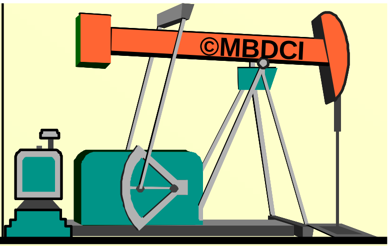
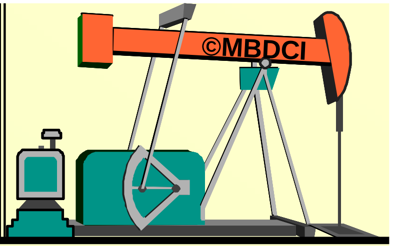


Rock and Rock Mass Deformability (Compressibility, Stiffness…)

Maurice Dusseault

1-D Measuring Rock Properties

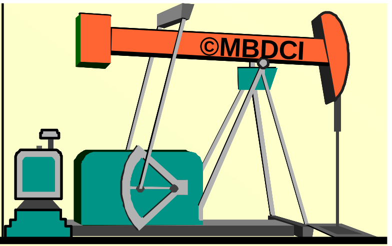
Common Symbols in RM



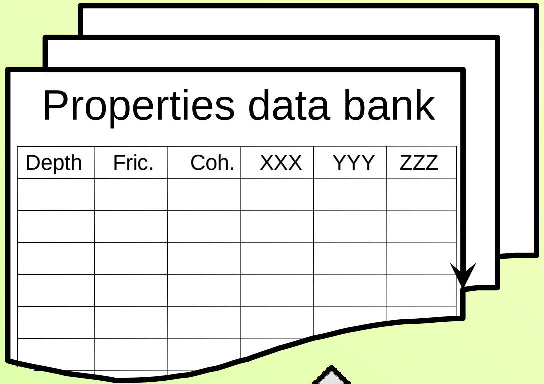
- E, ν: Young’s modulus, Poisson’s ratio
- ϕ: Porosity (e.g. 0.25, or 25%)
- c', ϕ', T_o: Cohesion, friction ∠, tensile strength
- T, p, p_o: Temperature, pressure, initial pres.
- σ_v, σ_h: Vertical and horizontal stress
- σ_{hmin}, σ_{HMAX}: Smallest, largest horizontal σ
- $\sigma_1,\sigma_2,\sigma_3$: Major, intermediate, minor stress
- ρ, γ: Density, unit weight ($\gamma = \rho \times \mathbf{g}$)
- K, C: Bulk modulus, compressibility

These are the most common symbols we use

Obtaining Rock Deformability



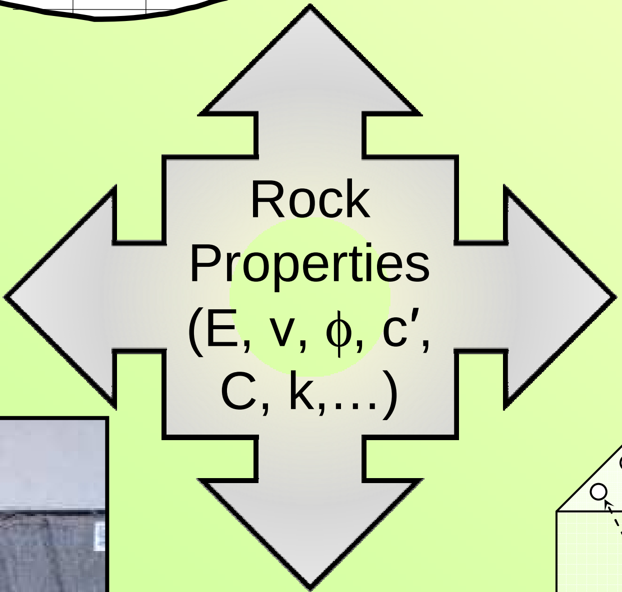
Lab tests



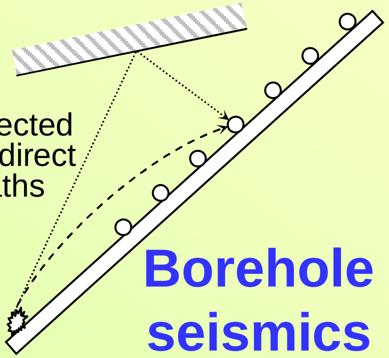
Properties data bank

Depth	Fric.	Coh.	XXX	YYY	ZZZ

**Commercial,
in-house
data banks**

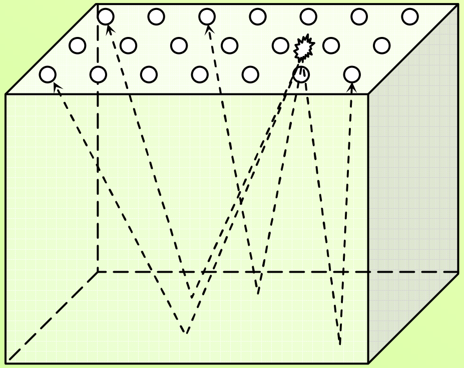


Rock
Properties
(E, ν, ϕ, c′,
C, k,…)



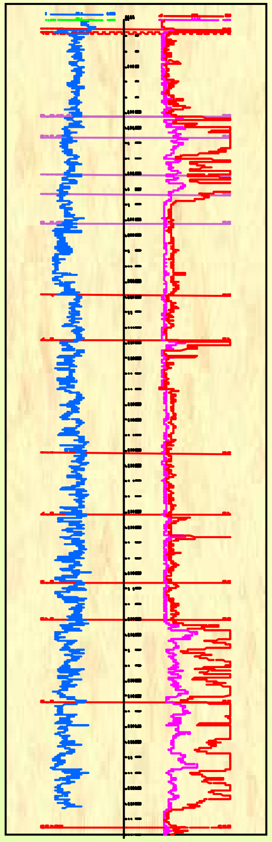
**Borehole
seismics**

3-D Seismics



Log data

REG. TIPO



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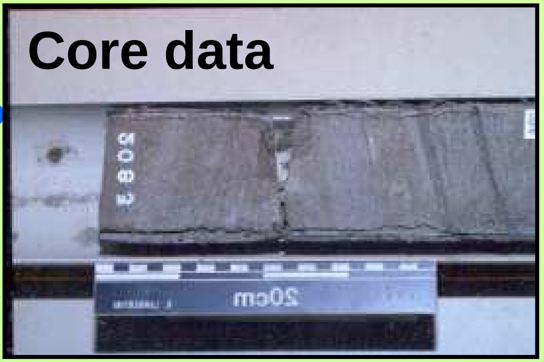
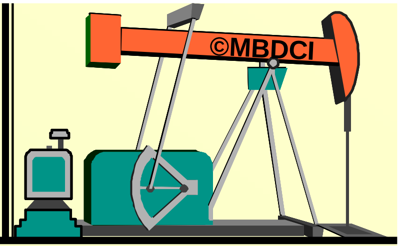
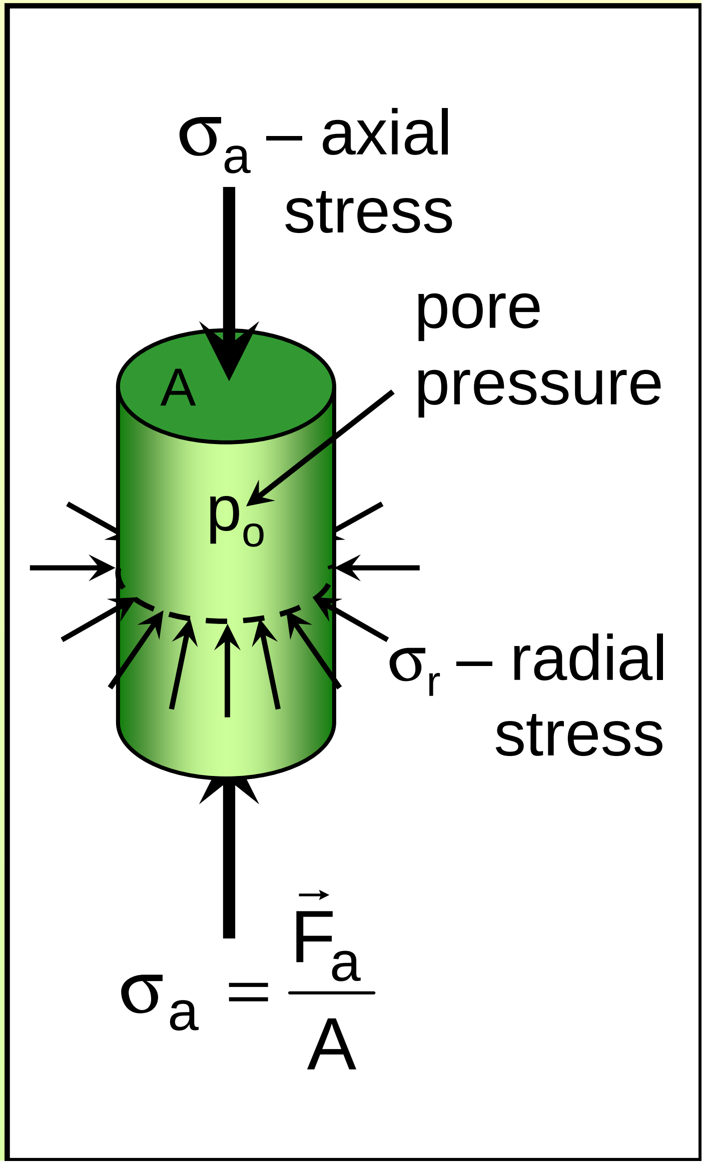


Core data

Stress and Pressure

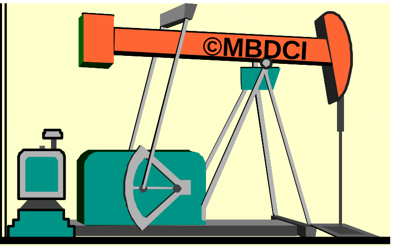


- Petroleum geomechanics deals with stress & pressure
- Effective stress: “solid stress”
- Pressure is in the fluid phase
- To assess the effects of $\Delta\sigma'$, Δp, ΔT, ΔC…
- **<u>Rock properties</u>** are needed
  - Deformation properties…
  - Fluid transport properties…
  - Thermal properties…



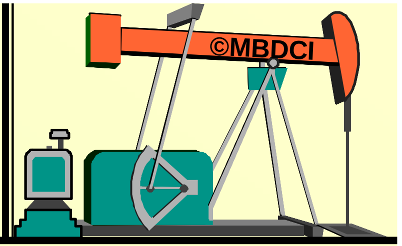
$$\sigma_a = \frac{\vec{F}_a}{A}$$

Rock Stiffness, Deformation

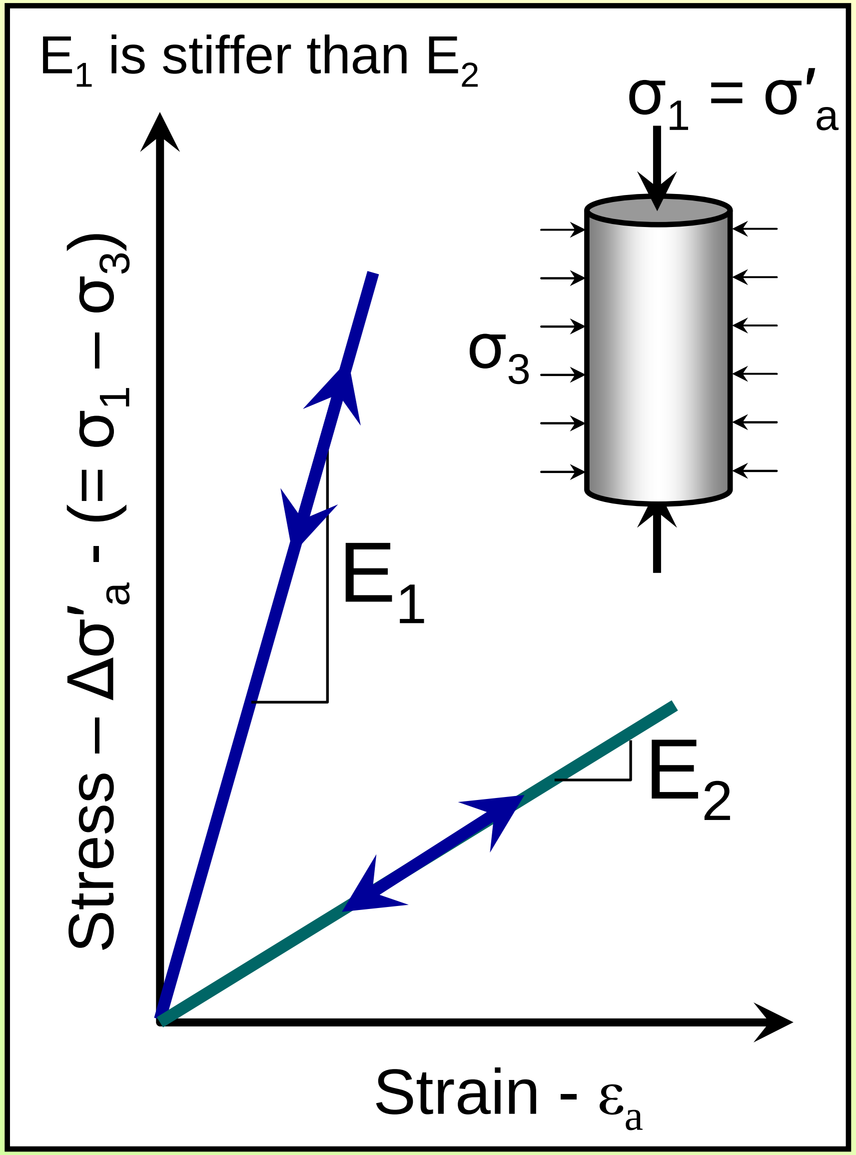


- To solve a σ′-ε problem, we must know how the rock deforms (strain - ε) in response to Δσ′
- This is often referred to as the "**stiffness**" (or compliance, or elasticity, or compressibility…)
- For "**linear elastic**" rock, only two parameters are needed: Young's modulus, E, and Poisson's ratio, ν (see example, next slide)
- For more complicated cases - plasticity, dilation, anisotropic rock, salt, etc. - more and different parameters are needed

The Linear Elastic Model

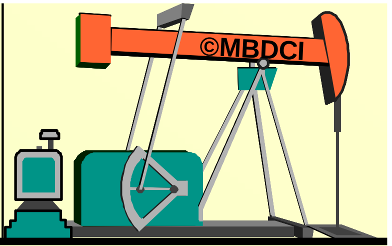


- The stiffness is assumed to be constant (E)
- When loads are removed, deformation are reversed
- Suitable for metals, low ϕ rocks such as…
  - ➔ Anhydrite, carbonates, granite, cemented sands…
- For many petroleum geomechanics problems, **linear elastic assumptions are sufficient**



1-D Measuring Rock Properties

Definitions of E and ν?



