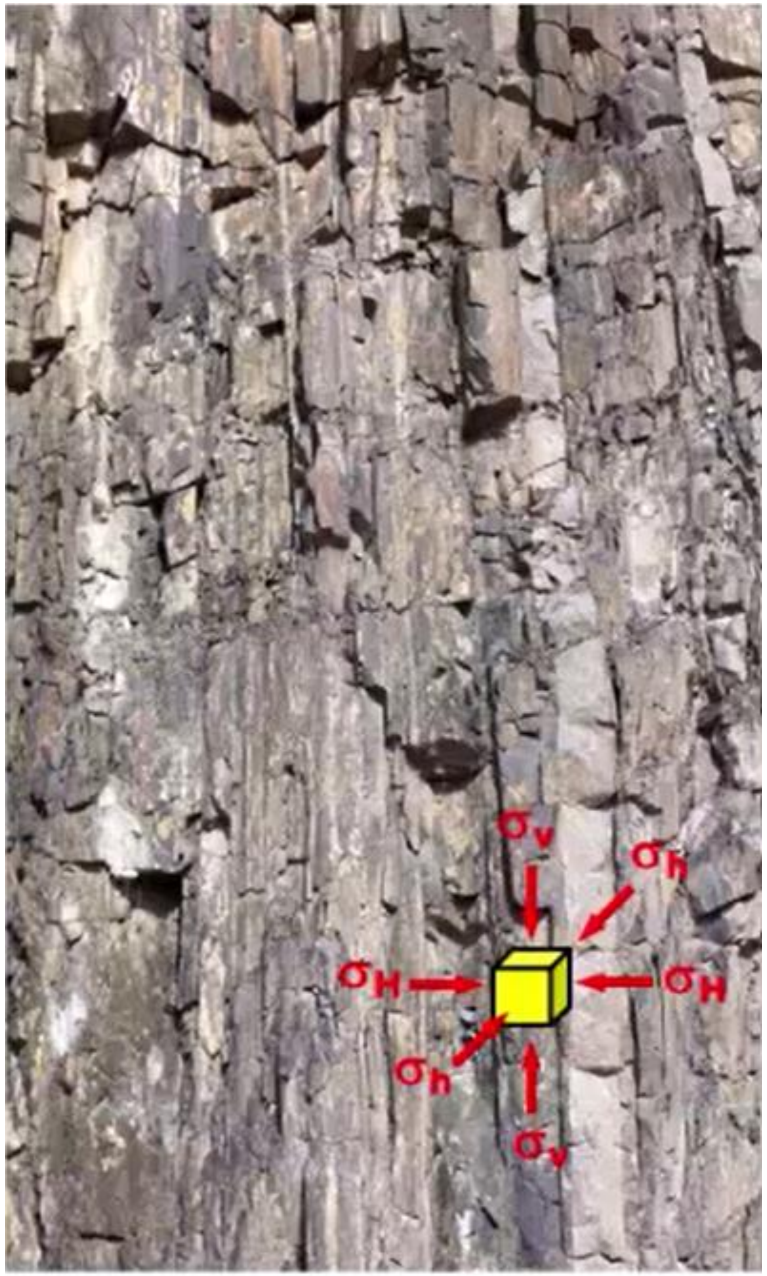
Learning objectives

- Develop an understanding of in-situ stresses and their influence factors
- Learn common techniques for in-situ stresses measurements and how to interpret results

Stress condition under ground

- Rock mass related engineering is subsurface/underground, where rock is subjected to existing (in-situ) stresses
- The stresses underground is 3D, commonly referred to vertical stress (σ_v) and two horizontal stresses (σ_H, σ_h)

