Lecture 3

Tectonic stress field and its determination

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Introduction
Objectives of the course

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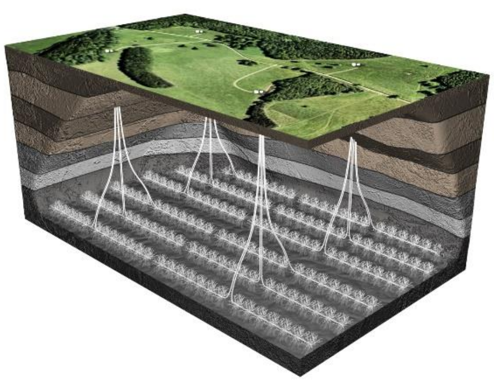
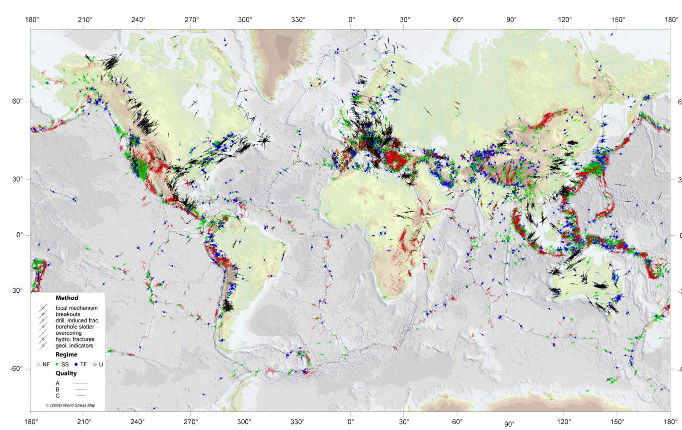
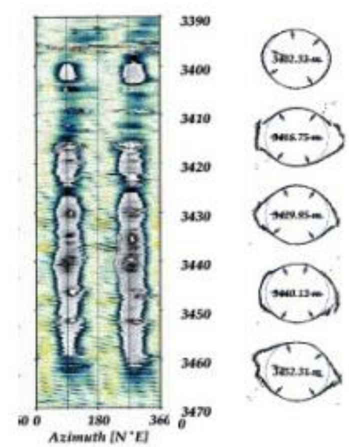
- Objective;
  - Understand the importance of in situ stress for geomechanics
  - In situ stress measurement;
  - Estimation
    - Integrated method
    - World Stress

Introduction
Importance

- Boundary condition for a engineering problem
  - In situ stress orientation and magnitude is a critical factor for various geomechanics applications
    - Hydraulic fracturing
    - Borehole stability
    - Earthquake analysis
    - Tunnel/mine/opening design/stability







Berad and Cornet (2003)

Introduction
Definition of stress

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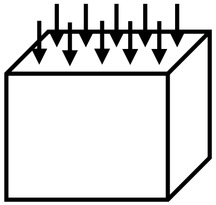
– Stress

  ✎: a force acting over a given area, F/A ← simple definition

  ✎ the internal distribution of force per unit area that balances and reacts to external loads applied to a body← exact definition

– Normal stress: Normal force/Area



$$\sigma = \frac{F_n}{A}$$

– Shear stress: Shear force/Area

$$\tau = \frac{F_s}{A}$$

– Unit: N/m^2=Pa, 10^6Pa=MPa, 10^9Pa=GPa
  145 psi = 1 MPa = 10 bar = 10 kg중/cm^2

Introduction
Definition of stress

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- Six components → three components + three angles

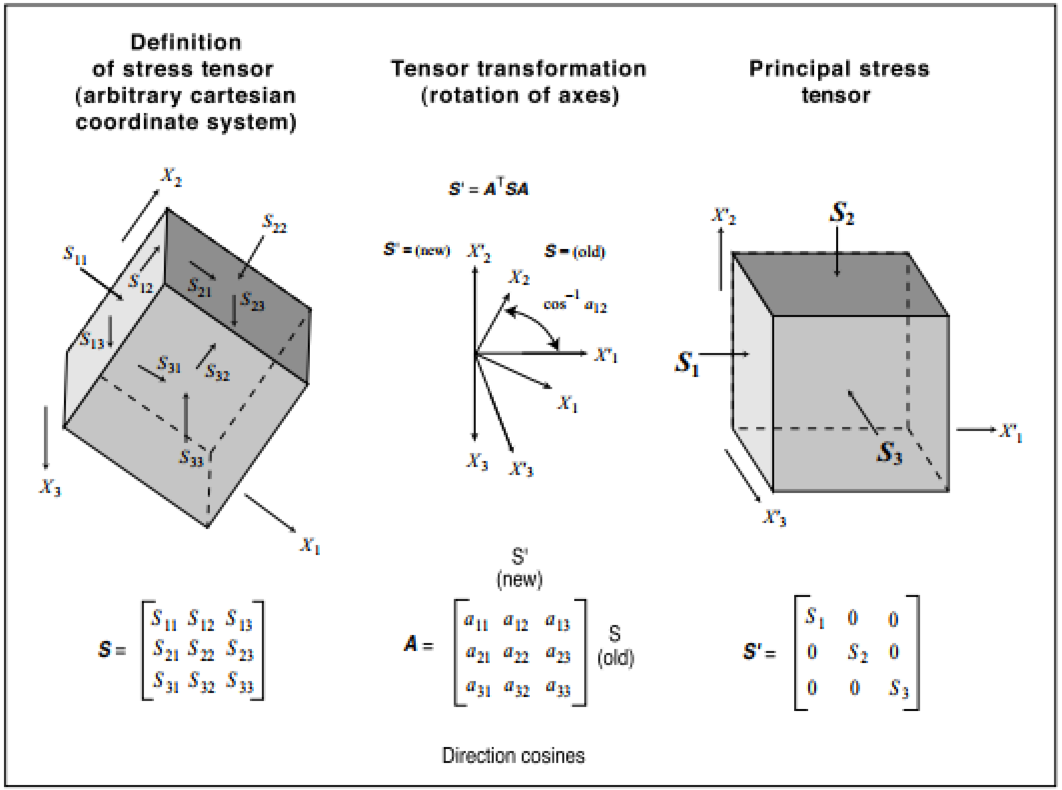
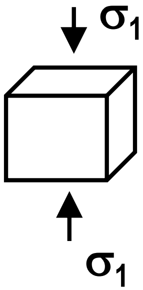
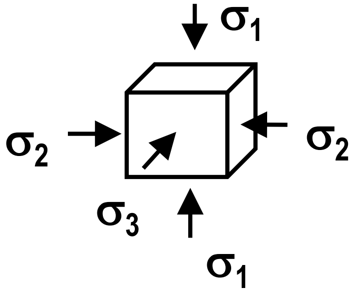


Figure 1.1. Definition of stress tensor in an arbitrary cartesian coordinate system (Engelder and Leftwich 1997), rotation of stress coordinate systems through tensor transformation (center) and principal stresses as defined in a coordinate system in which shear stresses vanish (right).

Introduction
State of stress underground



Uniaxial stress



Triaxial stress

Close to the reality in deep underground

Introduction
Nature of in situ stress estimation in underground

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- Structural Engineering
  - Stress (force) can be directly measurable or,
  - Stress (force) can be calculated
  - Less uncertainties
- Underground Engineering
  - Stress (force) has to be indirectly measured
  - Stress (force) has to be estimated
  - Large uncertainties

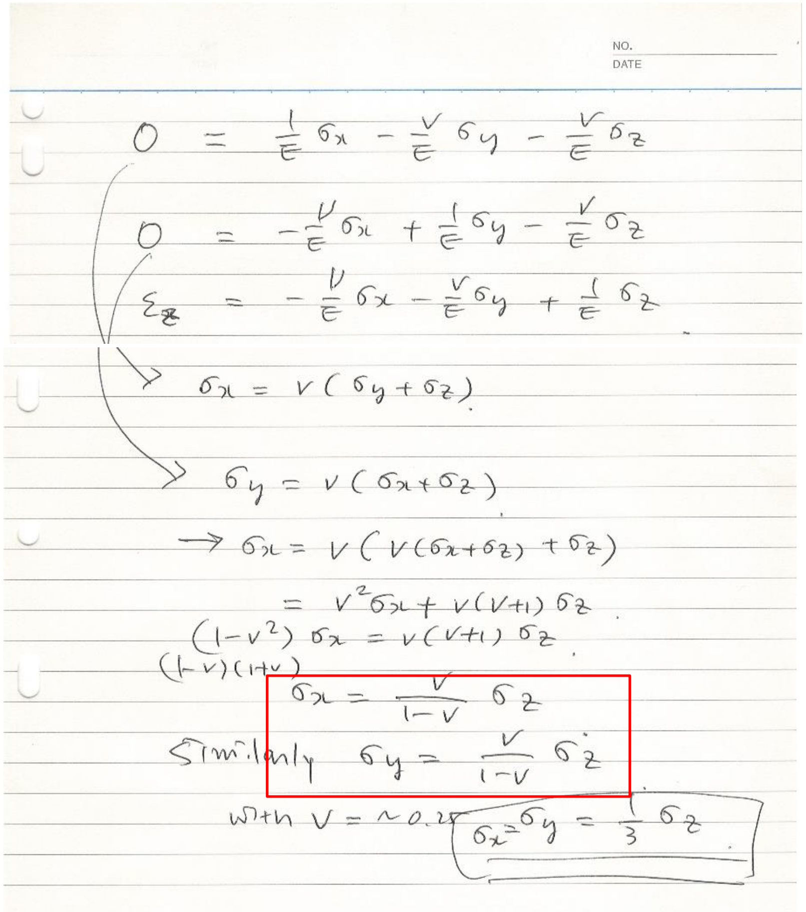
What is my weight? Hence force and stress at my ankles?

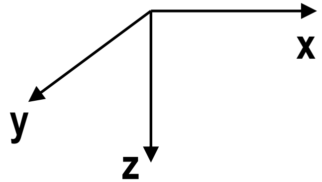
What is in situ stress here?

Introduction
Prediction of in situ stress

- Heim's rule
  - Assumption: no lateral deformation

$$
\begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{pmatrix} = \begin{pmatrix} \frac{1}{E} & -\frac{\nu}{E} & -\frac{\nu}{E} & 0 & 0 & 0 \\ -\frac{\nu}{E} & \frac{1}{E} & -\frac{\nu}{E} & 0 & 0 & 0 \\ -\frac{\nu}{E} & -\frac{\nu}{E} & \frac{1}{E} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G} \end{pmatrix} \begin{pmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{pmatrix}
$$





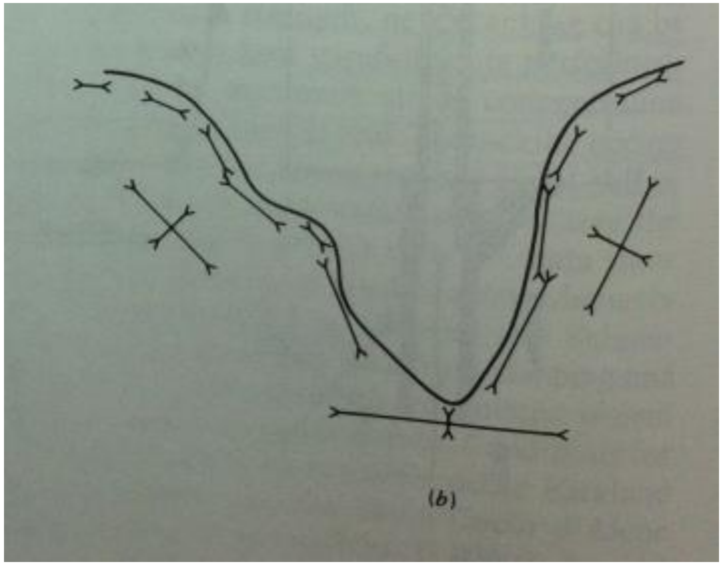
This rule usually works for soils. It does not generally works in rock/reservoir due to tectonic activities, erosion, …

