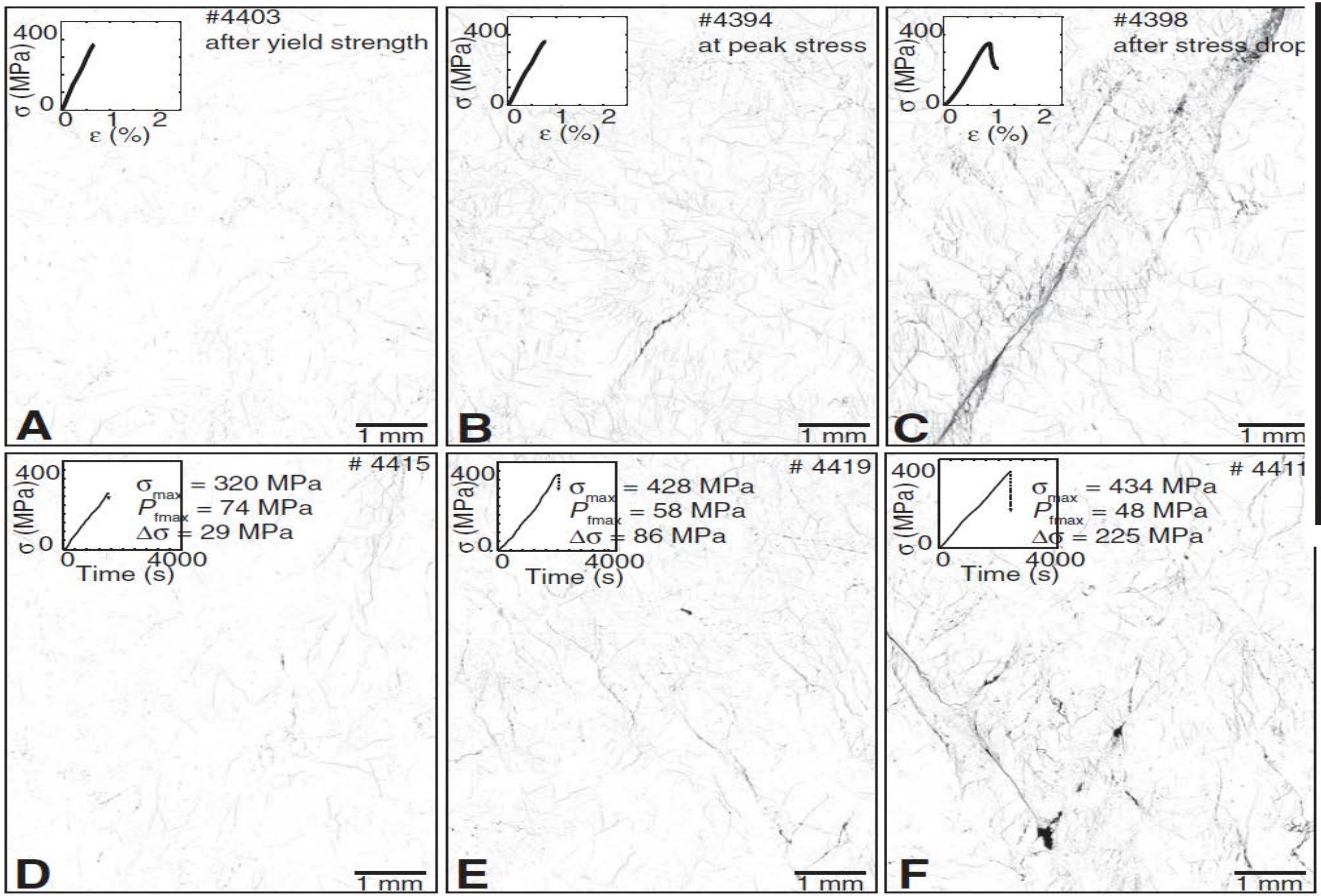
Transition to inelasticity

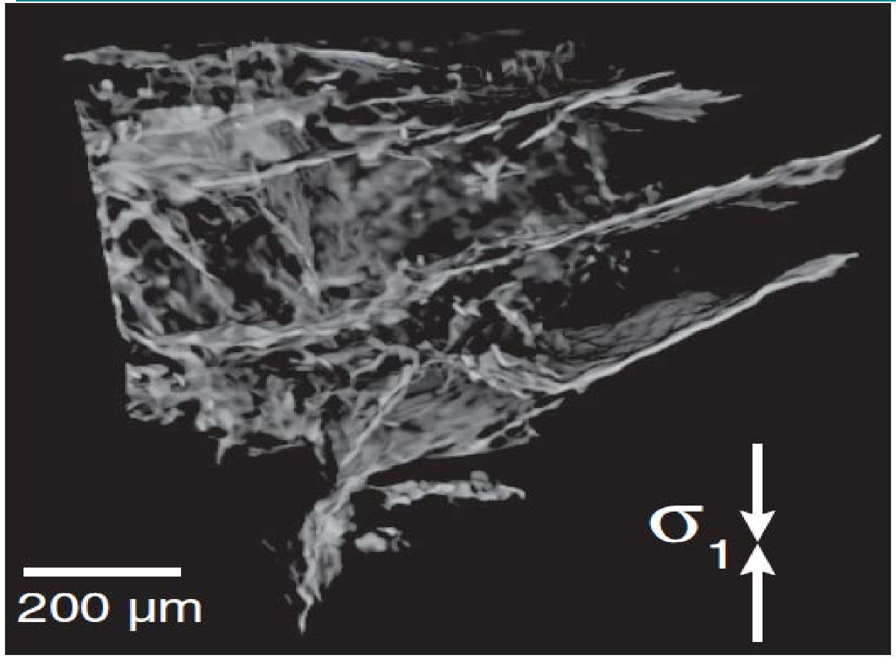
Above a certain stress known as the elastic limit or the yield strength of an elastic material, the relationship between stress and strain becomes non-linear. Beyond this limit, the solid may deform irreversibly, exhibiting plasticity.

Brittle deformation: Typical rupture



Brittle deformation: Experiments

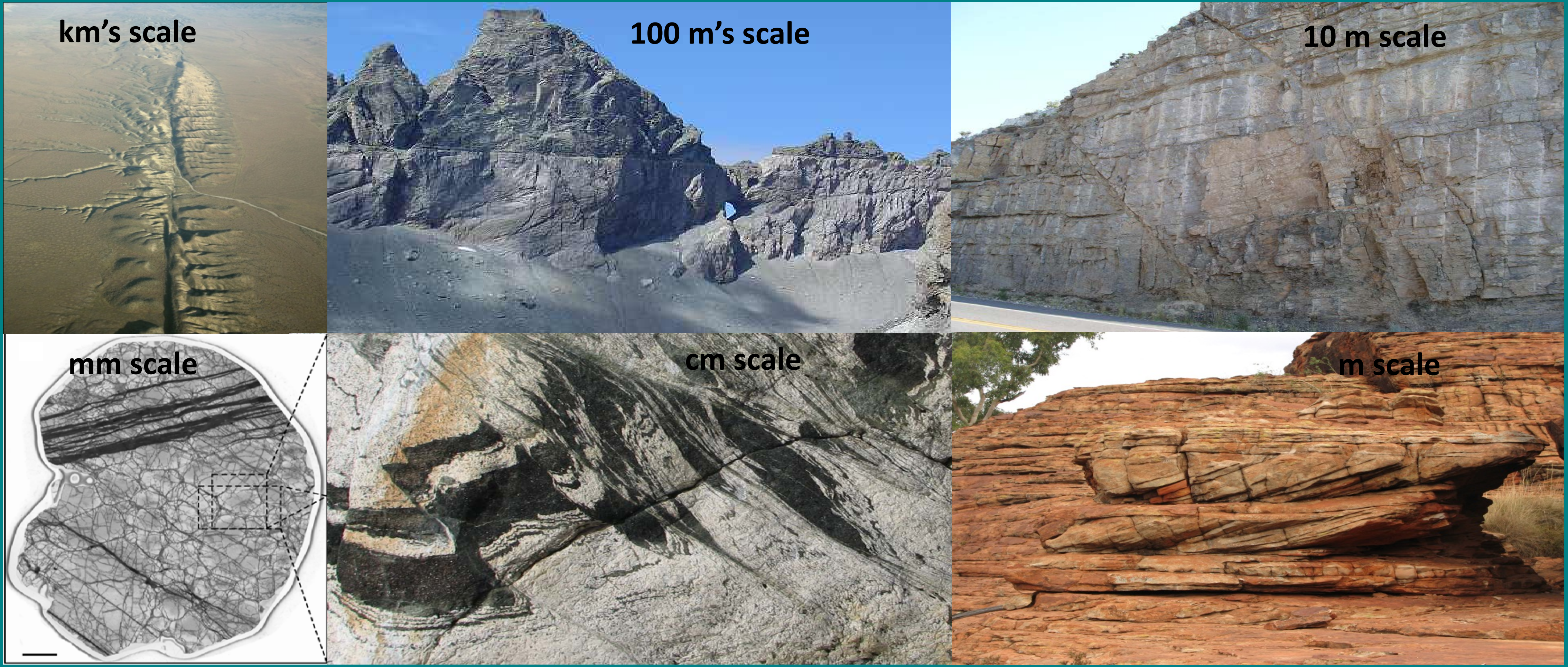




Very low strain before fracturing occurs

Barnhoorn et al., 2010

Fractures

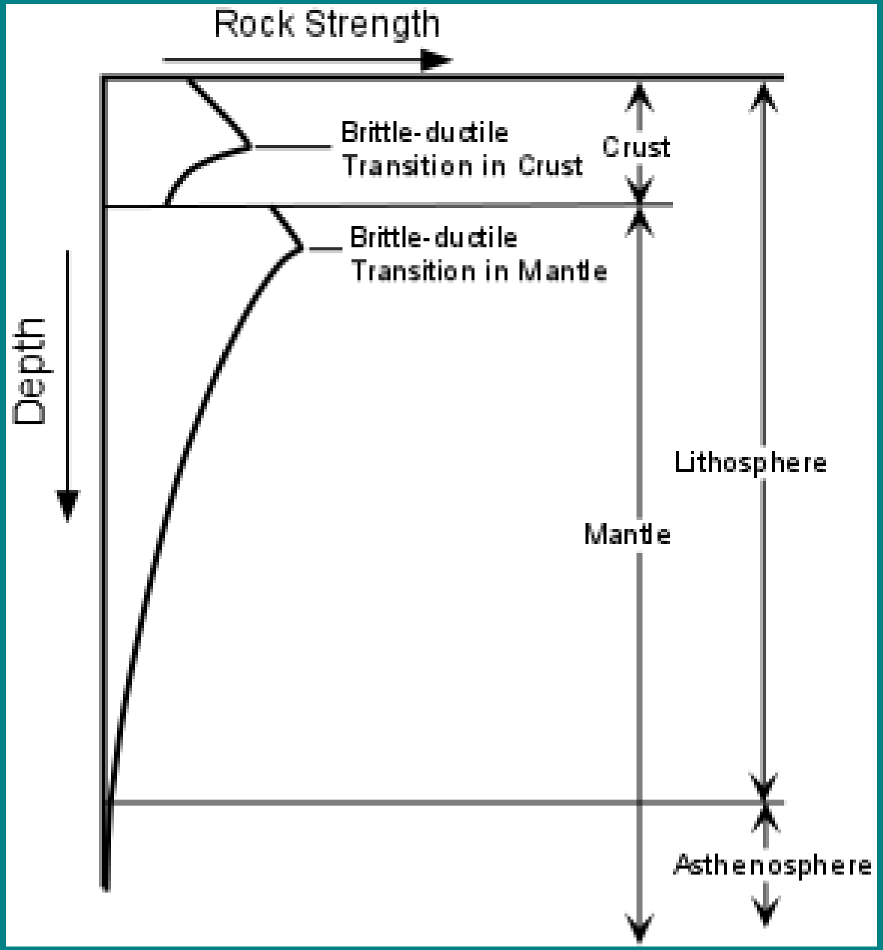


Brittle vs. Ductile deformation

- Brittle
  - Shallow in the Earth
  - Relatively low temperature and pressure conditions

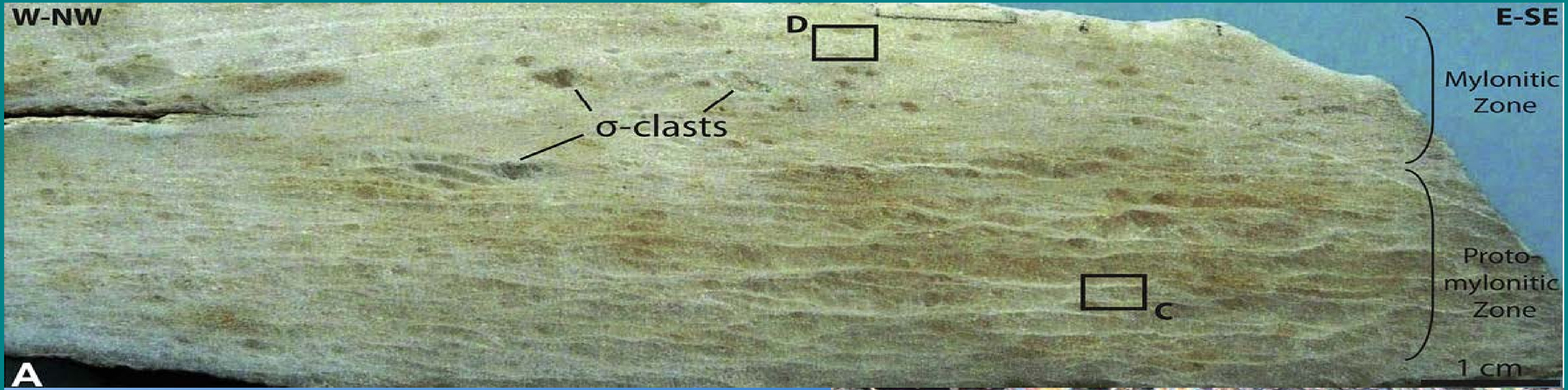
  - Breakage of bonds
  - Fracturing intense at low strain

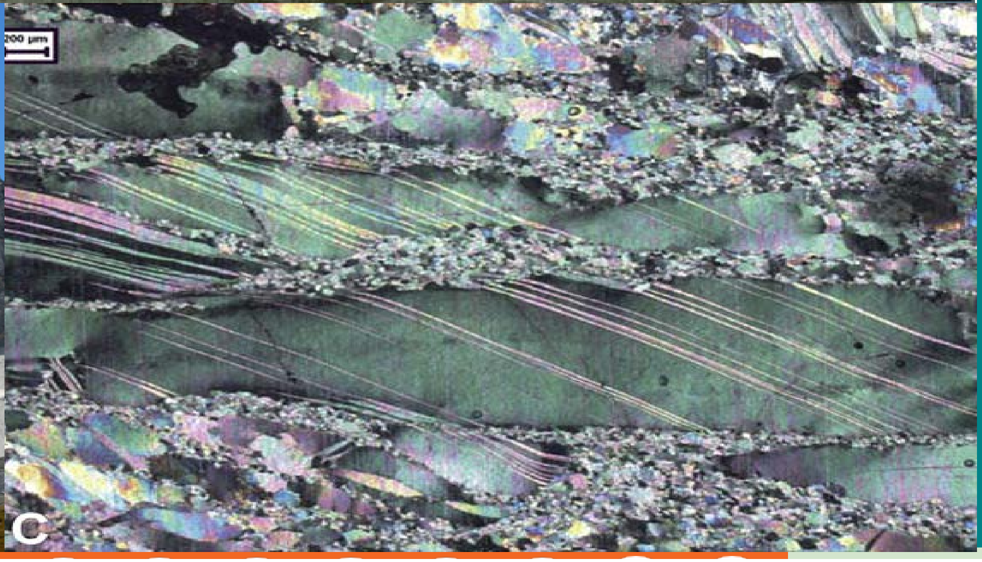
  - Strength is pressure dependent
  - Time-independent
  - Seismicity



http://www.tulane.edu/~sanelson/eens1110/deform.htm

Ductile deformation: Deformation structures in the field

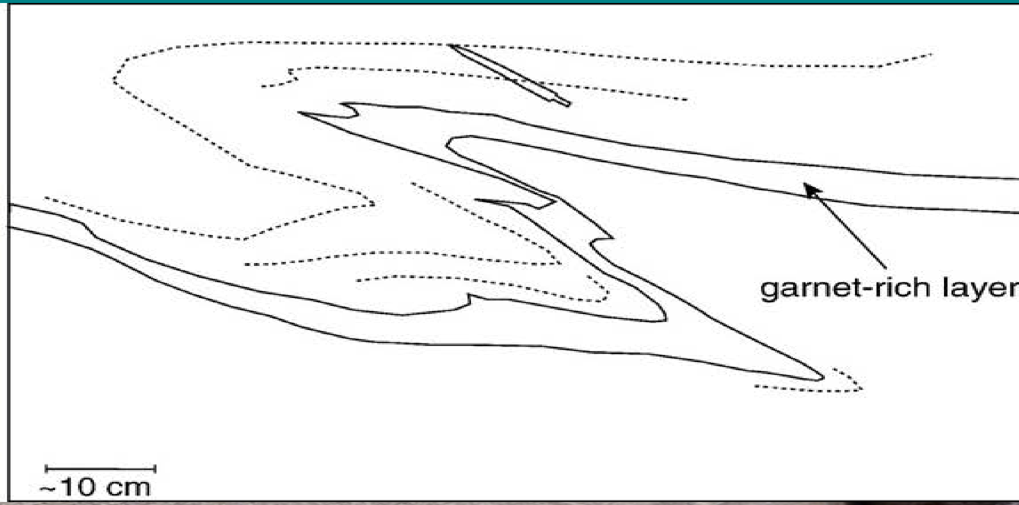




Calcite Mylonites Switzerland & Turkey (Lefebvre et al., 2011)

Ductile deformation: Deformation structures in the field

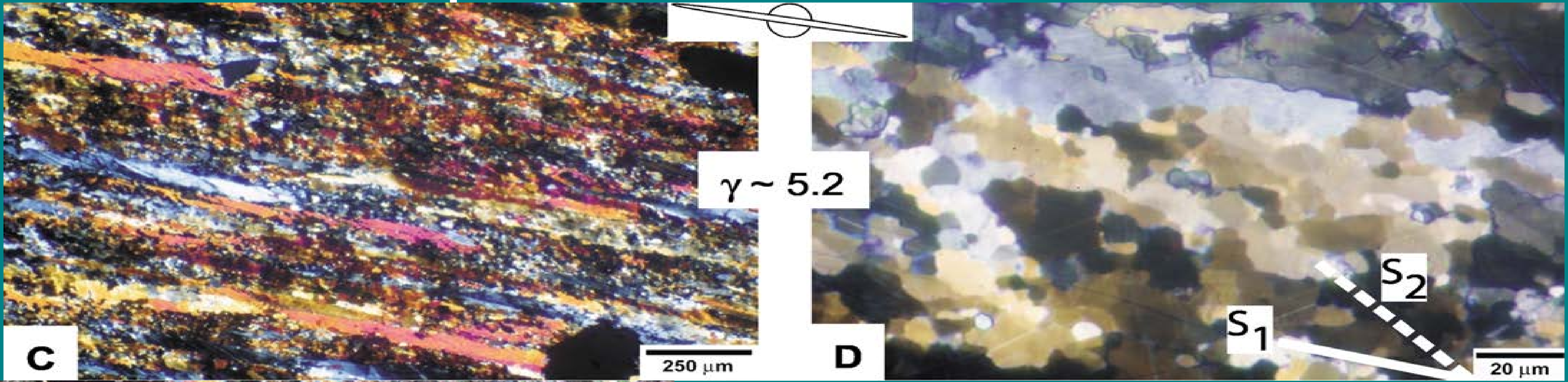
Mantle rocks in Norway: Barnhoorn et al., 2010