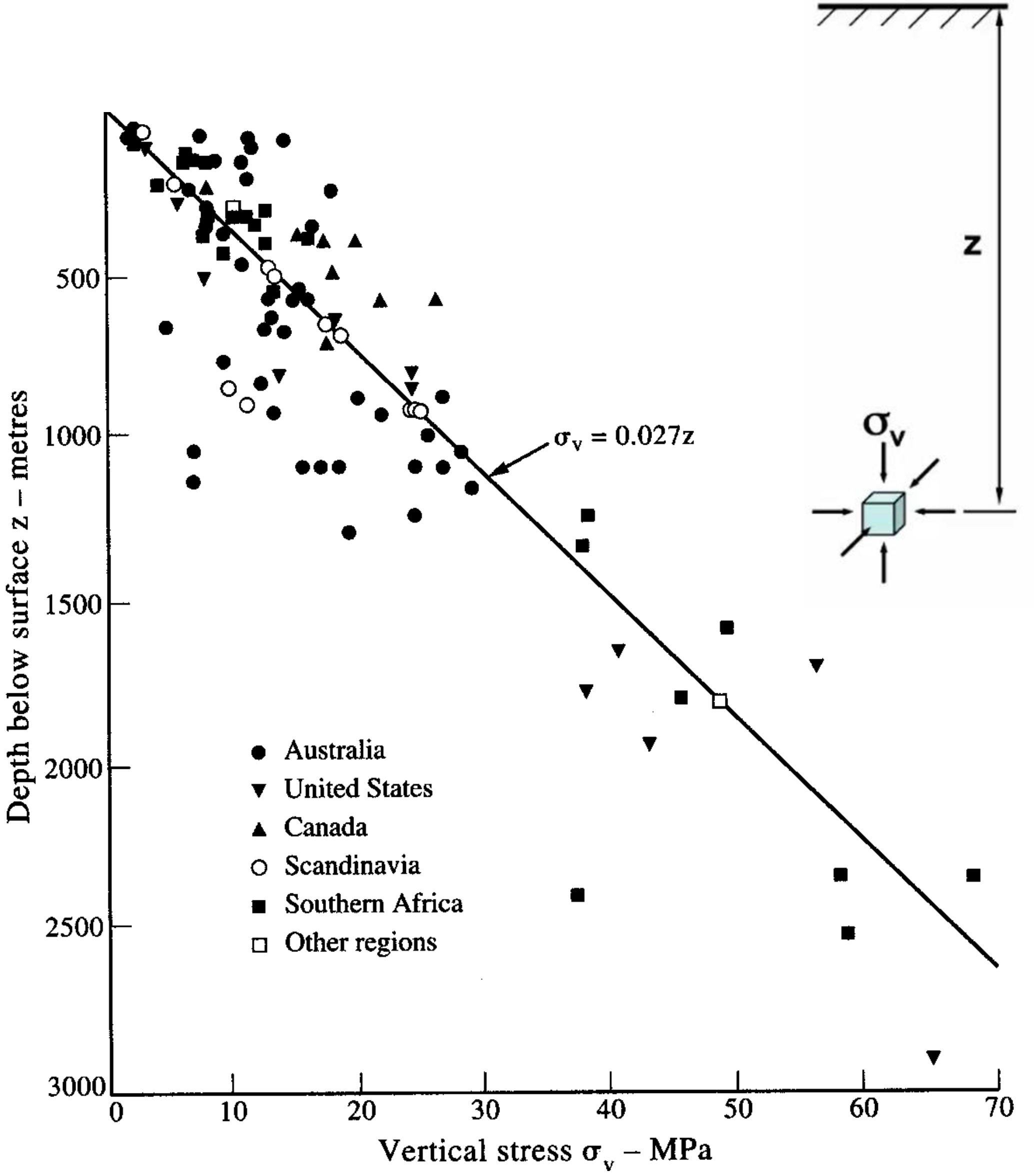


Courtesy of Jian Zhao

Overburden stresses

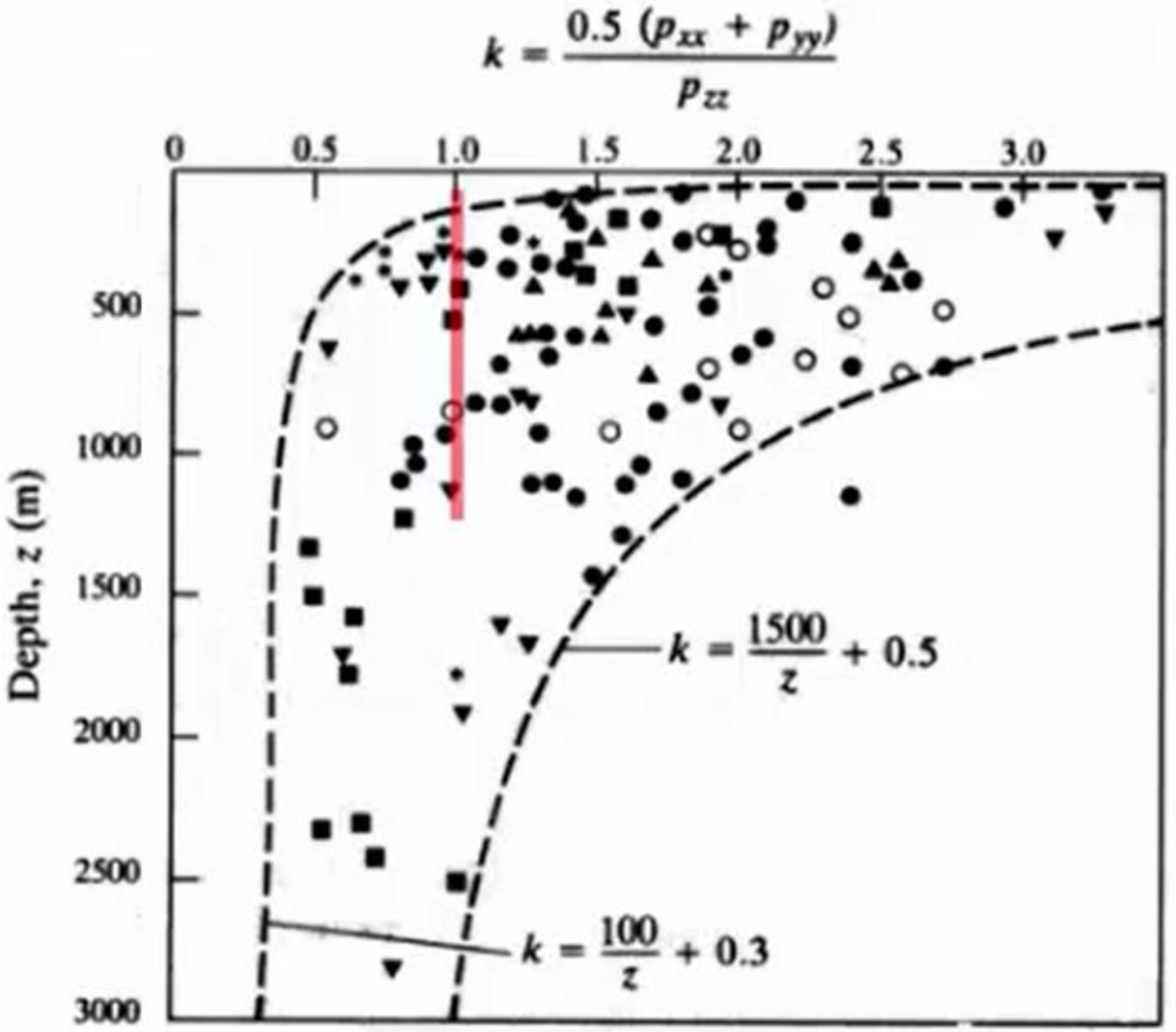
- In situ overburden stress is the stress contributed by the weight of the overburden above. It is governed by the overburden thickness and specific weight
- The average specific weight of rocks is about 27 kN/m^3. The vertical stress at depth is estimated as:

$$\sigma_v \text{ (MPa)} \approx 0.027 \, z \text{ (m)}$$



Horizontal stresses

- For rocks below the ground, the in-situ horizontal stresses are different from vertical stress
- Ratio k = average horizontal stress/vertical stress has a wide variation in shallow depths and can be larger than 1.0
- At great depth, it approaches to hydrostatic stress condition (k=1.0)



E. Hoek and E.T. Brown 1981

Major principal stress

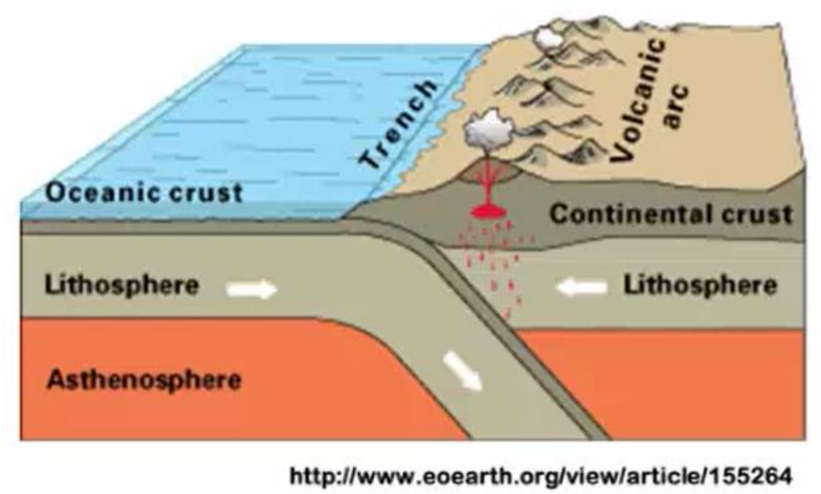
- Major, intermediate, and minor principal stresses depending on the magnitude of σ_H, σ_h, and σ_v
- Usually at shallow depth, the major principal stress is one of the horizontal stresses, i.e.,

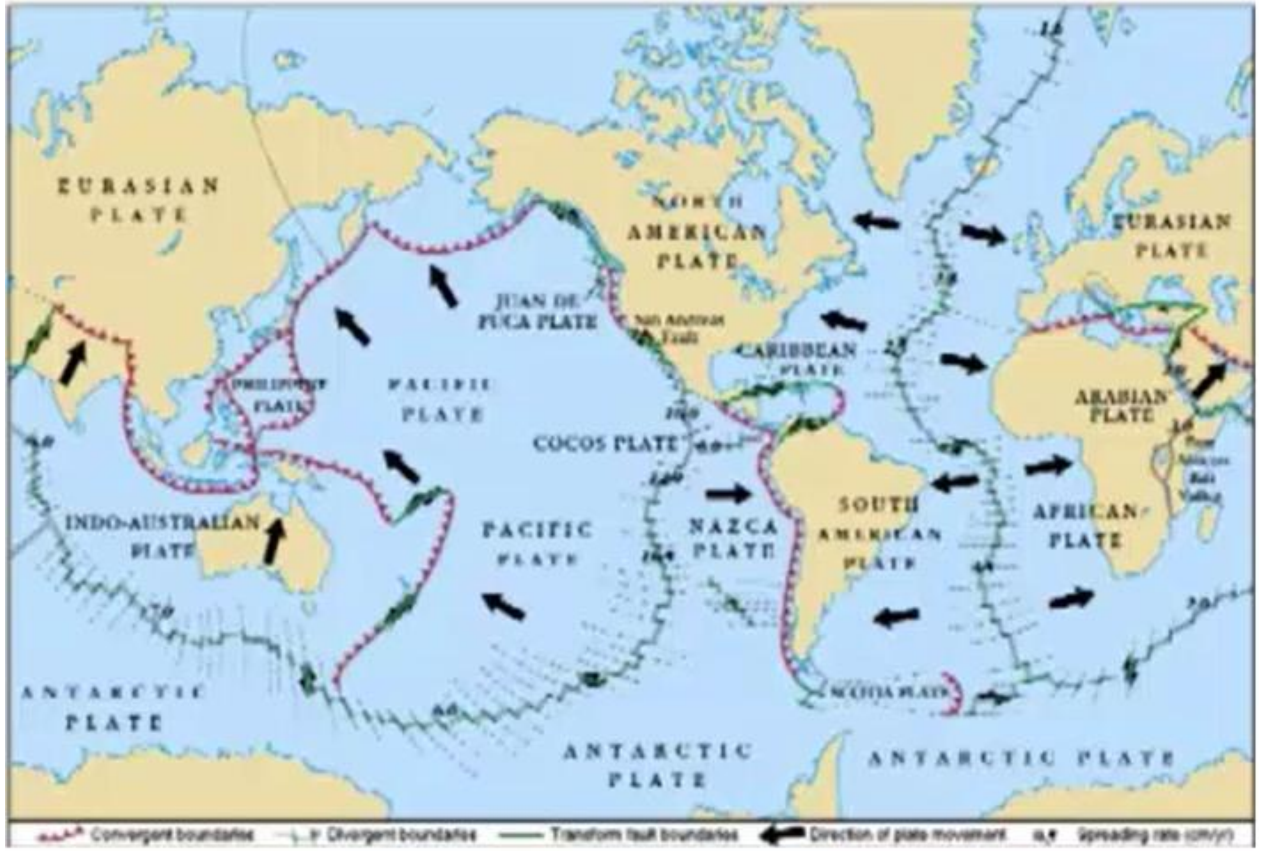
$$\sigma_H > \sigma_h > \sigma_v \quad \text{or} \quad \sigma_H > \sigma_v > \sigma_h$$