Factors affecting in situ stress measurement

- Erosion
- topography
- Rock anisotropy
- Discontinuity
- Tectonic activity:
  - Prime interest for Reservoir Engineering ~ km depths

Factors affecting in situ stress measurement
Topography

- Topography


(b)

Goodman, 1989, Introduction to Rock Mechanics, Wiley

Factors affecting in situ stress measurement
Effect of discontinuities

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- Discontinuity

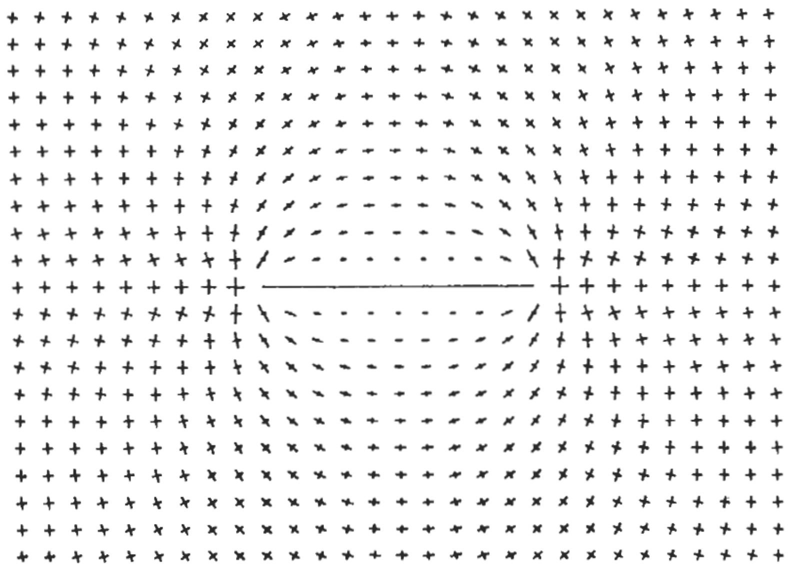
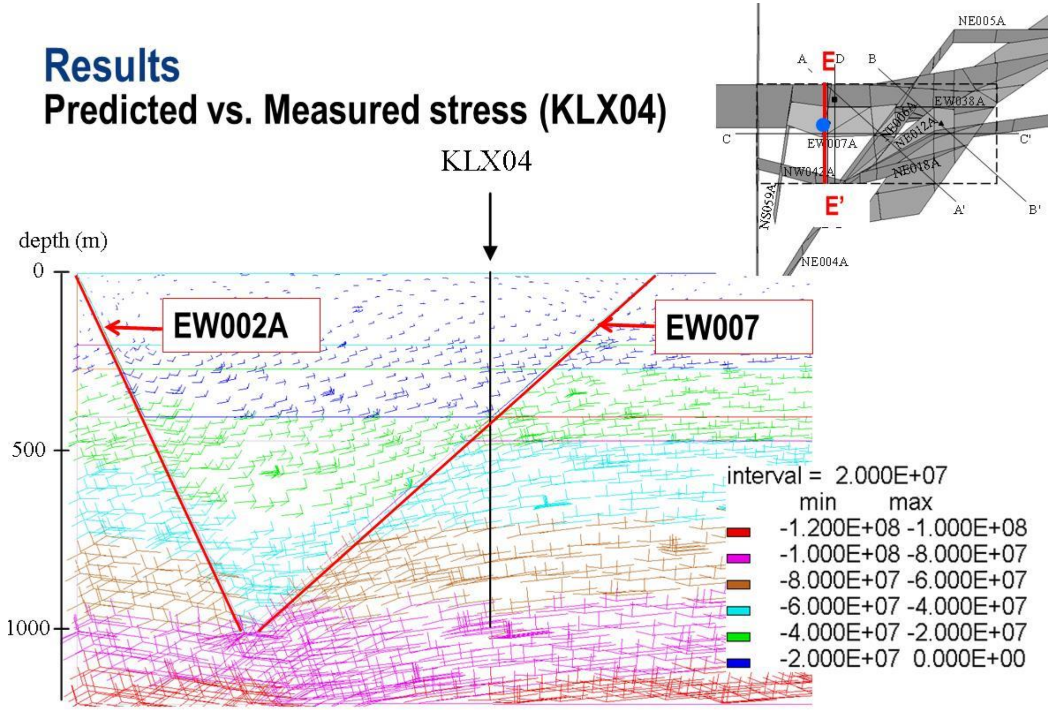


Figure 4.19 Example of the effect of a discontinuity on the near-field stress state, for an applied hydrostatic two-dimensional stress with the discontinuity having a modulus of 10% of the host rock (from Hyett, 1990). The crosses represent the magnitudes and directions of the principal stresses. Note how the stress field close to the discontinuity is quite different from the far-field stress.

Results

Predicted vs. Measured stress (KLX04)



Borehole passes deformation zone EW007 at around 300 ~ 400 m depth
Dramatic change of stress occur due to the deformation zone – smaller stress in the wedge formed by two deformation zones (EW002A and EW007A).

Min KB, Effect of Deformation Zones on the State of *In Situ* Stress at a Candidate Site of Geological Repository of Nuclear Waste in Sweden, *Tunnel & Underground Space: Journal of Korean Society for Rock Mechanics*, 2008;18(2):134-148

Factors affecting in situ stress measurement

Effect of discontinuities - Predicted vs. Measured stress (KLX04)

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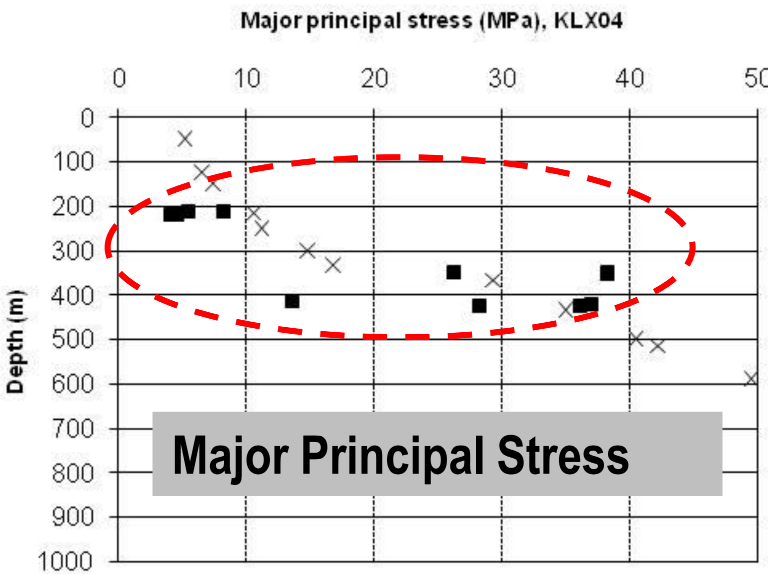

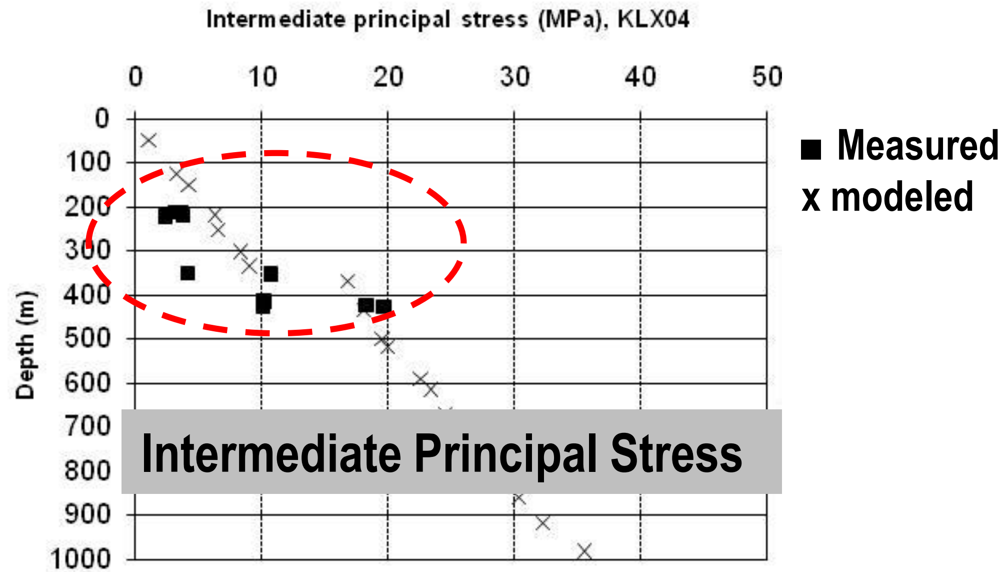

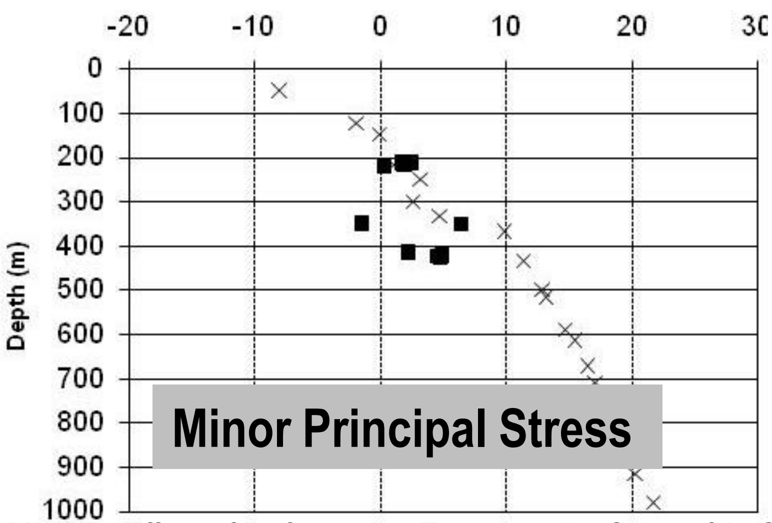

Stress anomaly due to the presence of large scale fault

Min KB, Effect of Deformation Zones on the State of *In Situ* Stress at a Candidate Site of Geological Repository of Nuclear Waste in Sweden, *Tunnel & Underground Space: Journal of Korean Society for Rock Mechanics*, 2008;18(2):134-148

Vertical Stress

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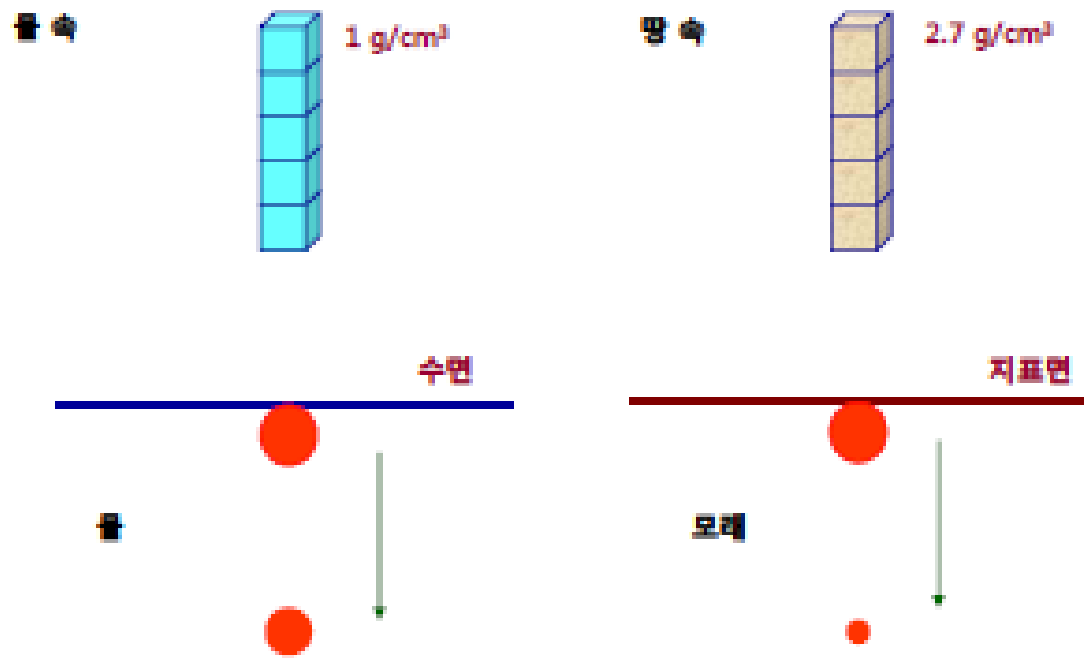
$$p = \rho g z = \text{밀도} \times \text{중력가속도} \times \text{심도}$$



$$p = \rho g z = 0.01 \times z(MPa) \qquad p = \rho g z = 0.027 \times z(MPa)$$

전석원, 2008

- Calculation of vertical stress
  - onshore

The magnitude of S_v is equivalent to integration of rock densities from the surface to the depth of interest, z. In other words,

$$S_v = \int_0^z \rho(z) g \mathrm{d}z \approx \overline{\rho} g z \tag{1.5}$$

where $\rho(z)$ is the density as a function of depth, g is gravitational acceleration and $\overline{\rho}$ is the mean overburden density (Jaeger and Cook 1971).