Young's modulus (E): E is how much a material compresses under a uniaxial change in effective stress - Δσ′

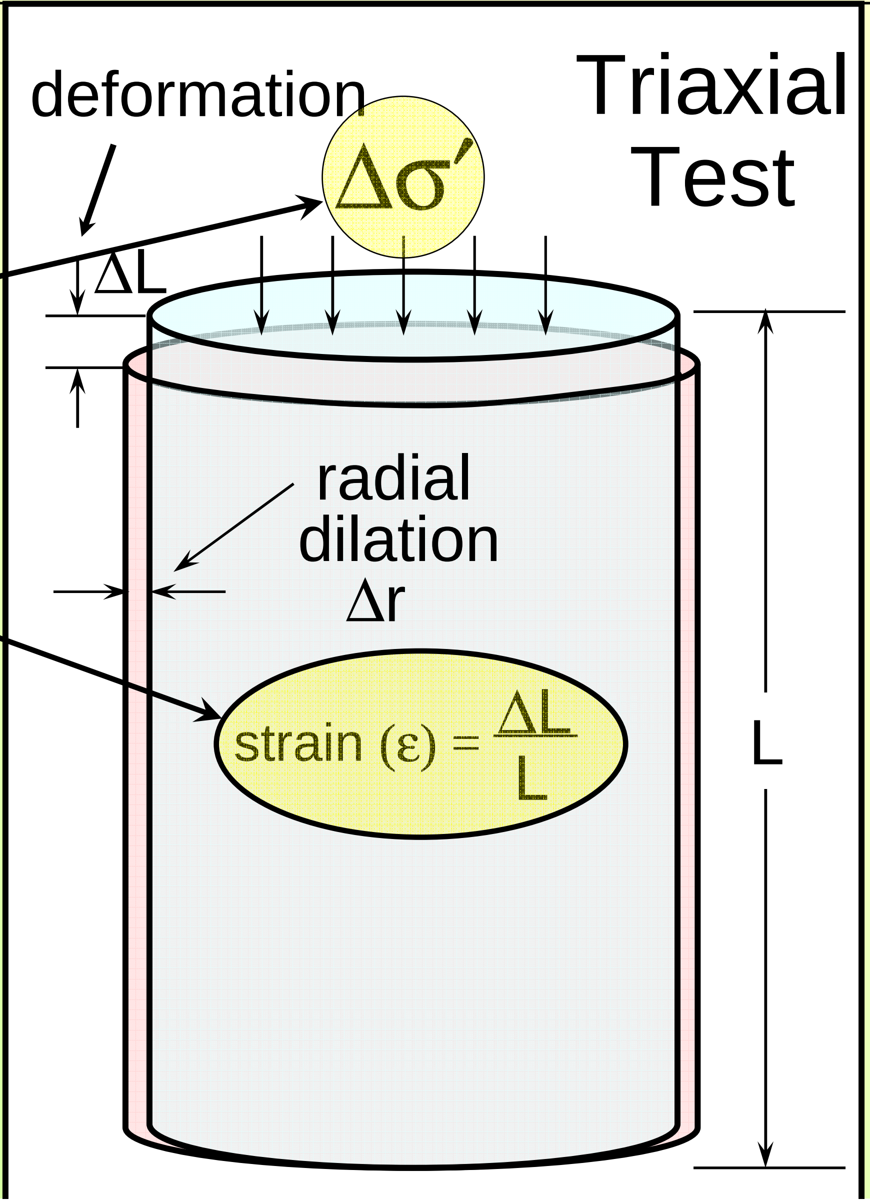
$$E = \frac{\Delta\sigma'}{\varepsilon}$$

Poisson's ratio (ν): ν is how much rock expands laterally when compressed. If ν = 0, no expansion (e.g.: a sponge).

-For sandstones, ν ~ 0.2-0.3

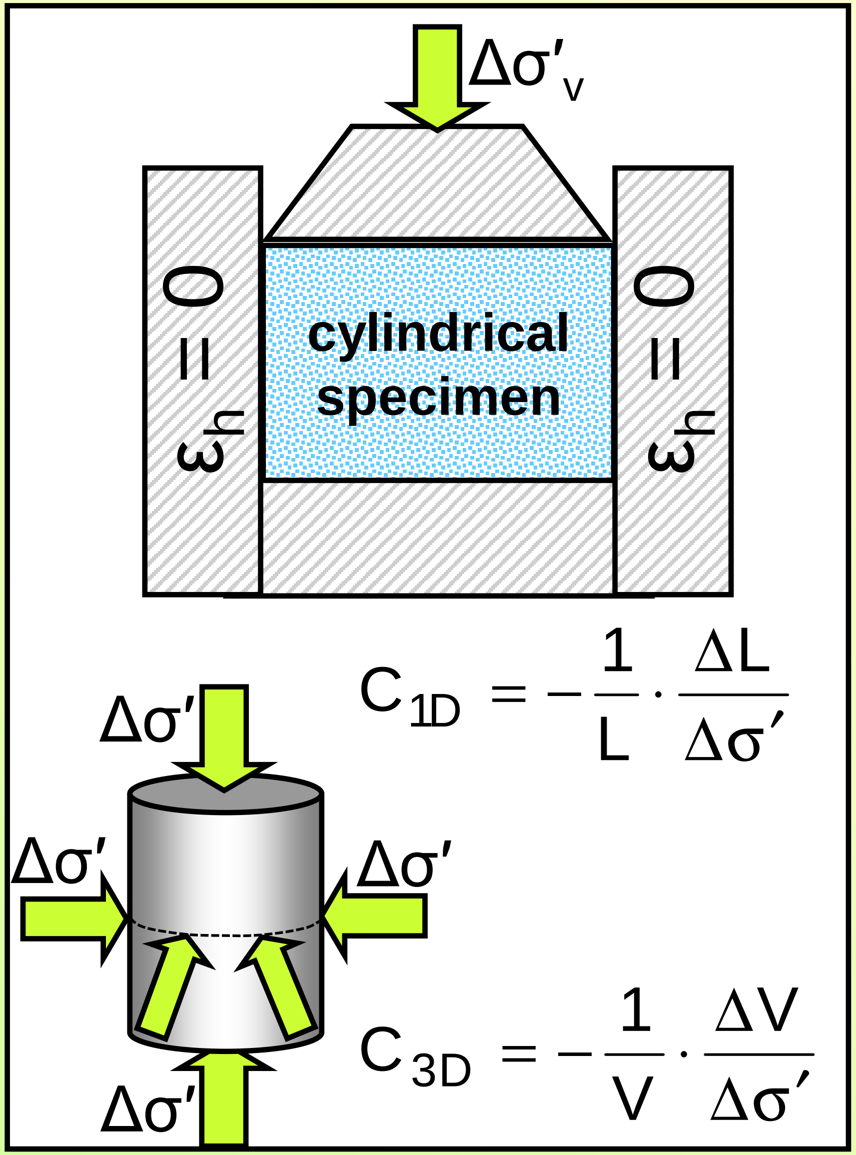
-For shales, ν ~ 0.3-0.4

$$\nu = \frac{\Delta r}{\Delta L}$$



1D and 3D Compressibility?

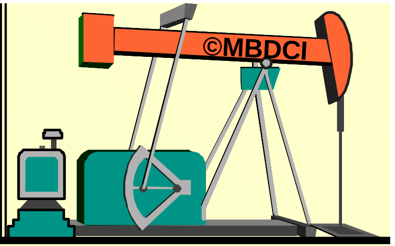
- Change in volume with a change in stress
- In 1-D compressibility, lateral strain, ε_h, = 0
  - ➔ Often used for flat-strata compaction analysis
- 3-D compressibility involves all-around $\Delta\sigma'$
- $C_{3D} = 1/K$, where K is the bulk modulus of elasticity



$$C_{1D} = -\frac{1}{L} \cdot \frac{\Delta L}{\Delta\sigma'}$$

$$C_{3D} = -\frac{1}{V} \cdot \frac{\Delta V}{\Delta\sigma'}$$

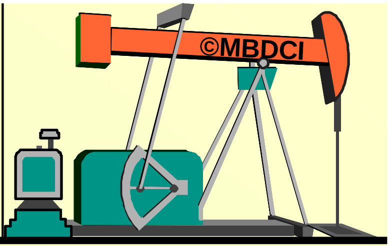
Some Guidelines for Testing…



- Use high quality core, as “undisturbed” as possible, under the circumstances…
    - Avoid freezing, other severe treatments
    - Preserve RM specimens on the rig floor if you can
- Use as large a specimen as possible
    - A large specimen is more representative
    - Avoid “plugging” if possible (more disturbance)
- If undisturbed core is unavailable
    - Analogues may be used
    - Data banks can be queried
    - Disturbed samples may be tested with “judgment”

1-D Measuring Rock Properties

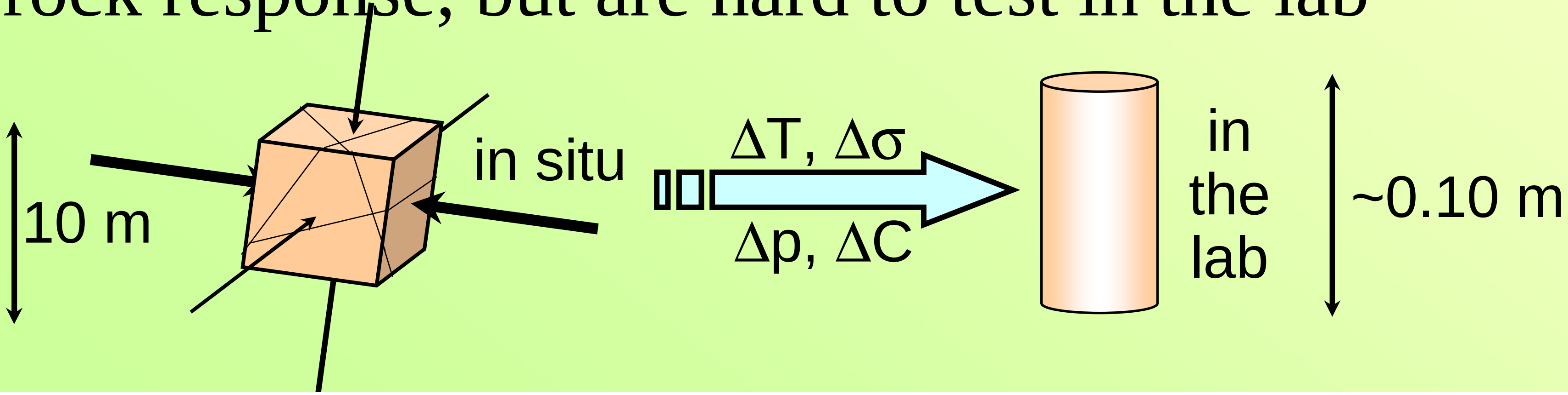
More Guidelines for Testing…



- Replicating *in situ* conditions of T, p, [σ] is “best practice” (but not always necessary)
- Following the stress path that the rock experiences during exploitation is “best practice”
- Test “representative” specimens of the GMU
- Testing jointed rock masses in the laboratory is not feasible; only the “matrix” of the blocks…
- It is best to combine laboratory test data with log data, seismic data, geological models, and update the data base as new data arrive…

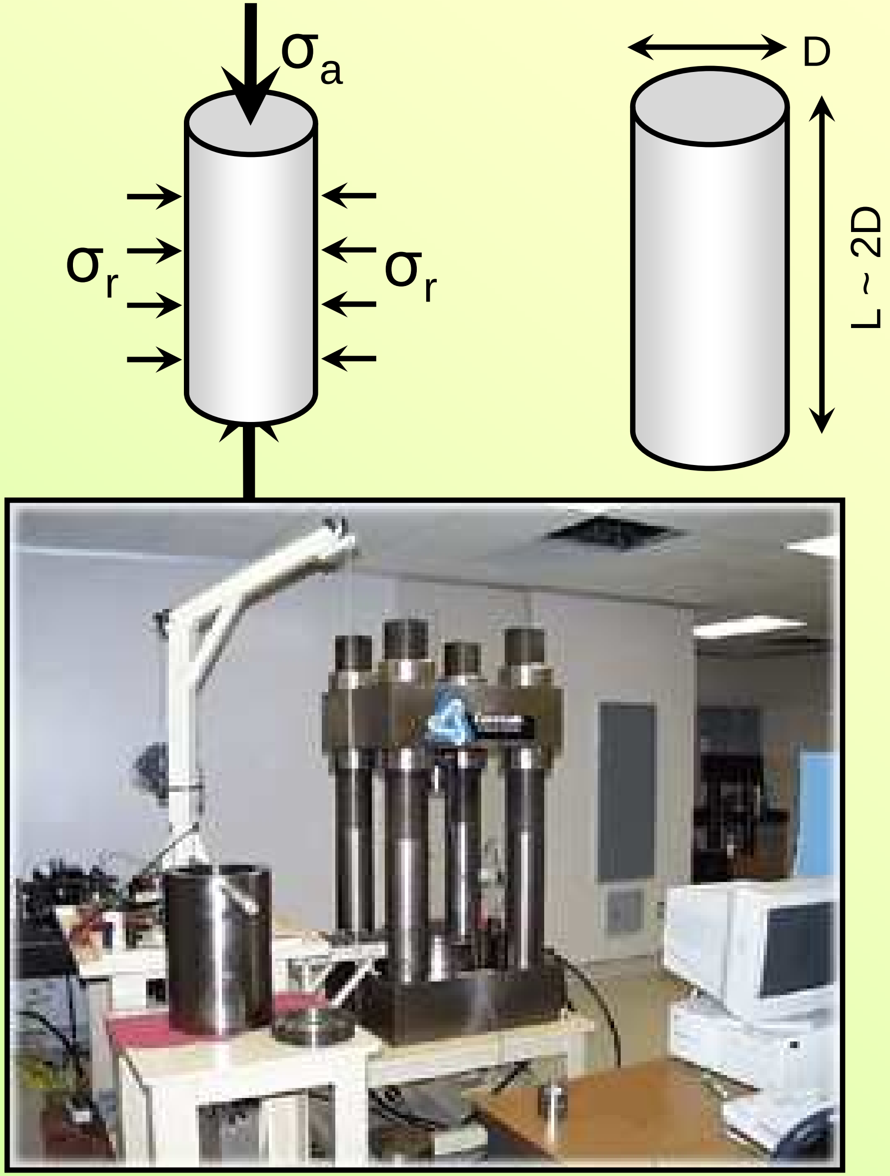
Laboratory Stiffness of Rocks

- From cores, other samples: however, these may be microfissured (E_{field} may be underestimated)
- In microfissured or porous rock, crack closure, slip, contact deformation may dominate stiffness
- E_S and ν_S (static) under σ'_3 gives best values
- If joints are common *in situ*, they may dominate rock response, but are hard to test in the lab