- In rocks, the main influence of horizontal stress is from the tectonic stresses. This makes the horizontal stresses in rock varies significantly and in some cases, much higher than vertical stress

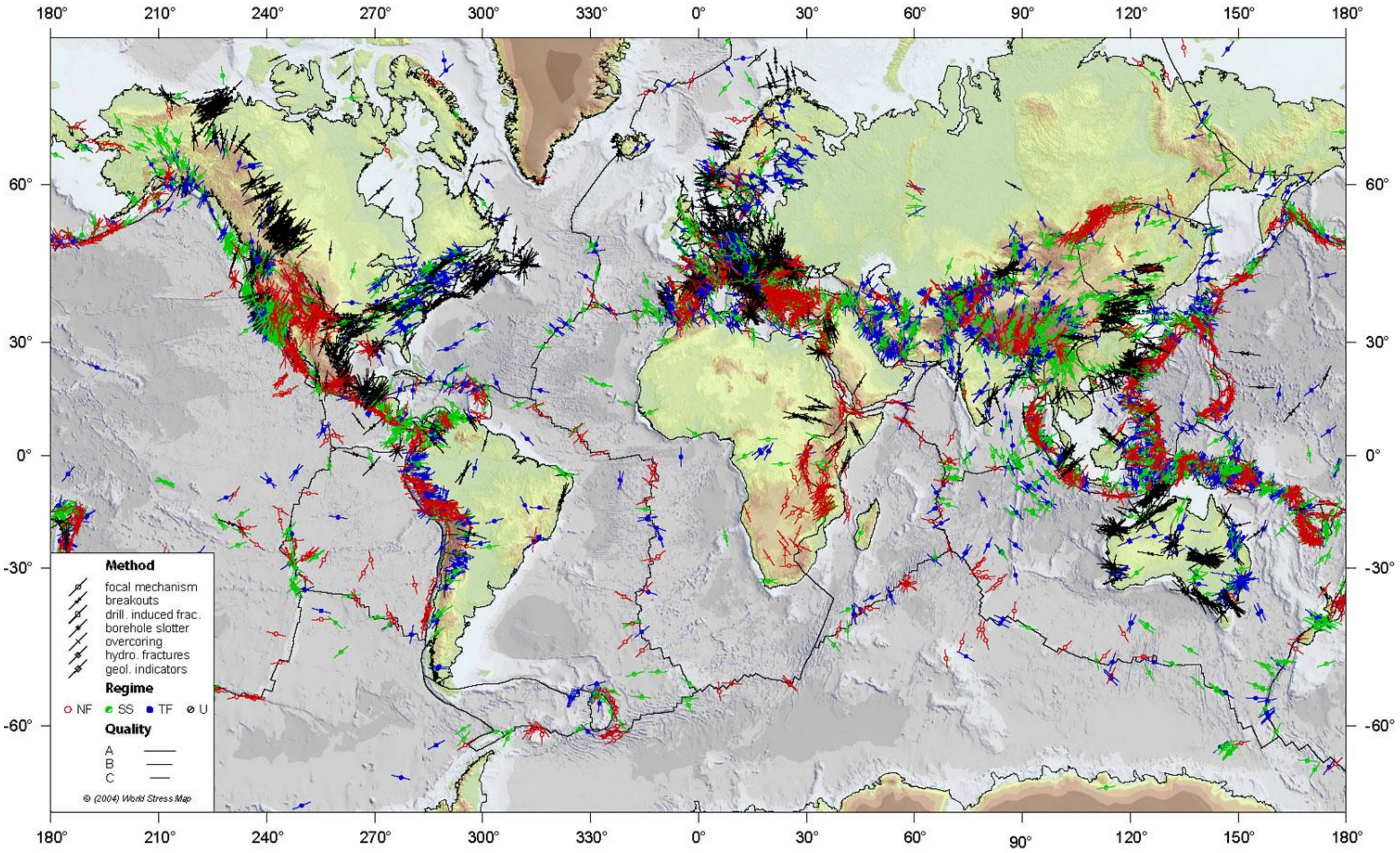
Tectonic plate movement and stress

- The earth lithosphere is divided by a number of tectonic plates and these plates are moving
- High stresses often found in plate boundaries





World stress map (tectonic)



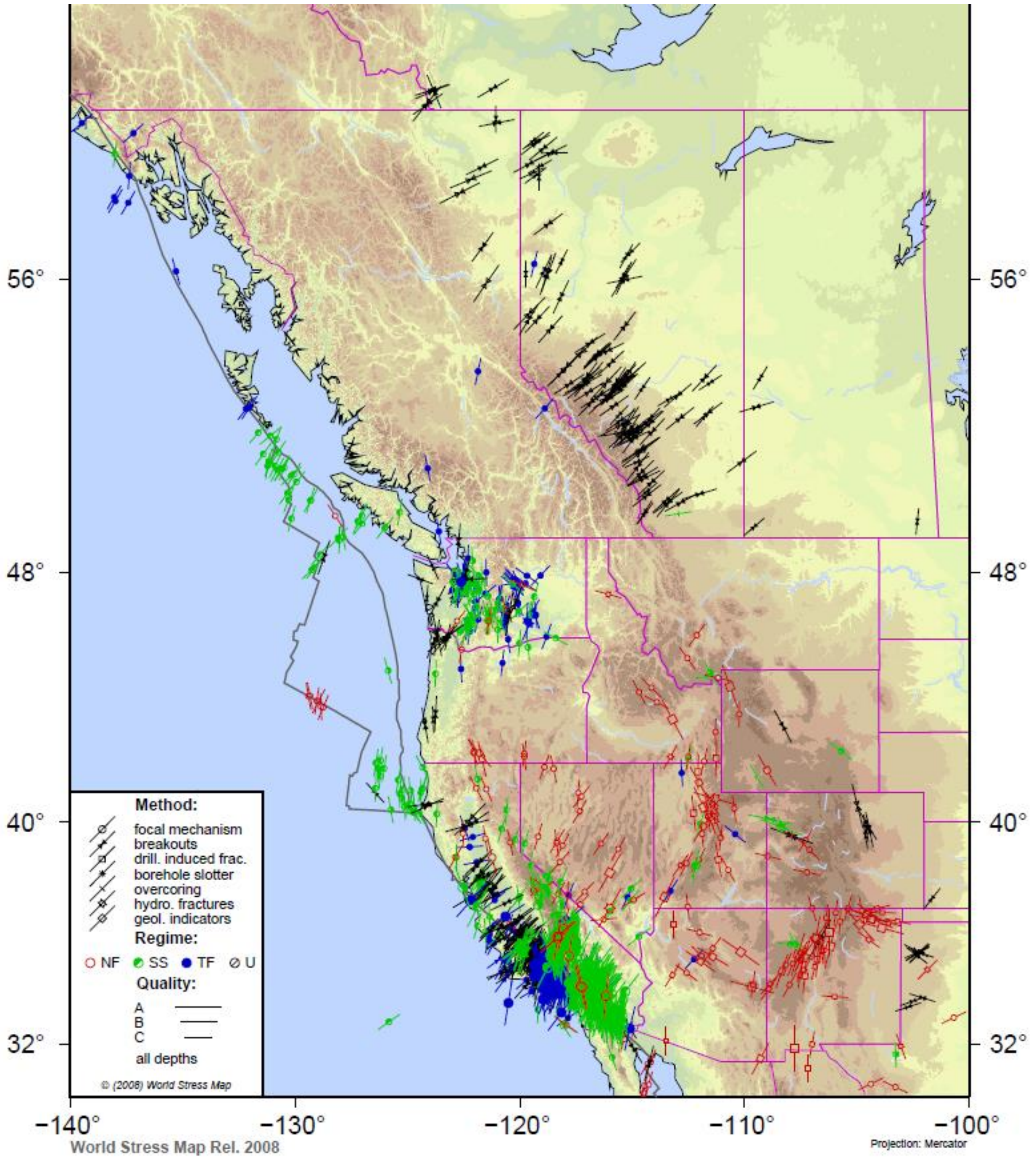
NF = Normal Faulting, SS = Strike Slip Faulting, TF = Thrust faulting, U = unknown