  - Offshore

$$S_v = \rho_w g z_w + \int_{z_w}^z \rho(z) g \mathrm{d}z \approx \rho_w g z_w + \overline{\rho} g (z - z_w) \tag{1.6}$$

where ρ_w is the density of water and z_w is the water depth. As $\rho_w \sim 1\ \mathrm{g/cm^3}$ (1.0 SG), water pressure (hydrostatic pressure) increases at a rate of 10 MPa/km (0.44 psi/ft).

Vertical Stress
Calculation - example

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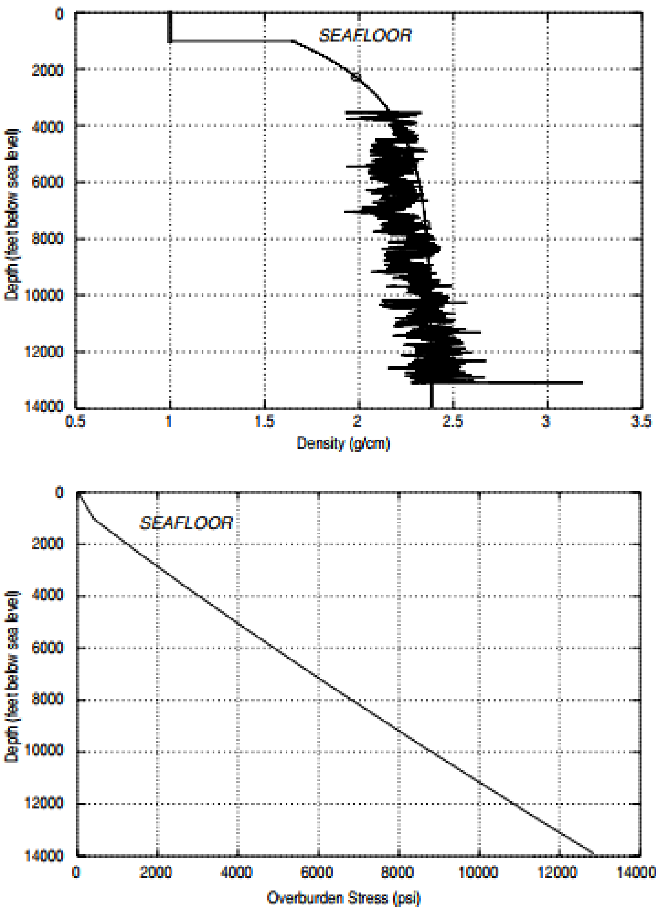
- Estimation of overburden at depth
  - Uncertainty: variability of density log + missing data



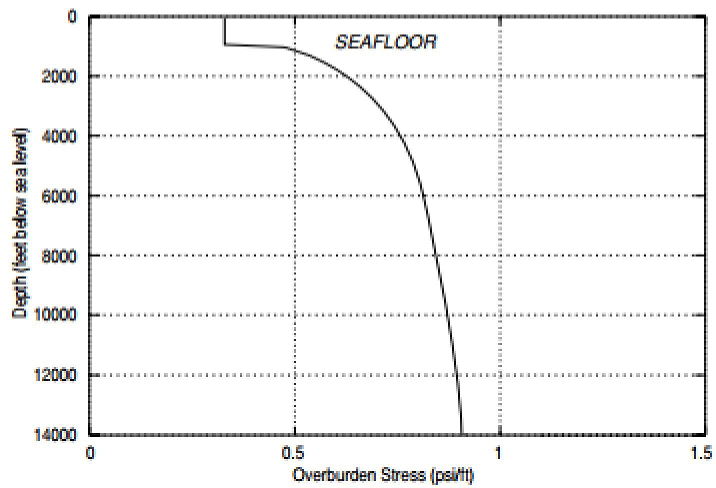


Figure 1.3. Illustration of how integration of density logs (upper figure) can be used to estimate overburden stress at depth (center figure) or overburden stress gradient (lower figure). Variability of the density logs, as well as the fact that they are often not obtained over the total depth of interest, leads to uncertainty in the calculated overburden (see text).

Zoback MD, 2007, Reservoir Geomechanics, Cambridge University Press

Density log

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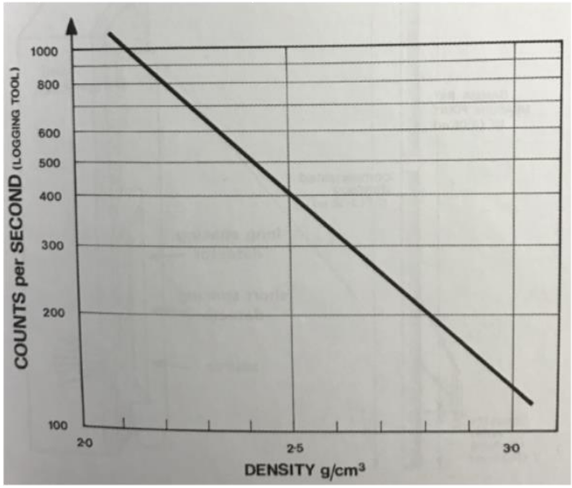
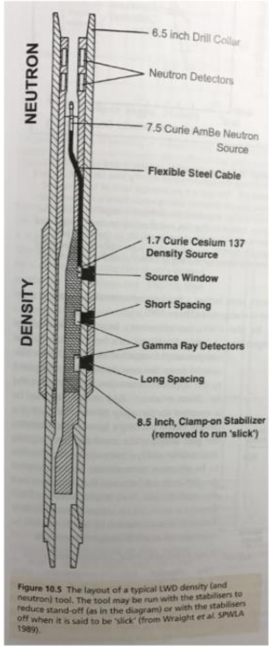
- Density log
  - Continuous record of a formation's bulk density including solid matrix and fluid in the pores.
- Principal uses
  - Density, or Porosity derived from density
  - Useful lithology indicator
- Principles of measurement
  - Exploit 'gamma-gamma' scattering to measure density
  - A radioactive source emits a continuous beam of high energy gamma rays into the formation → some of these are scattered back to a pair of gamma ray detectors.
  - The count rate at a detector depends on density



Density tool radiation count vs. bulk density



Rider M and Kennedy M, 2011, The geological interpretation of well logs, 3rd ed., Rider French

Vertical Stress
World wide in situ stress data

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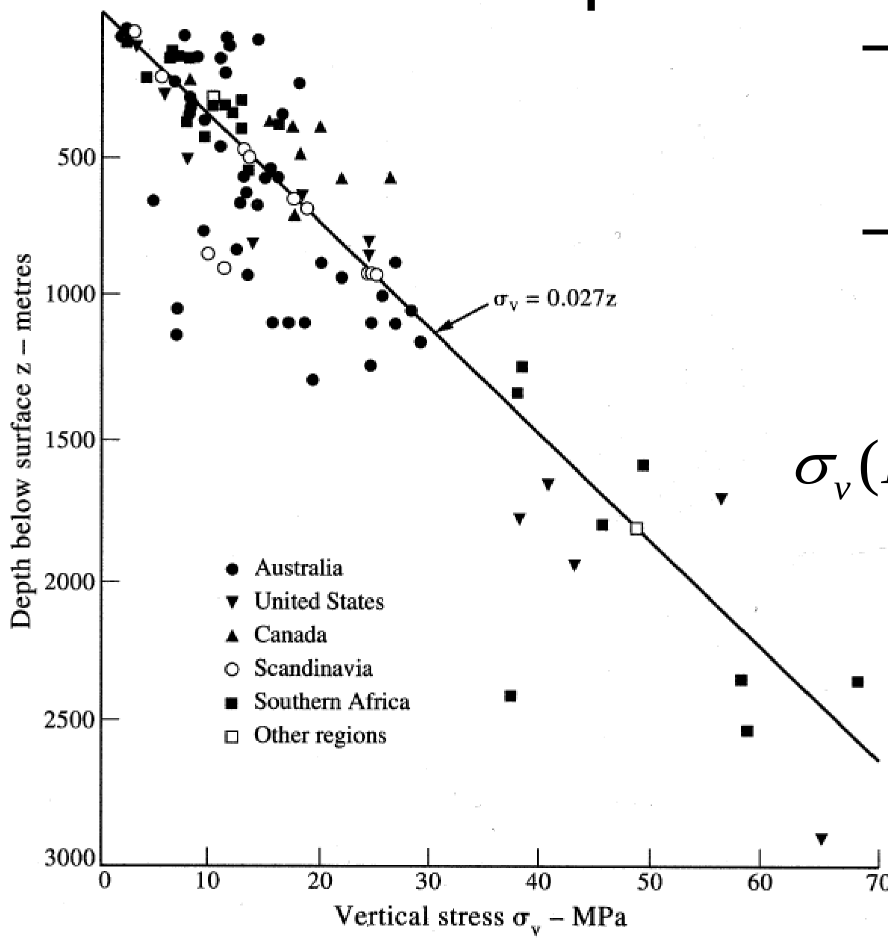
Vertical stress vs depth



– Vertical component of in situ stress

– More or less similar to predicted stress

$$\sigma_v(MPa) = \rho g h = 0.027 \times h(m)$$

Hudson & Harrison, 1997, Engineering Rock Mechanics, Elsevier

Anderson's Classification of stress magnitude

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Table 1.1. *Relative stress magnitudes and faulting regimes*

Regime	Stress		
	S_1	S_2	S_3
Normal	S_v	S_{Hmax}	S_{hmin}
Strike-slip	S_{Hmax}	S_v	S_{hmin}
Reverse	S_{Hmax}	S_{hmin}	S_v

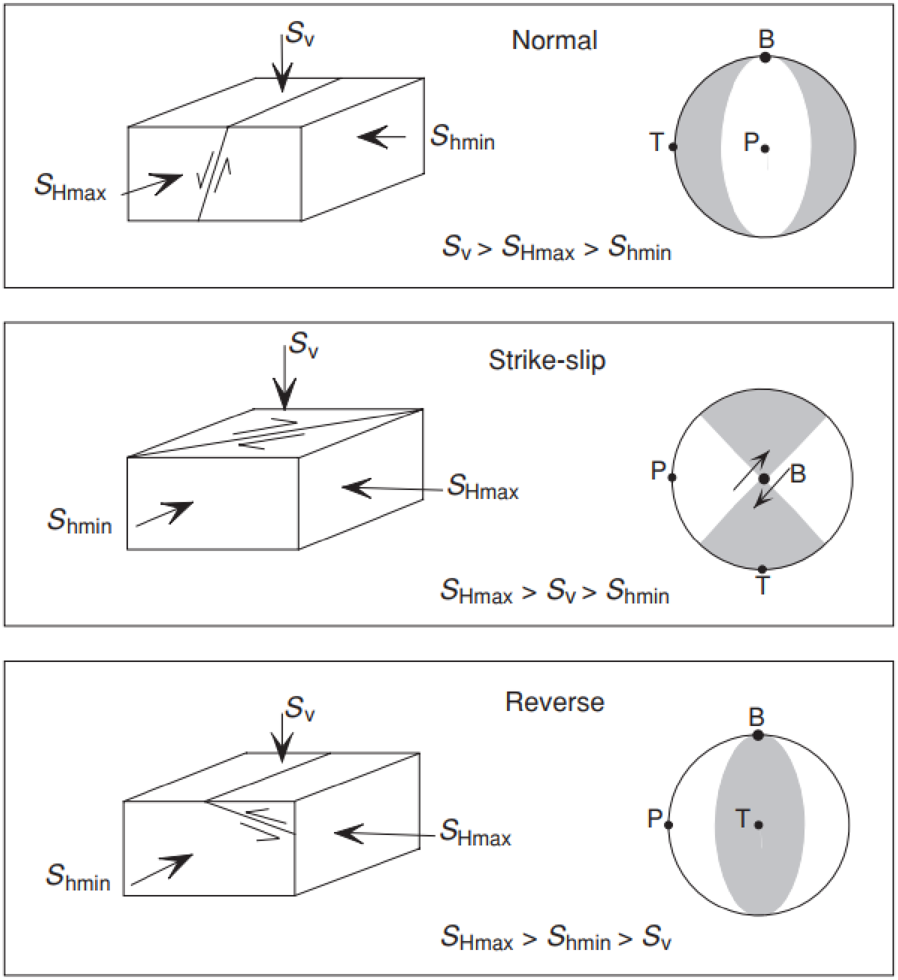

Figure 1.2. E. M. Anderson's classification scheme for relative stress magnitudes in normal, strike-slip and reverse faulting regions. Earthquake focal mechanisms, the *beach balls* on the right, are explained in Chapter 5.