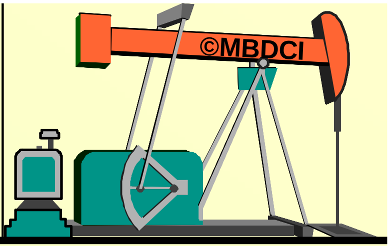


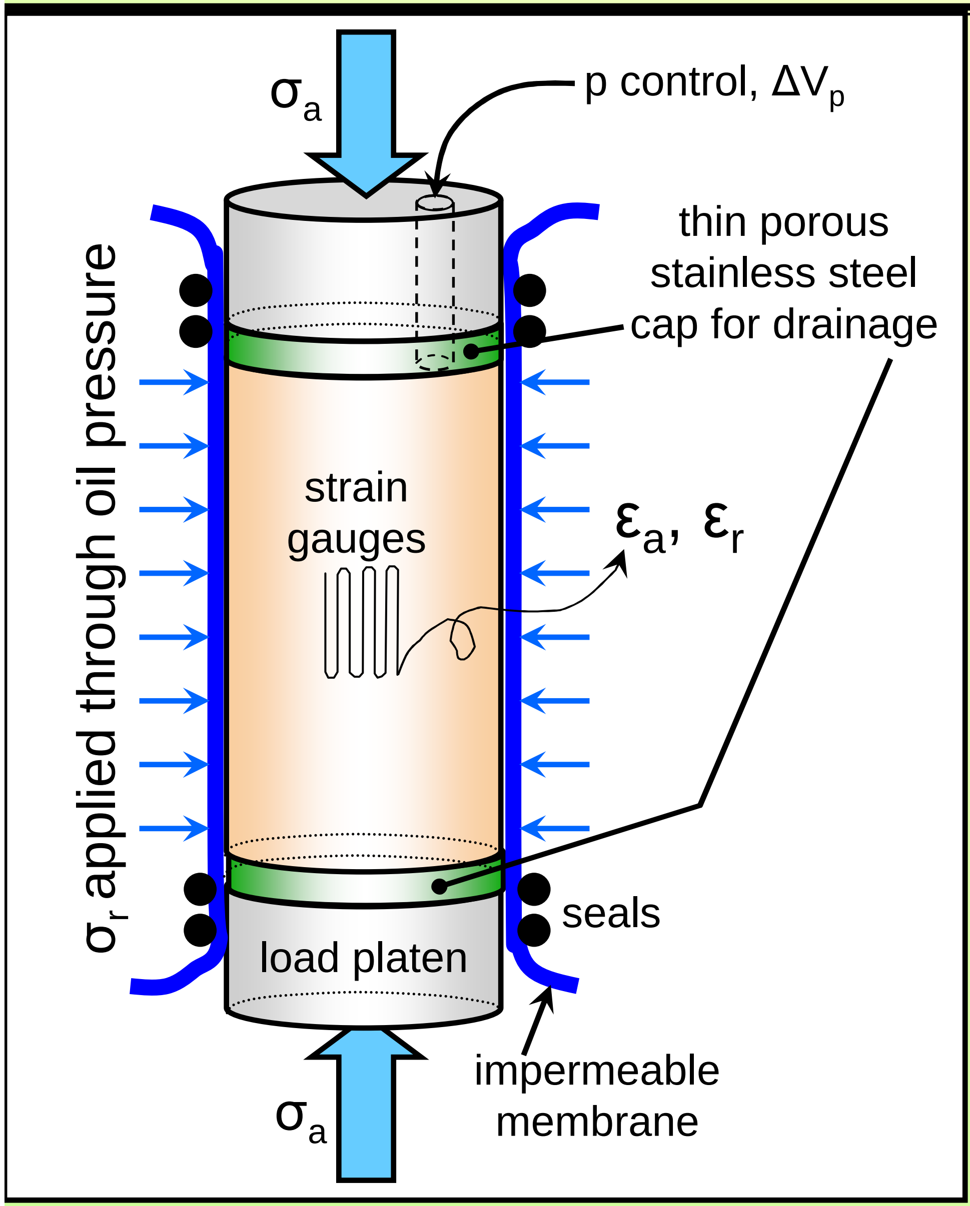
Typical Test Configuration…

- An “undamaged”, homogeneous rock interval is selected
- A cylinder is prepared with flat parallel ends
- The cylinder is jacketed
- Confining stress & pore pressure are applied
- The axial stress is increased gradually
- ε_a, ε_r (ε_r) measured



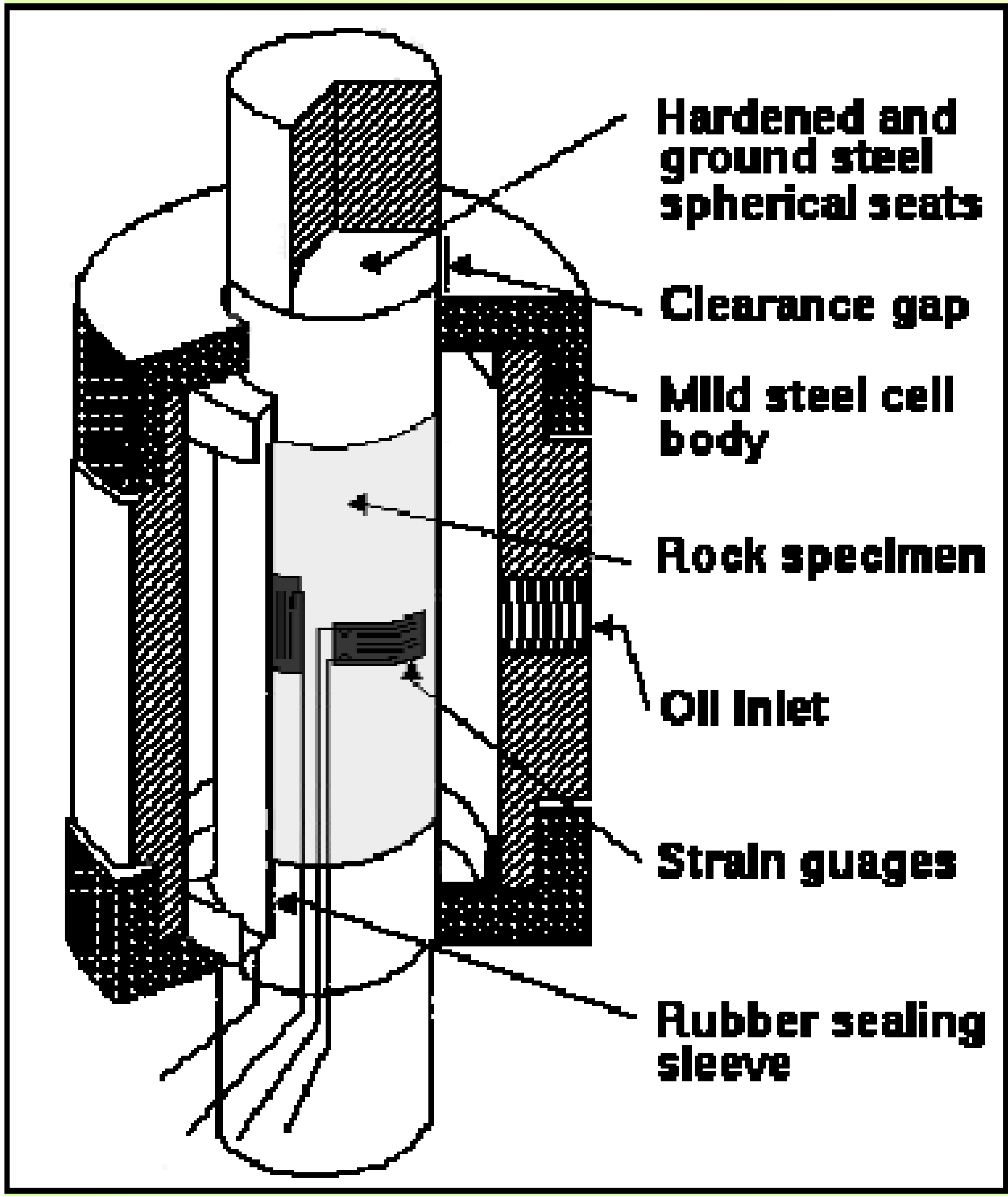
Jacketed Cylindrical Rock Specimen





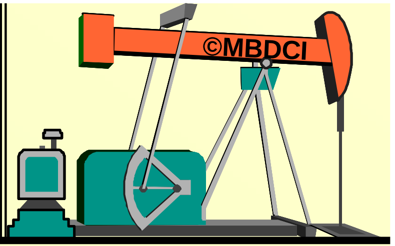
- Strain gauges measure strains (or other special devices can be used)
- Pore pressure can be controlled, and…
- ΔV_{pore} can be measured at constant backpressure
- Similar set-up for high-T tests and creep tests
- Acoustic wave end caps
- Etc…

A Simpler Standard Triaxial Cell



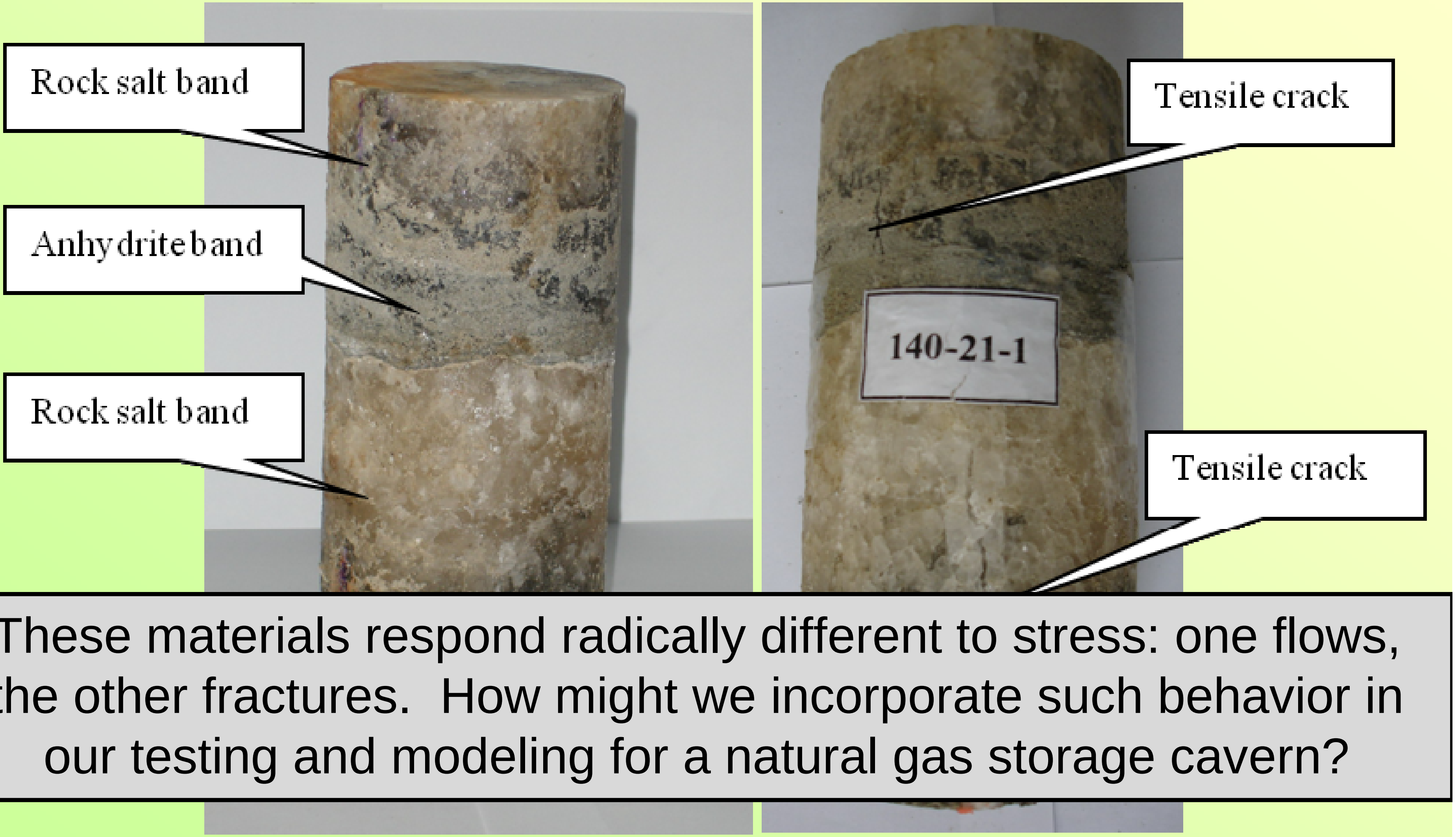
- Developed by Evert Hoek & John Franklin
- Is a good basic cell for rock testing
- Standard test methods are published by the **International Society for Rock Mechanics (ISRM)**

In the Laboratory…



- Axial deformation is measured directly by the movement of the test platens
- Bonded strain gauges on the specimen sides are also used
  - Gives axial strain (calculate E)
  - Also gives the lateral strain (calculate ν)
- Special methods for porous rocks or shales because strain gauges don’t work well
- High T tests, acoustic velocity measurements during tests, etc., etc.