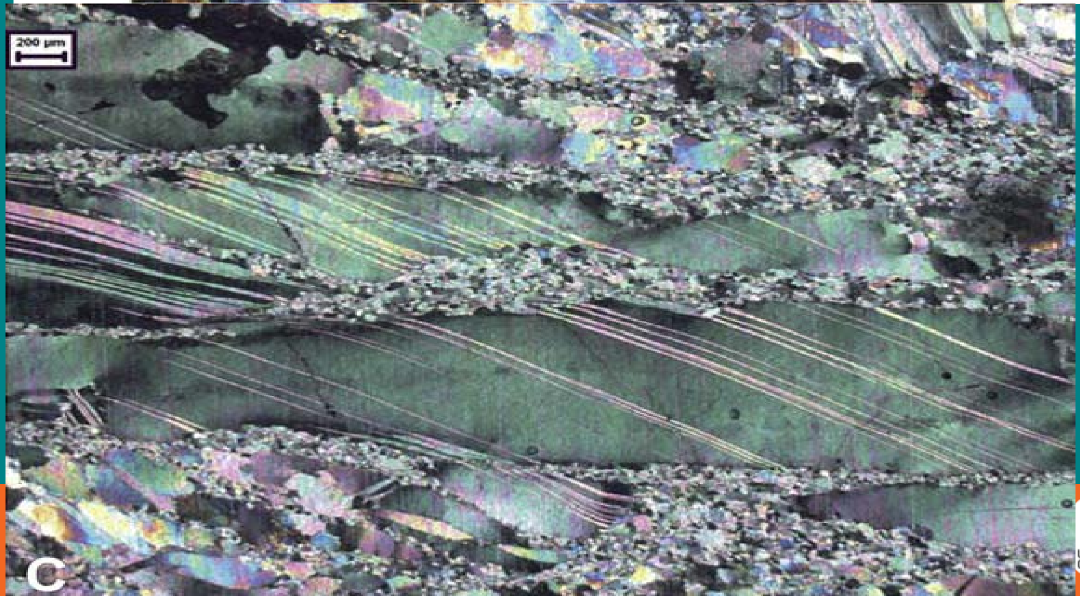


Relative viscosity contrast in folds and boudins

Crustal rocks

Ductile deformation: Comparison field and experiment

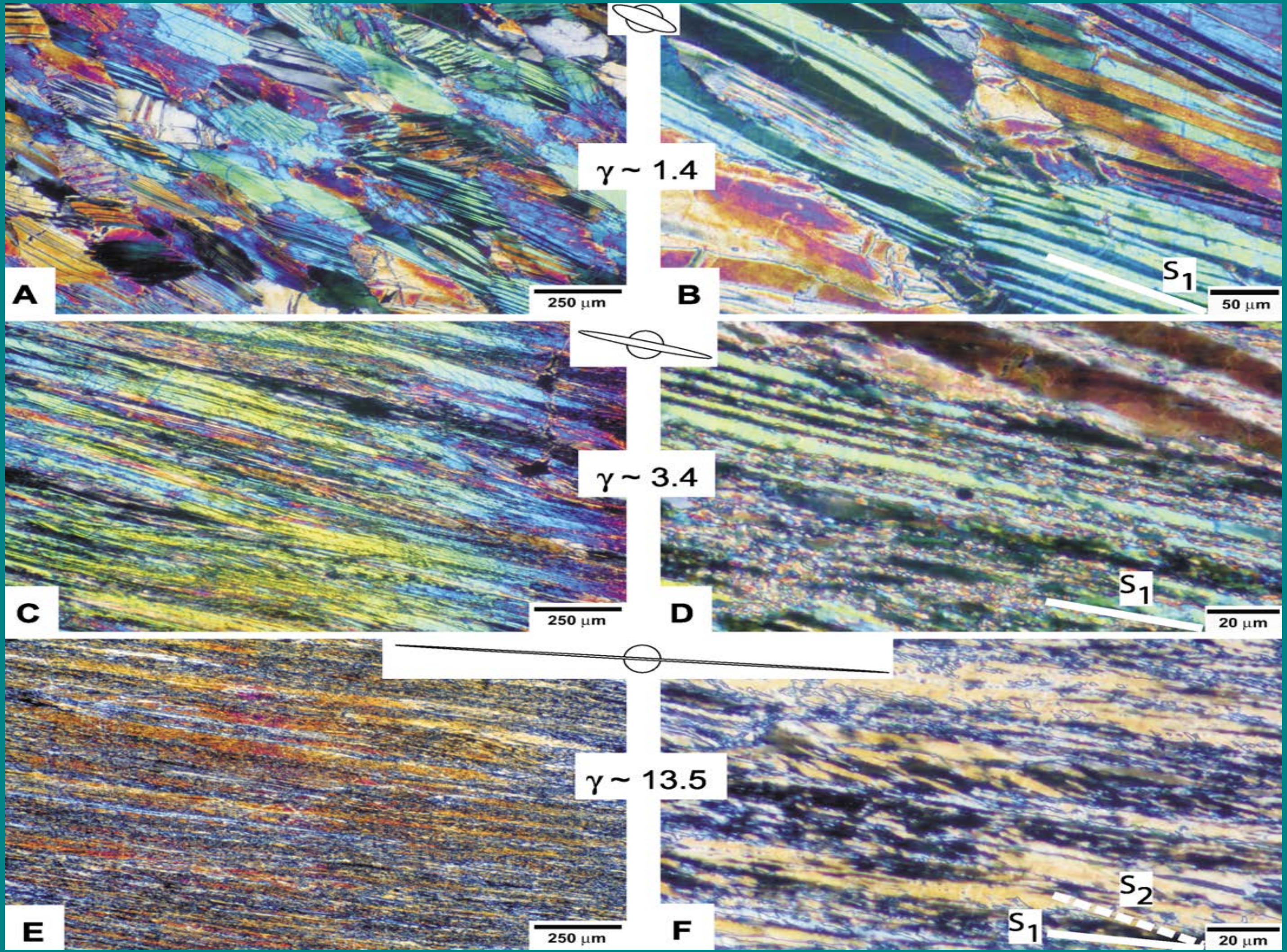




Lab and field: similar structures formed by similar deformation mechanisms

Barnhoorn et al., 2004
Lefebvre et al. 2011

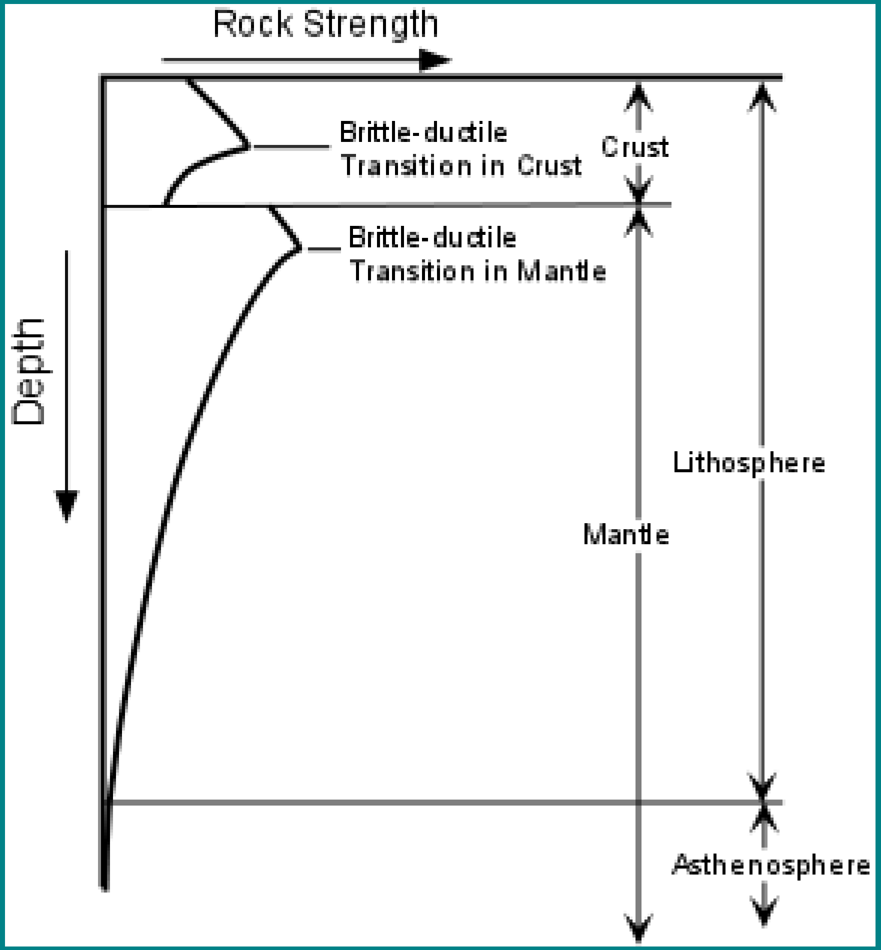
Ductile shear zone experiments



Barnhoorn et al., 2004

Very high shear strains

Brittle vs. Ductile deformation



http://www.tulane.edu/~sanelson/eens1110/deform.htm

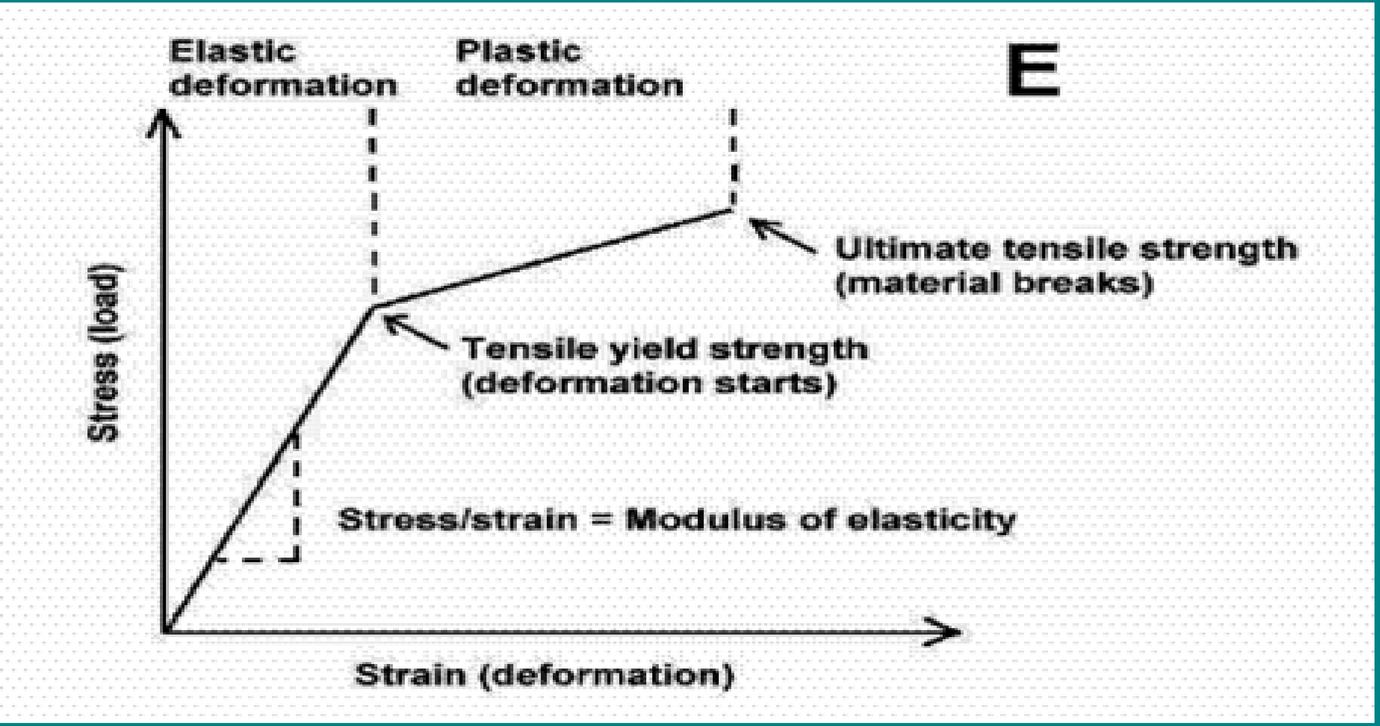
- Ductile
  - Deep in the Earth
  - Relatively high temperature and pressure conditions
  - Very high strain can be achieved without breakage of bonds
  - Deformation primarily temperature controlled
  - Time dependent process
  - Occurs on geological time-scales

Brittle vs. Ductile deformation

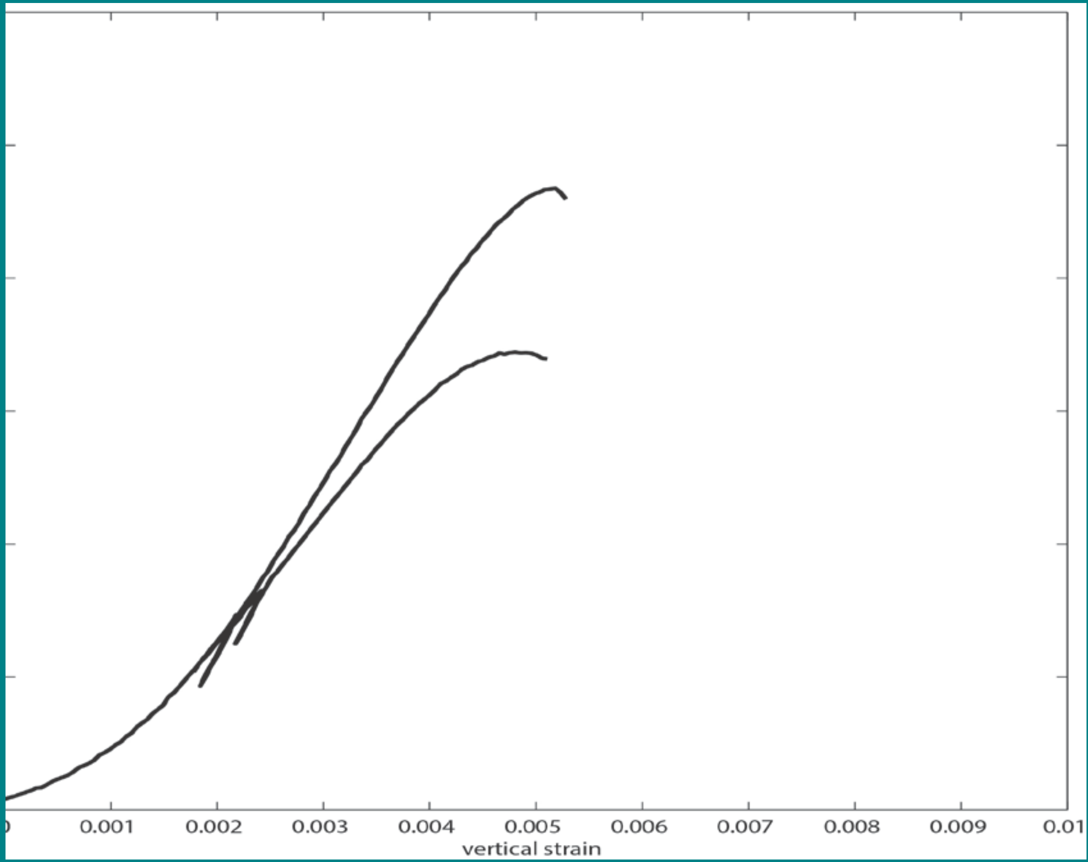
- Brittle
  - Shallow in the Earth
  - Relatively low temperature and pressure conditions
  - Breakage of bonds
  - Fracturing intense at low strain
  - Strength is pressure dependent
  - Time-independent
  - Seismicity

- Ductile
  - Deep in the Earth
  - Relatively high temperature and pressure conditions
  - Very high strain can be achieved without breakage of bonds
  - Deformation primarily temperature controlled
  - Time dependent process
  - Occurs on geological time-scales

Elasticity



sandstone



Four Elastic Moduli

- Elastic moduli describe the elastic behaviour of a rock
  - Rock type dependent
  - Can vary with change in conditions (P,T)

  - Used to predict & quantify elastic mechanical behaviour of rocks
    - Experiments
    - Geomechanical numerical modelling
    - Reservoir simulations
    - Etc.

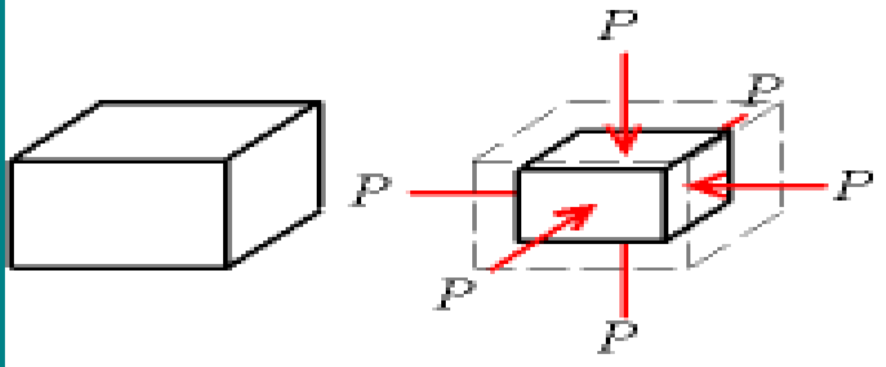
- Wave propagation in seismics/geophysics can almost always be described by elasticity.

Bulk modulus

The elastic mechanical behaviour of a material can completely be described by the bulk and shear modulus.