NF = Normal Faulting

SS = Strike Slip Faulting

TF = Thrust faulting

U = unknown



Factors influencing in-situ stresses

- Local in-situ stress field can be altered by geological factors and processes:

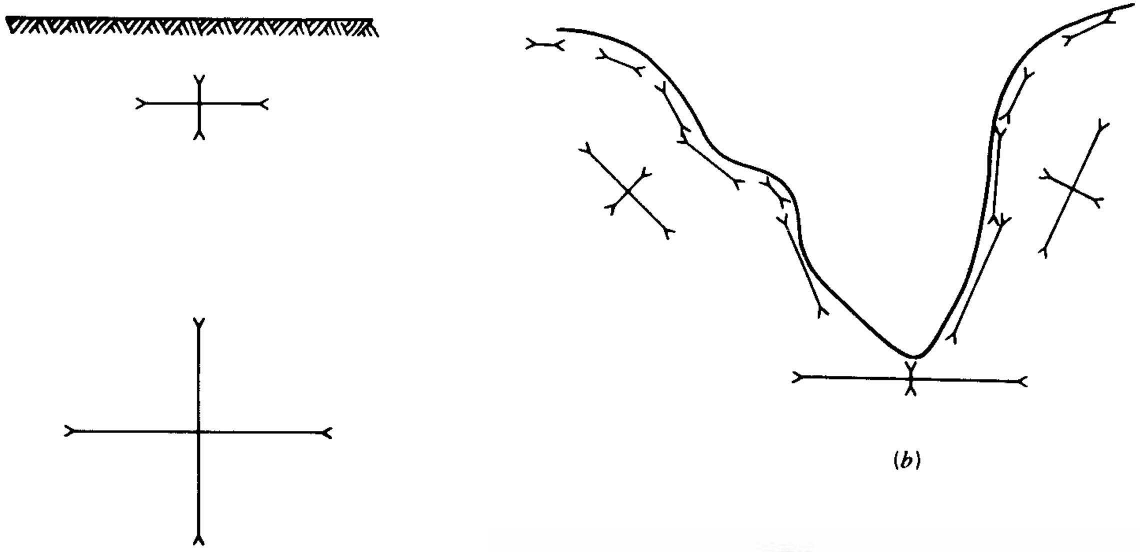
✓ Surface topography;

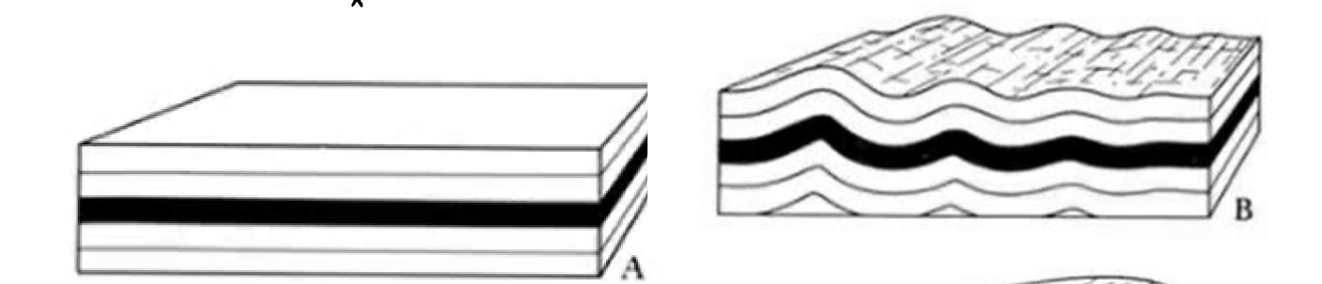
✓ Erosion;

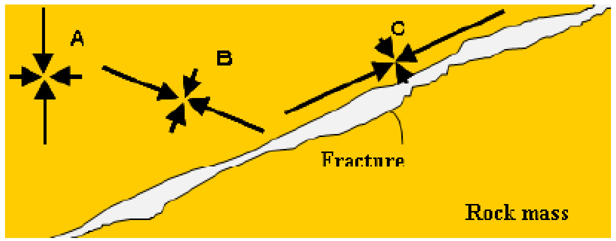
✓ Intrusion;

✓ Fault and faulting

✓ Engineering







http://www.nps.gov

Direct stress measurement techniques

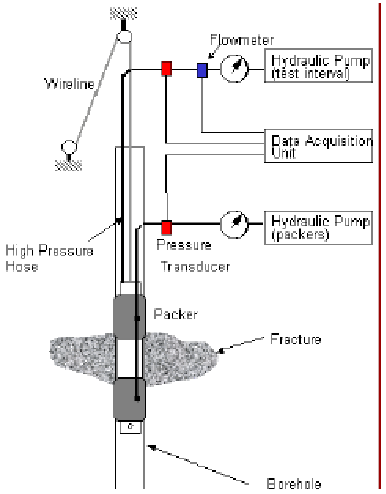
$$\begin{bmatrix} \boxed{\sigma_{xx}} & \tau_{xy} & \tau_{xz} \\ & \sigma_{yy} & \tau_{yz} \\ \text{Symm.} & & \sigma_{zz} \end{bmatrix}$$

One normal stress component determined, say parallel to *x*-axis.

Flat jack test

$$\begin{bmatrix} \boxed{\sigma_1} & 0 & 0 \\ & \sigma_2 & 0 \\ \text{Symm.} & & \boxed{\sigma_3} \end{bmatrix}$$

Principal stresses assumed parallel to axes i.e. plane of the fracture, two determined, say σ_1 and σ_3, one estimated, say σ_2.



Hydraulic fracture test

$$\begin{bmatrix} \boxed{\sigma_{xx}} & \boxed{\tau_{xy}} & \tau_{xz} \\ & \boxed{\sigma_{yy}} & \tau_{yz} \\ \text{Symm.} & & \sigma_{zz} \end{bmatrix}$$

Three components in 2-D determined from three measurements of borehole diameter change.