Reminder: Heterogeneity!



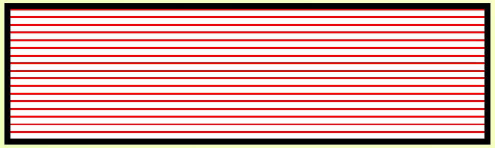
These materials respond radically different to stress: one flows, the other fractures. How might we incorporate such behavior in our testing and modeling for a natural gas storage cavern?

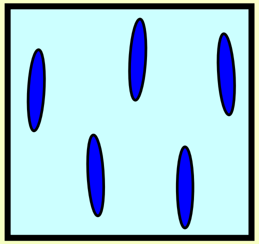
Original specimen - Post-test appearance

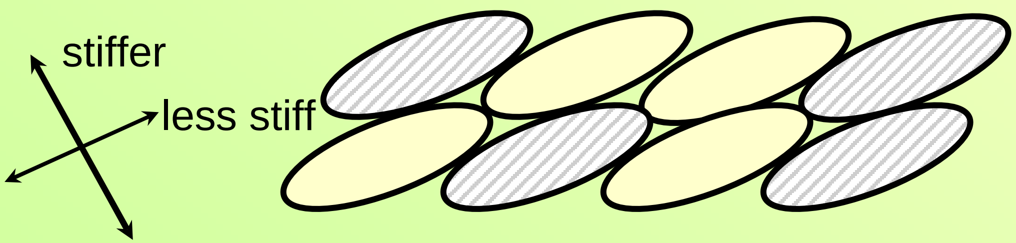
Reminder: Scale and Heterogenity

Reminder: Anisotropy

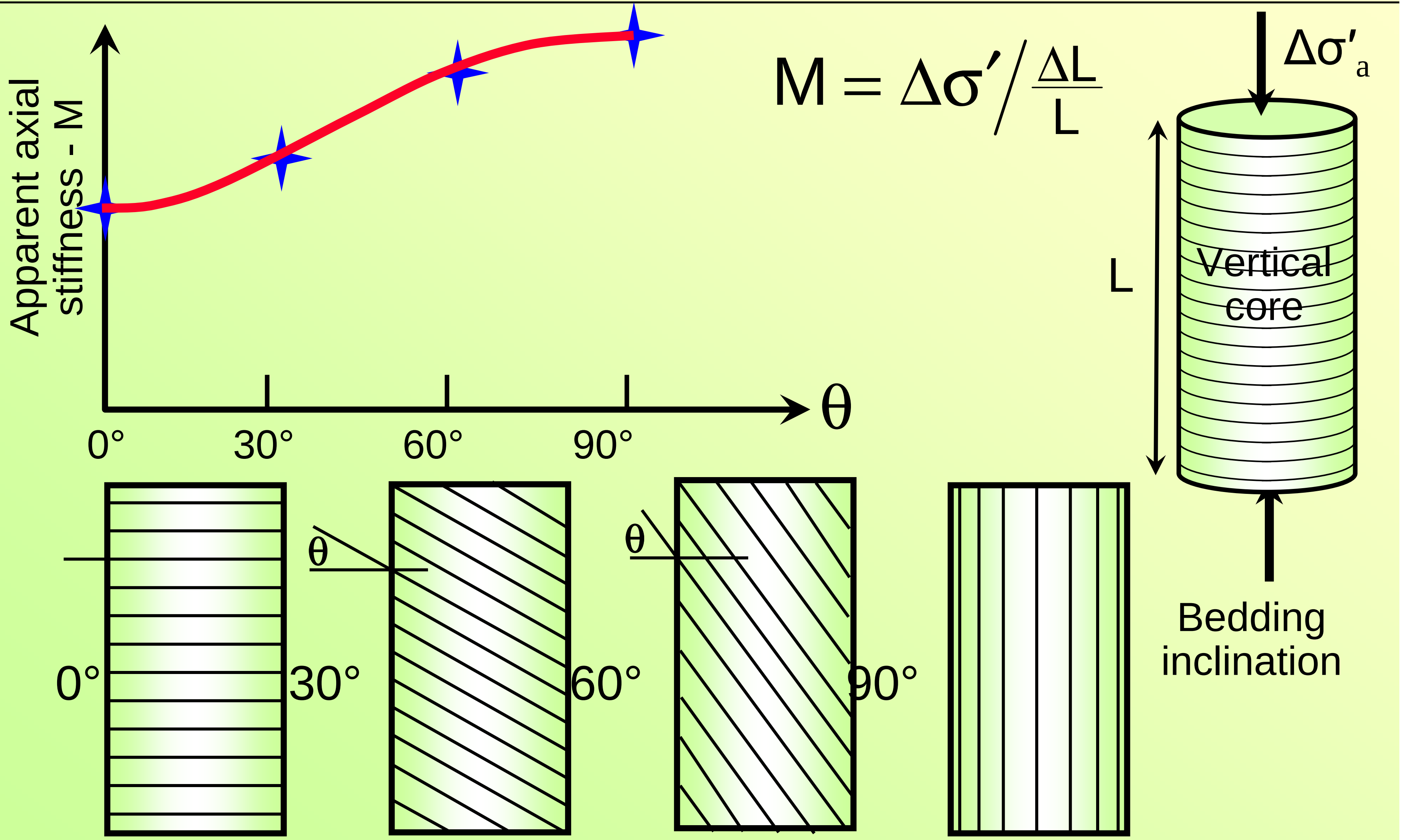
- Different directional stiffness is common!
  - Bedding planes
  - Oriented minerals (clays usually)
  - Oriented microcracks, joints, fissures…
  - Close alternation of thin beds of different inherent stiffness (laminated or schistose)
  - Imbricated grains
  - Different stresses = anisotropic response
  - Anisotropic grain contact fabric, etc.







Reminder: Anisotropy

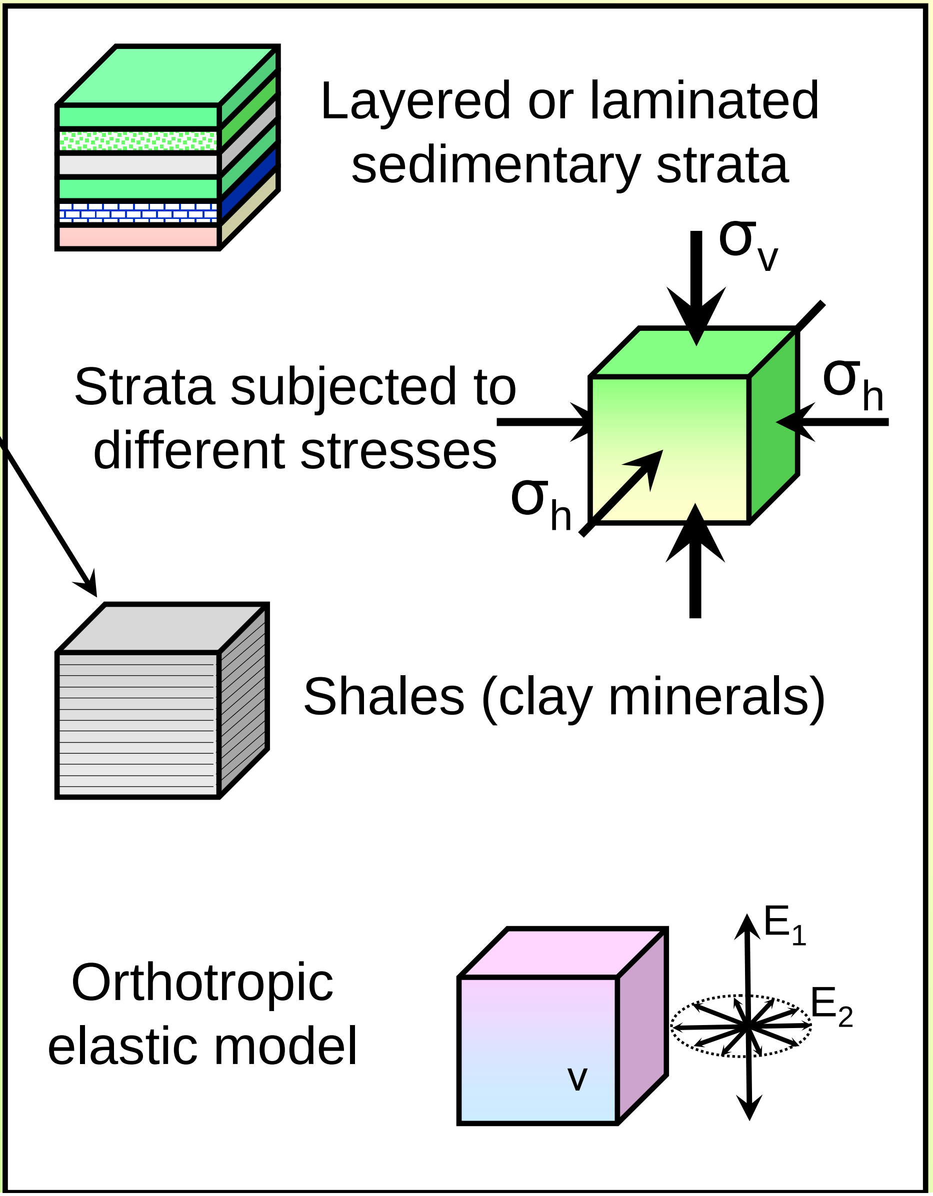


$$M = \Delta\sigma' \Big/ \frac{\Delta L}{L}$$

e.g.: shales, laminated strata

Orthotropic Stiffness Model

- In some cases, it is best to use an orthotropic stiffness model - shale
- Vertical stiffness and Poisson's ratio are different than the horizontal ones
- Properties in the horizontal plane the same
- This is as complex as we want: E_1, E_2, ν



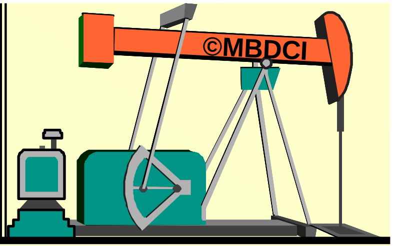
Layered or laminated sedimentary strata

Strata subjected to different stresses

Shales (clay minerals)

Orthotropic elastic model

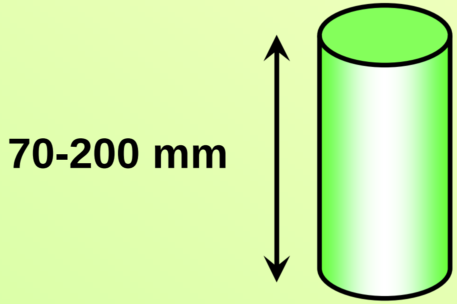
Lab Data, Then What?



- Clearly, laboratory tests are valuable, but insufficient for design and optimization…
- We also use correlations from geophysical logs
  - ➔ Obtain relevant, high-quality log data
  - ➔ Calibrate using lab test data
  - ➔ Use logs and 3-D seismic to extrapolate and interpolate (generating a 3-D whole earth model)

1-D Measuring Rock Properties

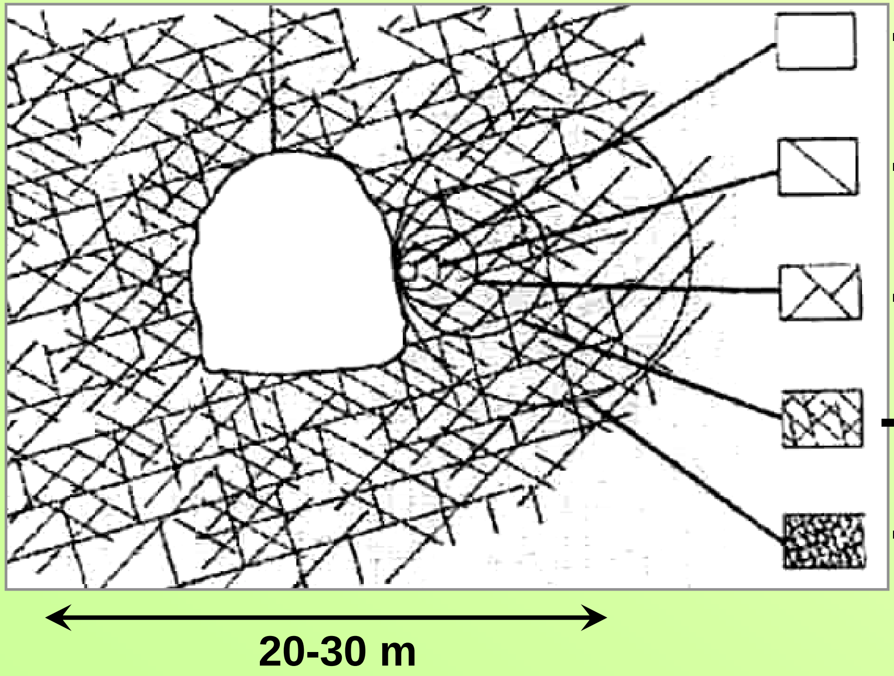
Reminder: Scale Issues…



Laboratory specimen ("intact")

A tunnel in a rock mass

Rock vs Rock mass



--Intact rock

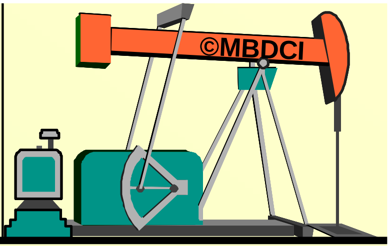
--Single discontinuities

--Two discontinuities

--Several disc.