Zoback MD, 2007, Reservoir Geomechanics, Cambridge University Press

In Situ Stress Measurement Method
Direct/Indirect method

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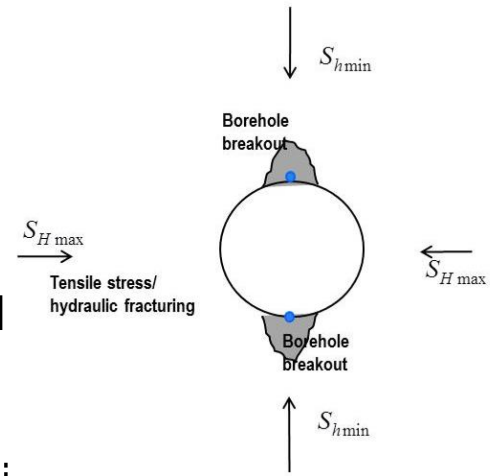
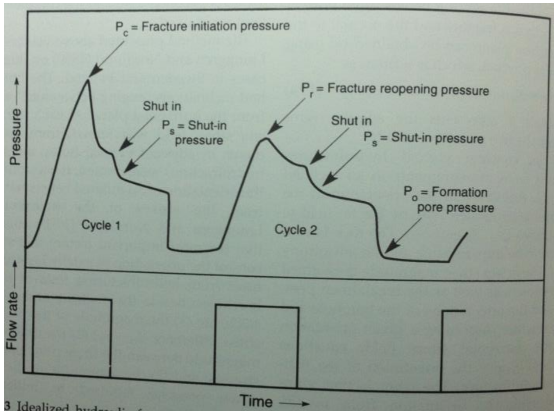
- Direct method
  - Flatjack method
  - USBM overcoring method
  - CSIRO (type) overcoring method
  - Hydraulic fracturing method (mini-frac or micro-frac)
- Indicator method (indirect method)
  - Borehole breakout
  - Anelastic Strain Recovery (ASR)
  - Kaiser effect
  - Core disking
  - Focal Mechanism of earthquake

Zang A, Stephansson O (2010) Stress field of the Earth's crust. Springer Science and Business Media BV, Dordrecht

In Situ Stress Measurement Method
Direct method

- Direct method
  - Flatjack method
  - USBM overcoring method
  - CSIRO (type) overcoring method
  - Hydraulic fracturing method (mini-frac or micro-frac) → More relevant for reservoir engineering at deep depth
    - Very different from hydraulic fracturing for enhanced production
    - In Civil/Mining Industry: hydraulic fracturing (in open hole)
    - Petroleum Industry: mini-frac, microfrac (in cased well with perforation). Leak-off test (open hole below cementing)





Hydraulic fracturing method

In open circular hole!

$$P_b = 3S_{h\min} - S_{H\max} + T_o$$

$$P_s = S_{h\min}$$

$$T_o = P_b - P_r$$ or from Lab Test

Hudson & Harrison, 1997, Engineering Rock Mechanics, Elsevier

In Situ Stress Measurement Method
Direct - Flatjack method

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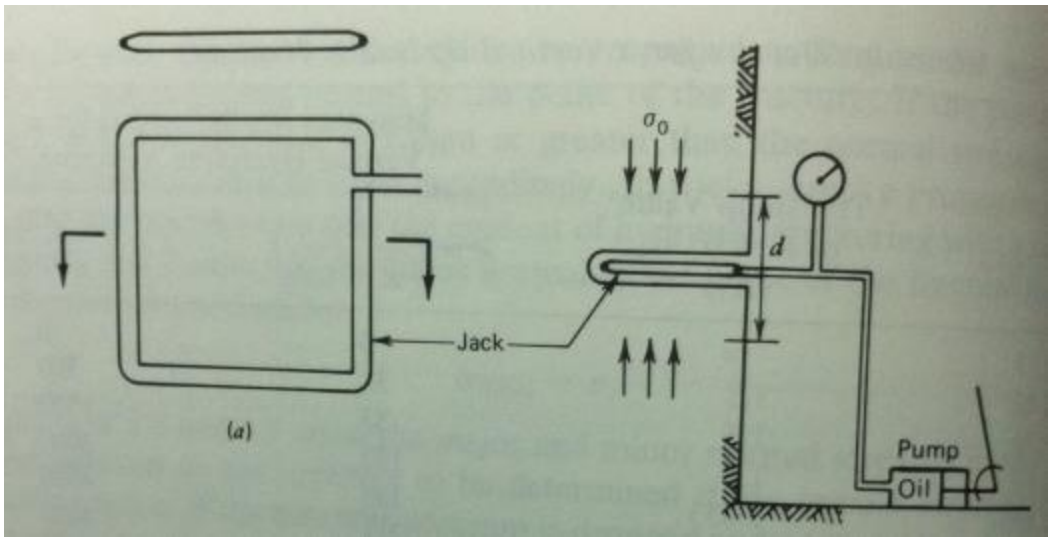
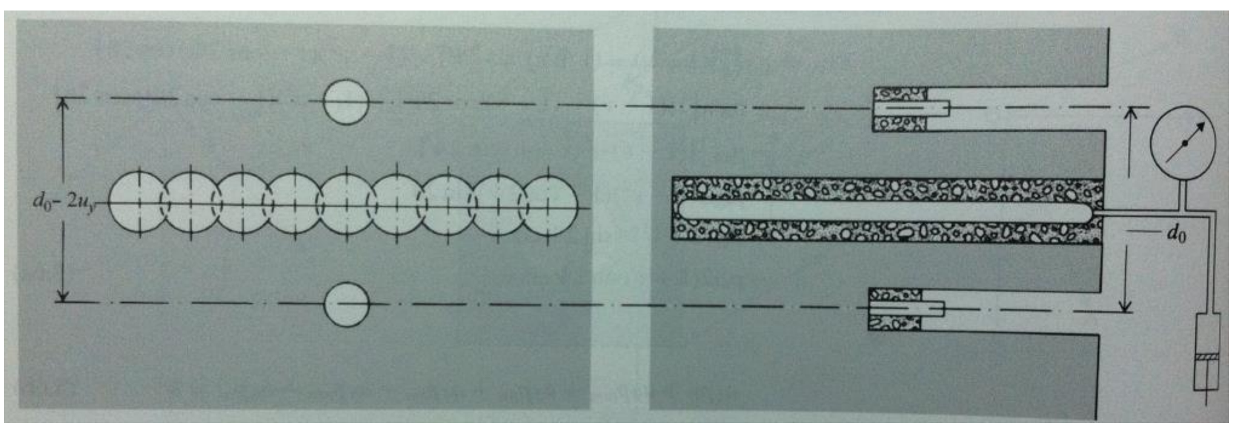
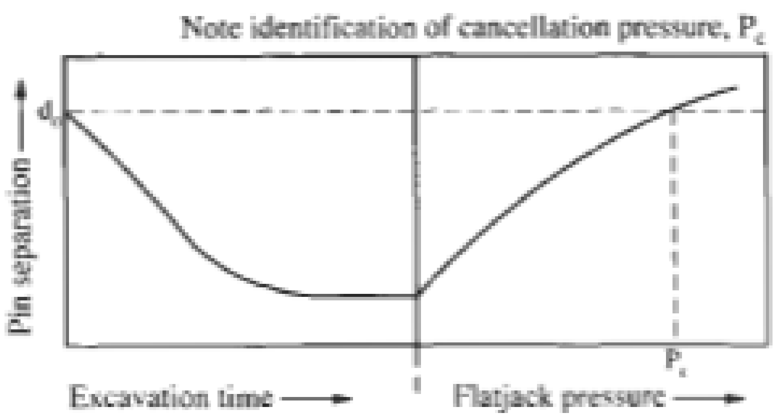
- Directly measure the tangential stress

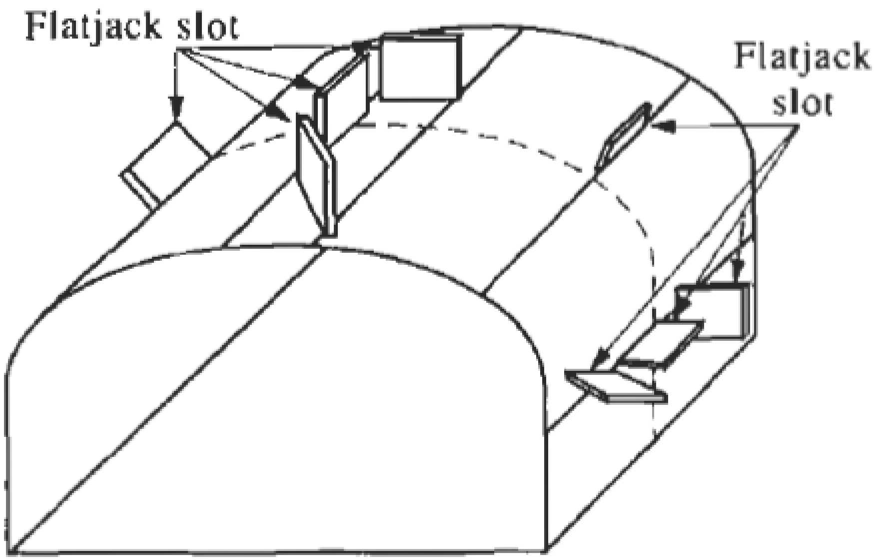




Brady & Brown, 2004, Rock Mechanics for underground mining, Kluwer Academic Publishers

In Situ Stress Measurement Method
Direct - Flatjack method





Hudson & Harrison, 1997, Engineering Rock Mechanics, Elsevier

In Situ Stress Measurement Method
Direct - CSIRO type overcoring method

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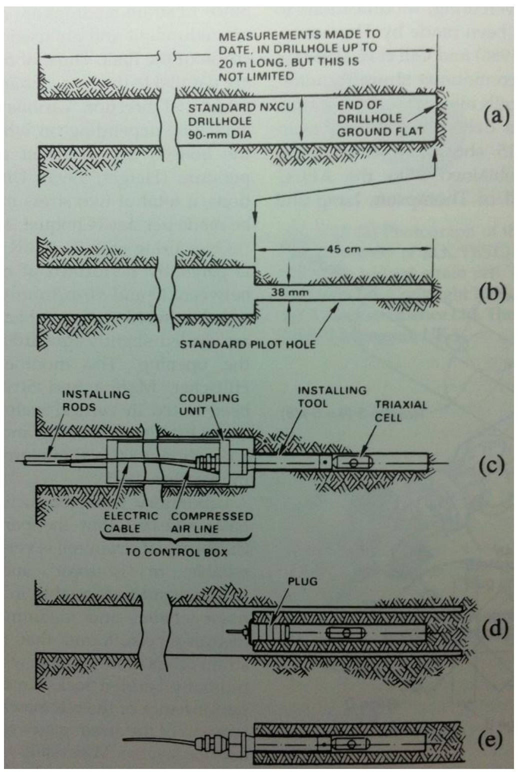
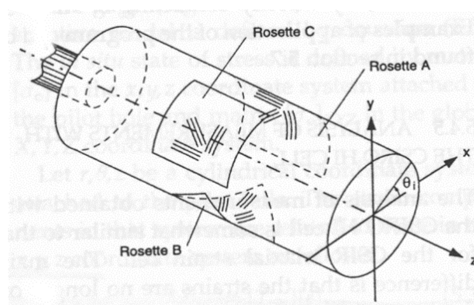
- Complete stress tensor can be determined from minimum of six strain gauges.