USBM overcore

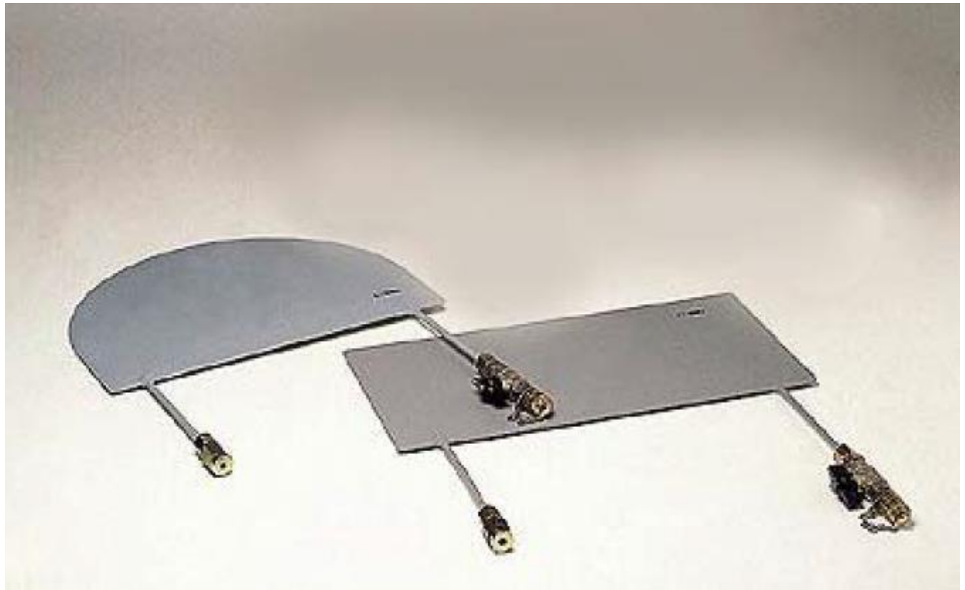
$$\begin{bmatrix} \boxed{\sigma_{xx}} & \boxed{\tau_{xy}} & \boxed{\tau_{xz}} \\ & \boxed{\sigma_{yy}} & \boxed{\tau_{yz}} \\ \text{Symm.} & & \boxed{\sigma_{zz}} \end{bmatrix}$$

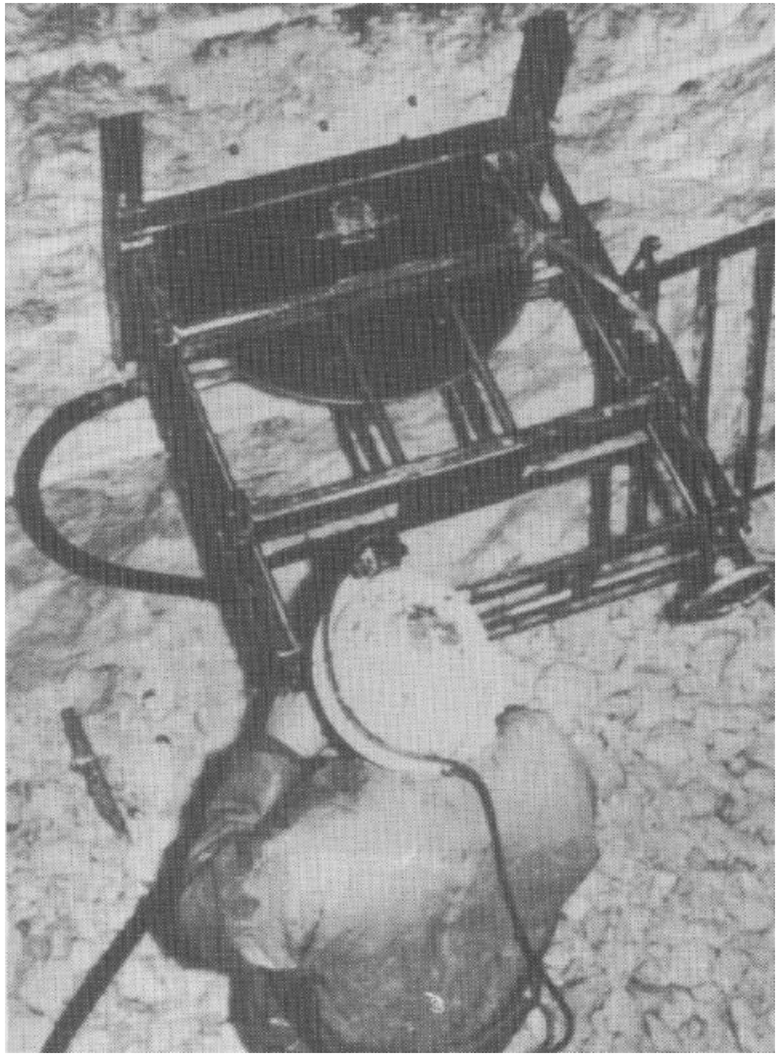
All six components determined from six (or more) measurements of strain at one time.

CSIRO overcore

Flat jack test

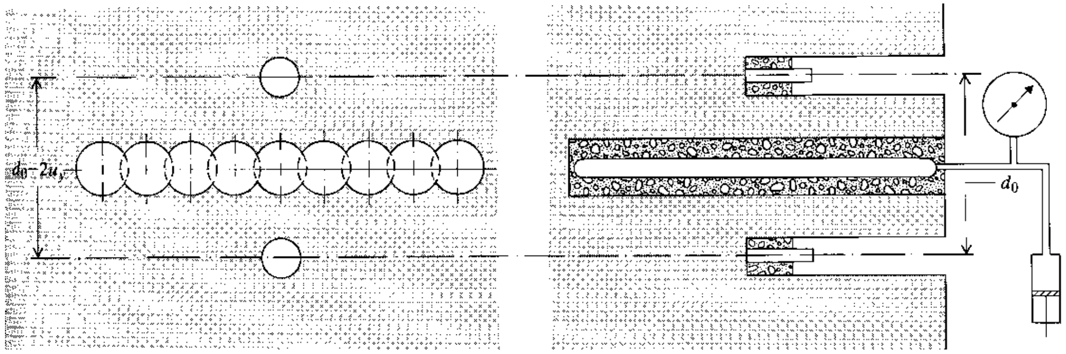
- A flatjack is comprised of two metal sheets placed together and welded around their periphery. A feeder tube inserted in the middle allows the flatjack to be pressurized with oil or water

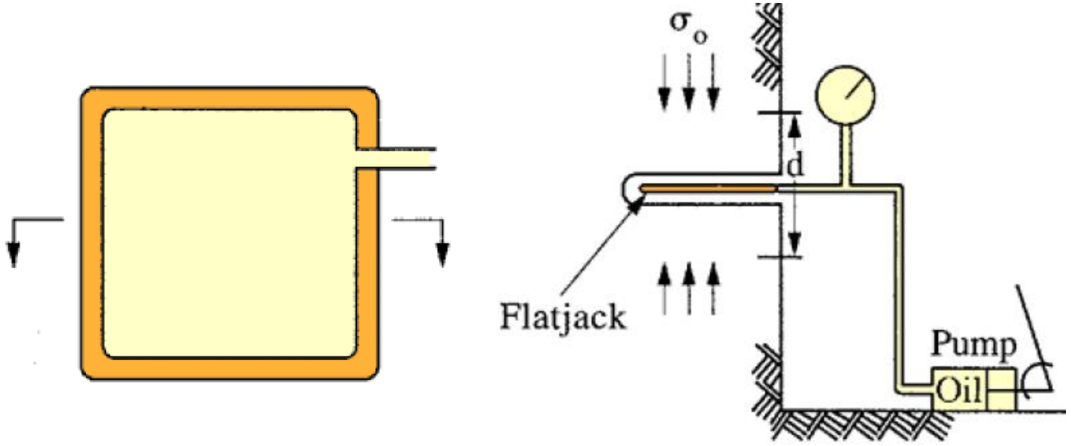


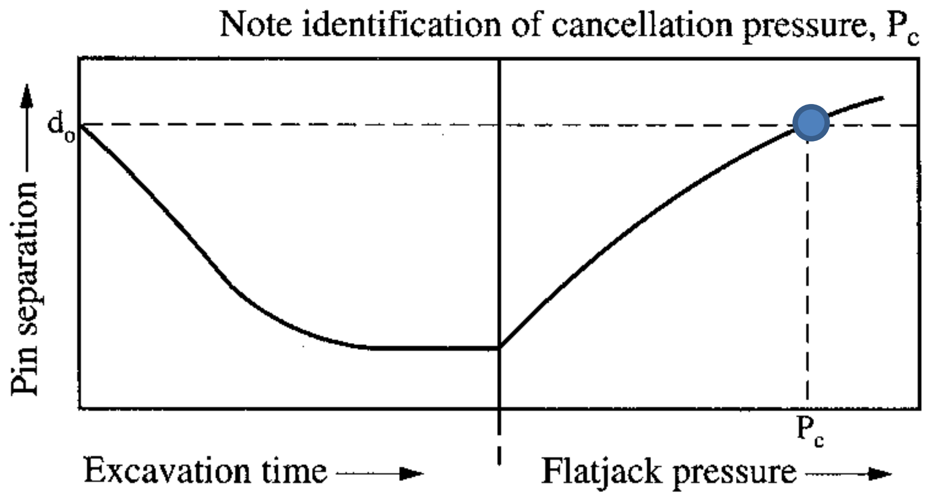


Flat jack test (cont.)