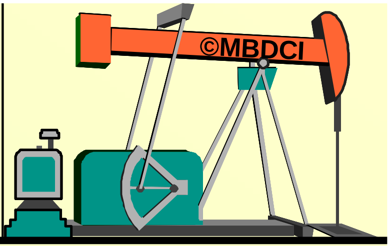
--Rockmass

Rock Mass Stiffness Determination



- Use correlations based on geology, density, porosity, lithology…
- Use seismic velocities (v_P, v_S) for an upper-bound limit (invariably an overestimate)
- Measurements on specimens in the lab? (problems of scale and joints)
- *In situ* measurements
- Back-analysis using monitoring data such as compaction measurements…
- Reservoir response to earth tides…

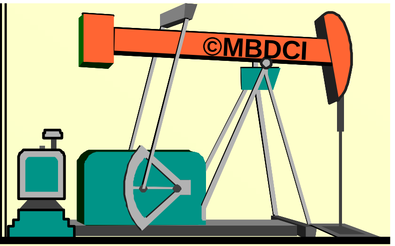
In Situ Stiffness Measurements



- Pressurization of a packer-isolated zone, with measurement of radial deformation ($\Delta r/\Delta\sigma'$), in an “impermeable material” so that $\Delta\sigma' = \Delta p_w$
- Direct borehole jack methods (mining only)
- Geotechnical pressure-meter modified for high pressures (membrane inflated at high pressure, radial deformation measured)
- Hydrofracture flexing (THE™ tool, rarely used and quite expensive)
- Correlations (penetration, indentation, others?)

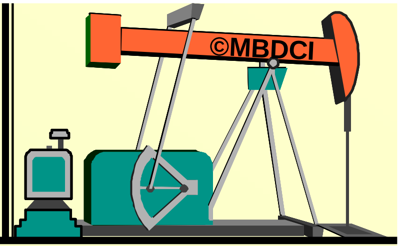
1-D Measuring Rock Properties

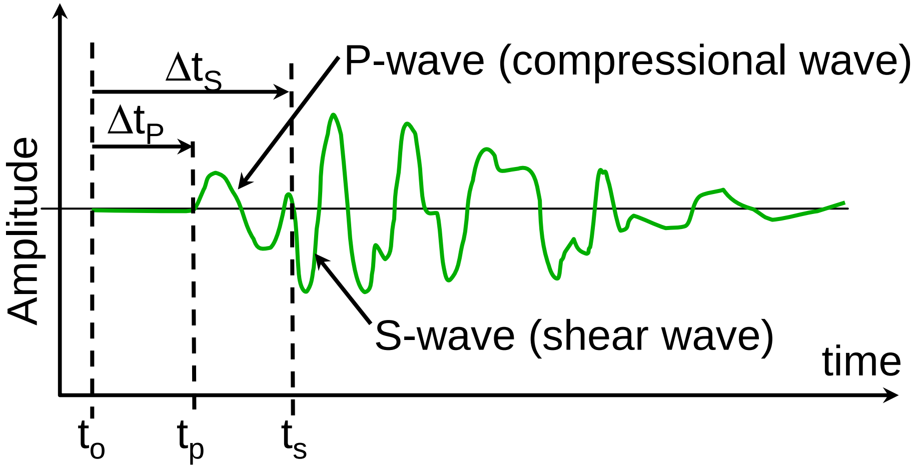
Seismic Wave Stiffness (E_D, ν_D)



- v_P, v_S: dynamic responses are affected by stress, density and elastic properties (σ, ρ, E, ν)
- Seismic strains are tiny ($<10^{-8}$-10^{-7}), they do not compress microcracks, pores, or contacts
- Thus, E_D is **always higher** than the static test moduli, E_S
- The more microfissures, pores, point contacts, the more $E_D > E_S$, x 1.3 to x 10 (for UCSS)
- If porosity ~ 0, σ' very high, E_S approaches E_D
- Seismic moduli should be calibrated by testing

Seismic (Dynamic) Parameters





Δt is transit time, plotted in micro-seconds per foot or per metre

V_p and V_s are calculated from the transit time and the distance – L – between the receiver and the transmitter in the acoustic sonde

$V_p = L/\Delta t_p$

$V_s = L/\Delta t_s$

Dynamic Elastic Parameters:

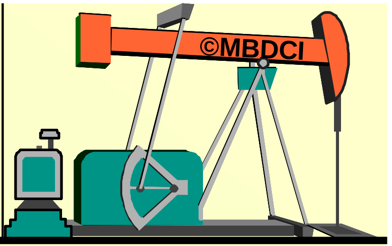
$$\nu_D = [V_p^2 - 2V_s^2]/[2(V_p^2 - V_s^2)]$$

$$E_D = [\rho_b.V_s^2(3V_p^2 - 4V_s^2)]/(V_p^2 - V_s^2)$$

$$\mu_D = \rho_b.V_s^2 \text{ (shear modulus)}$$

1-D Measuring Rock Properties

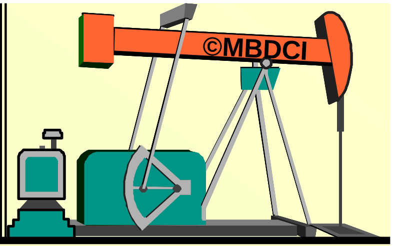
Deformation Properties from Logs

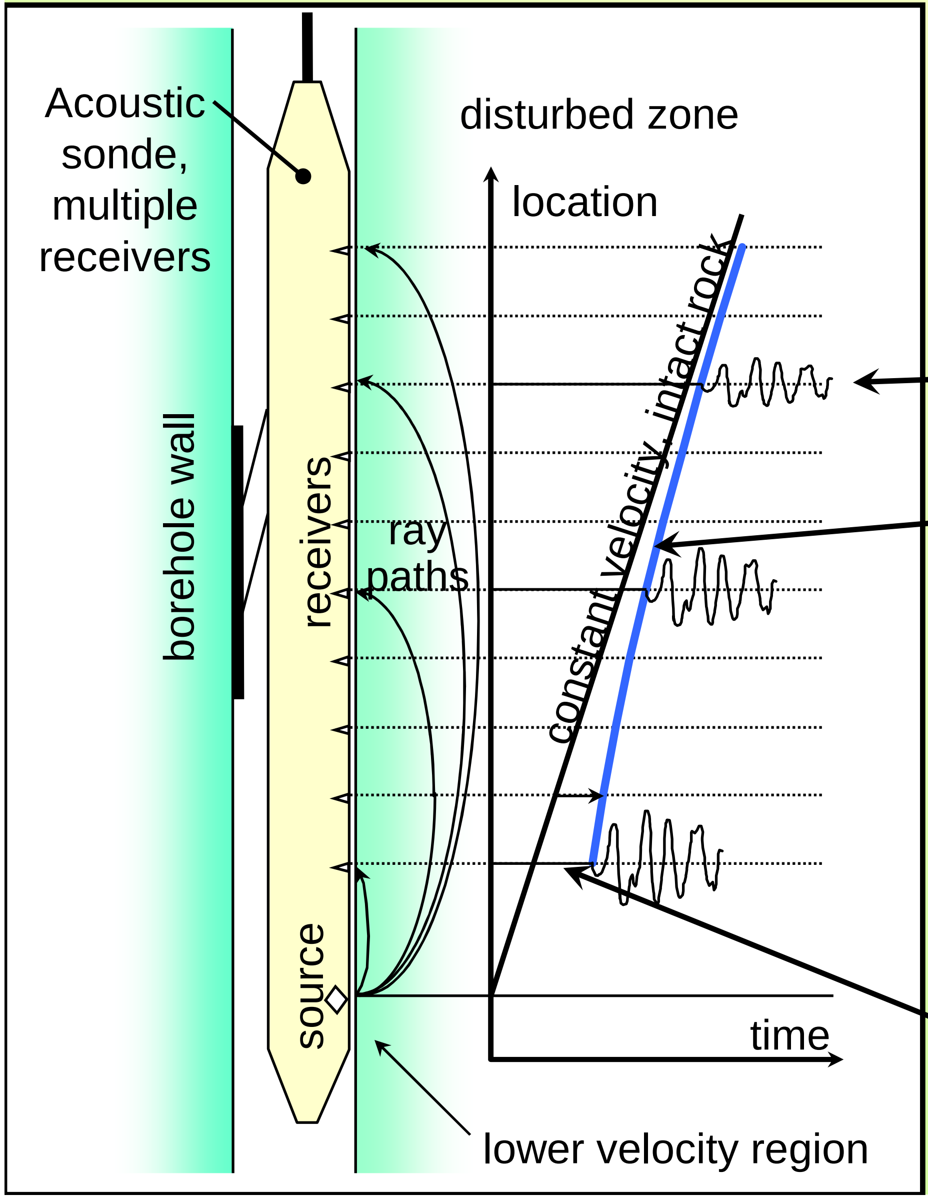


- Simple P-wave transit time correlations
- Dipole sonic data - V_p and
  - Often dipole sonic dat able
  - Estimate V_s from atios, lithology…
- Basic data ne estimation:
  - Sonic lo ipole
  - Density l ma-gamma)
  - Water saturation log (for corrections)
  - Mineralogy/lithology logs (for corrections)
- Service companies provide these methods

Use with
JUDGMENT!

Multiple Receiver Sonic Log





Damage will alter the sonic velocities.

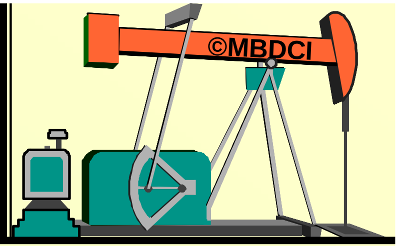
Wave trains

Velocity curve is offset because of lower v near the borehole wall (damage)

Attentuation per metre can also be used to relate to damage

Arrival time delay from damage

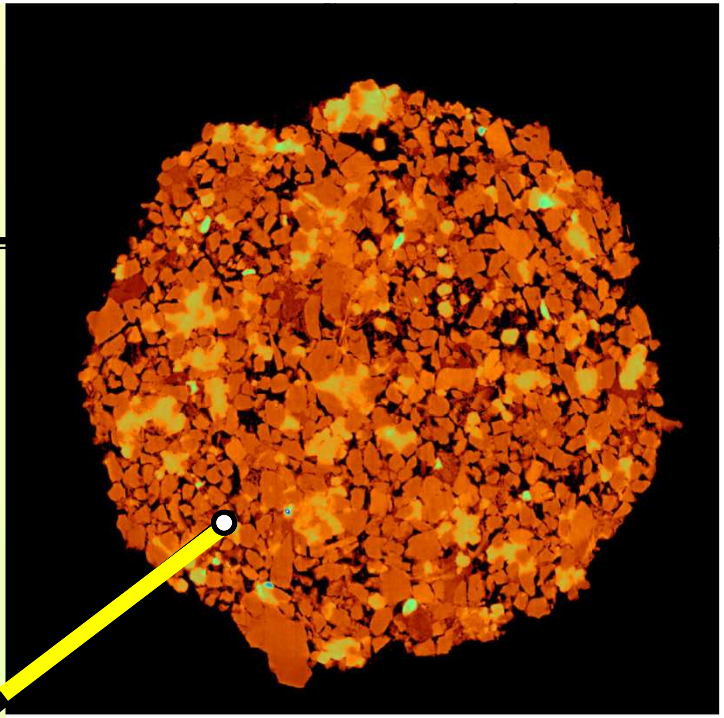
Back-Analysis for Stiffness

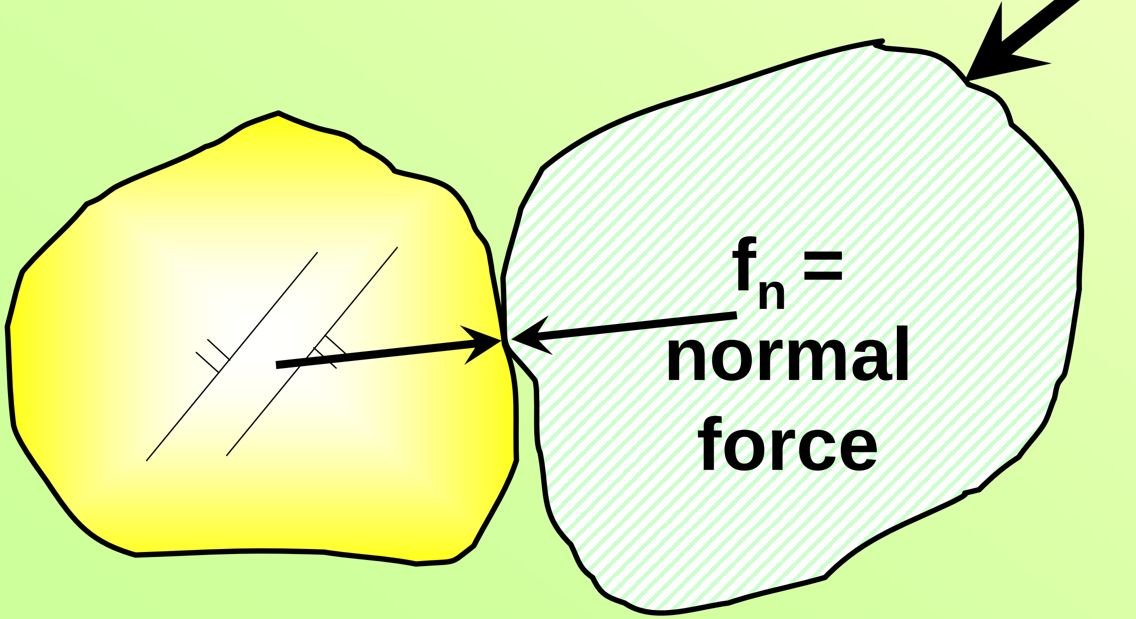


- Apply a known effective stress change, measure deformations (eg: uplift, compaction)
- Use a mathematical model to back-calculate the rock properties (best-fit approach)
- Includes all large-scale effects
- Can be confounded by heterogeneity, anisotropy, poor choice of GMU, ...
- Often used as a check of assumptions
- One must commit to some monitoring (e.g. $\{\Delta z\}$) in order to achieve such results