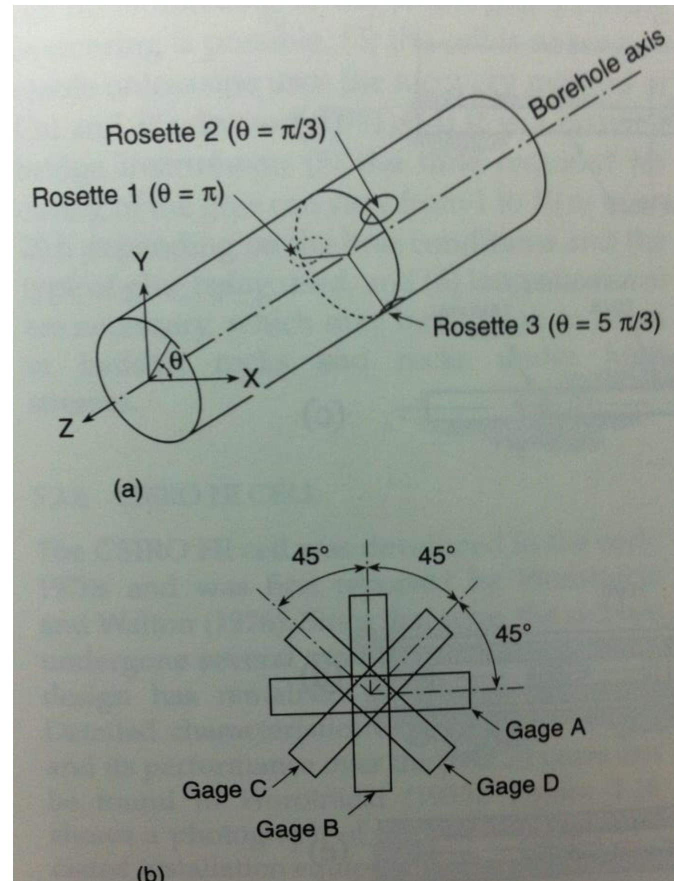


Fig. 5.13 Position of the CSIR triaxial strain cell rosettes in (a) and strain gage configuration in (b). (After Van Heerden, 1976.)

Amadei, B. and O. Stephansson (1997). Rock Stress and its measurement. London, Chapman & Hall

In Situ Stress Measurement Method

Direct - CSIRO type overcoring method

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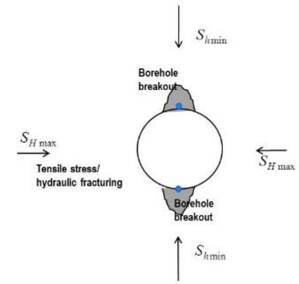
Hudson & Harrison, 1997, Engineering Rock Mechanics, Elsevier

In Situ Stress Measurement Method
Direct – mini-frac

- Mini-frac (or microfrac)
  - In reservoir engineering, only magnitude and direction of minimum principal stress is measured through mini-frac.
  - Usually conducted in cased hole.
  - Leak-off test
    - In open section after drilling a short distance



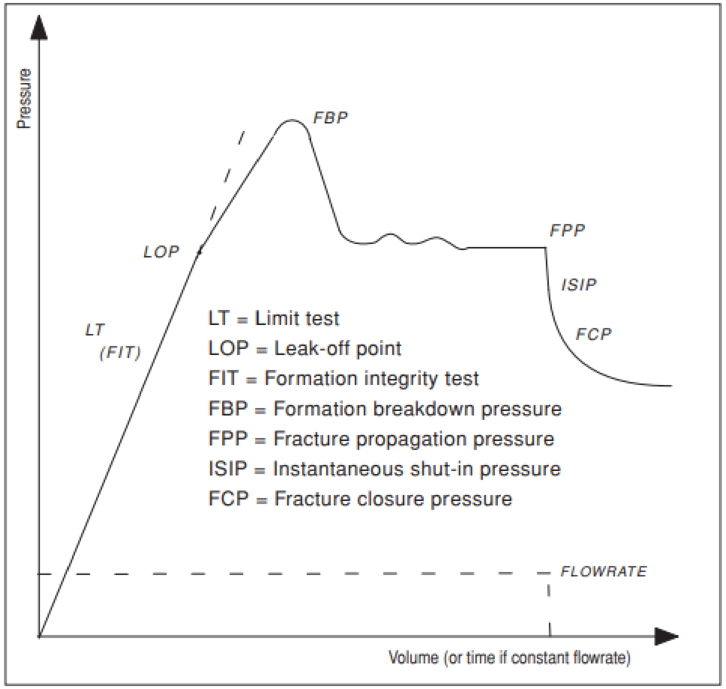


Figure 7.2. A schematic mini-frac or extended leak-off test showing pressure as a function of volume, or equivalently time (if the flow rate is constant). Modified after Gaarenstroom, Tromp *et al.* (1993). The significance of the various points indicated on the pressure record is discussed in the text.

Zoback MD, 2007, Reservoir Geomechanics, Cambridge University Press

In Situ Stress Measurement Method
Direct – mini-frac

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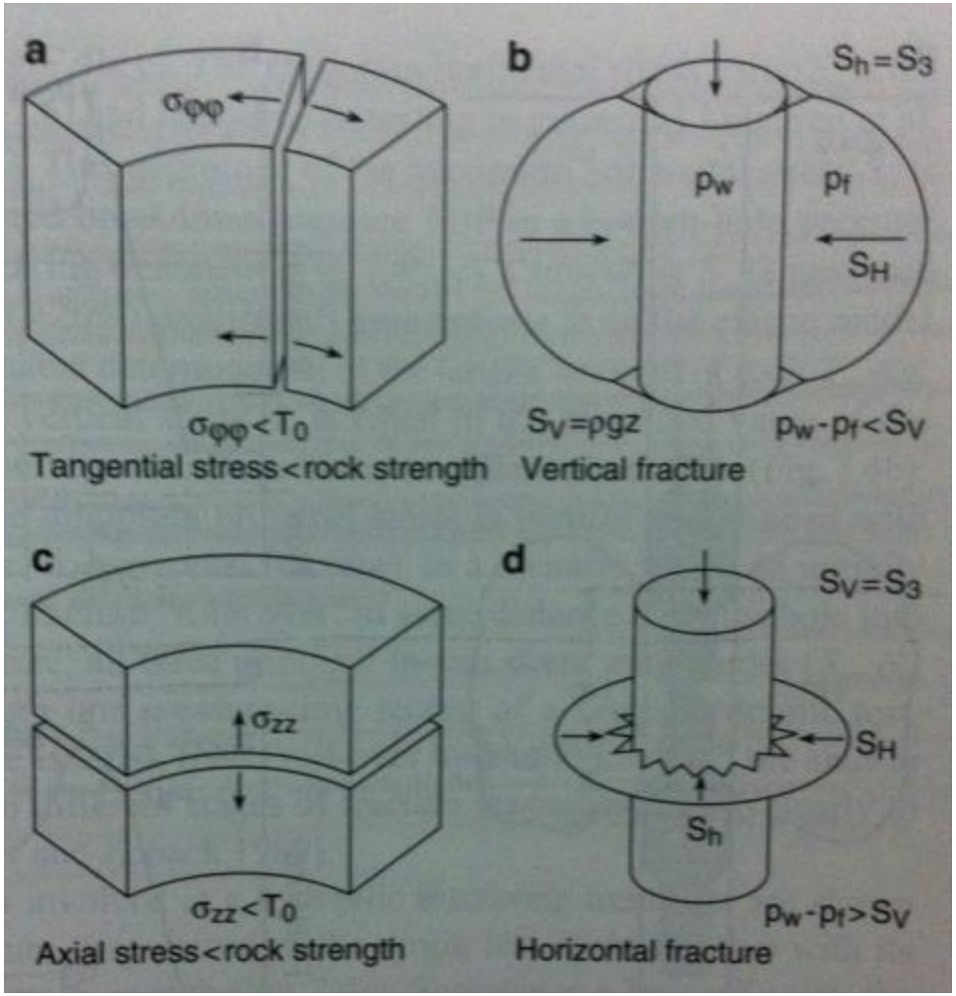
- Vertical fracture vs. horizontal fracture (in vertical hole)



Zang A, Stephansson O (2010) Stress field of the Earth's crust. Springer Science and Business Media BV, Dordrecht

In Situ Stress Measurement Method
Direct – mini-frac

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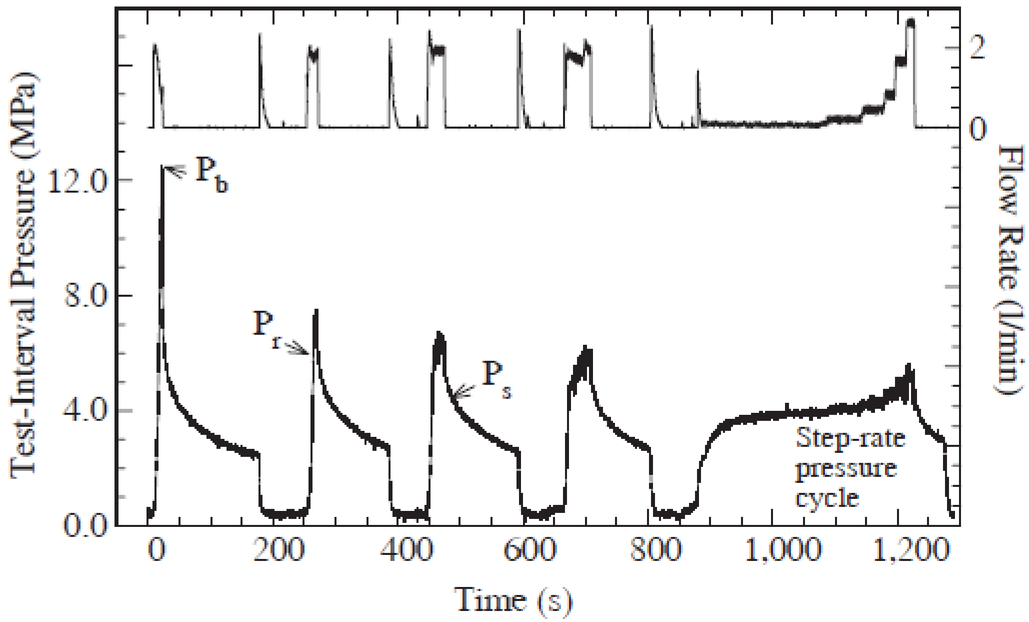
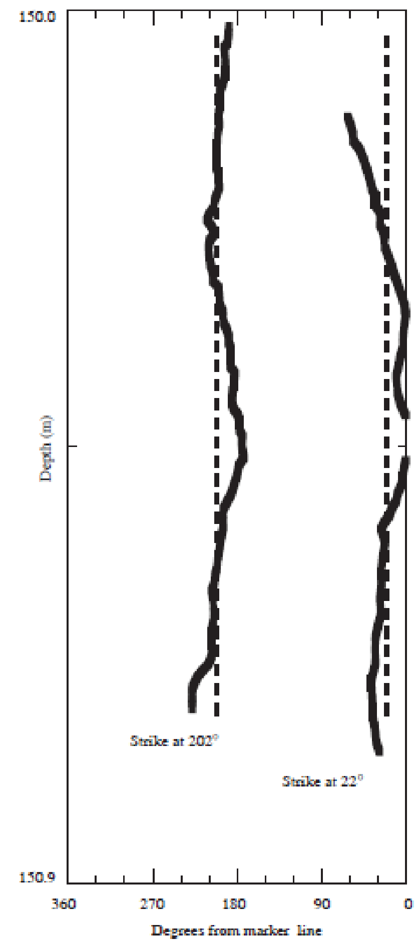
- Actual records