- the placement of two pins fixed into the wall of an excavation. The distance, d, is then measured accurately.
- A slot is cut into the rock between the pins. The pins will move together as the slot is cut. The flatjack is then placed and grouted into the slot
- The flatjack is pressurized to return the pin distance to d and the corresponding pressure is measured



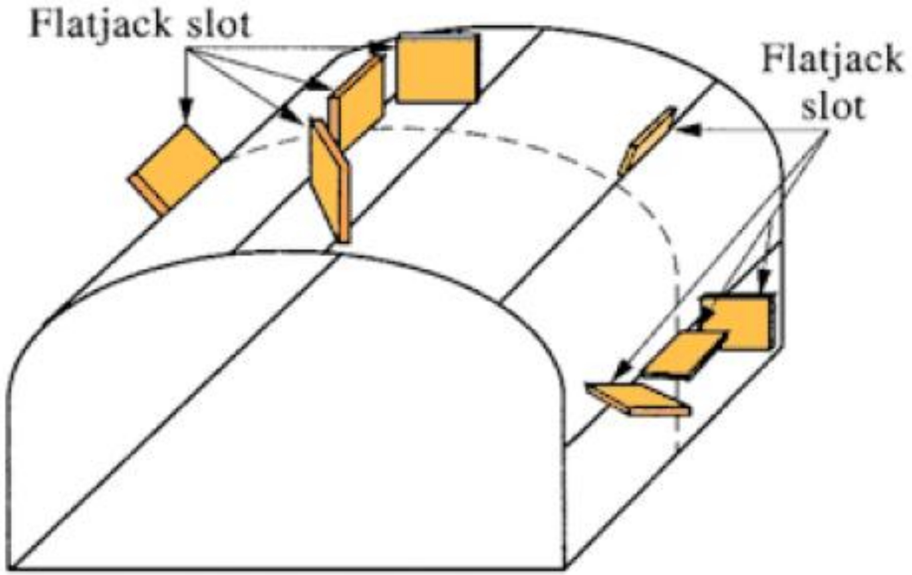




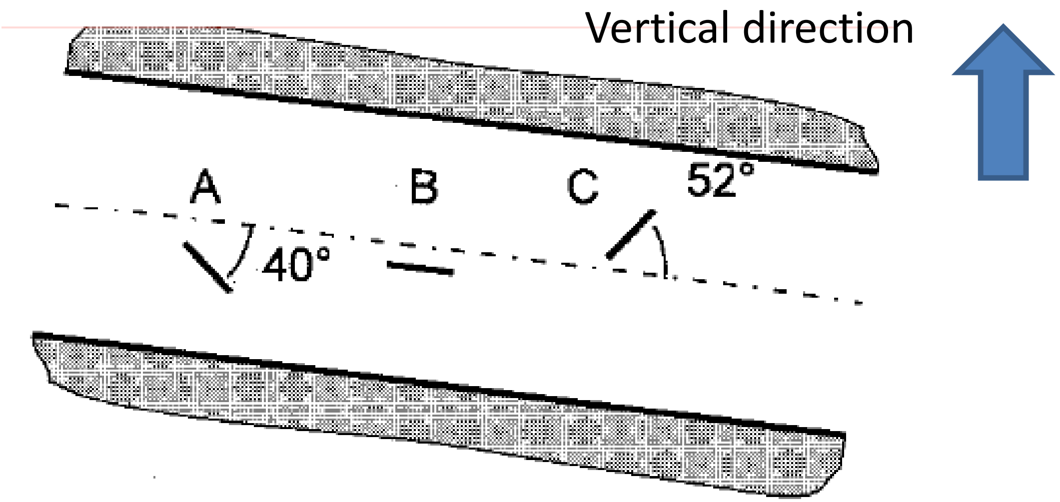
Flat jack test (cont.)

- The major disadvantage is that 6 measurements need to be completed to get the full stress tensor

$$\begin{bmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ & \sigma_{yy} & \tau_{yz} \\ \text{Symm.} & & \sigma_{zz} \end{bmatrix}$$