- The bulk modulus K_b [Pa] (also compression modulus) gives the resistance against deformation due to uniform compression and is defined by the hydrostatic pressure increase Δp that is necessary for a relative volume decrease $\Delta V/V$:

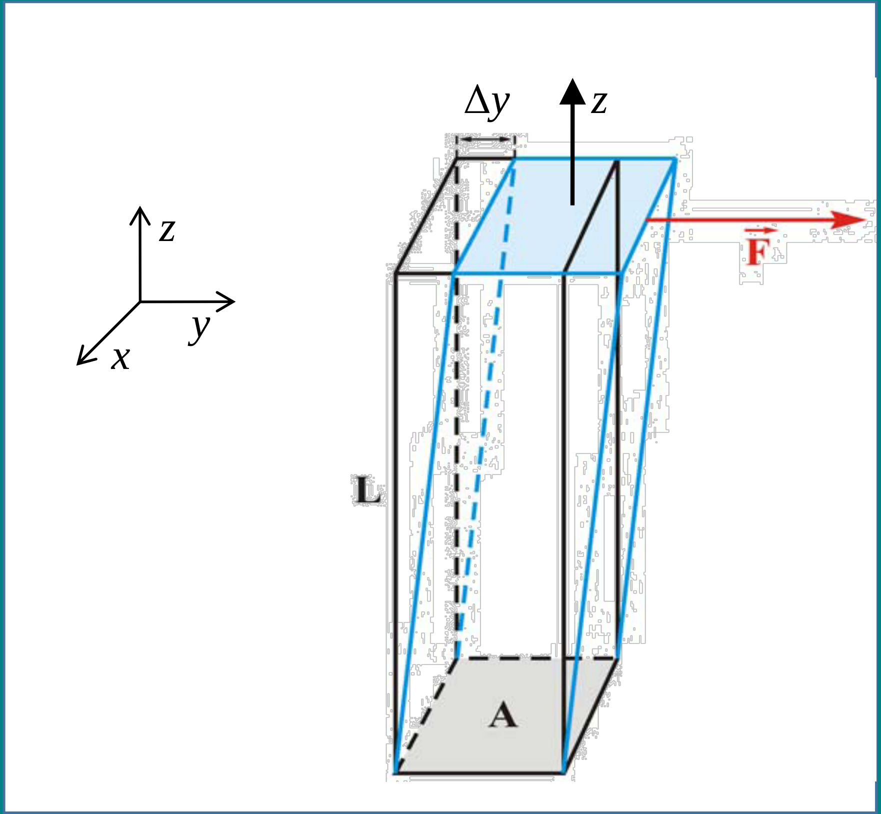
$$K_b = -V\frac{\partial p}{\partial V}$$



in which V is the initial volume that changes ΔV due to Δp.

Shear modulus

- The shear modulus μ (or G) [Pa] gives the resistance against deformation due to shearing and is defined by the shear strain ε_{ij} as a result of a shearing stress σ_{ij}. For example:

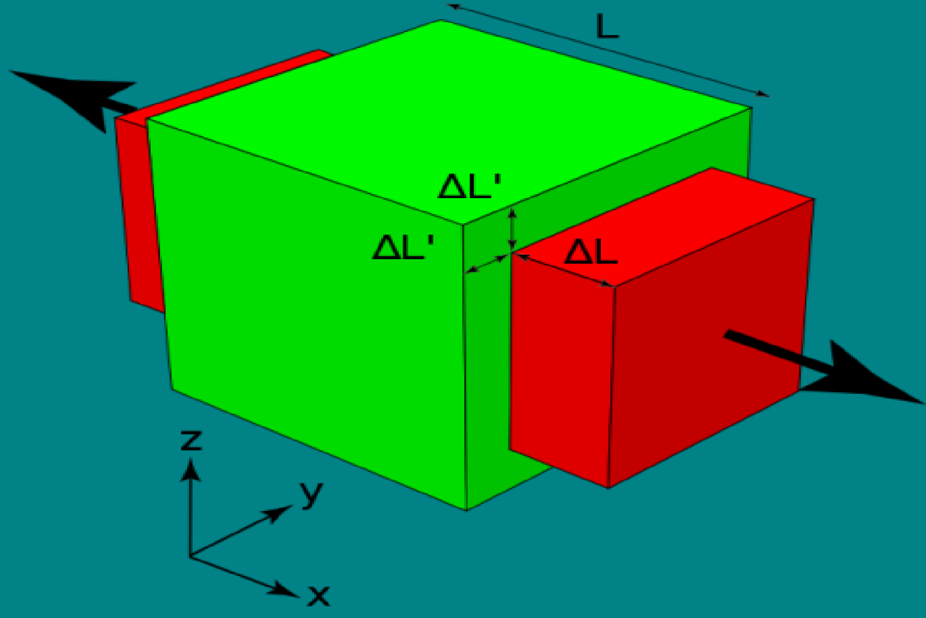


in which $$\mu = \frac{\sigma_{zy}}{2\varepsilon_{zy}}$$

- the shear stress $\sigma_{zy} = F/A$ is the force F in the y-direction per area A with normal z.
- the shear strain $\varepsilon_{zy} = \Delta y/L$ is the transversal displacement Δy over the initial length L perpendicular to A (in the z-direction).

Young’s modulus

Young’s modulus *E* [Pa] is a measure of the stiffness of the material and is given by the ratio of uniaxial stress σ_{xx} [Pa] and uniaxial strain ε_{xx} [-].



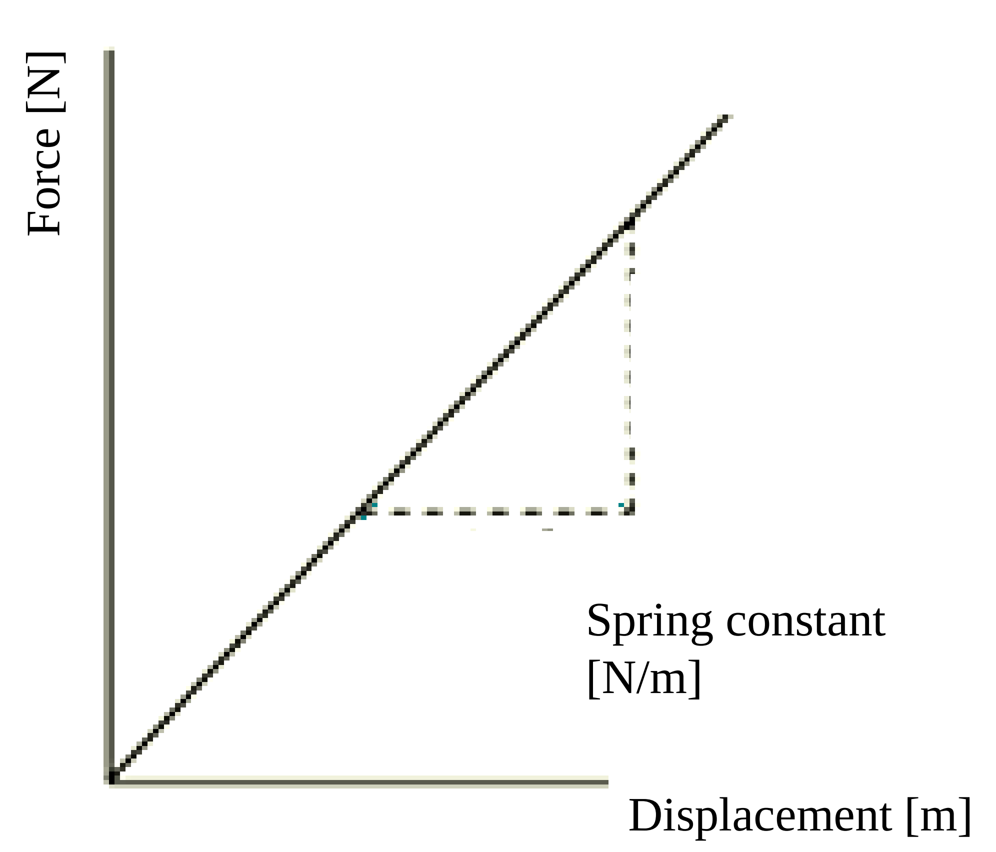
with $$E = \frac{\sigma_{xx}}{\varepsilon_{xx}}$$

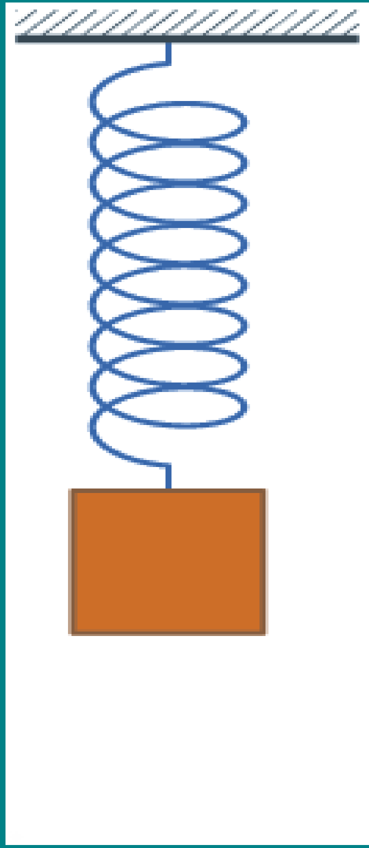
- $\sigma_{xx} = F/A$ is the force *F* in the *x*-direction per area *A* with the normal in the *x*-direction.

- $\varepsilon_{xx} = \Delta L/L$ is the relative change in length (tension or compression) in the *x*-direction due to a force in the *x*-direction.

Hooke's law for an isotropic elastic solid

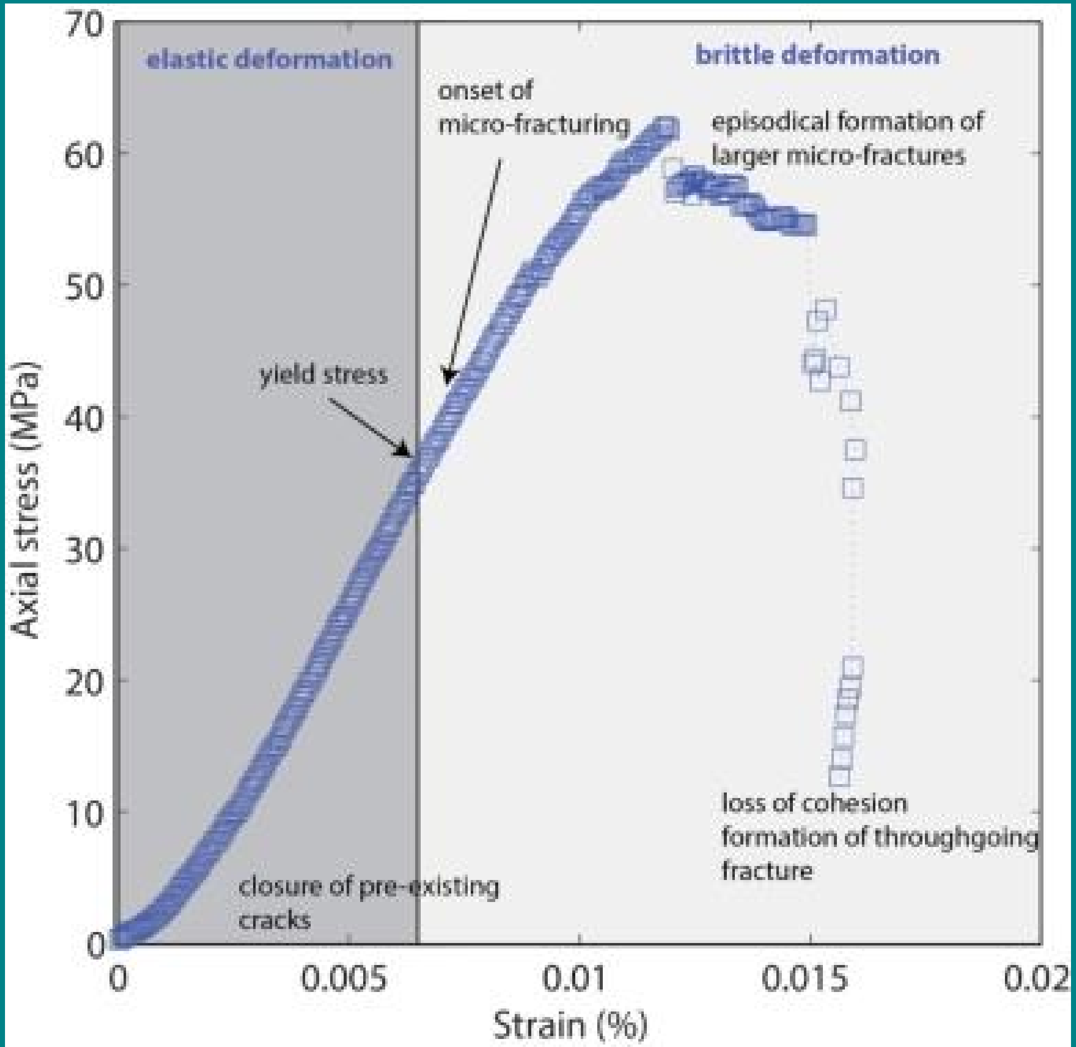
Hooke's law states that the strain *ε* (= *ΔL/L*) in an isotropic elastic solid in 1D is proportional to the stress (force per unit area) via the Young's modulus *E*.





$$\sigma = E\varepsilon$$

In-class stress-strain exercise - 3

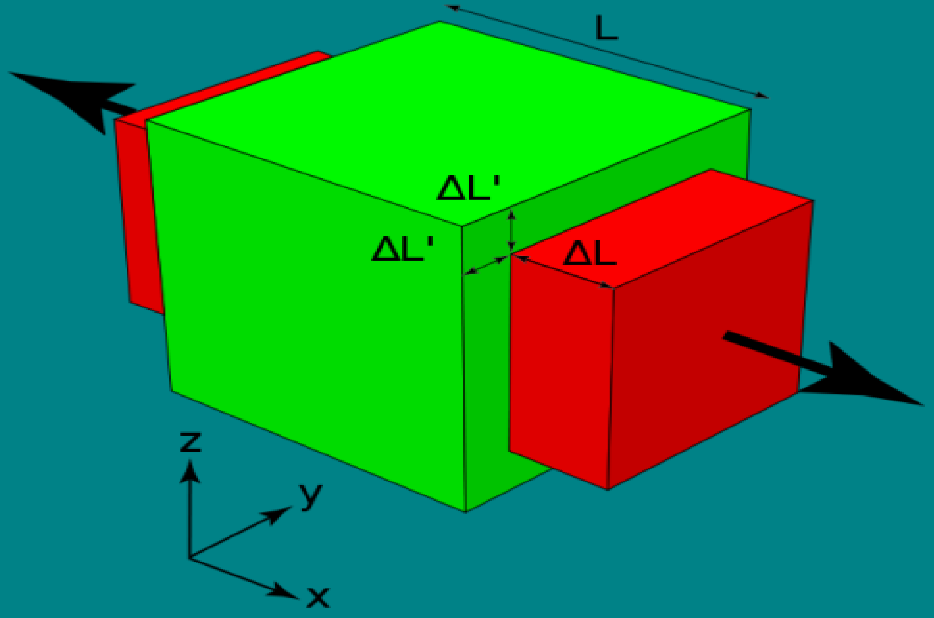


- What is the stress-strain ratio ($^{\Delta\sigma}/_{\Delta\varepsilon}$) of this experimentally deformed shale sample? Determine the stress-strain ratio only in the gray part of the diagram. The unit of the stress-strain ratio is in GPa.

Poisson’s ratio

Poisson’s ratio v [-] describes the strain in the transversal direction (e.g. y and z), which originates from tension (stretching) or compression in the axial direction (e.g. x).

with $$\nu = -\frac{\varepsilon_{yy}}{\varepsilon_{xx}}$$



- $\varepsilon_{xx} = \Delta L/L$ is the uniaxial strain.
- $\varepsilon_{yy} = \Delta L'/L'$ is the transversal (or lateral) strain.

Elastic relationships in isotropic materials

K	E	λ	ν	M	μ
$\lambda + 2\mu/3$	$\mu \frac{3\lambda + 2\mu}{\lambda + \mu}$	—	$\frac{\lambda}{2(\lambda + \mu)}$	$\lambda + 2\mu$	—
—	$9K \frac{K - \lambda}{3K - \lambda}$	—	$\frac{\lambda}{3K - \lambda}$	$3K - 2\lambda$	$3(K - \lambda)/2$
—	$\frac{9K\mu}{3K + \mu}$	$K - 2\mu/3$	$\frac{3K - 2\mu}{2(3K + \mu)}$	$K + 4\mu/3$	—
$\frac{E\mu}{3(3\mu - E)}$	—	$\mu \frac{E - 2\mu}{(3\mu - E)}$	$E/(2\mu) - 1$	$\mu \frac{4\mu - E}{3\mu - E}$	—
—	—	$3K \frac{3K - E}{9K - E}$	$\frac{3K - E}{6K}$	$3K \frac{3K + E}{9K - E}$	$\frac{3KE}{9K - E}$
$\lambda \frac{1 + \nu}{3\nu}$	$\lambda \frac{(1 + \nu)(1 - 2\nu)}{\nu}$	—	—	$\lambda \frac{1 - \nu}{\nu}$	$\lambda \frac{1 - 2\nu}{2\nu}$
$\mu \frac{2(1 + \nu)}{3(1 - 2\nu)}$	$2\mu(1 + \nu)$	$\mu \frac{2\nu}{1 - 2\nu}$	—	$\mu \frac{2 - 2\nu}{1 - 2\nu}$	—
—	$3K(1 - 2\nu)$	$3K \frac{\nu}{1 + \nu}$	—	$3K \frac{1 - \nu}{1 + \nu}$	$3K \frac{1 - 2\nu}{2 + 2\nu}$
$\frac{E}{3(1 - 2\nu)}$	—	$\frac{E\nu}{(1 + \nu)(1 - 2\nu)}$	—	$\frac{E(1 - \nu)}{(1 + \nu)(1 - 2\nu)}$	$\frac{E}{2 + 2\nu}$

Mavko, 2003

Determine Poisson's ratio using van Kb and μ

$$\nu = \frac{3K_b - 2\mu}{2(3K_b + \mu)}$$

Determine Young's modulus using Kb and μ

$$E = \frac{9K_b\mu}{3K_b + \mu}$$

Message: if you have 2 elastic constants, you can calculate all 4!!