"When open hole is available"



Actual impression packer record (Haimson & Cornet, 2003)

In Situ Stress Measurement Method
Indirect method

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- Borehole breakout
- Anelastic Strain Recovery (ASR)
- Kaiser effect
- Core disking
- Focal mechanism of earthquake

Zang A, Stephansson O (2010) Stress field of the Earth's crust. Springer Science and Business Media BV, Dordrecht

In Situ Stress Measurement Method
Indirect method – borehole breakout

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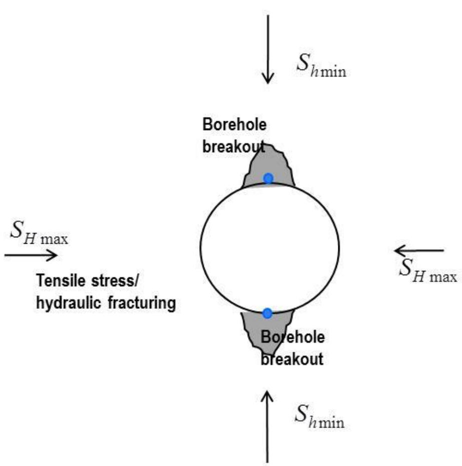
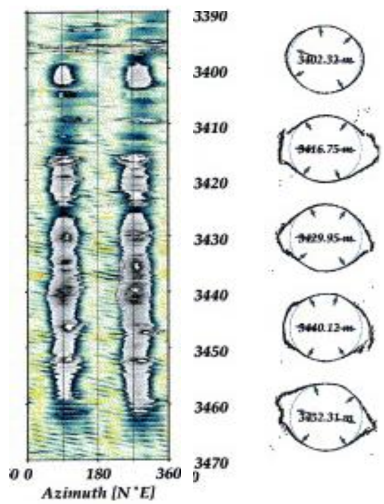
- Borehole breakout
  - Enlargements of the borehole wall caused by stress-induced failure of wells occurring 180° apart.
  - In vertical wells, the diametrically faced zones of broken material occur at direction of minimum horizontal stress.

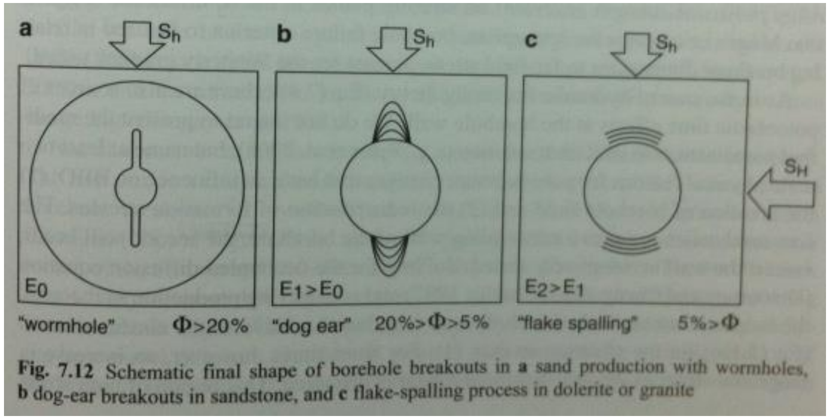
Borehole breakout



$$3S_{h\max} - S_{h\min} > \sigma_c$$



Berad and Cornet (2003)



Zang A, Stephansson O (2010) Stress field of the Earth's crust. Springer Science and Business Media BV, Dordrecht

In Situ Stress Measurement Method
Indirect method – borehole breakout

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- Stress map of southern San Joaquin

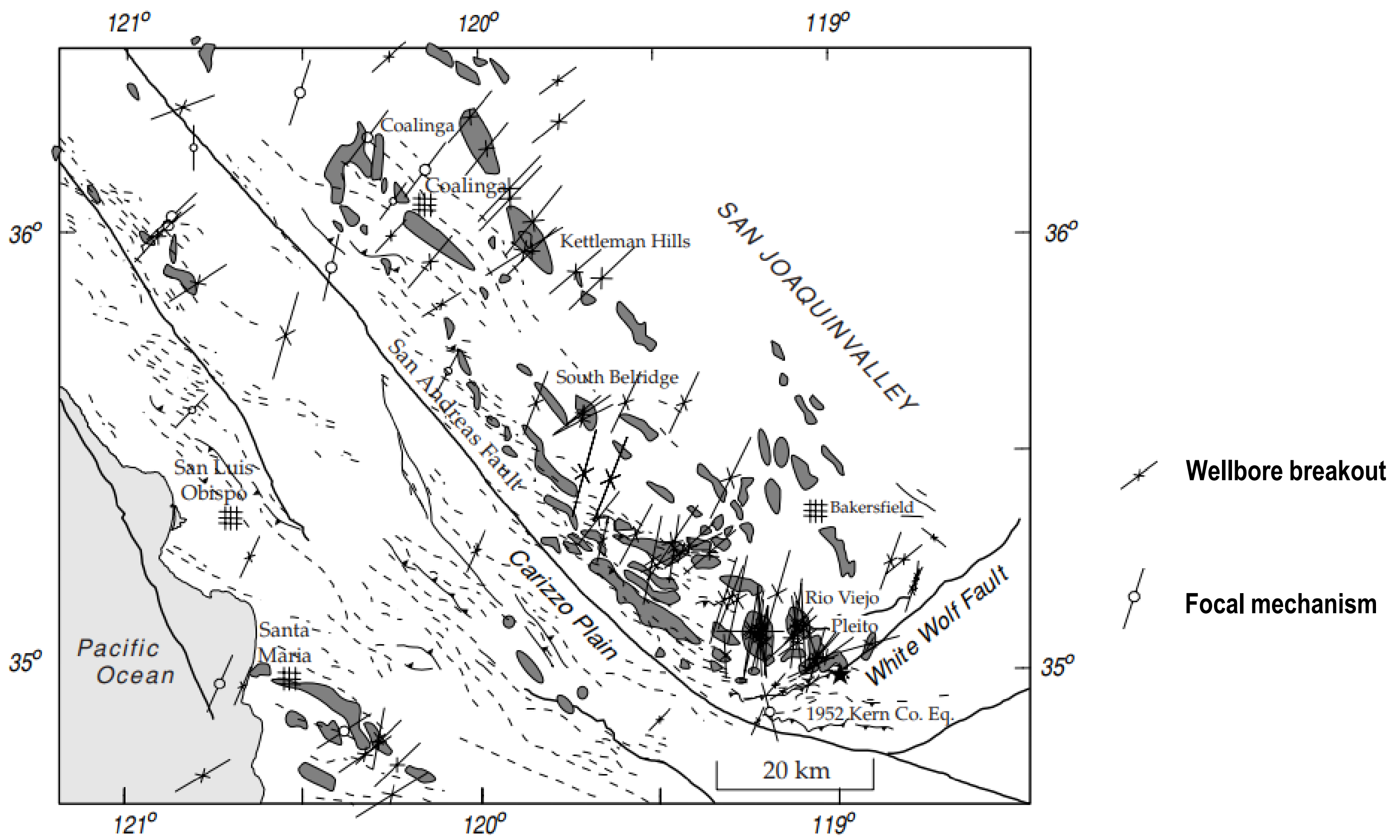


Figure 1.6. Stress map of central California (after Castillo and Zoback 1994) showing S_{Hmax} directions obtained from wellbore breakouts (inward pointed arrows) and earthquake focal plane mechanisms (symbols with open circle). *AAPG©1994 reprinted by permission of the AAPG whose permission is required for futher use.*

Zoback MD, 2007, Reservoir Geomechanics, Cambridge University Press

In Situ Stress Measurement Method
Indirect method – ASR

- Anelastic Strain Recovery (ASR)
  - Core-based method to estimate in-situ stress magnitudes and orientations from instrumenting a freshly recovered drill core obtained from deep wells.
  - The direction of maximum strain recovery is parallel to the maximum horizontal stress in the borehole.

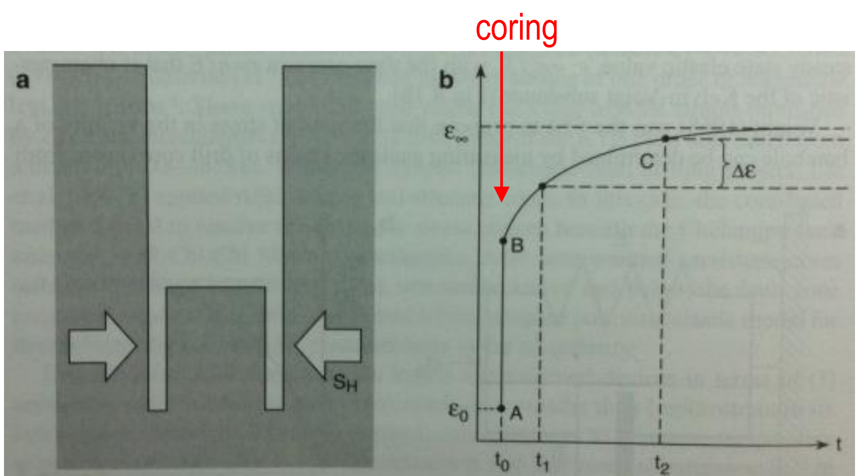
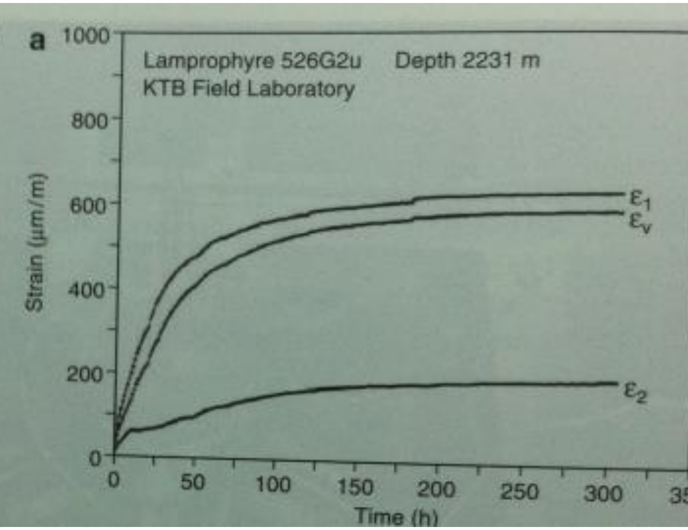


Fig. 8.2 In-situ drilling of core material (**a**) and instantaneous (elastic) plus time-dependent (anelastic) behaviour of the rock core (**b**) (modified after Teufel 1983). Time of in-situ coring is t_0, while $t_2 - t_1$ is the time interval for ASR measurements

Fig. 8.6 **a** Principal recovery strains and **b** semi-logarithmic, normalized recovery strains, both versus time for quasi-isotropic dyke rock (core #526G2u, depth of 2231 m) from the KTB pilot borehole (modified after Wolter and Berckhemer 1989)



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In Situ Stress Measurement Method
Indirect method – ASR