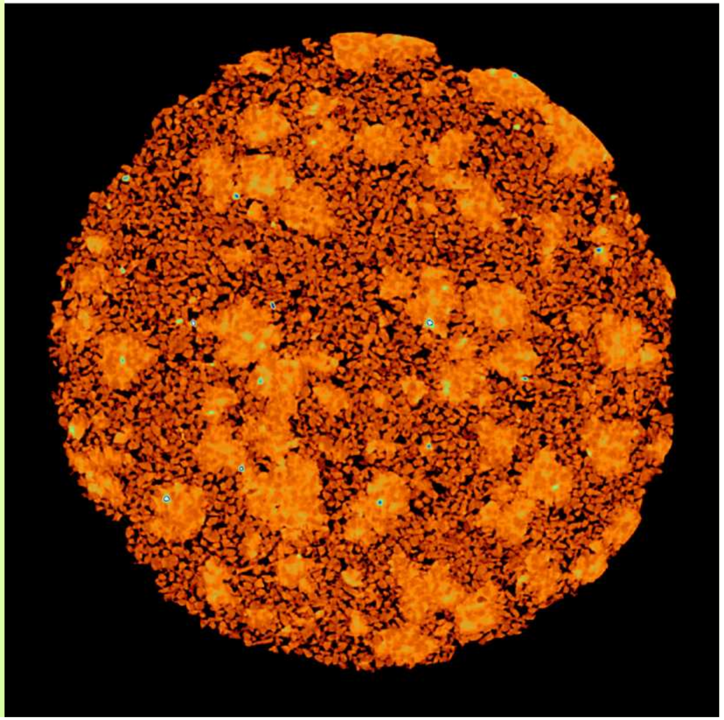
Discontinuities & E

- Grain contact deformability is responsible for sandstone stiffness
- These may be cemented or not, and in low-ϕ media, they become interlocked, rocks are stiffer

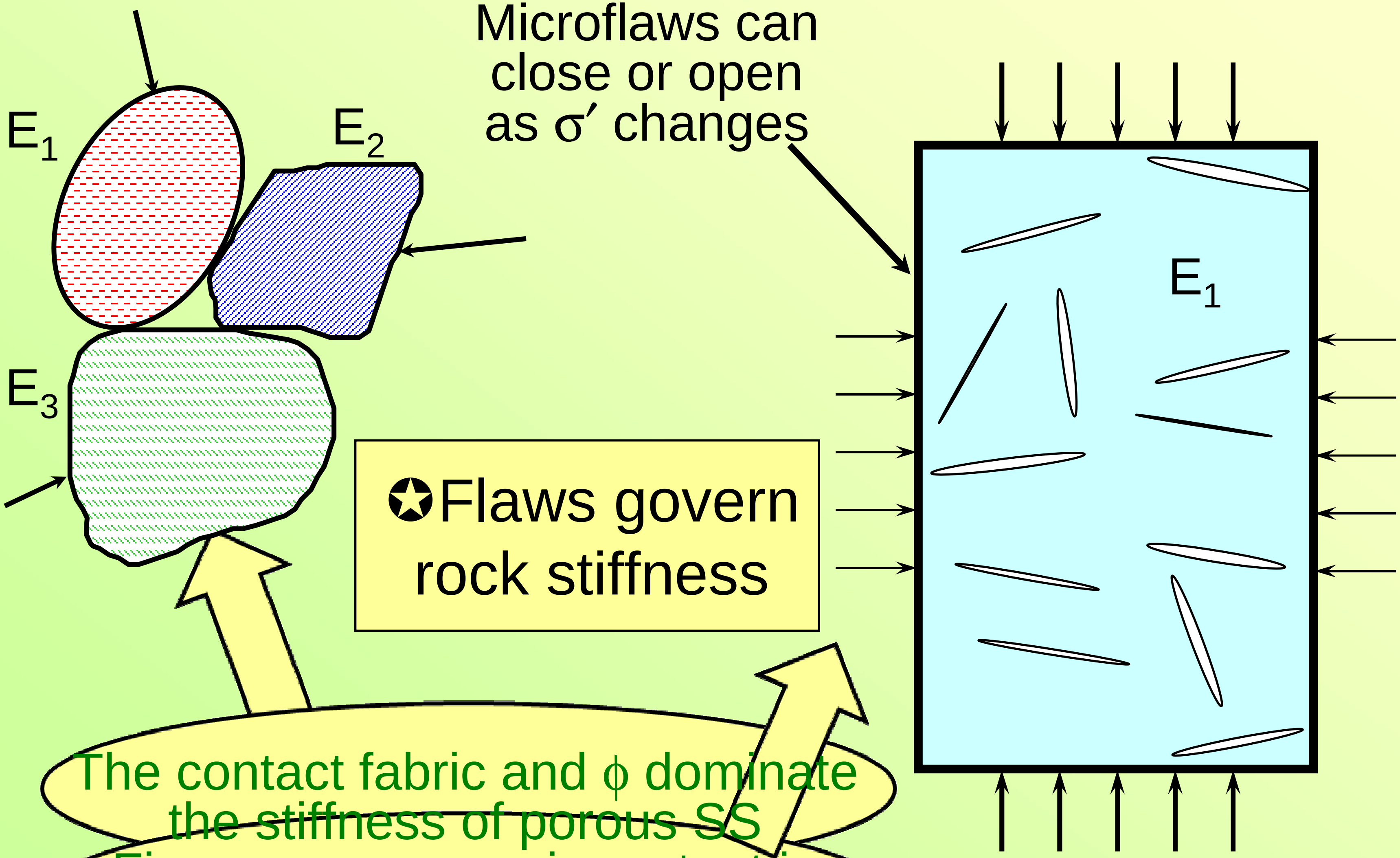




f_n = normal force



Cracks and Grain Contacts



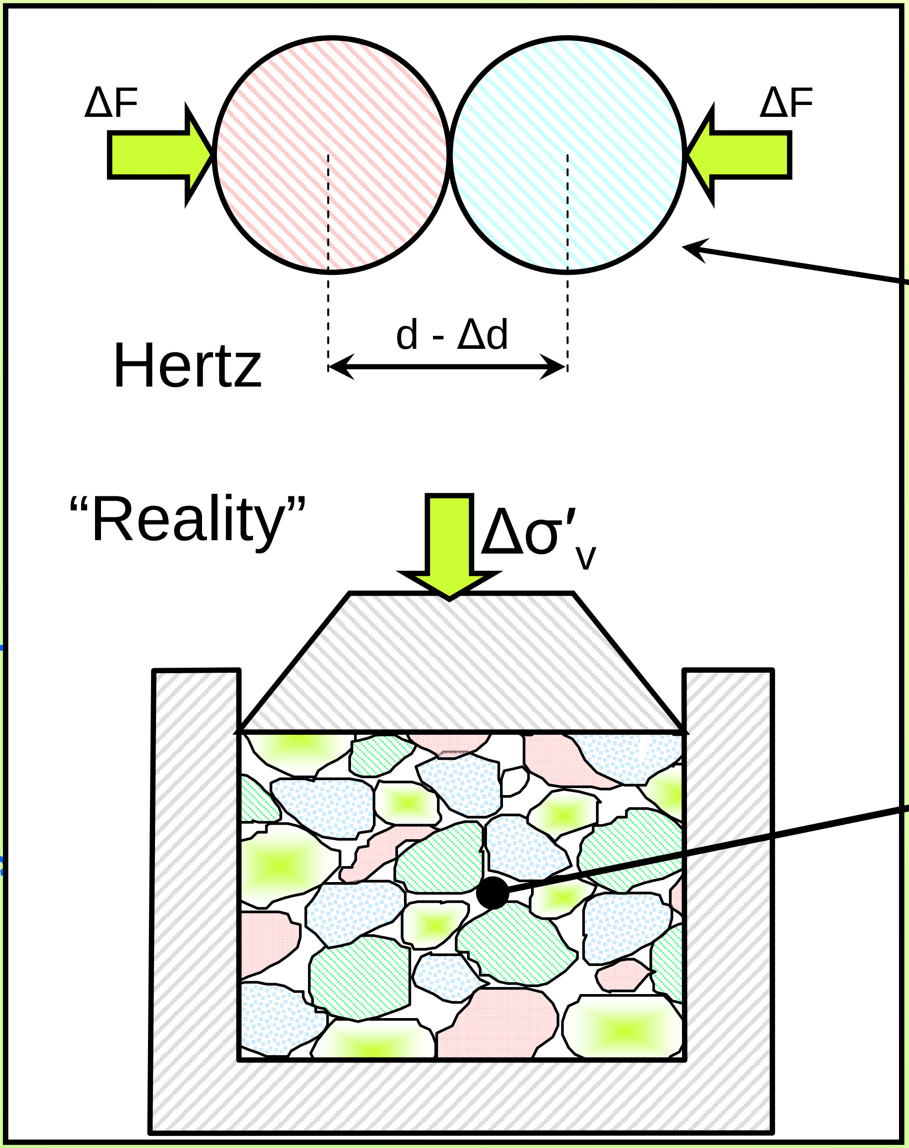
Microflaws can close or open as σ' changes

✪Flaws govern rock stiffness

The contact fabric and ϕ dominate the stiffness of porous SS

Fissures are more important in limestones, as well as ϕ

Grain Contact Stiffness

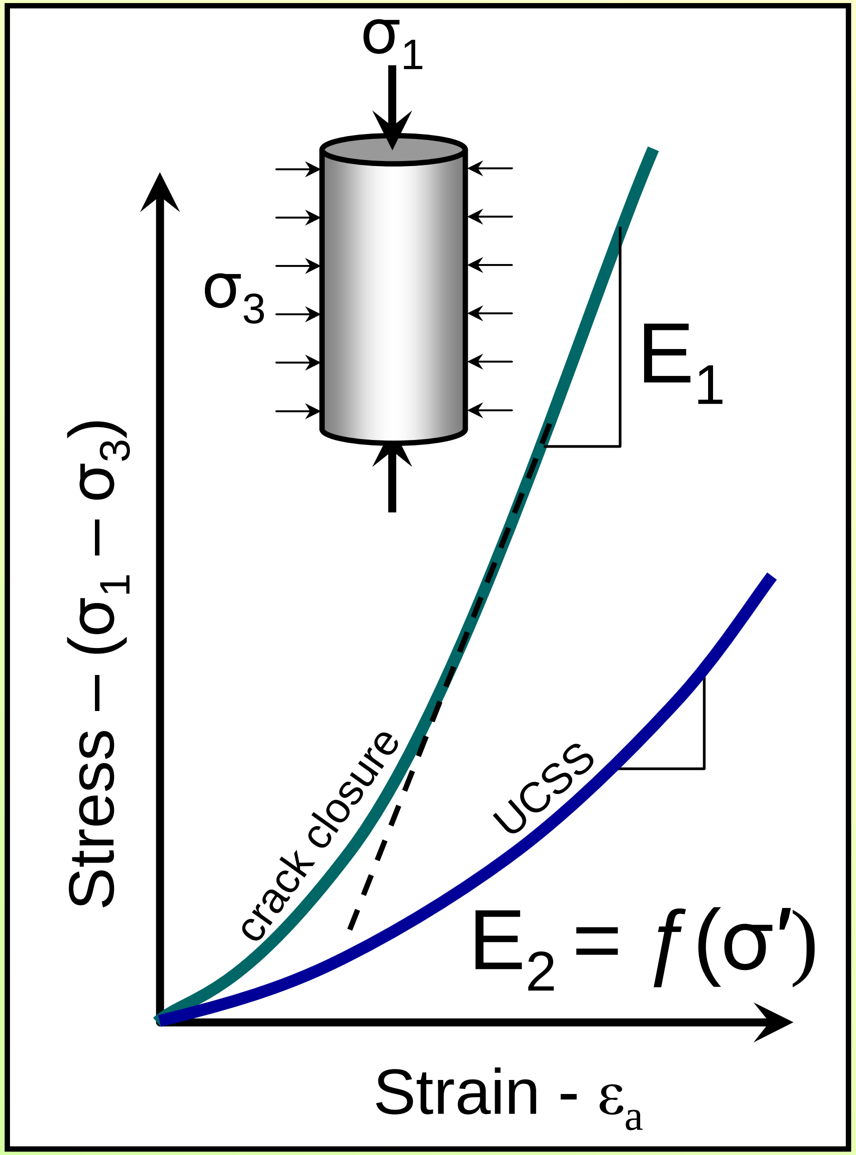


- A grain contact solution was developed 120 years ago by Hertz
  - $\Delta d \propto 1/E, (\Delta F)^{2/3}$
- It shows that grain-to-grain contacts become stiffer with higher load
- High ϕ rocks dominated by such contacts
- They are stiffer with stress: $C = f(\sigma')$

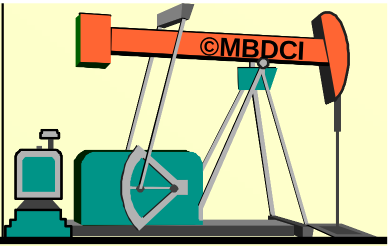
1-D Measuring Rock Properties

Non-Linear Elastic Behavior

- The stiffness is assumed to be variable – $E(\sigma'_3)$
- Deformation is still reversible
- Suitable for highly microfissured materials, high ϕ granular rocks
- For some geomechanics problems, a non-linear elastic solution is useful
  - Sand compaction, sand production…