Elastic relationships in isotropic materials

K	E	λ	ν	M	μ
$\lambda + 2\mu/3$	$\mu\dfrac{3\lambda + 2\mu}{\lambda + \mu}$	—	$\dfrac{\lambda}{2(\lambda + \mu)}$	$\lambda + 2\mu$	—
—	$9K\dfrac{K - \lambda}{3K - \lambda}$	—	$\dfrac{\lambda}{3K - \lambda}$	$3K - 2\lambda$	$3(K - \lambda)/2$
—	$\dfrac{9K\mu}{3K + \mu}$	$K - 2\mu/3$	$\dfrac{3K - 2\mu}{2(3K + \mu)}$	$K + 4\mu/3$	—
$\dfrac{E\mu}{3(3\mu - E)}$	—	$\mu\dfrac{E - 2\mu}{(3\mu - E)}$	$E/(2\mu) - 1$	$\mu\dfrac{4\mu - E}{3\mu - E}$	—
—	—	$3K\dfrac{3K - E}{9K - E}$	$\dfrac{3K - E}{6K}$	$3K\dfrac{3K + E}{9K - E}$	$\dfrac{3KE}{9K - E}$
$\lambda\dfrac{1 + \nu}{3\nu}$	$\lambda\dfrac{(1 + \nu)(1 - 2\nu)}{\nu}$	—	—	$\lambda\dfrac{1 - \nu}{\nu}$	$\lambda\dfrac{1 - 2\nu}{2\nu}$
$\mu\dfrac{2(1 + \nu)}{3(1 - 2\nu)}$	$2\mu(1 + \nu)$	$\mu\dfrac{2\nu}{1 - 2\nu}$	—	$\mu\dfrac{2 - 2\nu}{1 - 2\nu}$	—
—	$3K(1 - 2\nu)$	$3K\dfrac{\nu}{1 + \nu}$	—	$3K\dfrac{1 - \nu}{1 + \nu}$	$3K\dfrac{1 - 2\nu}{2 + 2\nu}$
$\dfrac{E}{3(1 - 2\nu)}$	—	$\dfrac{E\nu}{(1 + \nu)(1 - 2\nu)}$	—	$\dfrac{E(1 - \nu)}{(1 + \nu)(1 - 2\nu)}$	$\dfrac{E}{2 + 2\nu}$

Mavko, 2003

Examples of earth's materials

Mineral	Density	Young's Modulus	Bulk Modulus	Shear Modulus	Vp	Vs	Poisson's Ratio
Quartz	2.6500	95.756	36.600	45.000	6.0376	4.1208	0.063953
Calcite	2.7100	84.293	76.800	32.000	6.6395	3.4363	0.31707
Dolomite	2.8700	116.57	94.900	45.000	7.3465	3.9597	0.29527
Clay (kaolinite)	1.5800	3.2034	1.5000	1.4000	1.4597	0.94132	0.14407
Muscovite	2.7900	100.84	61.500	41.100	6.4563	3.8381	0.22673
Feldspar (Albite)	2.6300	69.010	75.600	25.600	6.4594	3.1199	0.34786
Halite	2.1600	37.242	24.800	14.900	4.5474	2.6264	0.24972
Anhydrite	2.9800	74.431	56.100	29.100	5.6432	3.1249	0.27888
Pyrite	4.9300	305.85	147.40	132.50	8.1076	5.1842	0.15417
Siderite	3.9600	134.51	123.70	51.000	6.9576	3.5887	0.31876
gas	0.00065000	0.0000	0.00013000	0.0000	0.44721	0.0000	0.50000
water	1.0000	0.0000	2.2500	0.0000	1.5000	0.0000	0.50000
oil	0.80000	0.0000	1.0200	0.0000	1.1292	0.0000	0.50000

Mavko, 2003

Modulus of Elasticity of Some Common Rocks

	Name of Rocks	Youngs Modulus (E), Gpa
Igneous Rocks	Basalt	20 – 100
	Diabase	30 – 90
	Gabbro	60 – 110
	Granite	26 – 70
	Syemite	60 – 80
Sedimentary Rocks	Dolomite	20 – 44
	Limestone	10 – 80
	Sandstone	5 – 86
	Shale	08 – 30
Metamorphic Rocks	Gneiss	20 – 60
	Marble	60 – 90
	Quartzite	26 – 102
	Schist	41 – 72

http://civilblog.org/2015/02/13/what-are-the-values-of-modulus-of-elasticity-poissons-ratio-for-different-rocks/

Values of Poisson's Ratio for Some Common Rocks

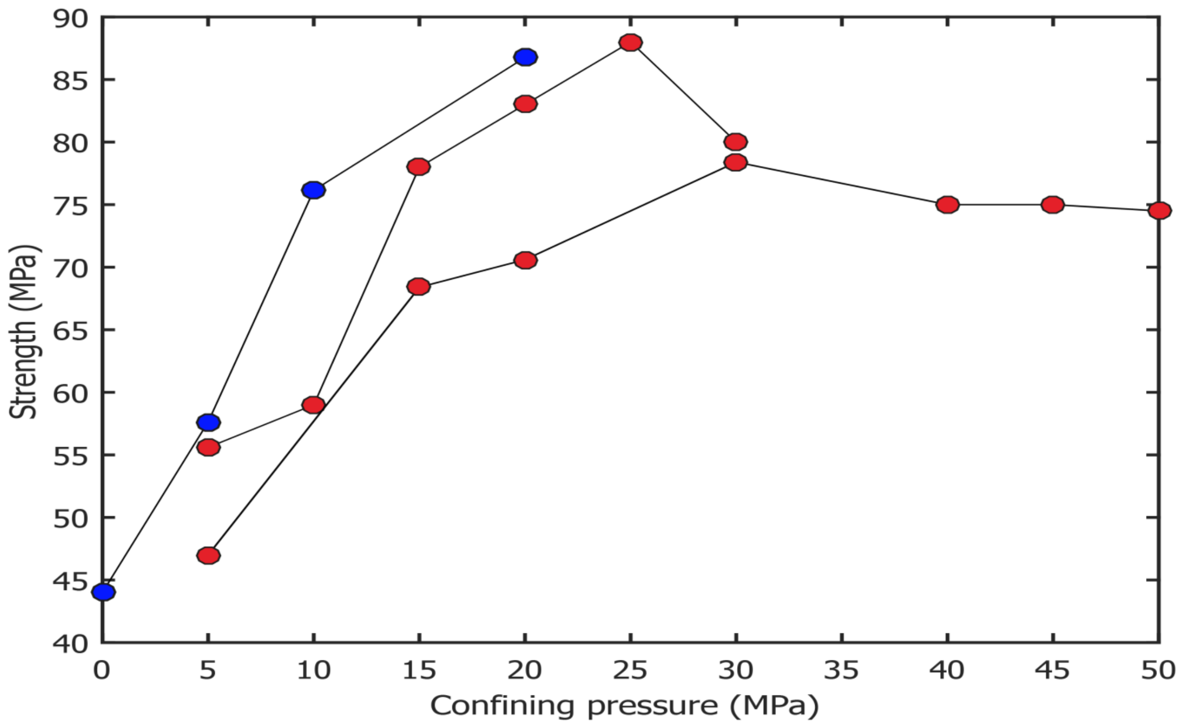
Types of Rocks	Name of Rocks	Average Values of Poisson's Ratio (ν)
Igneous Rocks	Basalt	0.14 – 0.20
	Diabase	0.125 – 0.25
	Gabbro	0.125 – 0.25
	Granite	0.125 – 0.25
	Syemite	0.25
Sedimentary Rocks	Dolomite	0.08 – 0.20
	Limestone	0.10 – 0.20
	Sandstone	0.066 – 0.125
	Shale	0.11 – 0.54
Metamorphic Rocks	Gneiss	0.091 – 0.25
	Marble	0.25 – 0.38
	Quartzite	0.23
	Schist	0.01 – 0.20

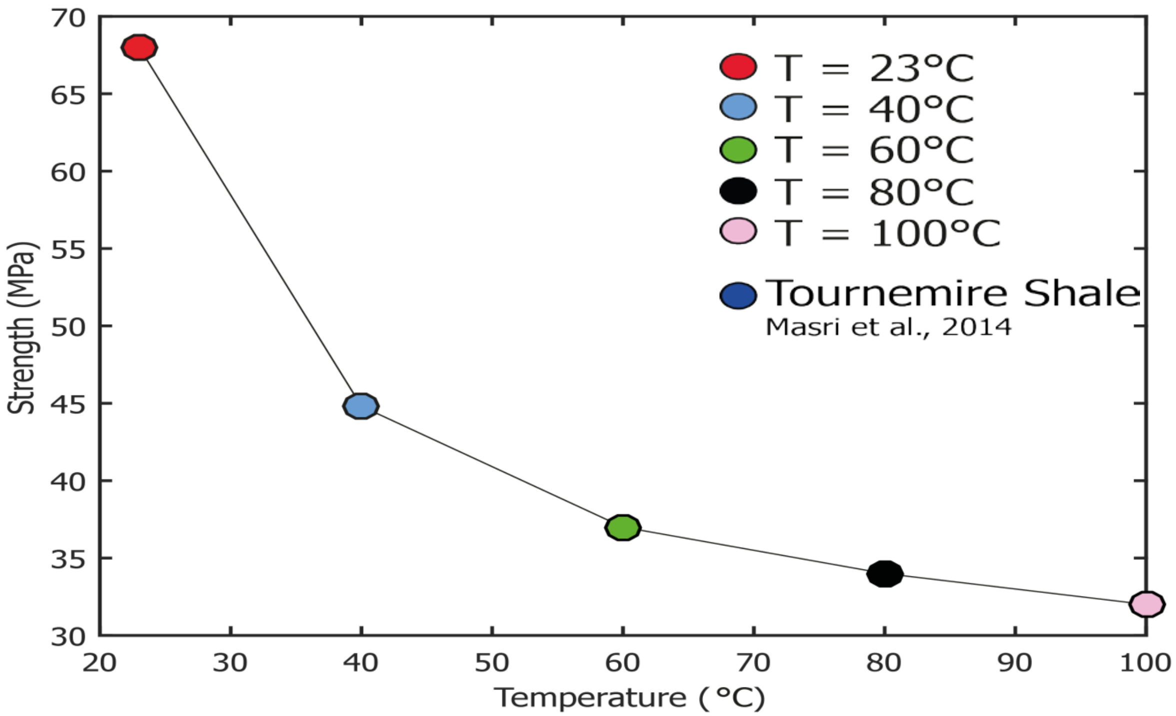
http://civilblog.org/2015/02/13/what-are-the-values-of-modulus-of-elasticity-poissons-ratio-for-different-rocks/

Elastic moduli

- If you know 2 elastic moduli (for isotropic materials) you can calculate all other moduli
- And thus fully describe the elastic behaviour of the material
  - Geomechanical reservoir simulations
  - Hydraulic fracturing
  - Seismicity studies

Important!!!
Rock mechanical constant change with depth and temperature

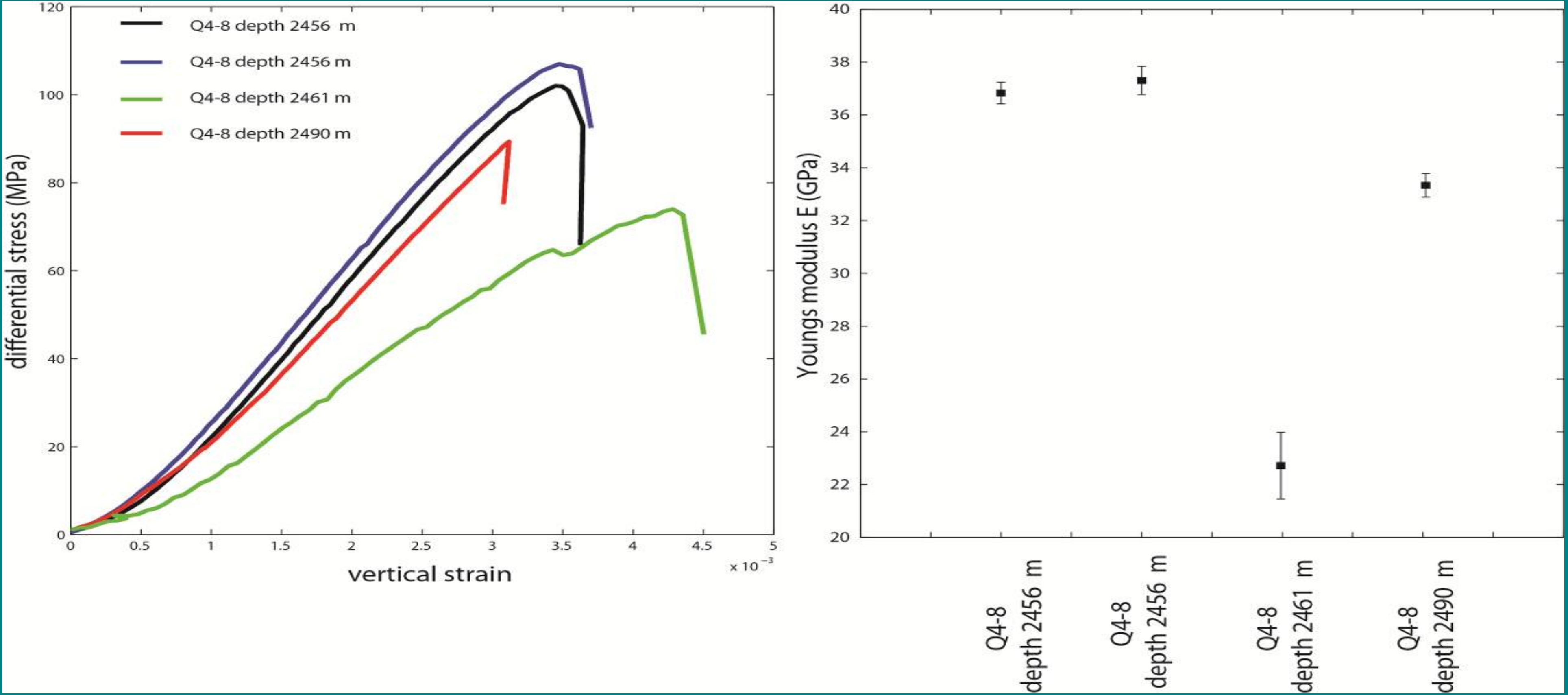




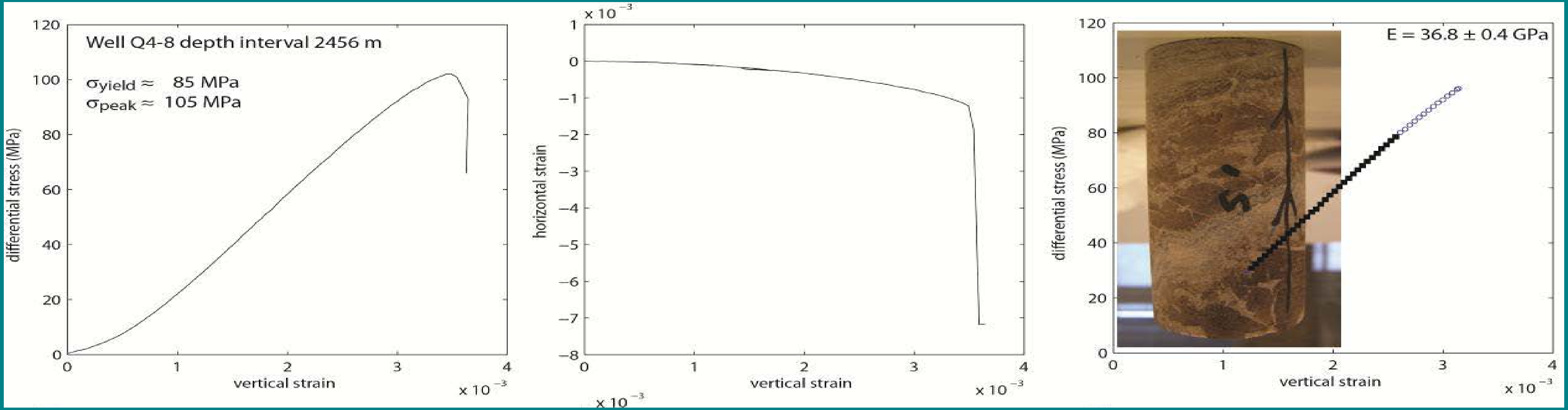
unpublished TU Delft work on shales

P_{conf} = 15 MPa

Rock mechanics: Shaley sandstone



Measurement of Stress, Horizontal strain and Vertical strain

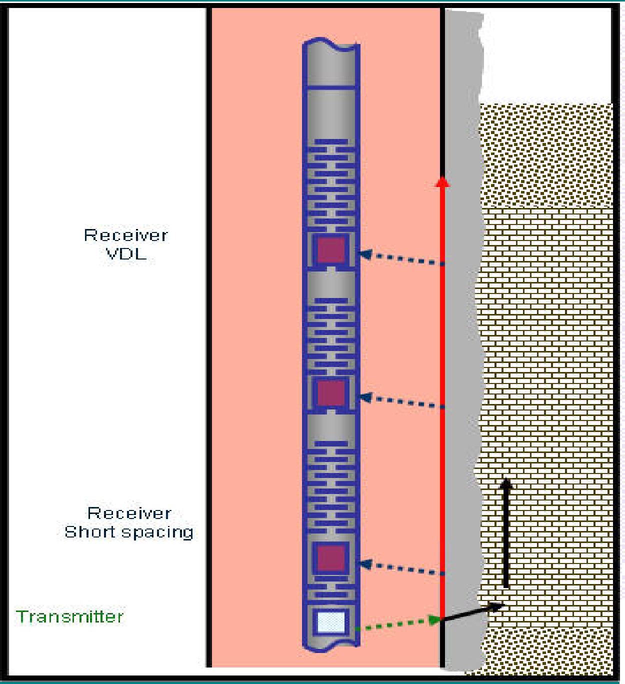


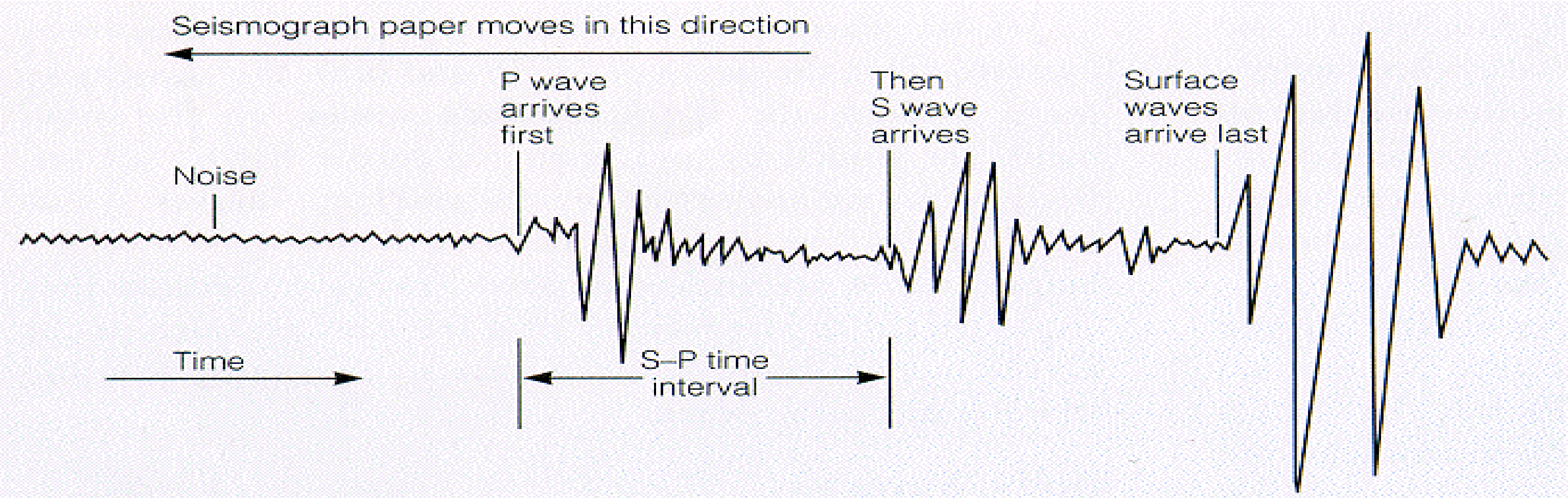
$$E = \frac{\sigma_{xx}}{\varepsilon_{xx}} = \frac{9K_b\mu}{3K_b + \mu}$$