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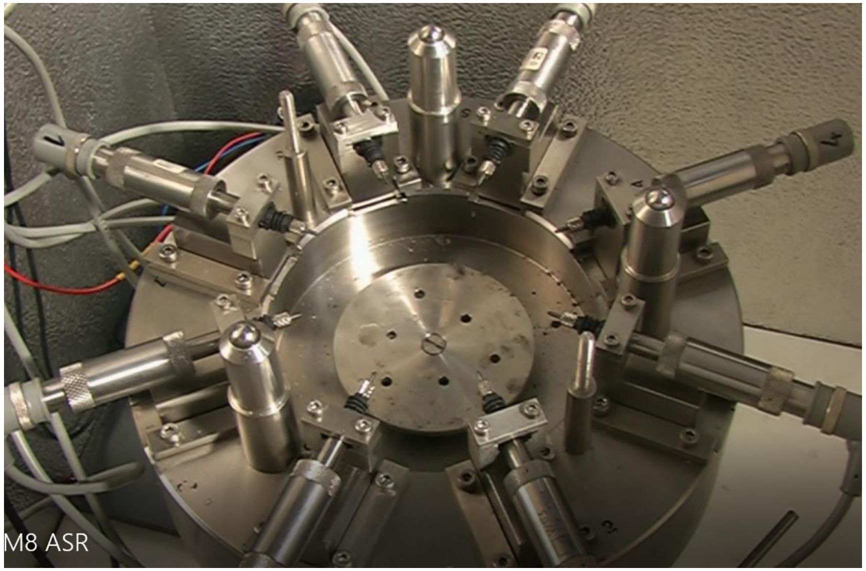
- Anelastic Strain Recovery (ASR) - video



In Situ Stress Measurement Method
Indirect method – Kaiser Effect

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- Kaiser effect
  - phenomenon that a material under stress emits acoustic emissions only after the previous maximum stress is reached.
  - Joseph Kaiser (1950, metal, rock and wood in tension)

PMS: previous maximum stress
RMS: Recalled maximum stress

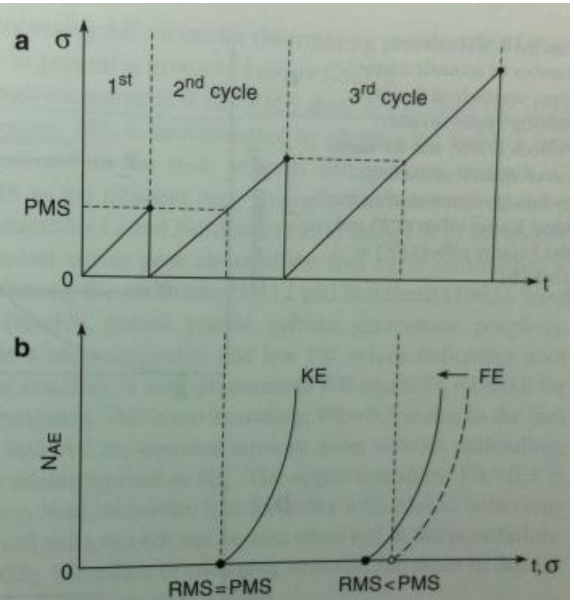

Fig. 8.9 Cyclic loading of a virgin rock core in the laboratory indicated by applied stress versus time curve (**a**), and a measured number of acoustic emissions versus time or applied stress in the second and third loading cycles (**b**)

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In Situ Stress Measurement Method
Indirect method – core discing

- Core disking
  - Assemblage of cored disks in highly stressed rock
  - Often shaped like a horse saddle (axis ~ maximum horizontal stress)
  - The thinner thickness, the greater the horizontal stress

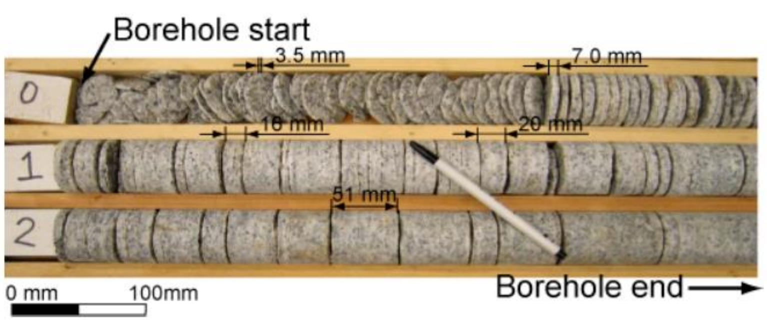
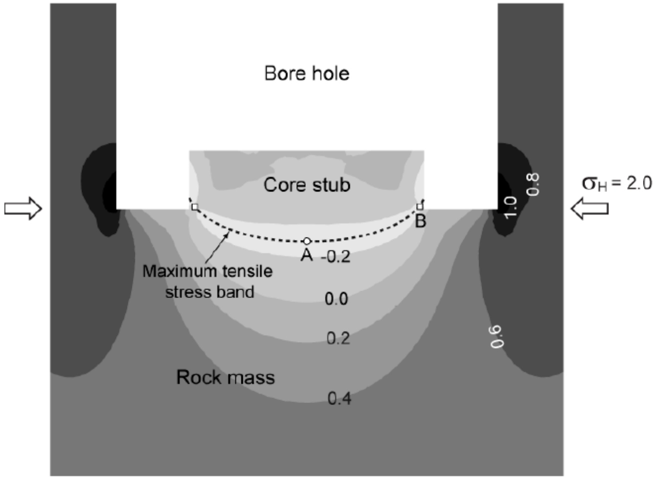


Fig. 1. Typical core disking observed in 75-mm-diameter boreholes drilled from tunnels at the 420-m depth Level of AECL's Underground Research Laboratory.



Lim, S. S., et al. Core Disking Observations and In-Situ Stress Magnitudes, 47 US Rock Mech Symp, Paper No.:13-152

In Situ Stress Measurement Method
Indirect method – Focal Mechanism (also available at ch.5)

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- Earthquake Focal mechanism (= fault plane solution)
  - Two orthogonal nodal planes = fault plane + auxiliary plane
  - 90 degrees ambiguity
- Definition:
  - P-axis: bisects dilatational quadrant
  - T-axis: bisects compressional quadrant
  - B-axis: orthogonal to P and T
- Usefulness:
  - 1) Style of faulting,
  - 2) approx. direction of the principal stress

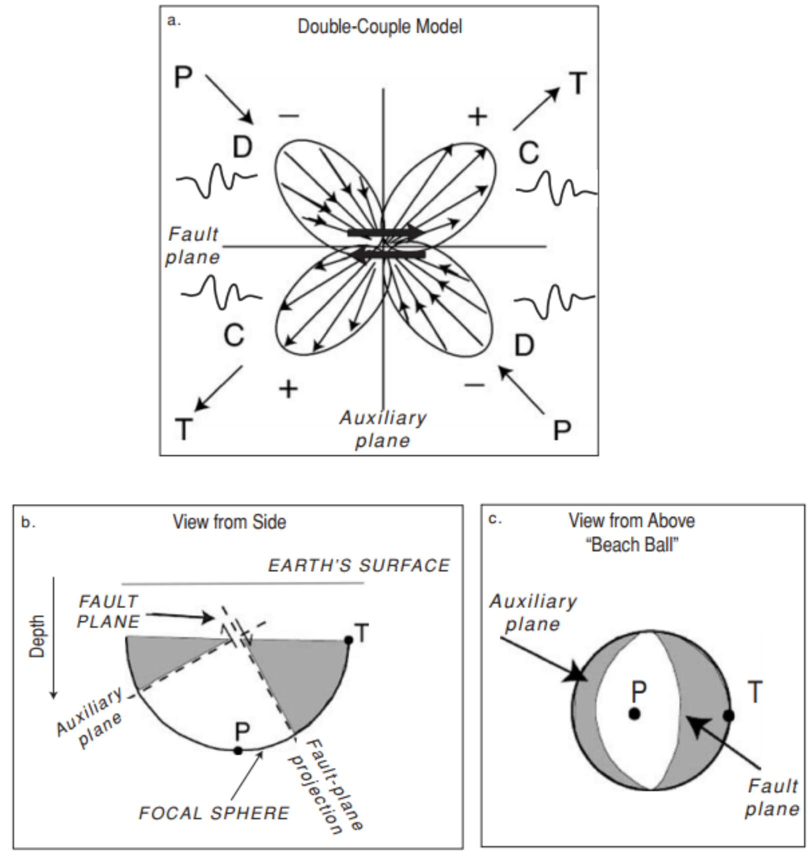

Figure 5.11. (a) Schematic illustration of the radiation pattern and force-couple associated with earthquakes as the basis earthquake focal plane mechanisms. An east–west striking, vertical right-lateral strike slip fault intersecting a half space is shown. The polarity of the P-waves defines the compressional and dilatational quadrants. (b) Cross-sectional view of the nodal planes, radiation pattern and *P*- and *T*-axes associated with an east-dipping normal fault. The radiation pattern does not uniquely distinguish the fault plane from the auxiliary plane. (c) Lower hemisphere stereonet representation of the normal faulting focal mechanism.

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Supplementary material
Stereographic lower hemisphere projection

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- Stereographic lower hemisphere projection
  - show the trace of a fracture plane (where it intersects the lower half of the hemisphere) or
  - the intersection of fracture poles (normals to the fracture planes) and the hemisphere
- The circular diagrams (Figure 5.6b) used to represent such projections: stereonet

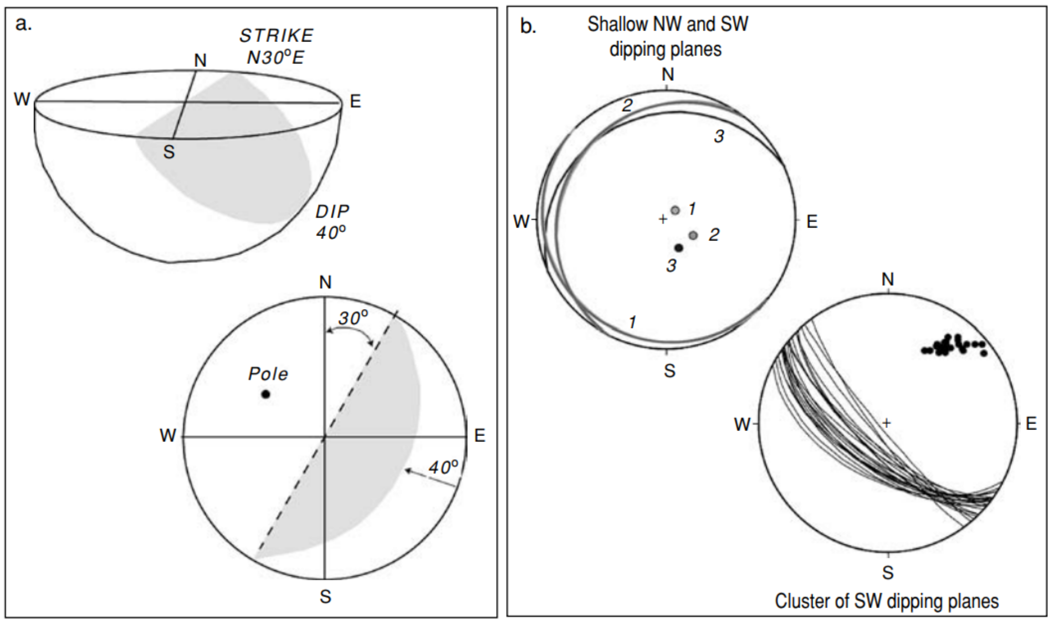

Figure 5.6. Illustration of the display of fracture and fault data using lower hemisphere stereographic projections. Either the intersection of the plane with the hemisphere can be shown or the pole to the plane. Planes which are sub-horizontal have poles that plot near the center of the stereonet whereas steeply dipping planes have poles which plot near the edge.