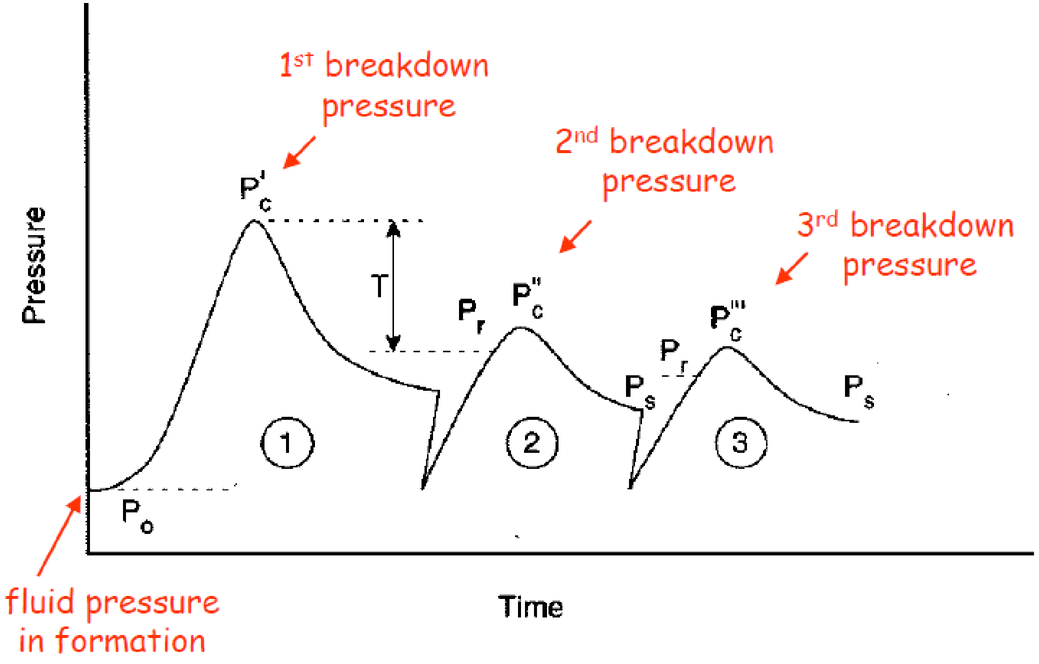


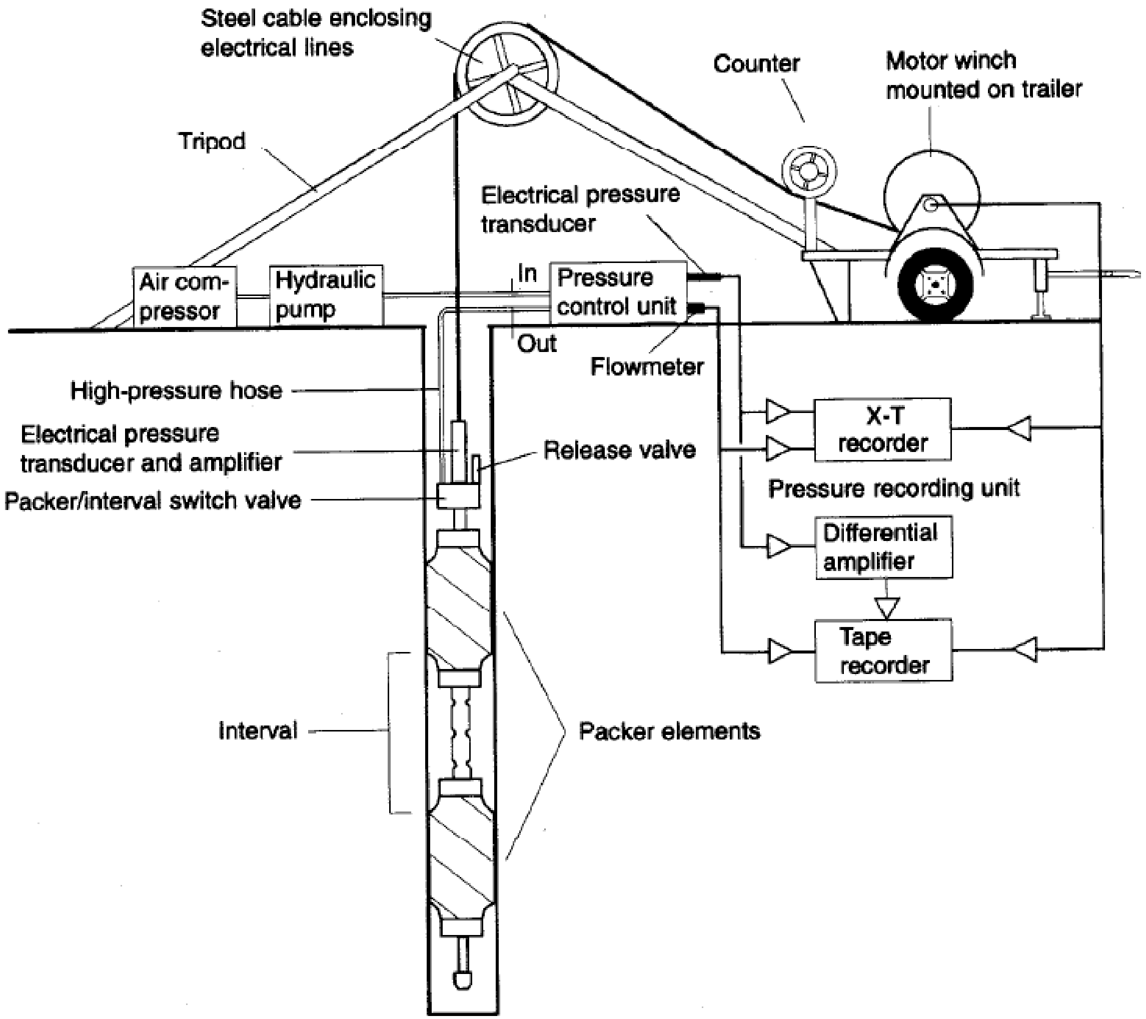
- Example: three flatjack tests have been made along a tunnel wall, the axis of which dips at 7 degrees. The measurement position is about 250 m below ground surface. The pressures measured for each flatjack were: A=7.56 Mpa; B=6.72 Mpa; C= 7.5 Mpa. Determine the principal stresses and their directions.



Hydraulic fracturing method

- Pressure a borehole interval using a packer system until a fracture occurs in the rock
- Breakdown pressure (P_c’ or P_B) and the shut-in pressure (P_s) are measured



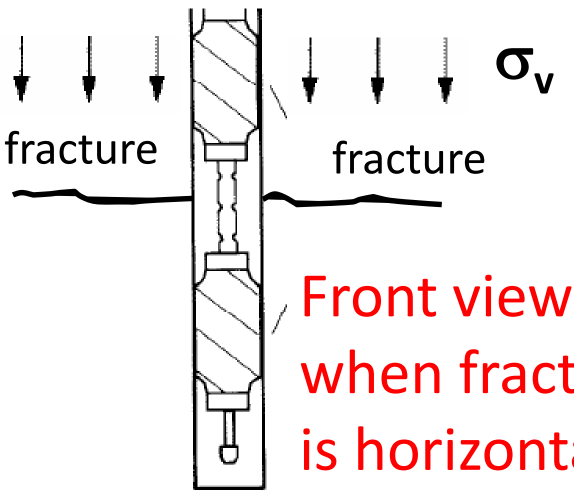


Hydraulic fracturing method (cont.)

- Direction of fracture is normal to the minimum principal stress
- Shut-in pressure (P_s) is assumed to be equal to the minimum principal stress
- When fractures are horizontal, vertical stress is the minor principal stress
- When fractures are vertical, then minor principal stress is the lower one of the two horizontal stresses, term as σ_h
- Both cases have the following equation to relate to the breakdown pressure

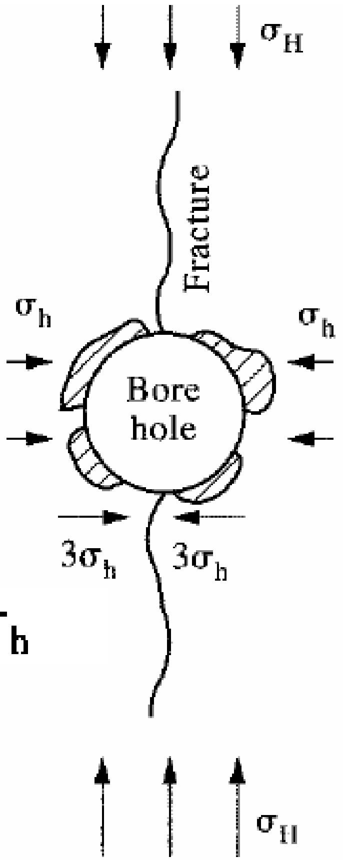
$$P_B = 3\sigma_h - \sigma_H + \sigma_t$$

σ_t = tensile strength of rock



Front view when fracture is horizontal

$P_s = \sigma_v$



$P_s = \sigma_h$

Planview when fracture is vertical

Hydraulic fracture examples

Vertical fracture
Depth = 800 m

P_b = 20 MPa

P_s = 15 MPa

σ_t = 10 MPa

Horizontal fracture
Depth = 650 m

P_b = 25 MPa

P_s = 17 MPa

σ_t = 8 MPa

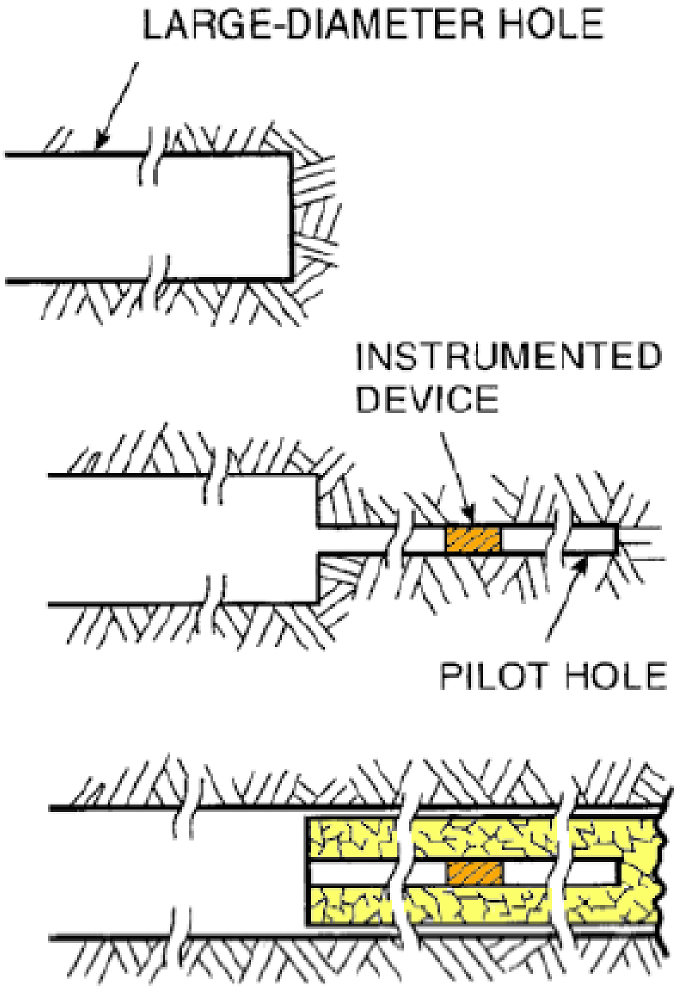
What if:

$\sigma_h = \sigma_H$ = 20 MPa

$\sigma_h = \sigma_H$ = 15 MPa

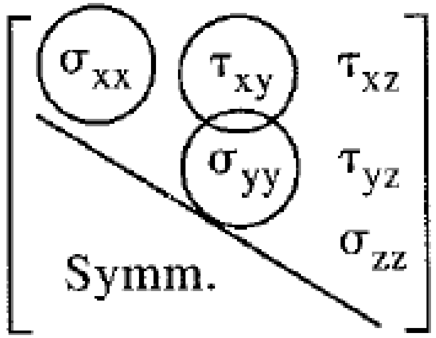
USBM overcore method

- The concept is to isolate a rock sample from the stress field and measure its strain response when releasing the rock sample
- Firstly, a larger diameter borehole is drilled;
- secondly, a small pilot hole (e.g. 38 mm) is drilled and a strain measuring probe is inserted to the hole; Six bottons of the probe press against the hole wall
- Thirdly, the large diameter hole is resumed, relieving stresses and strains in the hollow rock cylinder. The strain is measured with the probe



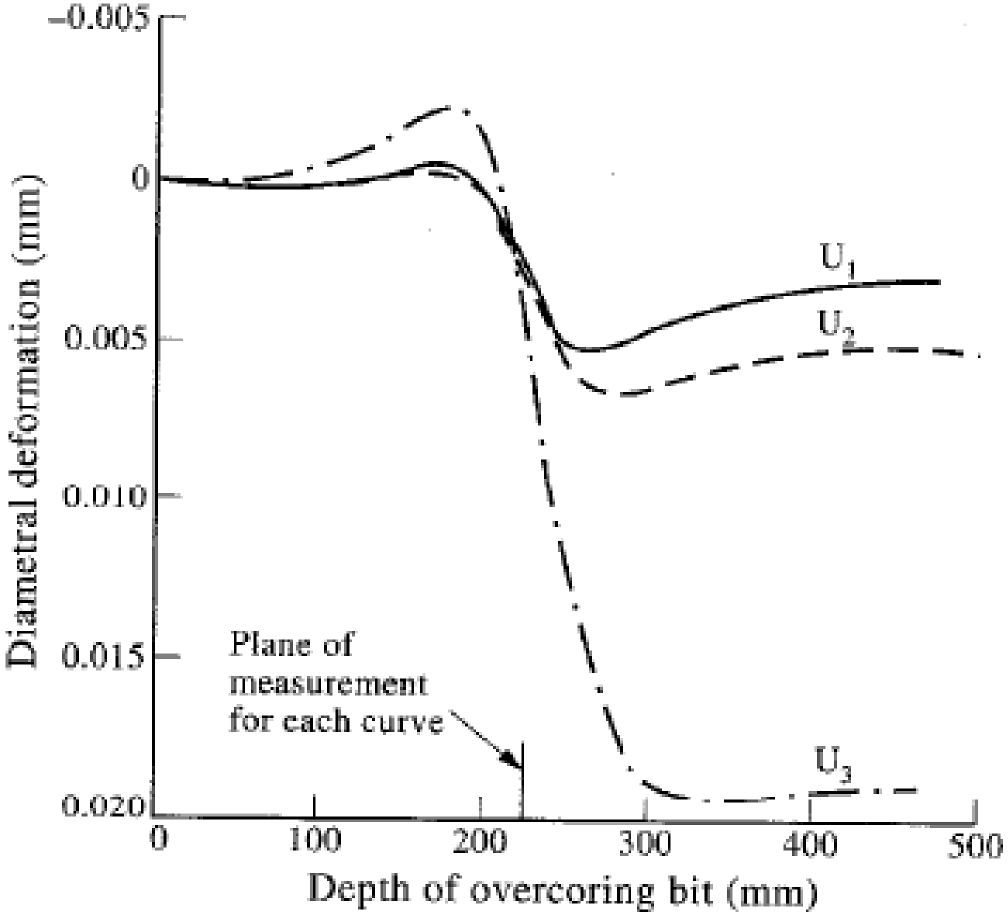
USBM overcore method (cont.)

- When the borehole is overcored by a larger diameter borehole, the stress is reduced to zero and the probe bottons move reflecting sample lateral deformation
- Use the theory of elasticity, the biaxial stress in the plane normal to the borehole axis is deduced



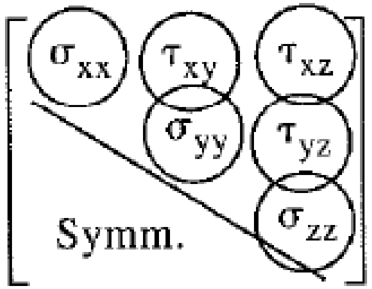
Three components in 2-D determined from three measurements of borehole diameter change.

The traces are the electrical output from the device plotted against time during overcoring and hence illustrate the evolution of diametral change during overcoring.

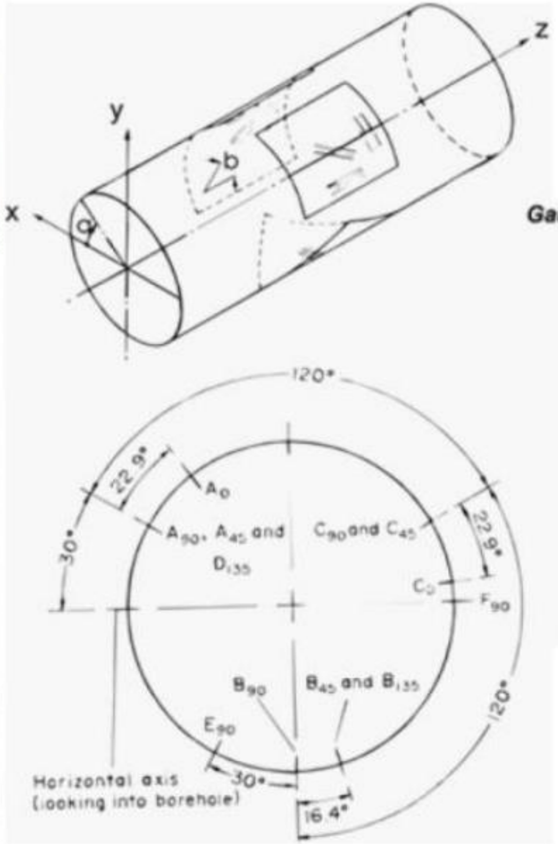


CSIRO overcore stress cell

- CSIRO stress cell operates on the sample concept to the USBM probe
- The difference is the CSIRO cell is glued into the borehole and can measure strains along different directions
- 12 strain gauges can be measured at the same time, and the extra readings can be used to incorporate rock anisotropy
- Bonding may be affected by water and loose materials



All six components determined from six (or more) measurements of strain at one time.



Gauge No.	Position	Gauge I.D.	a°	b°
1	A (axial)	A_0	323	0
2	A (circ.)	A_{90}	300	90
3	A (diag.)	A_{45}	300	45
4	B (diag.)	B_{45}	163.5	45
5	B (diag.)	B_{135}	163.5	135
6	B (circ.)	B_{90}	180	90
7	C (axial)	C_0	83	0
8	C (circ.)	C_{90}	60	90
9	C (diag.)	C_{45}	60	45
10	D (diag.)	D_{135}	300	135
11	E (circ.)	E_{90}	210	90
12	F (circ.)	F_{90}	90	90

Example

A hydrofracture test is used to measure the insitu stress in a vertical borehole. The breakdown pressure was 16 MPa and the shut-in pressure was 12 MPa. The estimated tensile strength of the rock is 2 MPa. An impression packer measures two vertical fractures on opposite sides of the borehole. These fractures have an orientation of 90°/220° (dip/dip direction). Determine the **magnitude** and **orientation** of the horizontal principal stresses.

Example

A hydrofracture test is performed in a horizontal borehole drilled at a trend of 060°. The breakdown pressure was 14 MPa and the shut-in pressure was 12 MPa. The estimated tensile strength of the rock is 2 MPa. An impression packer measures two horizontal fractures on opposite sides of the borehole. How deep was the borehole?

Thank you!!!