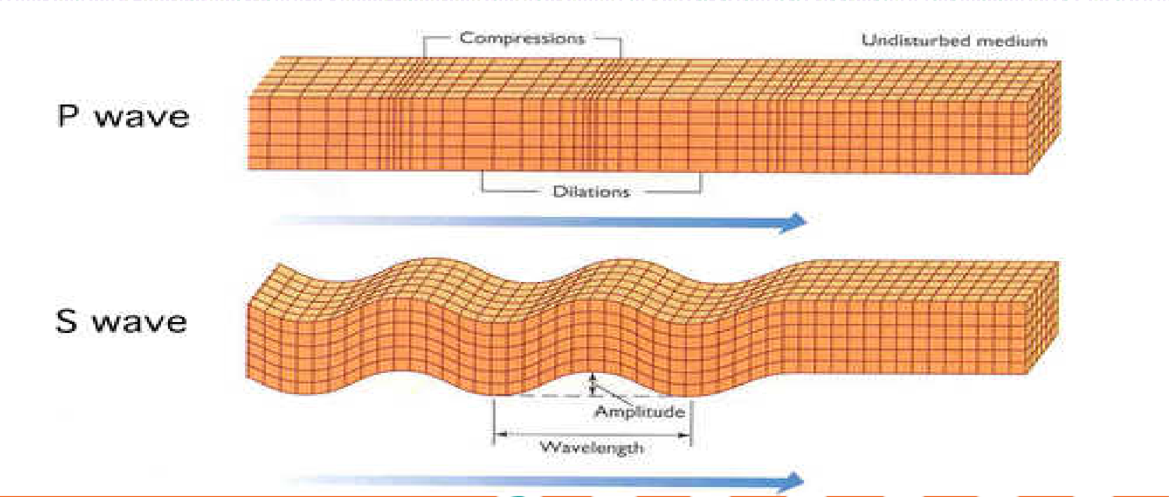
$$\nu = -\frac{\varepsilon_{yy}}{\varepsilon_{xx}} = \frac{3K_b - 2\mu}{2(3K_b + \mu)}$$

Acoustics logging

Seismic waves



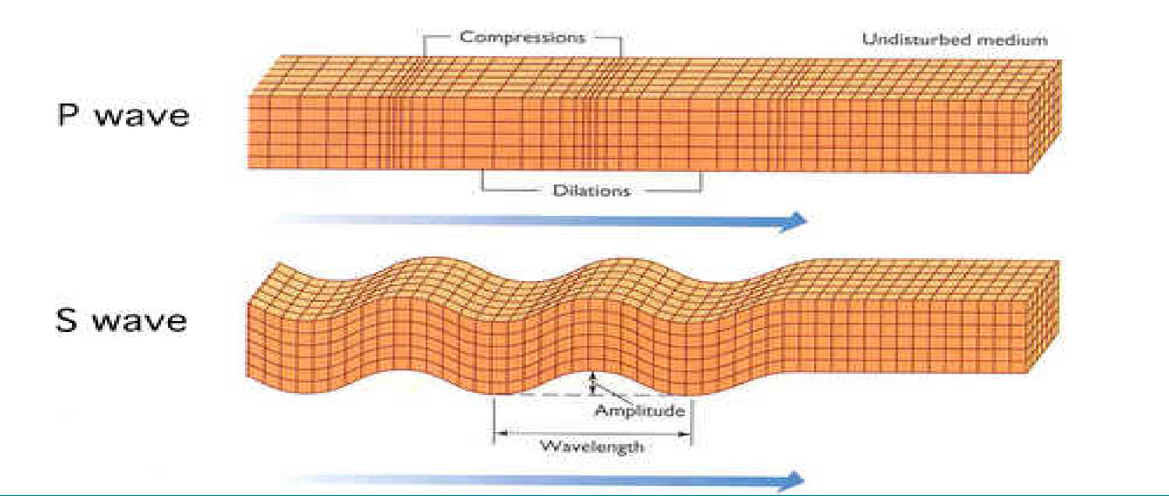




Vp and Vs

$$\mu = v_s^2 \rho$$

$$K_b = (v_p^2 - \frac{4}{3} v_s^2)\rho$$



Measurement of Vp, Vs and density

Vp and Vs

- You can calculate the P- and S-wave velocities for a specific rock type if the elastic moduli are known

$$V_p = \sqrt{\frac{K_b + \frac{4}{3}\mu}{\rho}} = \sqrt{\frac{\lambda + 2\mu}{\rho}} =$$

$$V_s = \sqrt{\frac{\mu}{\rho}} =$$

Poisson's ratio

$$\nu = \frac{v_p^2 - 2v_s^2}{2(v_p^2 - v_s^2)}$$

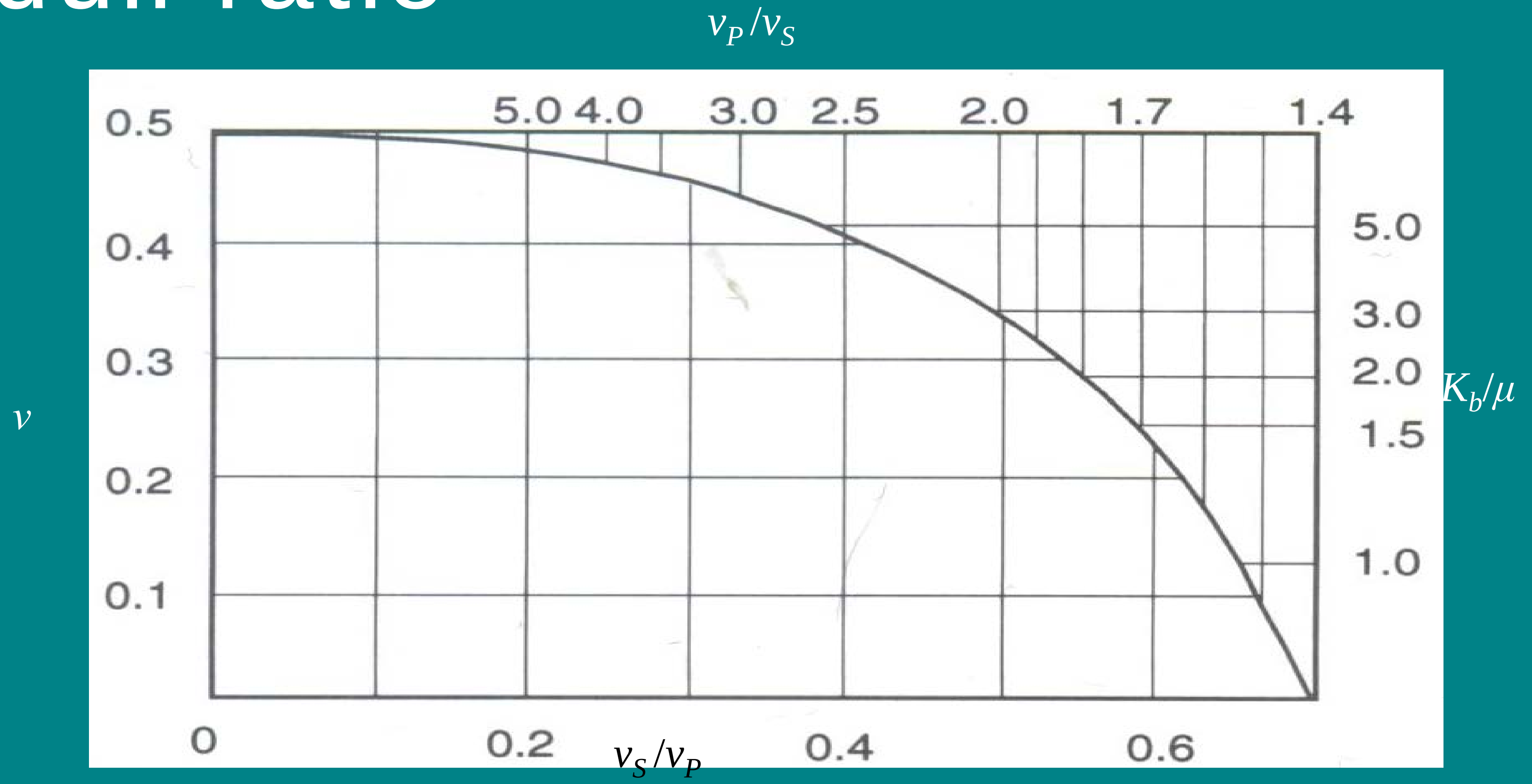
Because the elastic constants are always positive, v_P is always greater than v_S, and

$$\frac{v_s}{v_p} = \sqrt{\frac{\mu}{\lambda + 2\mu}} = \sqrt{\frac{0.5 - \nu}{1 - \nu}}$$

As v decreases from ½ to 0, v_S / v_P increases from 0 to its maximum value $1/\sqrt{2}$.

Thus the velocity of the S-wave ranges from 0 to 70% of the velocity of the P-wave.

Velocity ratio, Poisson's ratio, and moduli ratio



Sheriff and Geldart, 1995

In-class elastic moduli exercise - 10 min

- Sandstone ρ = 2.65 g/cm3, Vp = 5491 m/s. Vs = 3463 m/s
- Limestone ρ = 2.71 g/cm3, Vp = 6417 m/s. Vs = 3444 m/s
-

- Wat are Kb, μ, E and ν for these 2 rock types?

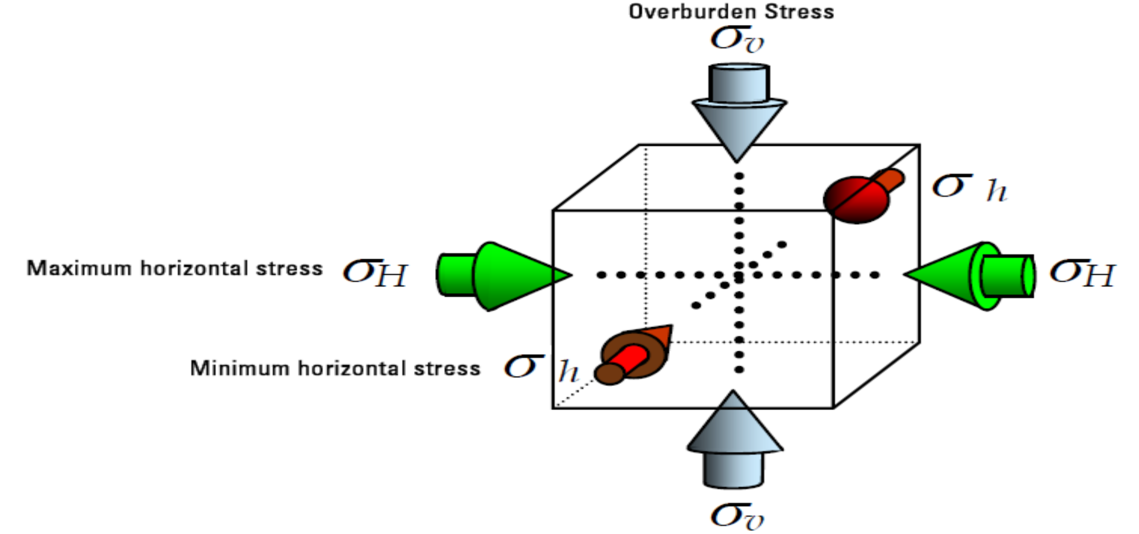
15 minute break

Stresses in the subsurface

Vertical or Overburden Stress (σ_v) Which often has the greatest magnitude. It is also the maximum in-situ stress.

Maximum Horizontal Stress (σ_H) which is the intermediate in situ stress.

Minimum Horizontal Stress ($\boldsymbol{\sigma_h}$) which has the lowest magnitude. It is also the minimum in-situ stress.



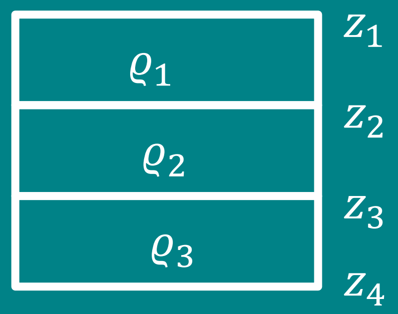
Stresses from borehole logs

- Vertical stress (σ_v)

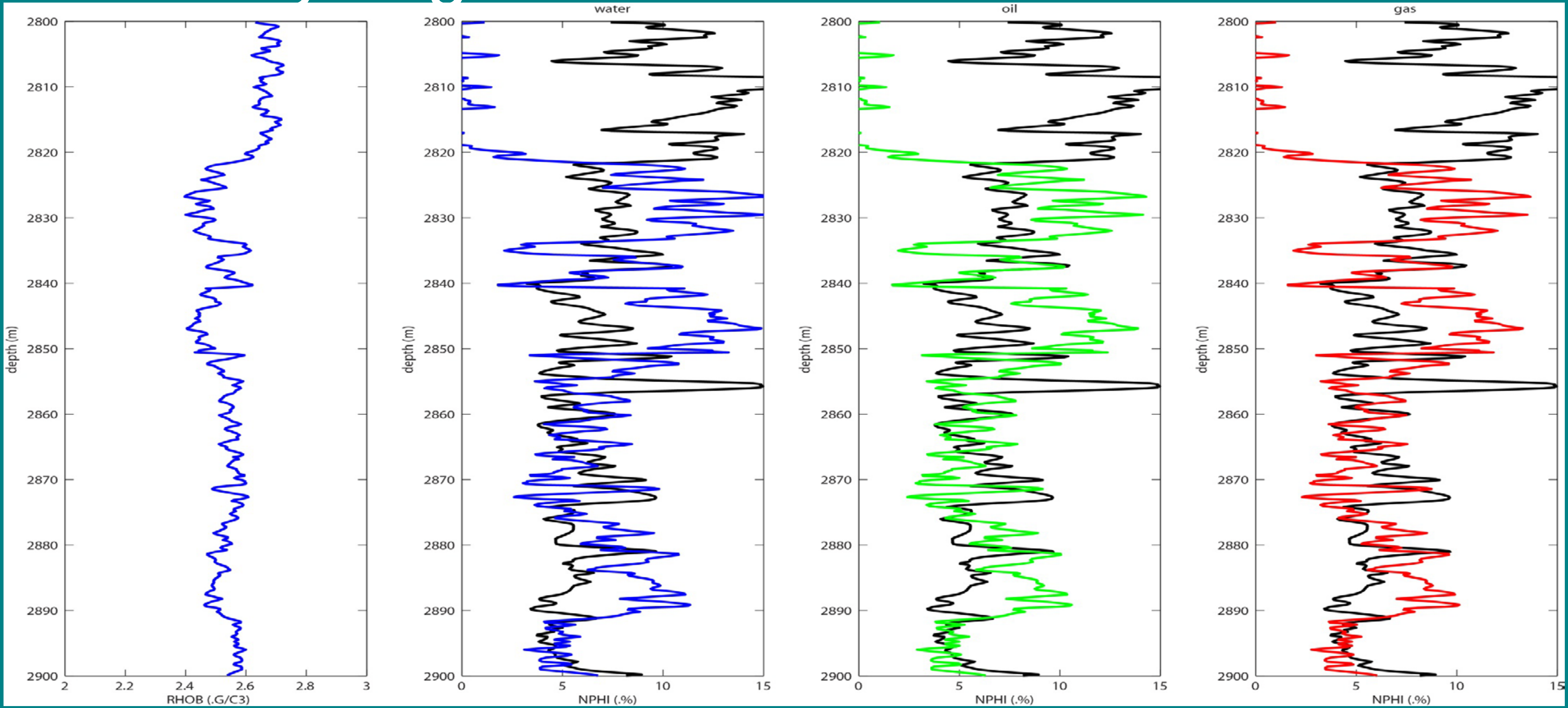
$$\sigma_v = \varrho \mathrm{gz}$$

- Density information or density logs
  - Summation of all density + heights of each lithology

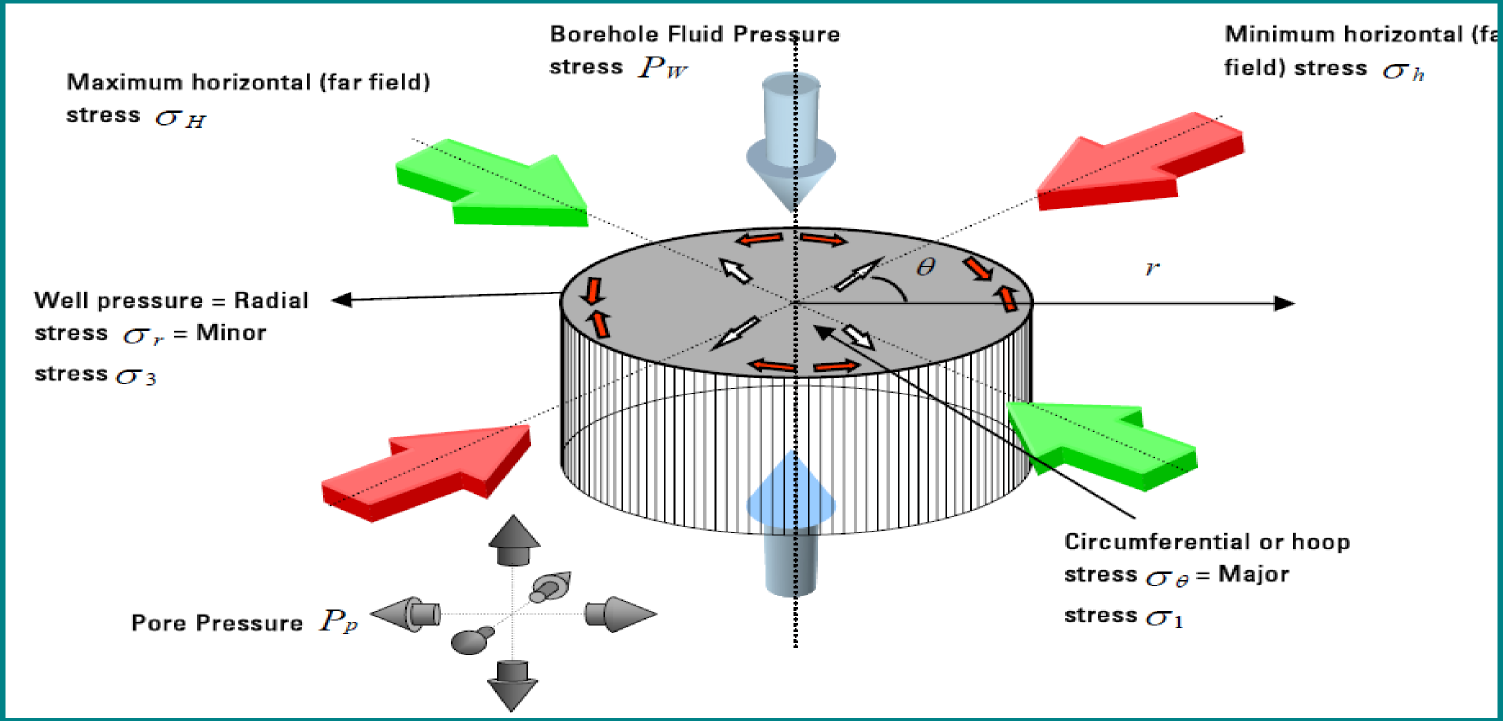
$$\sigma_v = \sum \varrho_i g(z_{i+1} - z_i)$$