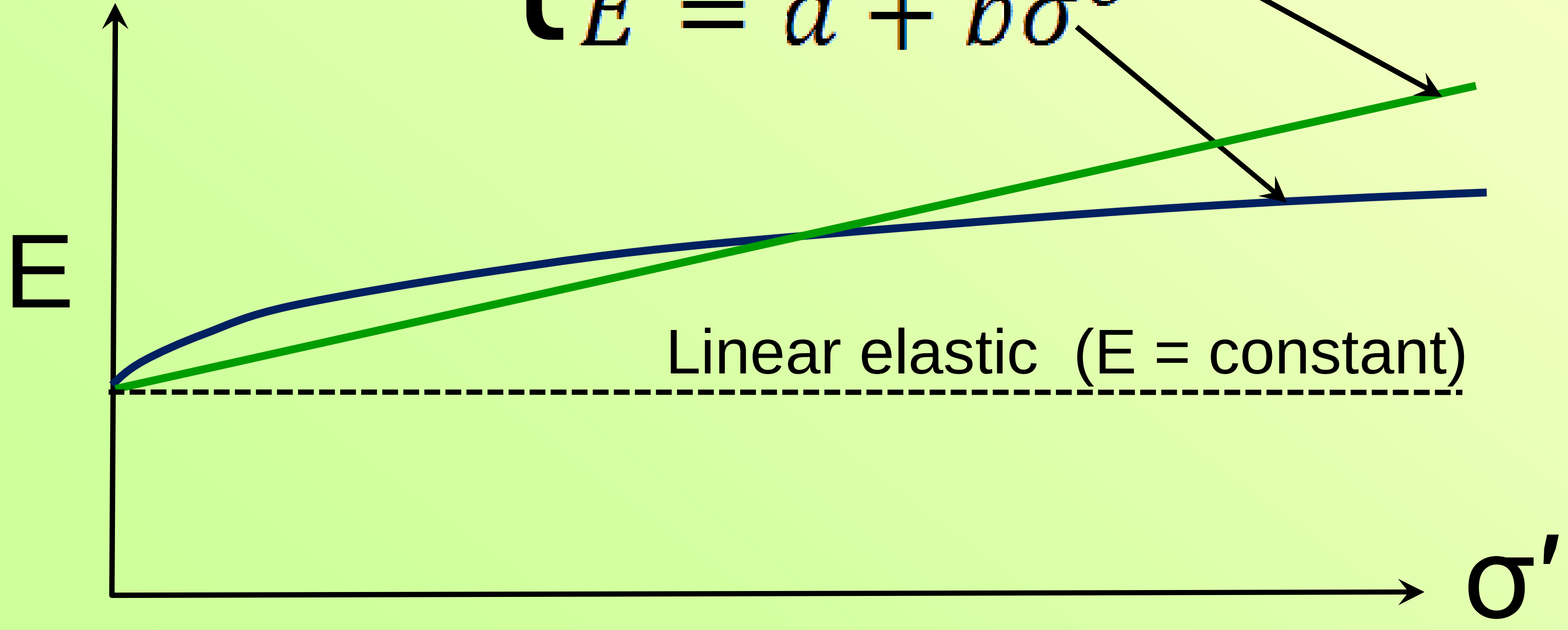
Real Rock Behavior



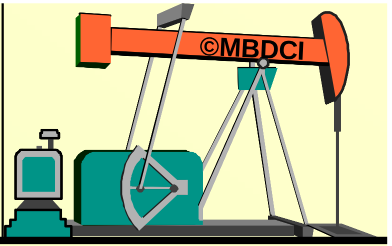
- Unconsolidated sandstones have a stiffness that is a function of effective stress - σ′:

Empirical relationships

$$\begin{cases} E = a + b\sigma' \\ E = a + b\sigma^{c} \end{cases}$$

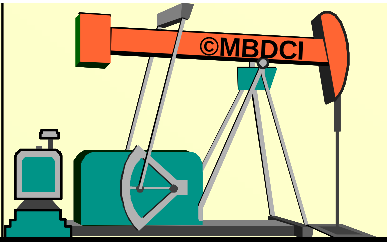


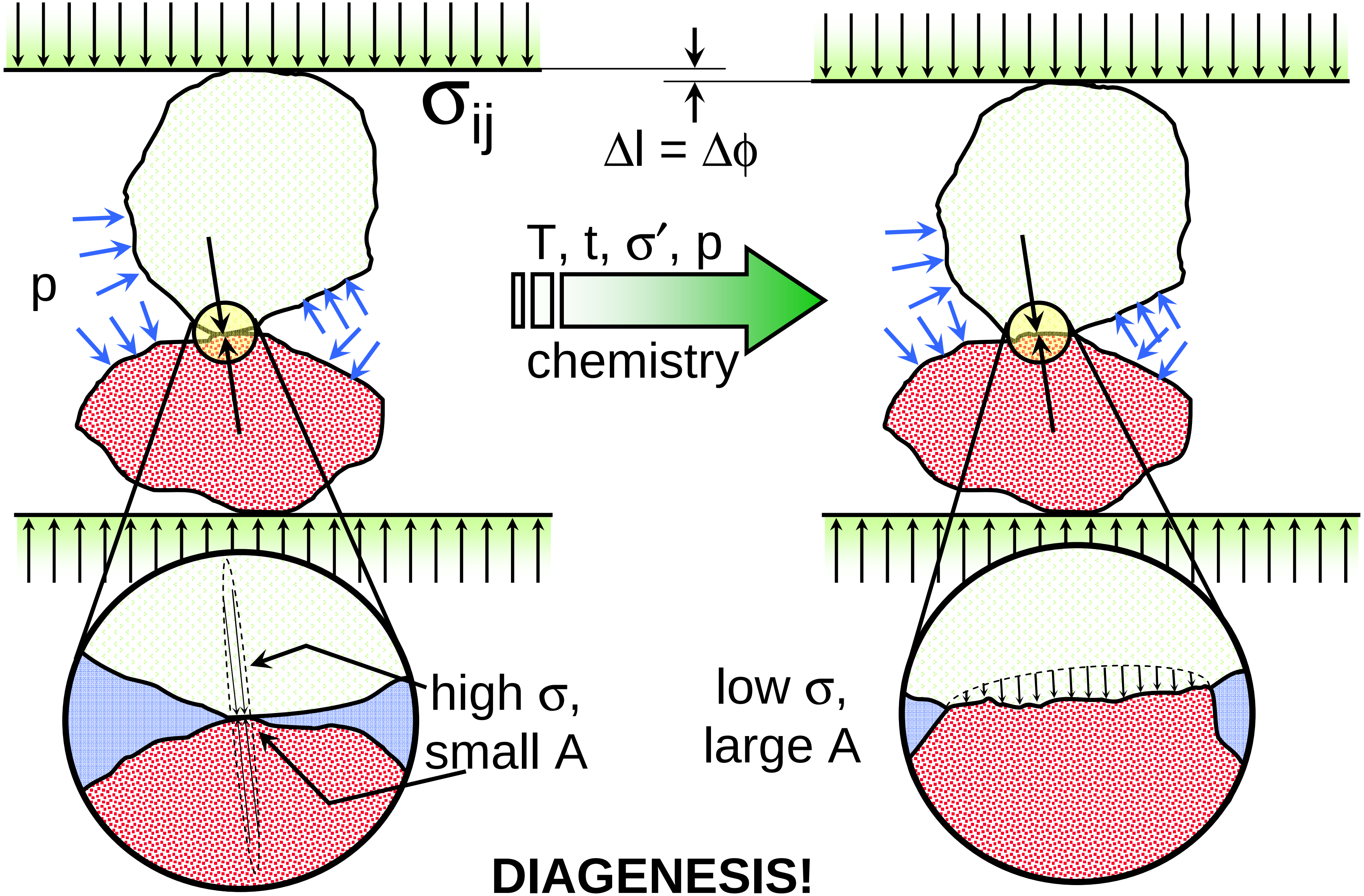
Geological Factors and Stiffness



- Geological history can help us infer the stiffness and the response to loading…
- Intense diagenesis
  - Reduces porosity
  - Cementation
- Deeper burial then erosion (precompaction)
- Age (in general correlated to stiffness)
- Porosity (lower ϕ, higher E)
- Mineralogy (SiO_2 vs. litharenite mineralogy)
- Tectonic loading (reduces ϕ…)

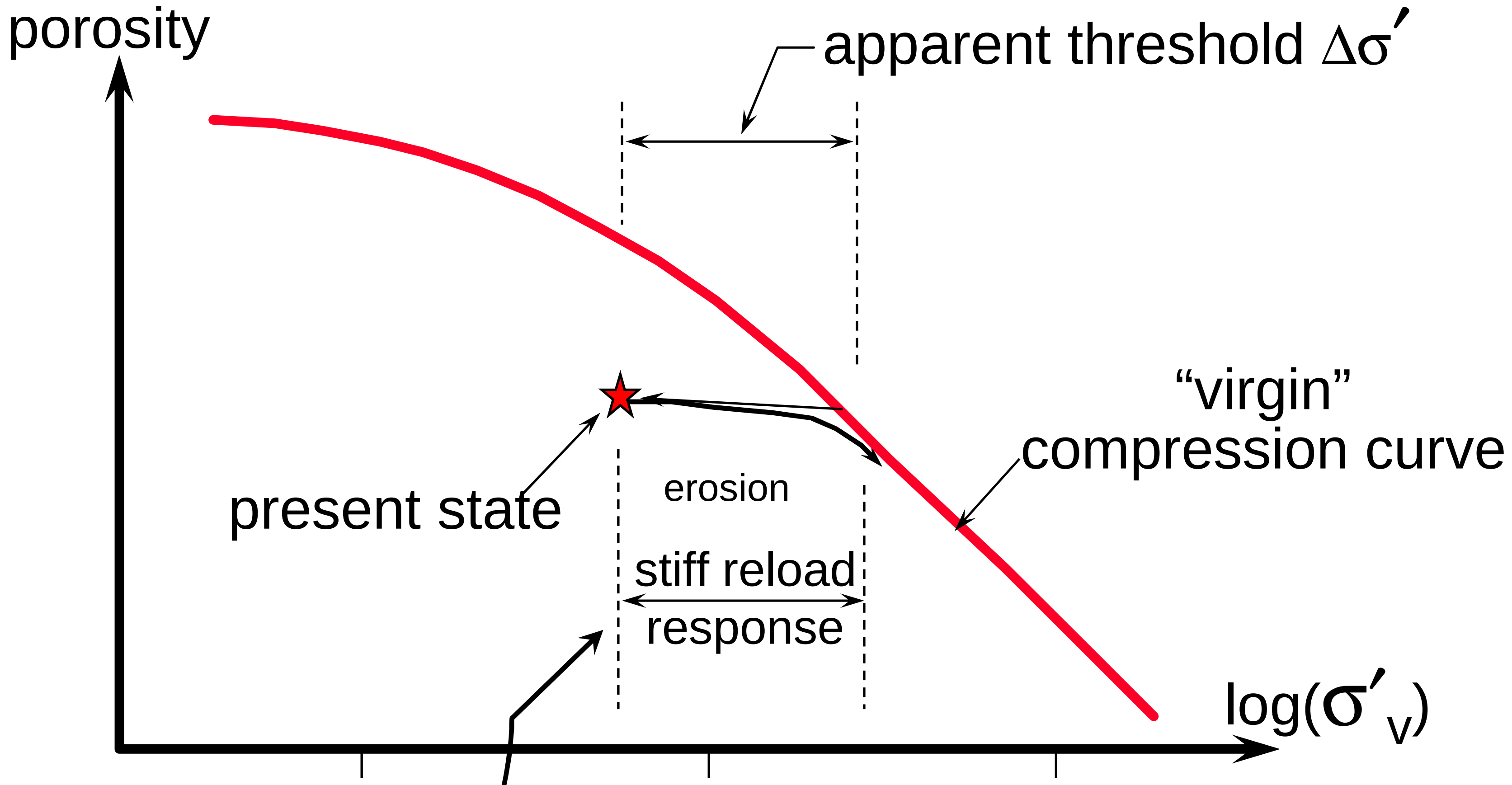
Sandstone Stiffness & Diagenesis





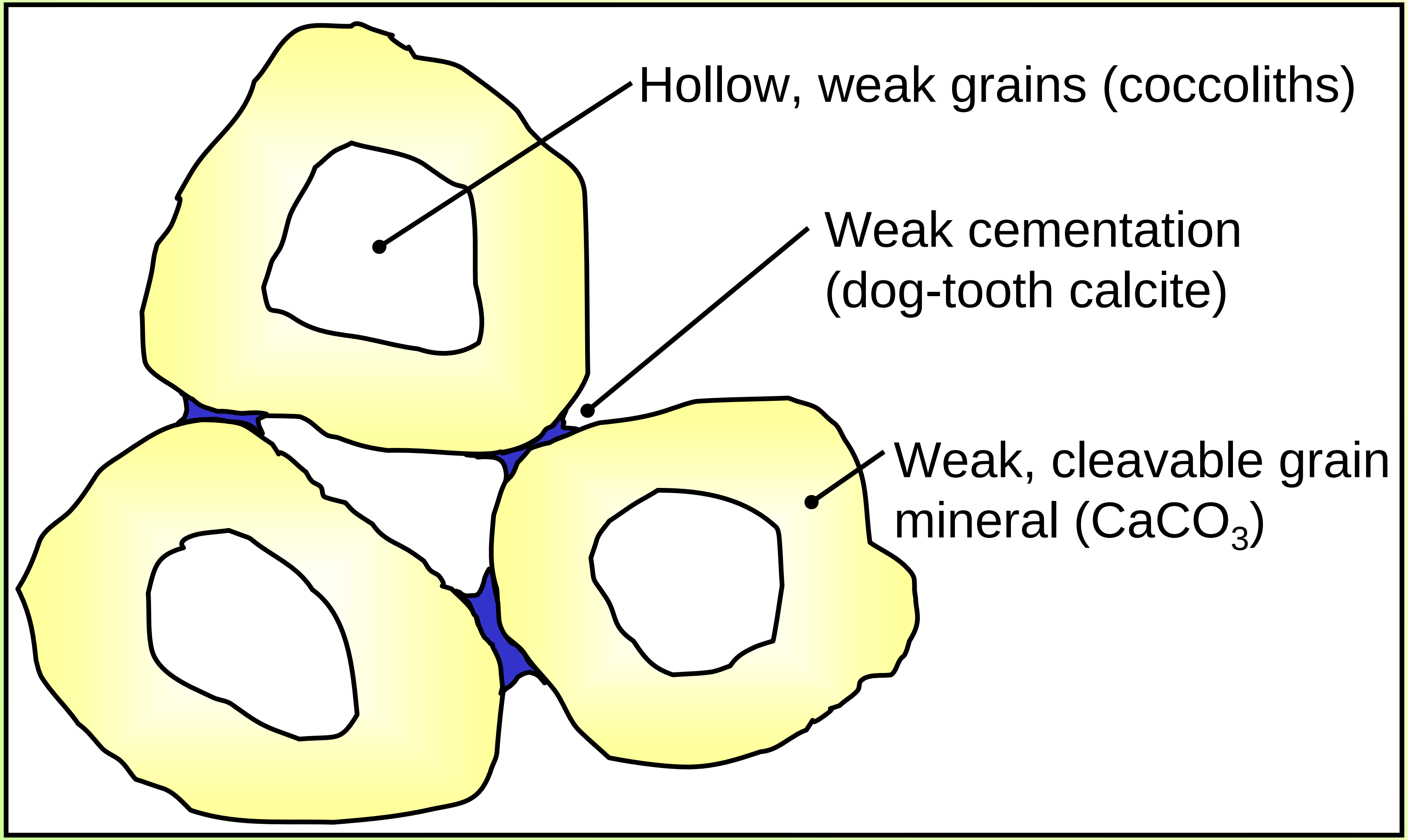
DIAGENESIS!