Density logs



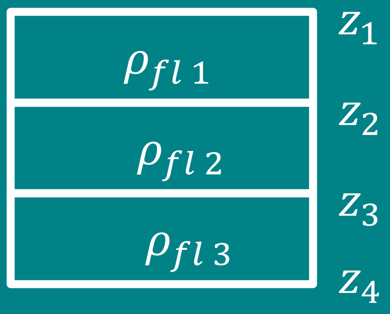
Stress configuration around borehole – no additional tectonics



Pore pressure

- Pressure of fluids in porous rock $P_p = \rho_{fl} g z$
- Acting against lithostatic rock pressure

$$P_p = \sum \rho_{fl\,i}\, g(z_{i+1} - z_i)$$



Biot constant, often 1

- Vertical effective stress $\sigma_v' = \sigma_v - \alpha P_p$

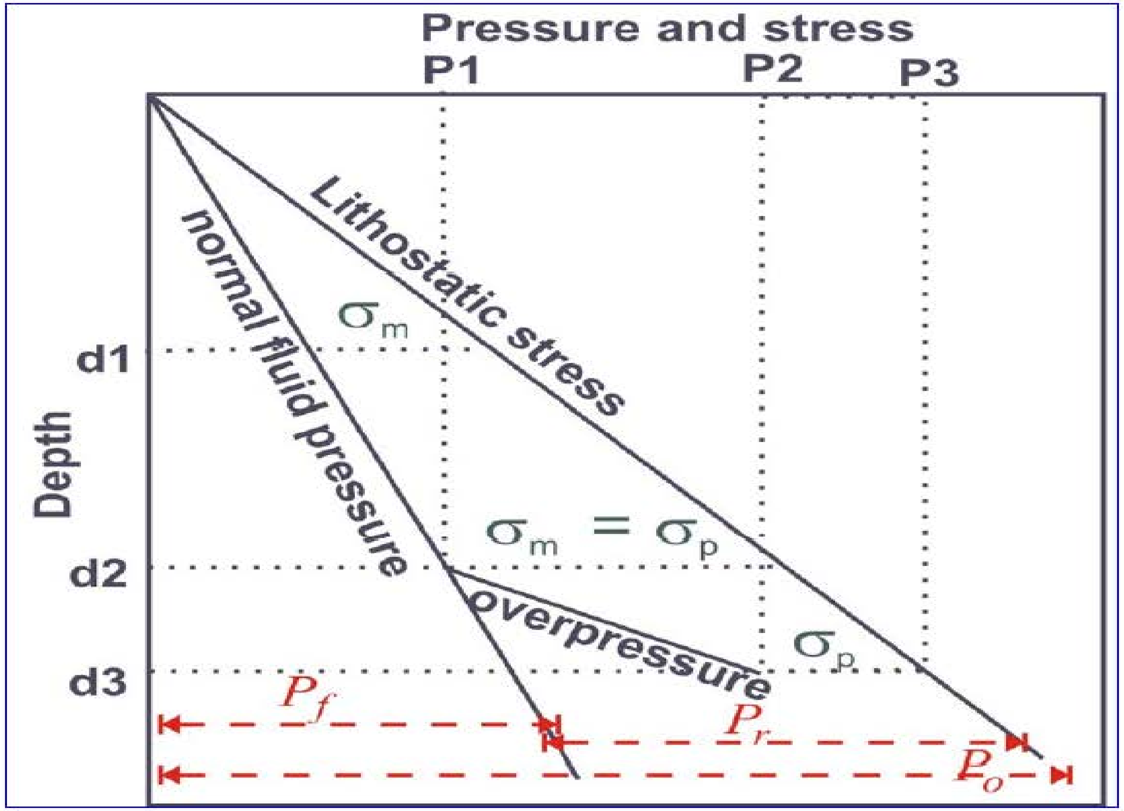
Vertical stress

- Average density of upper crustal sediments: 2.3 g/cm3
- Volcanics much higher density (2.8 - >3 g/cm3)
- Density of water: ~1 g/cm3

Effect of fluid overpressure

In-situ conditions: P,V,T,t: Pressure

Pressure - depth relation for normal compaction and non-equilibrium.



$$P_o = P_r + P_f$$

$$\sigma_p = P_0 - P_f$$

$$\sigma_p = \sigma_m$$

P_o	Total overburden pressure confining stress
P_f	Fluid pressure
P_r	Lithostatic (grain) pressure
σ_p	Effective stress
σ_m	Matrix stress or load on the grain framework

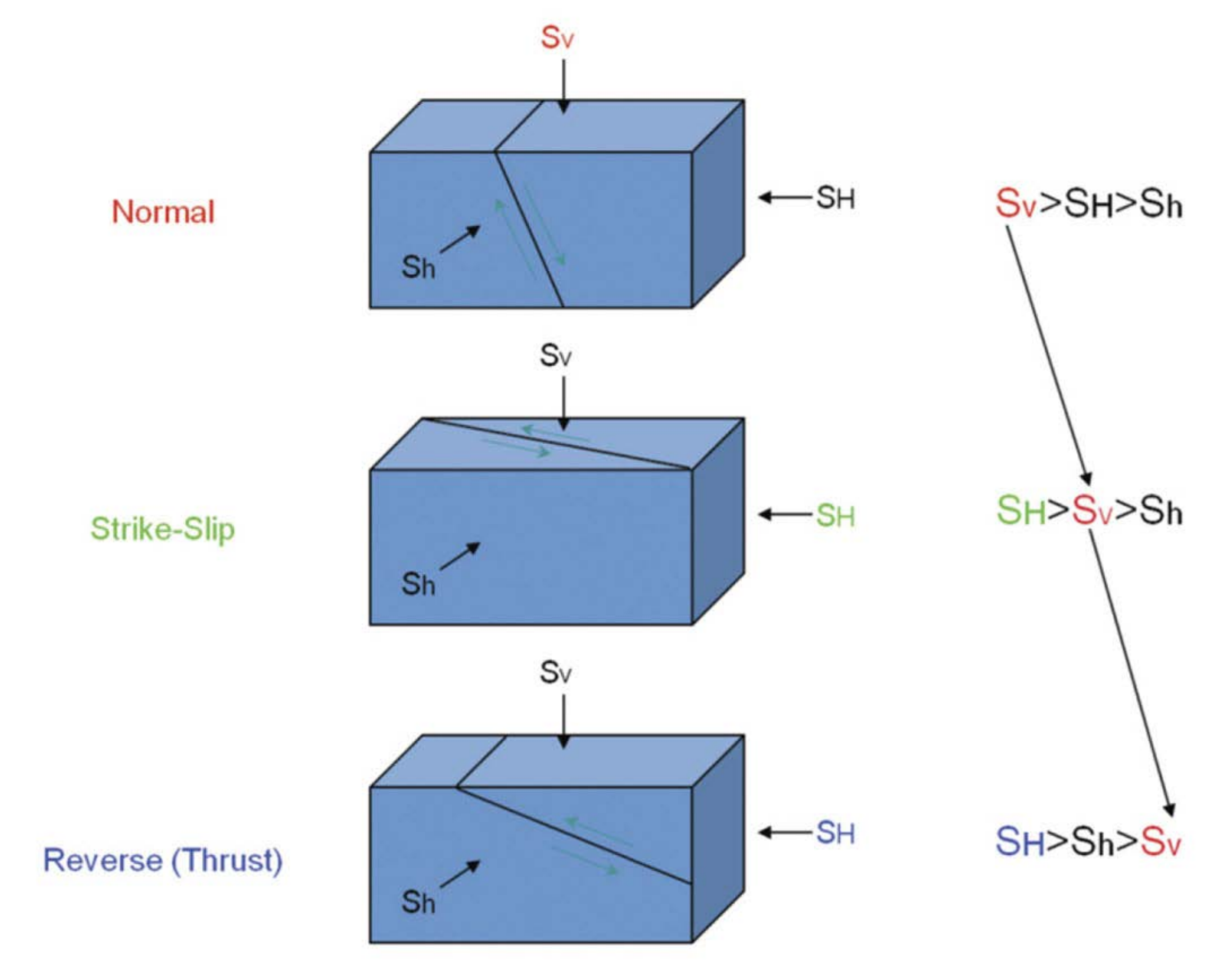
Minimum horizontal stress (σ_h)

$$\sigma_h = \frac{\nu}{1-\nu}(\sigma_v - \alpha P_p) + \alpha P_p$$

Poisson's ratio $$\nu = \frac{v_p^2 - 2v_s^2}{2(v_p^2 - v_s^2)}$$

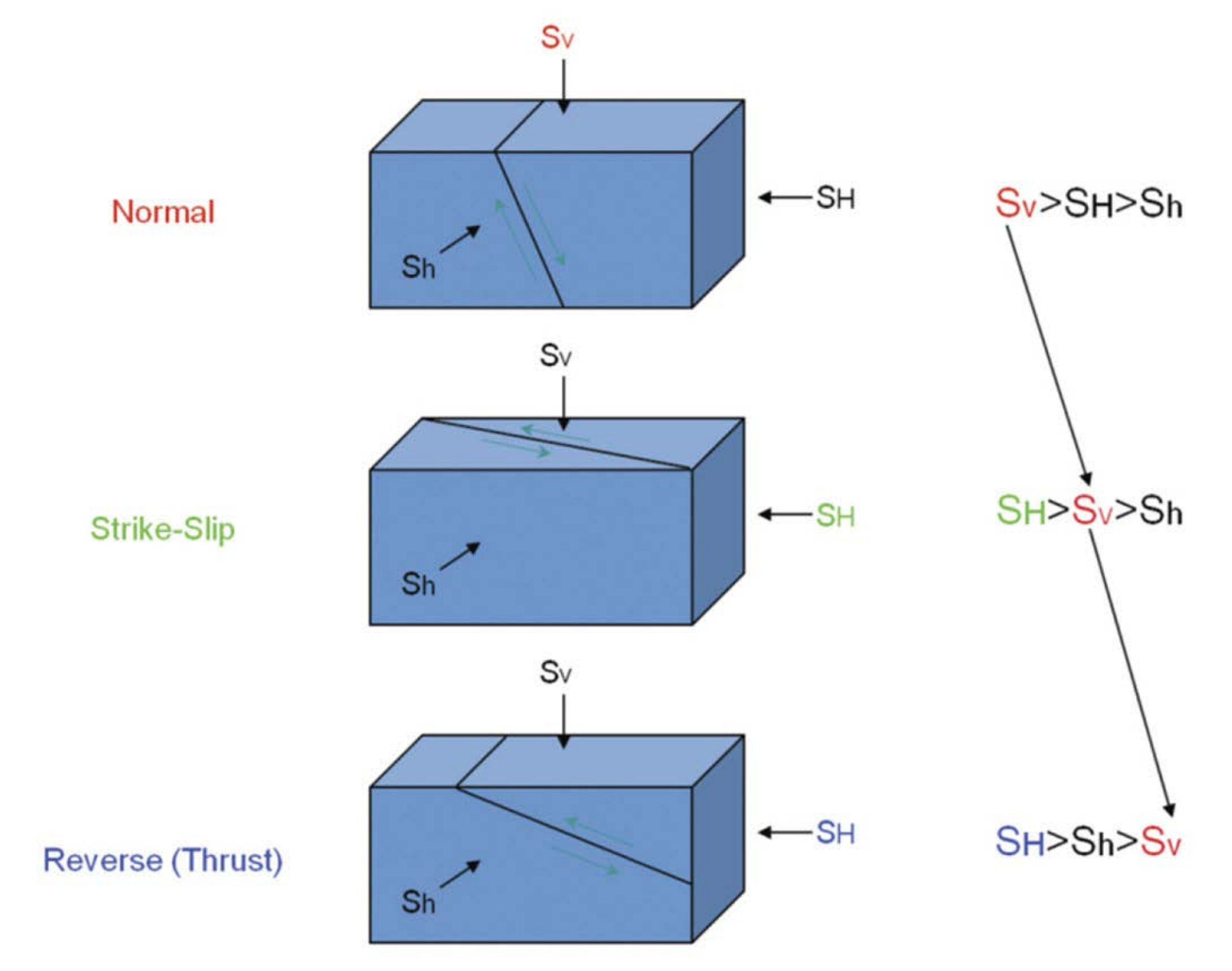
Maximum horizontal stress (σ_H)

The difference between the maximum and minimum horizontal stress is difficult to determine and depends on the tectonic stresses (are they large or are they small) and the tectonic setting (normal faulting, strike slip, or compression).



Normal faulting/extension

- In normal faulting scenarios which are also tectonically quiet (e.g. the Netherlands), it is often OK to assume that $\boldsymbol{\sigma_h \sim \sigma_H}$ and that they are both smaller than $\boldsymbol{\sigma_V}$.

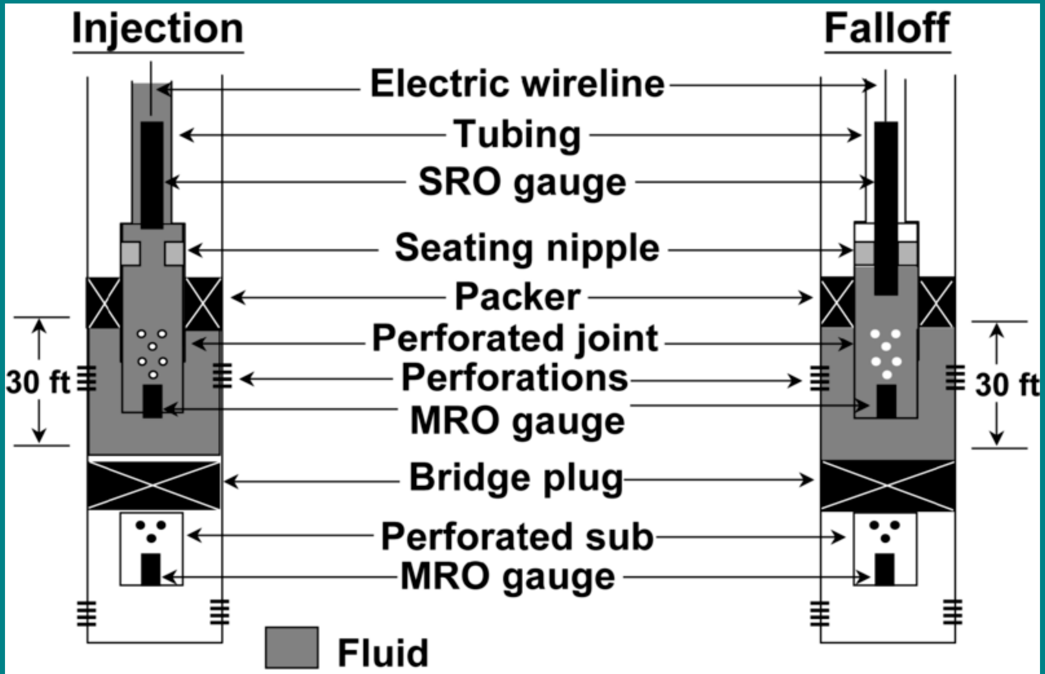


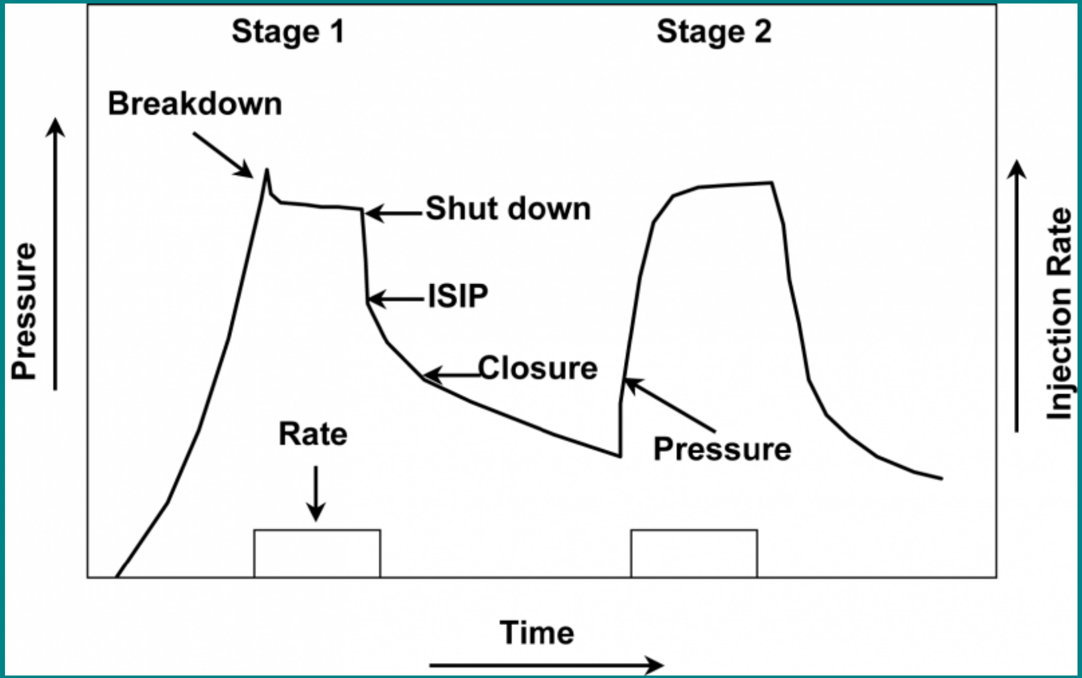
Important for Indonesia!

- In tectonically active areas, it is even more important to include the effects of tectonic activity in the analyses of the total stresses.
- To measure the tectonic stresses, injection tests are conducted to measure the minimum horizontal stress. The measured stress is then compared with the stress calculated by the poroelastic equation to determine the value of the tectonic stress.

- E.g. $\sigma_h = \frac{\nu}{1-\nu}(\sigma_v - \alpha P_p) + \alpha P_p + \sigma_{tect}$

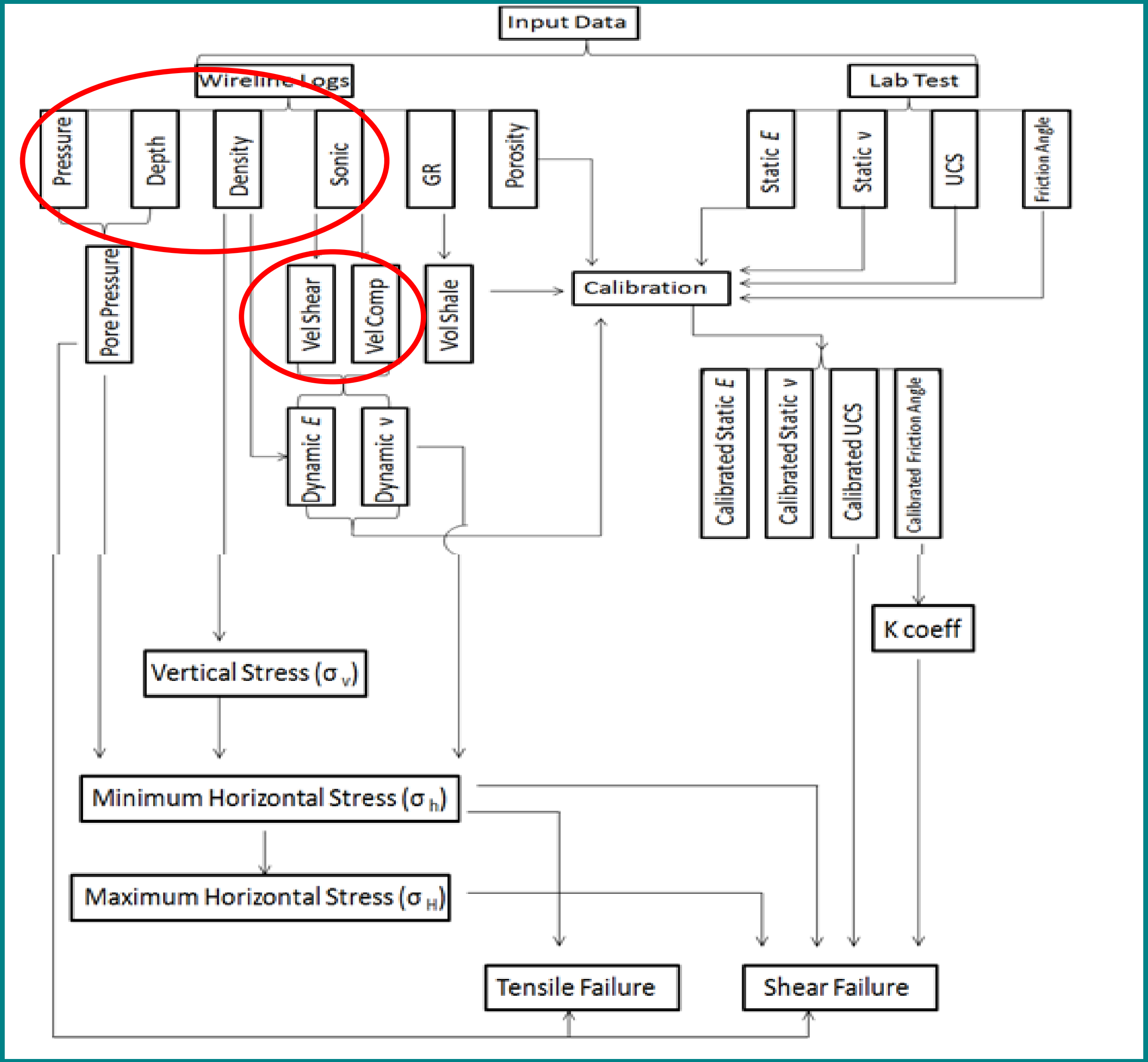
Injection tests





The in-situ stress test is conducted with small volumes of fluid (a few barrels) and injected at a low injection rate (tens of gal/min), normally with straddle packers to minimize wellbore storage effects, into a small number of perforations (1 to 2 ft). The objective is to pump a thin fluid (water or nitrogen) at a rate just sufficient to create a small fracture. Once the fracture is open, the pumps are shut down, and the pressure is recorded and analyzed to determine when the fracture closes. Thus, the term "fracture-closure pressure" is synonymous with minimum in-situ stress and minimum horizontal stress.

http://petrowiki.org/Fracture_mechanics



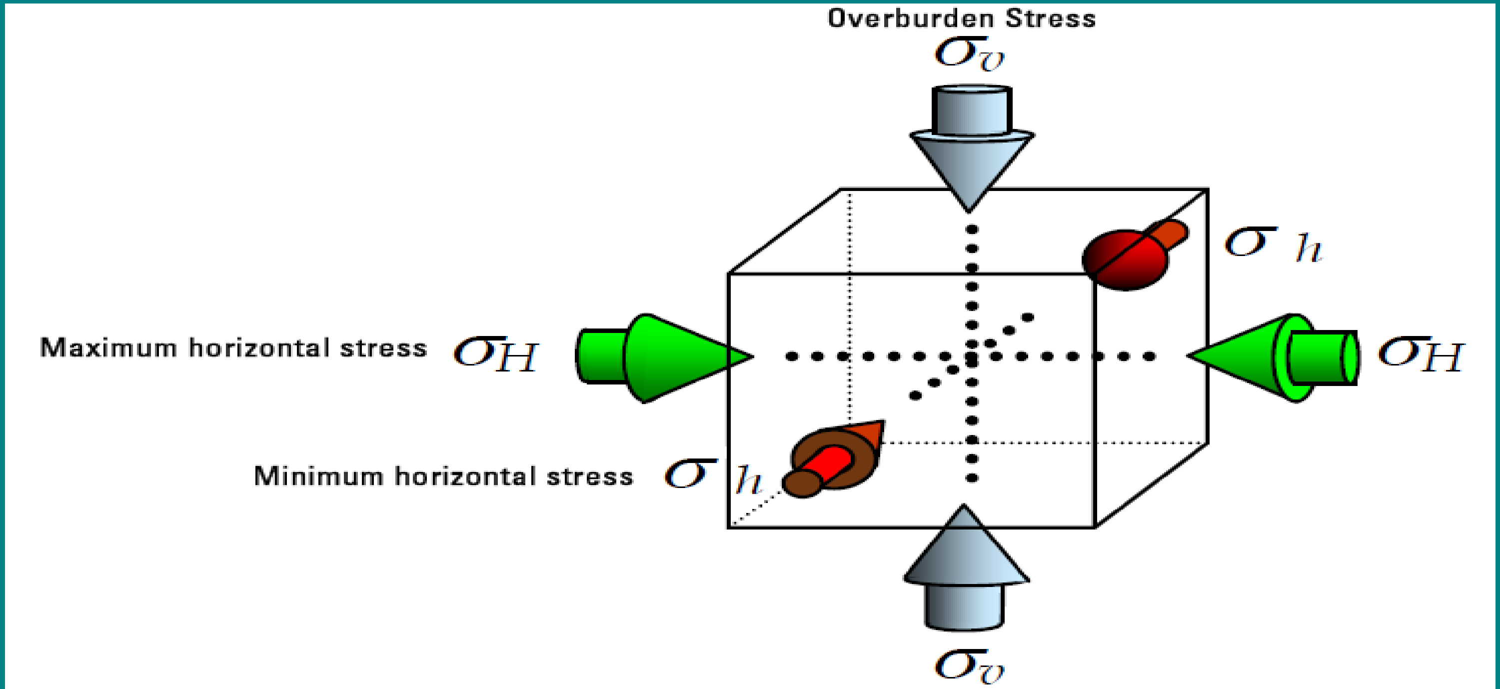
Wireline logs including:
- Depth
- Fluid pressure
- Density
- Compressional velocity
- Shear wave velocity

Enables you to determine stress state and elastic/geomechanical moduli for the reservoir!

Stress orientation

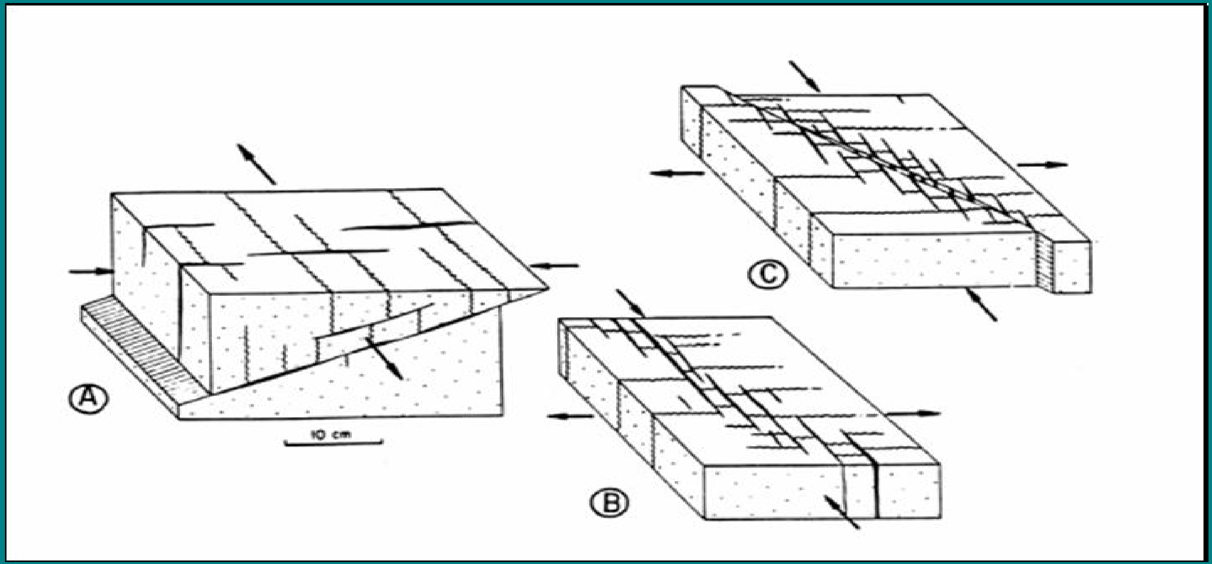
- Not from conventional wireline Logs

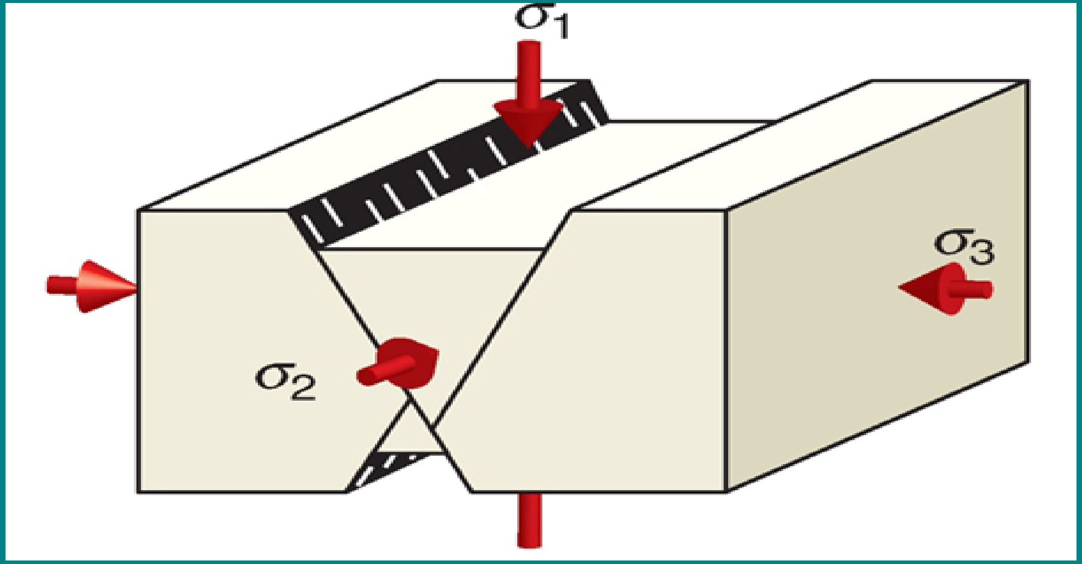
- Need to come from borehole images



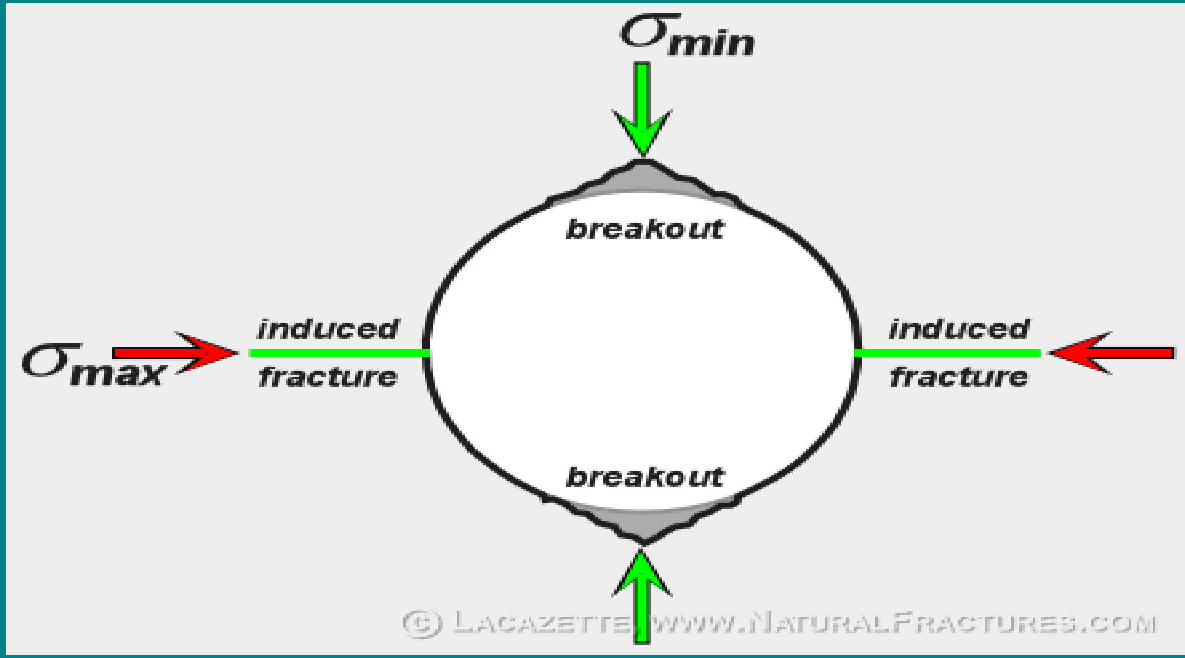
Extension fracturing

- In the σ1 - σ2 plane, perpendicular to σ3





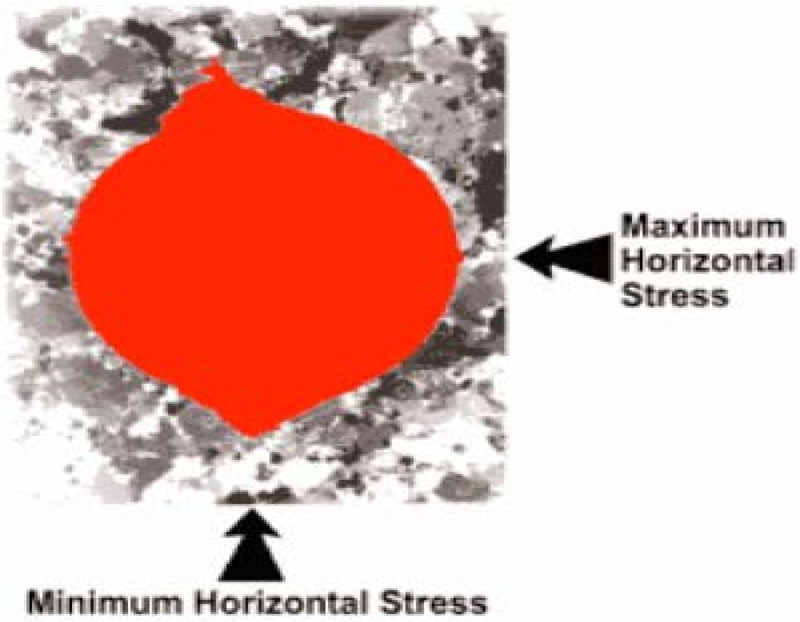
In borehole

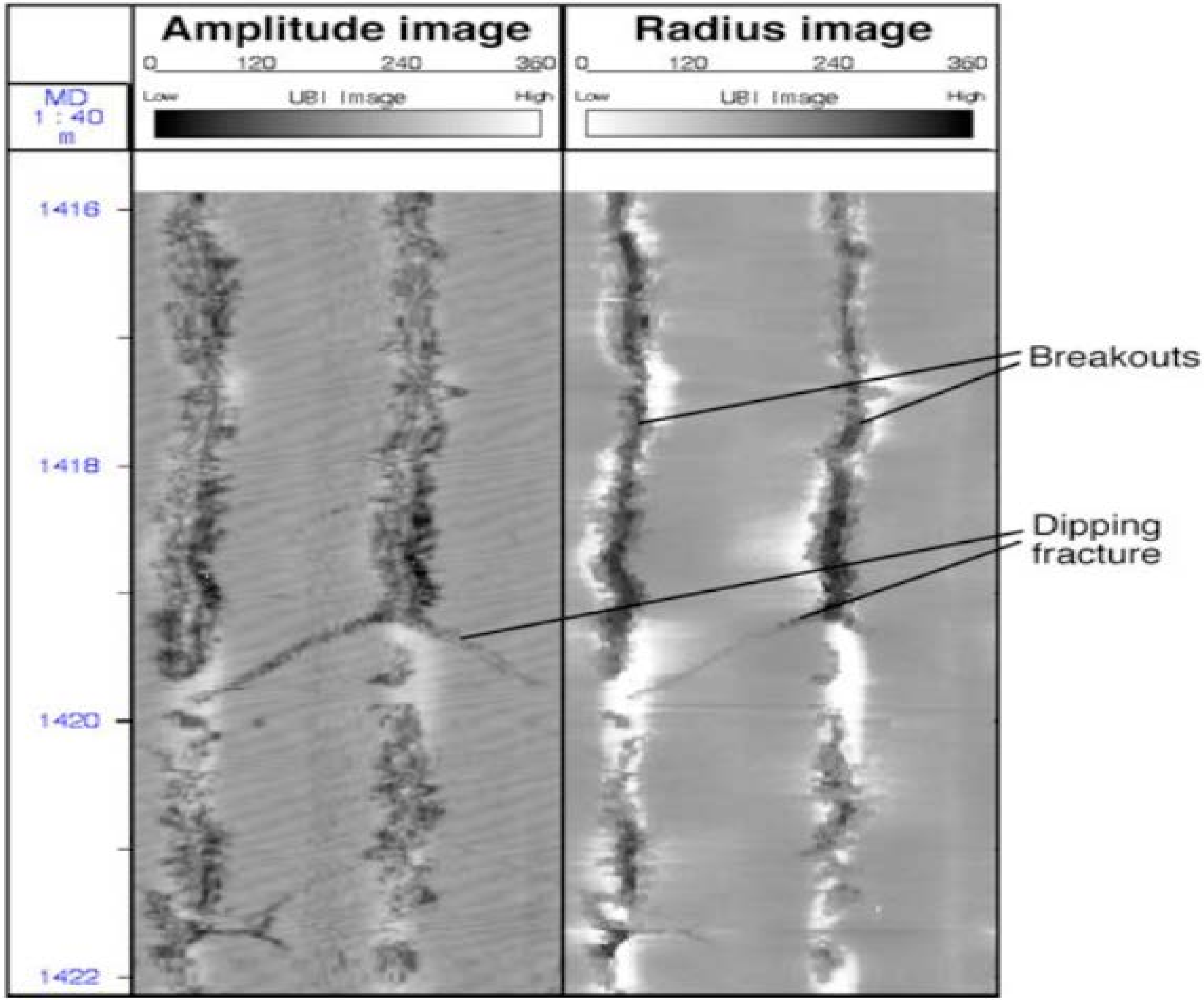


σ_{min}
breakout
induced fracture
σ_{max}
induced fracture
breakout
© Lacazette www.NaturalFractures.com