Precompaction Effect by Erosion



The sand is far stiffer than expected because of precompaction! - e.g. Athabasca Oil Sand

High-Porosity Chalk

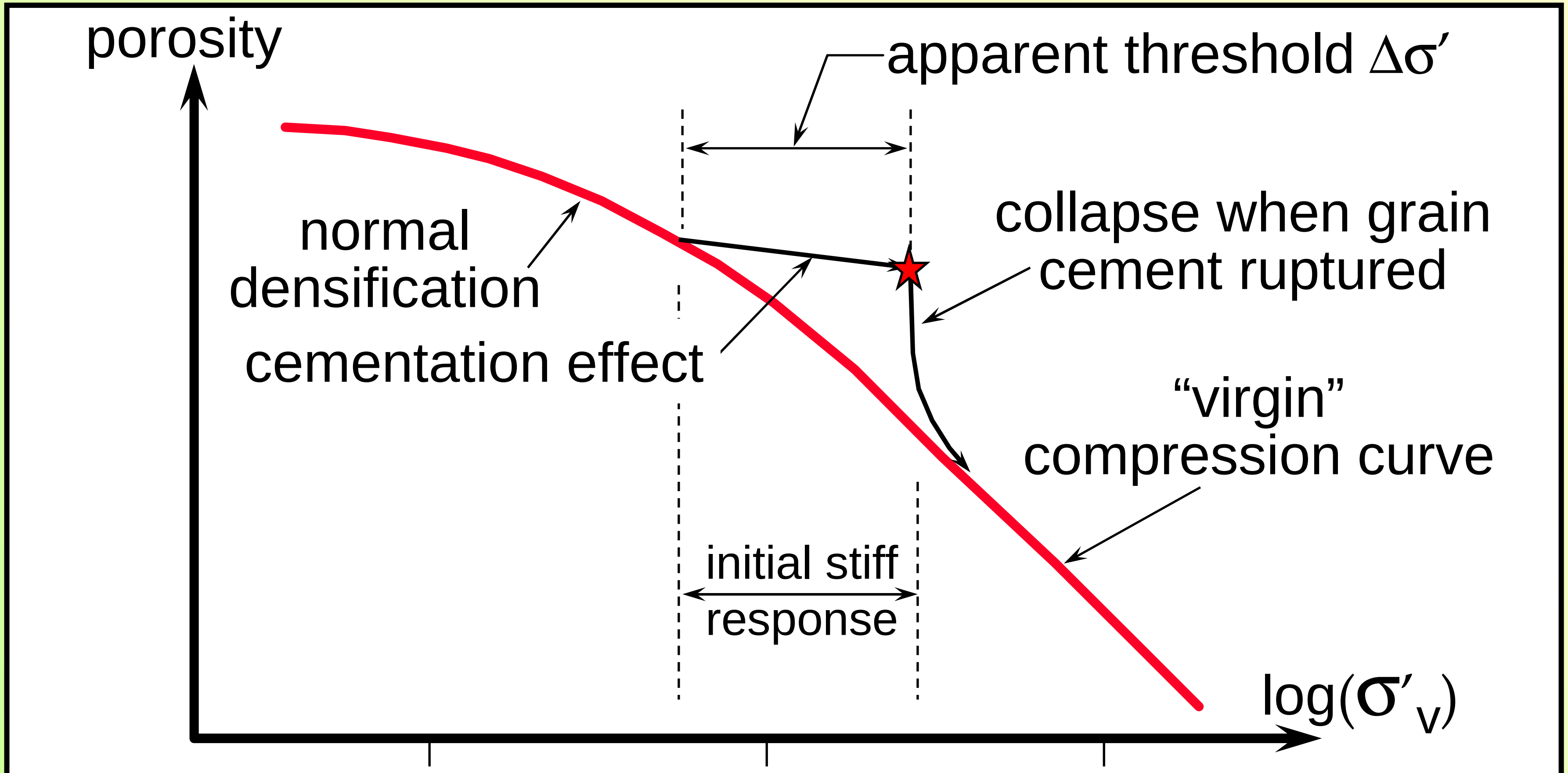


Hollow, weak grains (coccoliths)

Weak cementation
(dog-tooth calcite)

Weak, cleavable grain
mineral ($CaCO_3$)

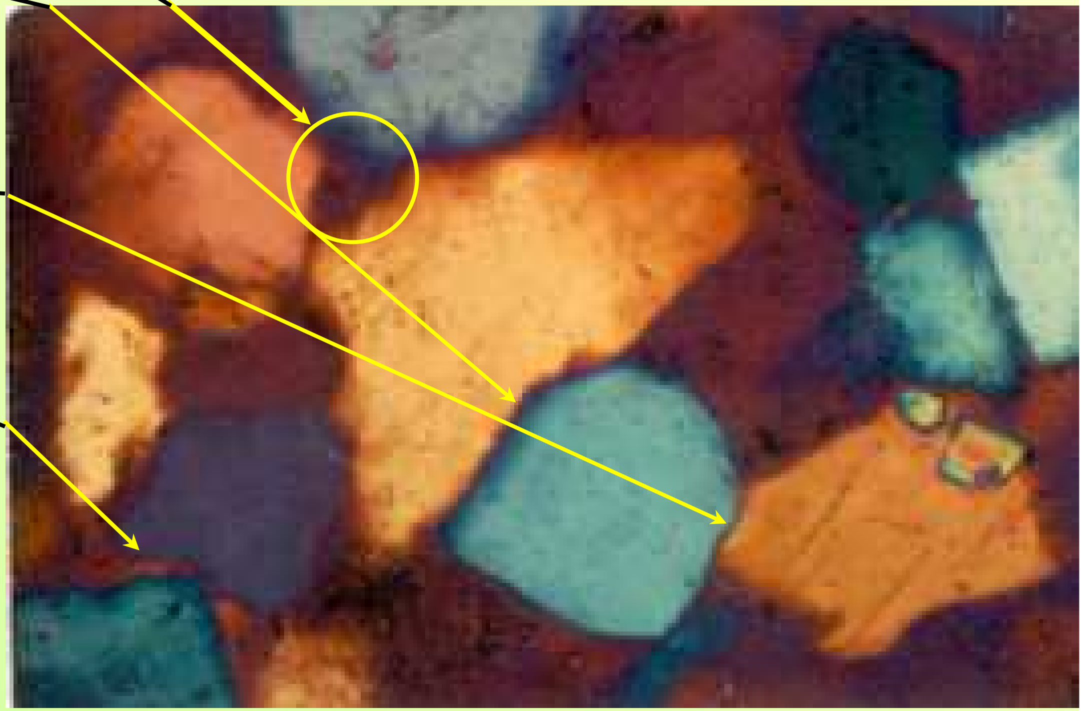
Cementation and Compaction



North Sea Chalk, high ϕ Coal, Diatomite, are quasi-stable, collapsing rocks at some σ'_v

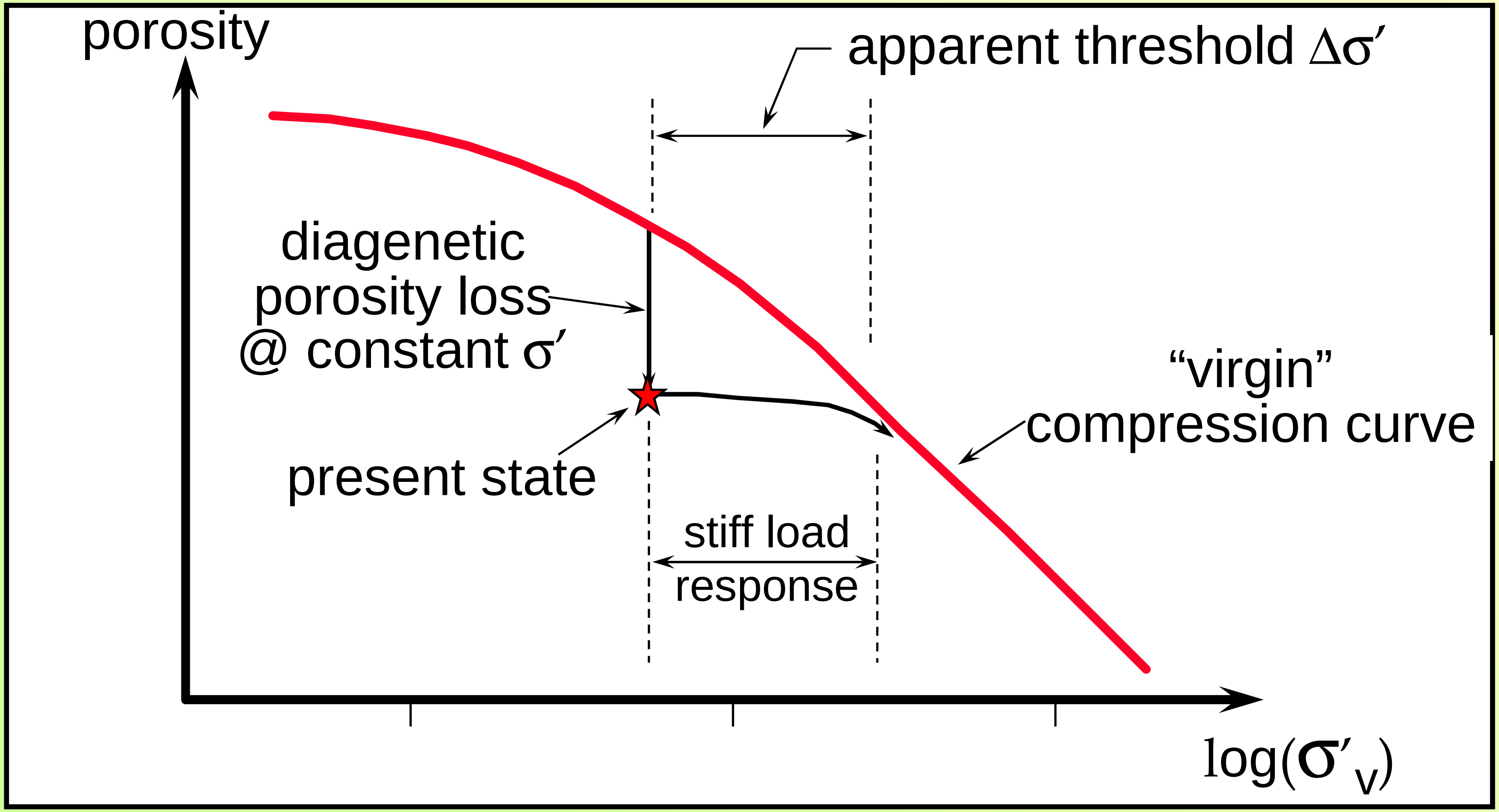
Sandstone Diagenesis

- Dense grain packing
- Many long contacts
- Concavo-convex grain contacts
- SiO_2 precipitated in interstitial regions
- Only 1% solution at contacts = 8% loss in volume
- -A stable interpenetrative fabric, high stiffness

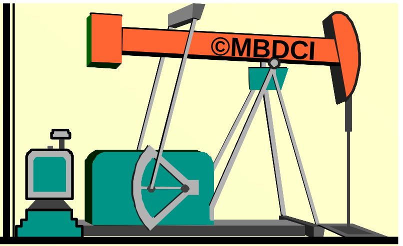


Fine-grained unconsolidated sandstone

Effect of Diagenetic Densification

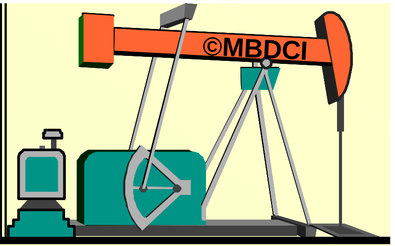


“Precompaction” Effect



- A threshold value is necessary before any non-elastic compression is triggered
- This may arise from three processes
    - ➔ True precompaction by burial then erosion
    - ➔ Cementation of grains = stiffer + stronger
    - ➔ Prolonged diagenesis increases stifeness
- Little deformation is seen in early drawdown, but occurs later
- This can confuse field planning

Issues to Remember…



- Stiffness (elastic modulus) is a fundamentally important rock property for analysis
- We can measure it with cored rock specimens
- Also, in boreholes (much more rarely)
- Sometimes, through correlations to other measures such as geophysical data
- Sometimes, through back-calculation, using deformation measurements
- Nevertheless, there is always uncertainty
- And, natural lithological heterogeneity