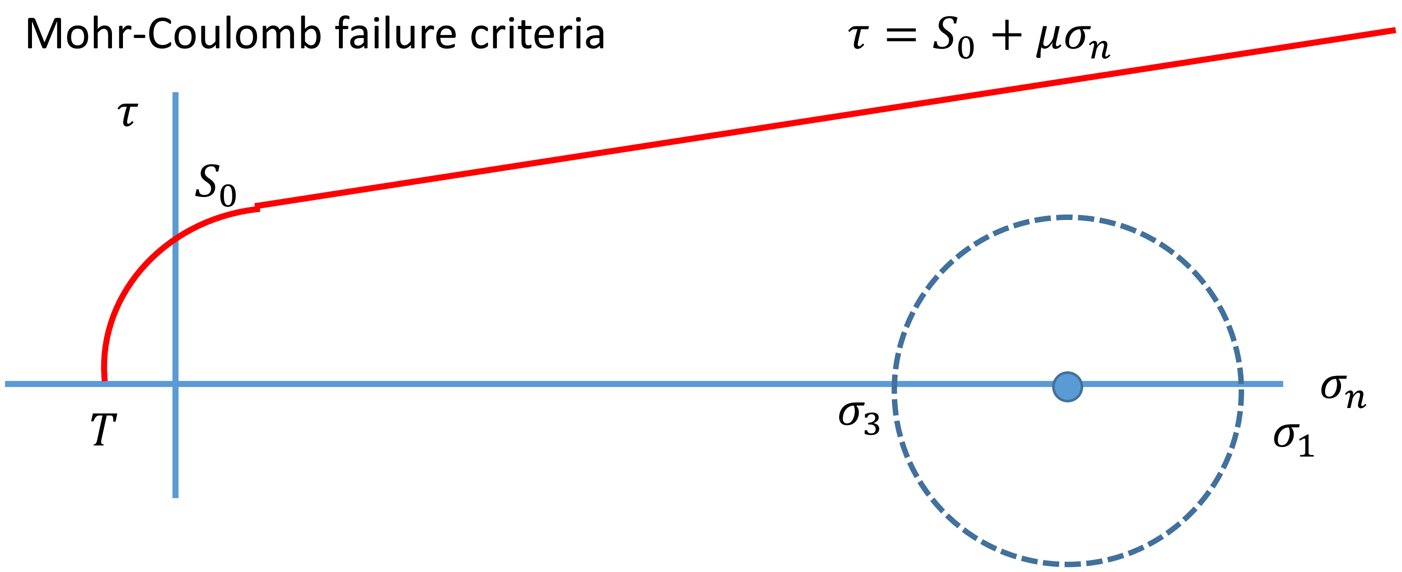
Borehole Breakouts

Mark the minimum stress direction

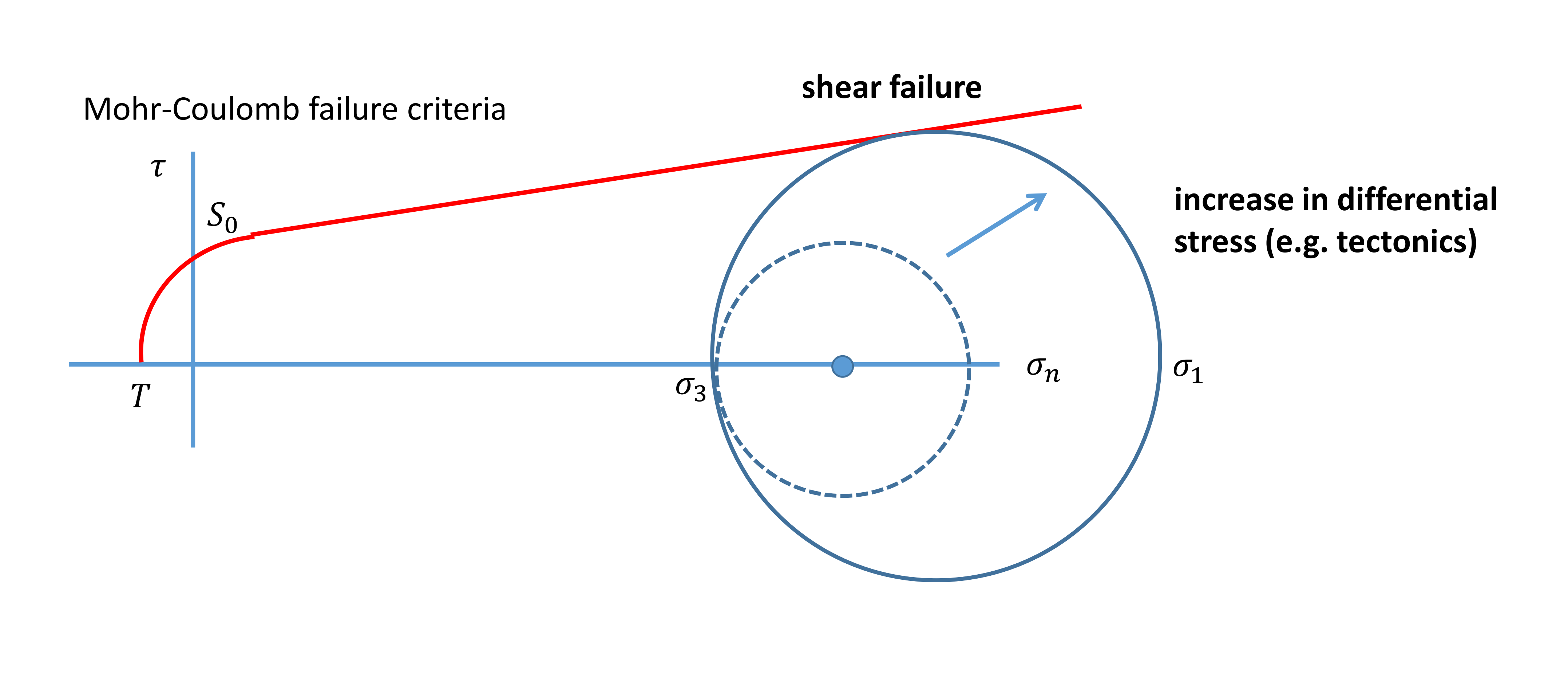




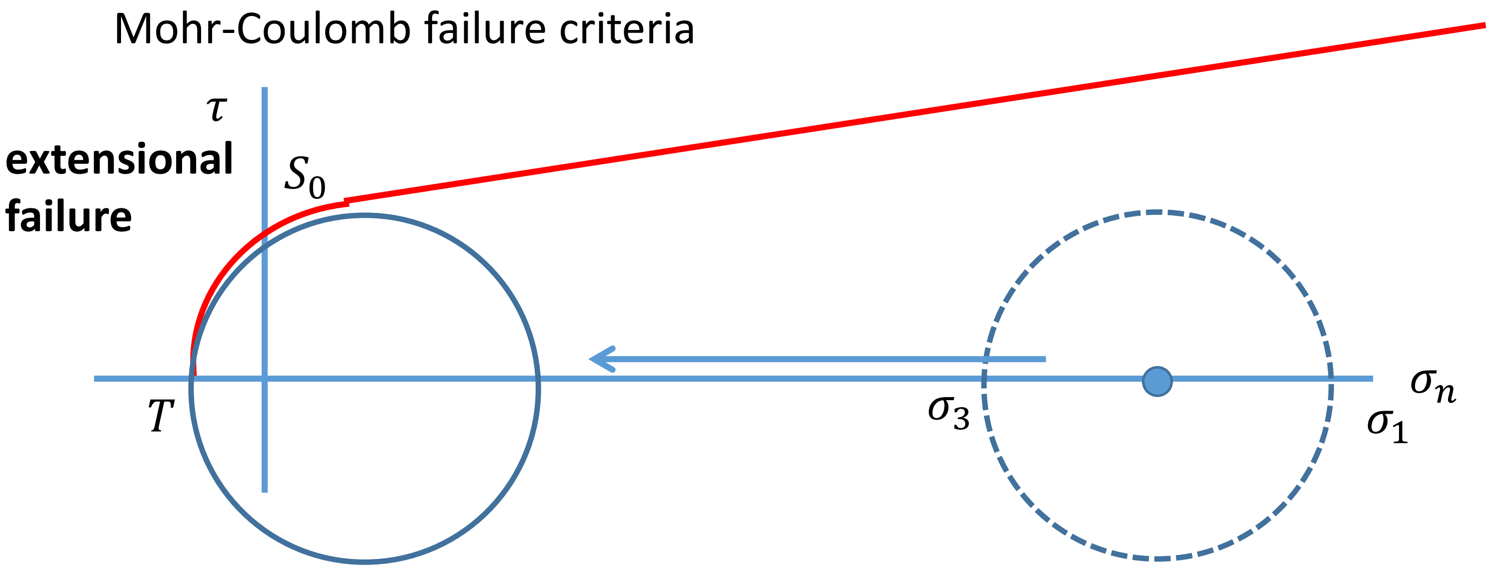
Mohr-Coulomb failure criterion



Mohr-Coulomb failure criterion



Mohr-Coulomb failure criterion



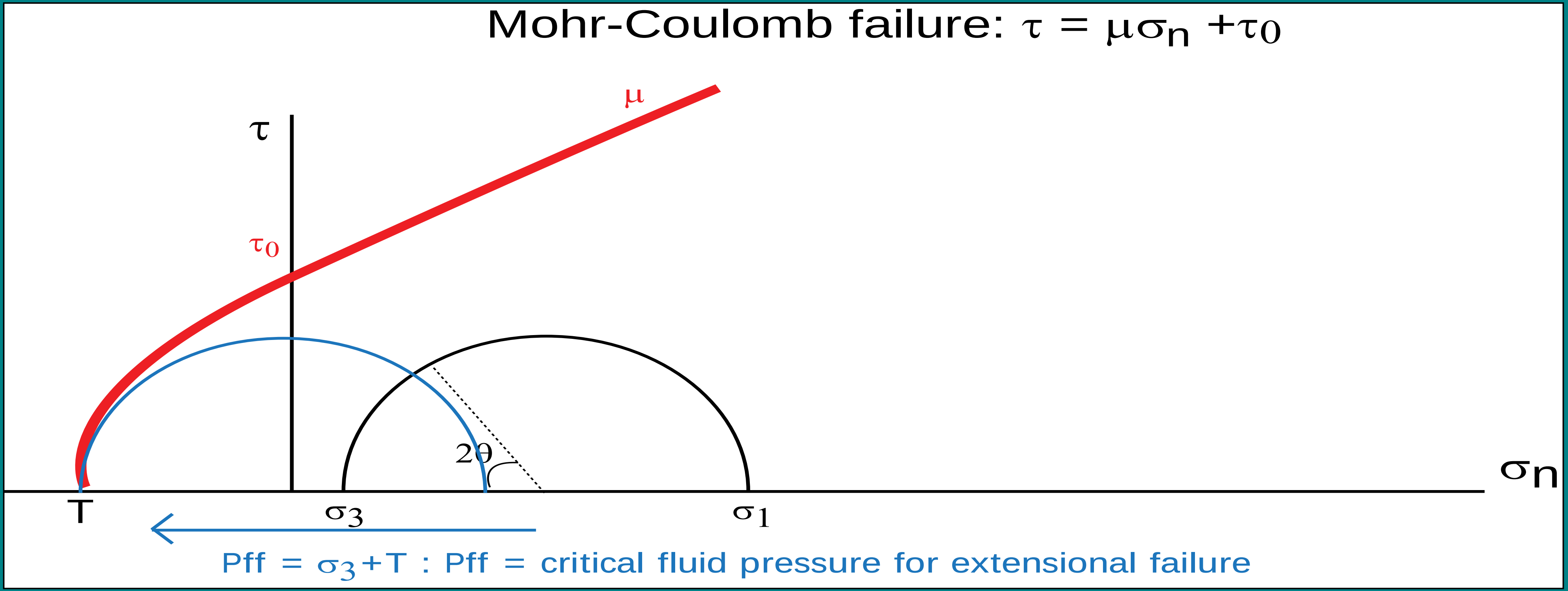
decrease in effective stress due to increase in fluid pressure

$$\sigma_v' = \sigma_v - \alpha P_p$$

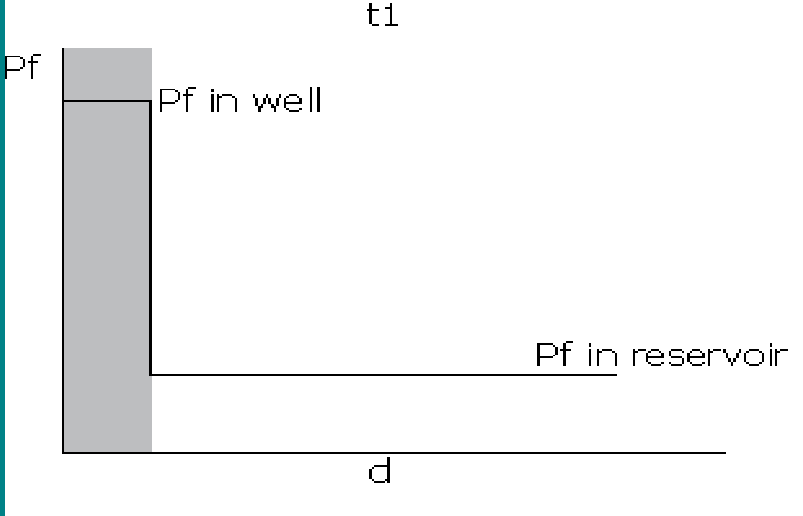
Hydraulic fracturing

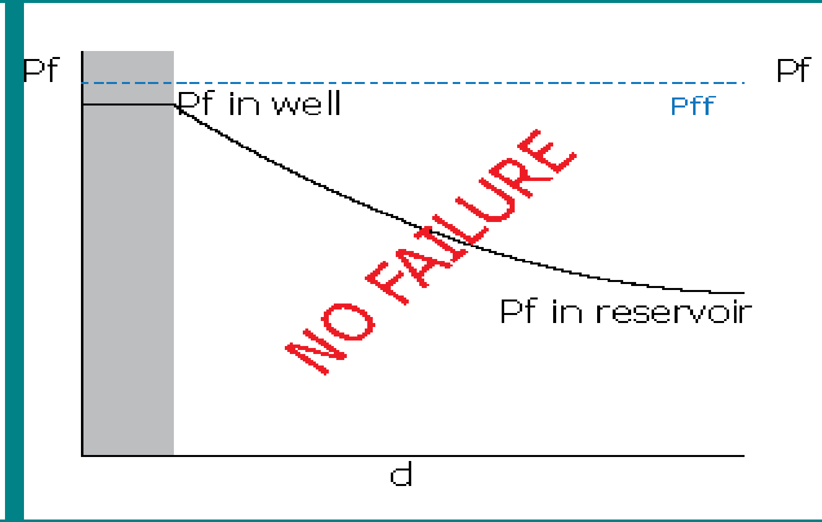
$$P_{ff} = \sigma_h + T$$

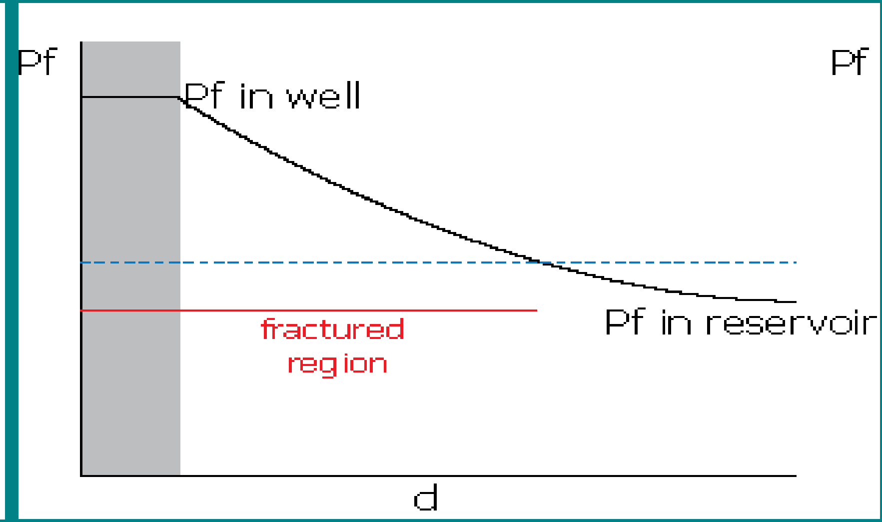
- Mohr-coulomb failure criterion



Fluid pressure in the well







Excel exercise -1 20 min

Open Excel file named 17052016GEOCAP_TTT1.04TUD-ReservoirGeomechanicsExerciseStressProfiles_withoutanswers.xls

1. Create a vertical stress profile through the Earth for a simplified Earth structure with an average density of 2.3 g/cm3 (sandstone with porosity) and a more dense volcanic crust with an average density of ~3 g/cm3
2. Create a fluid pressure profile through the same section.
3. If we assume an average Poisson's ratio for the crust 0f 0.25, what are then the minimum horizontal stresses.
4. How much do we need to increase the borehole fluid pressure to open fractures if the tensile strength of the sandstone is 8 MPa and that of the basalt is 22 MPa?
5. What do those borehole fluid pressures (Pff) mean if the intention is to avoid fracturing?

Excel exercise -2 60 min

A set of logs is available from a well between 3800 and 4400 m. The logs amongst others include density, vp and vs data and bottomhole pressure.

Open Excel file named 17052016GEOCAP_TTT1.04TUD-ReservoirGeomechanicsExerciseLoggingdata_withoutanswers.xls

1. Create again a vertical stress profile using the log data. For the first 3830m use an average density of 2.3 g/cm3, after that you can use the density of the logs.
2. Calculate the poisson's ratio log using the available data.
3. Calculate the minimum horizontal stress profile for the logged section and again calculate the borehole fluid pressure needed to induce fractures if we assume a tensile strength for the logged section (mainly carbonates) of ~ 12 MPa.
4. Since both Vp, Vs and density are measured you can also create logs for the Young's modulus, Bulk modulus and Shear modulus. How many layers would you assume to be present based on the geomechanical logs and how many based on the density and velocity logs alone. What causes this possible difference?

Good Books

Mark Zoback, 2007
Reservoir Geomechanics Cambridge University Press

Erling Fjaer et al., 2008
Petroleum Related Rock Mechanics

Jaeger et al., 1969
Fundamentals of Rock Mechanics

Djebbar Tiab and Erle Donaldson, 2011
Petrophysics

Good online geomechanics course

Mark Zoback's online geomechanics course (Stanford, US)

- https://lagunita.stanford.edu/courses/EarthSciences/ReservGeomech/Spring2016/about

  session 1 -introduction- is also on YouTube: https://www.youtube.com/watch?v=vxISqGZ7rAA

Thank you!

Contact Details

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