Zoback MD, 2007, Reservoir Geomechanics, Cambridge University Press

In Situ Stress Measurement Method
Indirect method – Focal Mechanism

- Focal mechanisms of earthquake
  - Provides the orientation of principal stresses using Coulomb failure criterion
  - Relative magnitude of the three principal stress
  - 77% of World Stress Map data
  - Based on the analysis of observed seismic waveform (first motion of P-wave). Upward: compression, downward: dilational

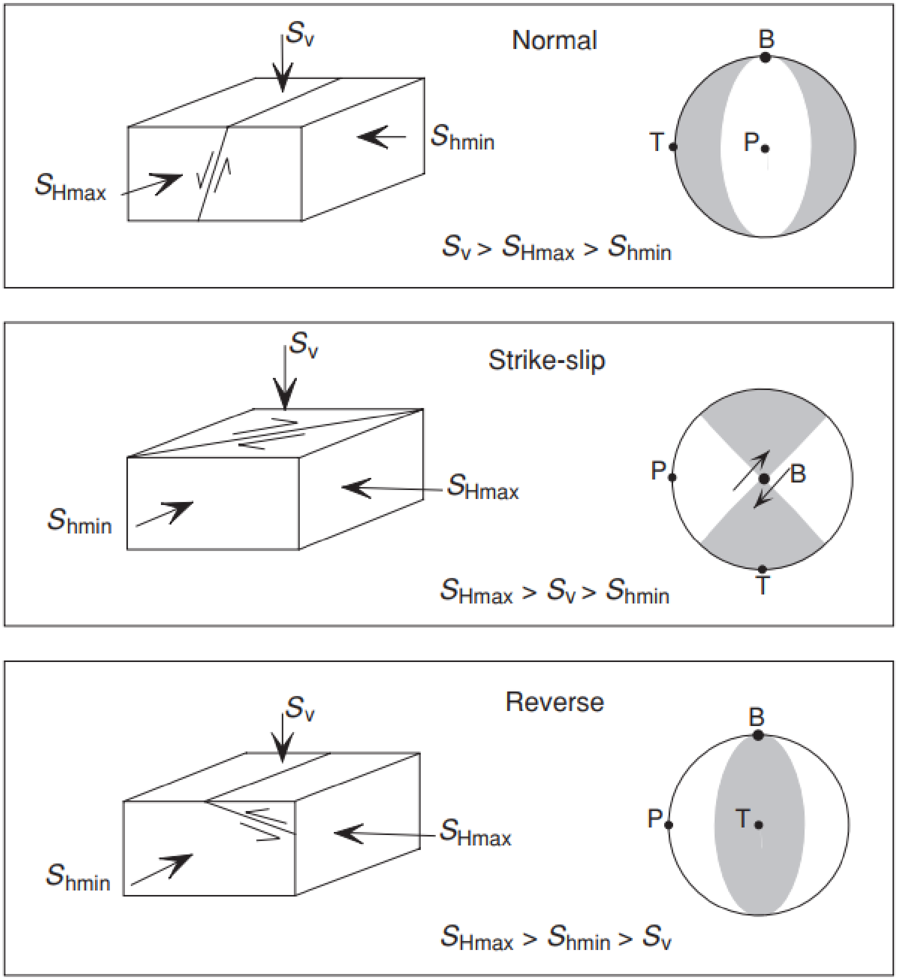

Figure 1.2. E. M. Anderson's classification scheme for relative stress magnitudes in normal, strike-slip and reverse faulting regions. Earthquake focal mechanisms, the *beach balls* on the right, are explained in Chapter 5.

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In Situ Stress Measurement Method
Indirect method – Focal Mechanism

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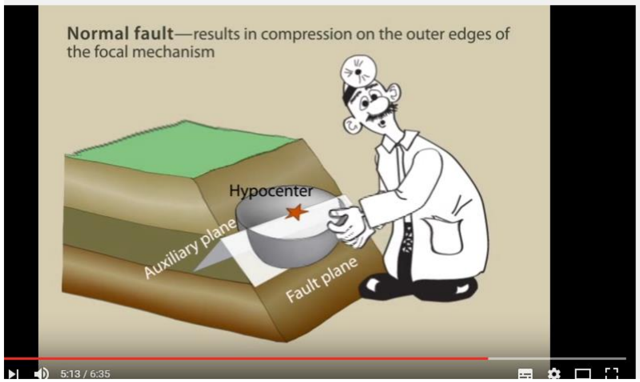
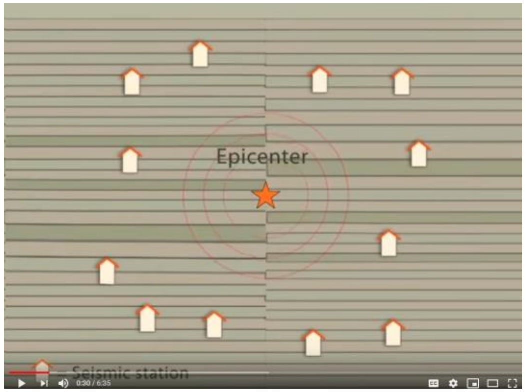
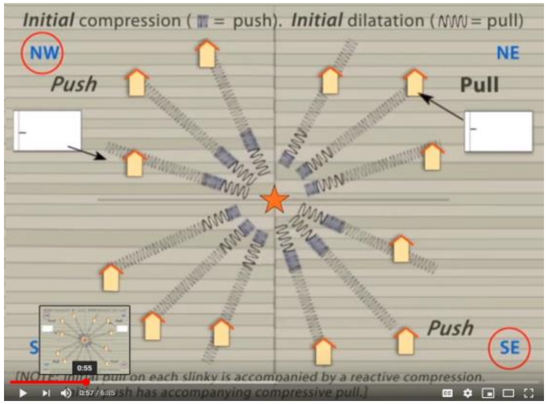
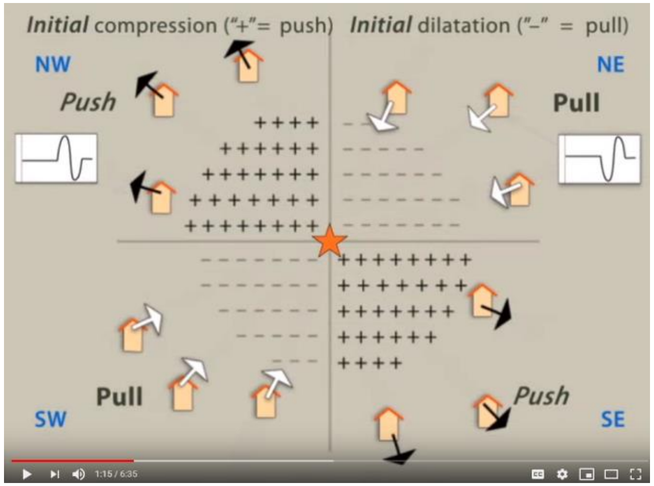
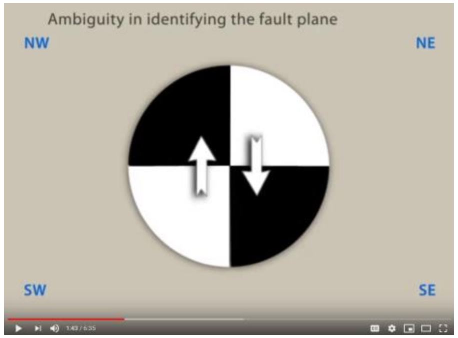
- You tube video
  - https://www.youtube.com/watch?v=MomVOkyDdLo

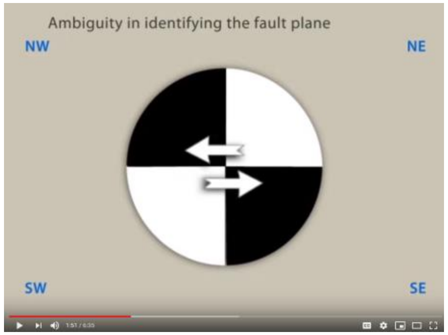












ambiguity

In Situ Stress Measurement Method
Indirect method – Focal Mechanism

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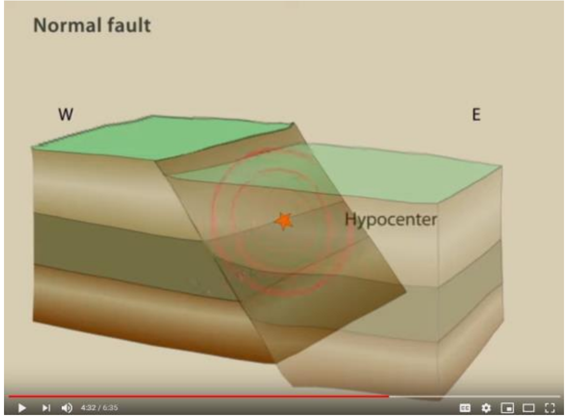
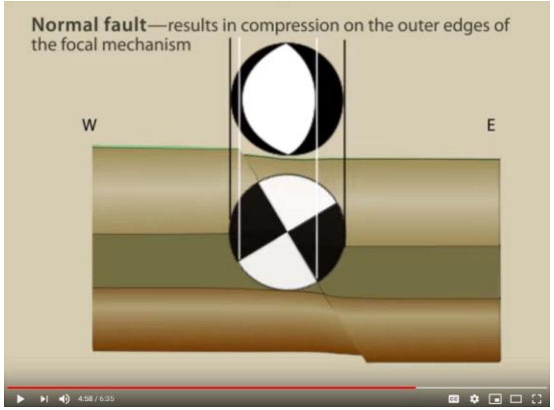
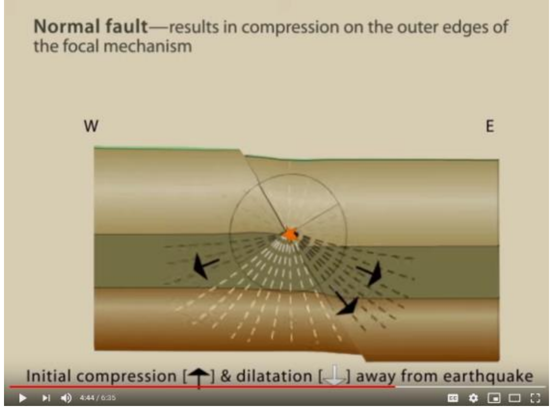
- Ambiguity can be clarified with additional knowledge, e.g., geology

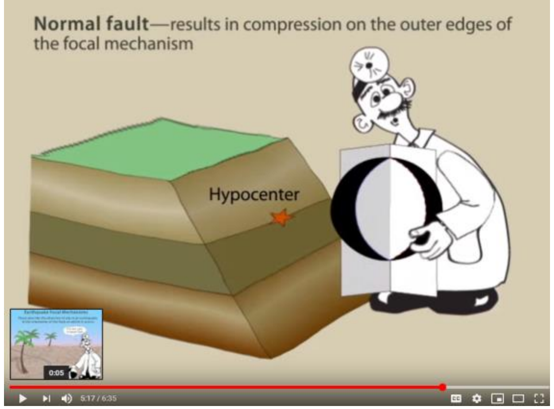
In Situ Stress Measurement Method
Indirect method – Focal Mechanism

- Normal fault



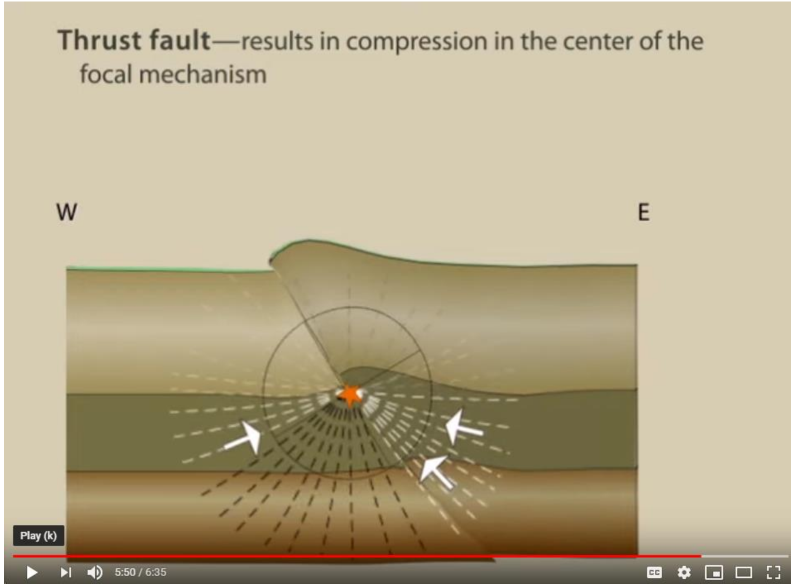


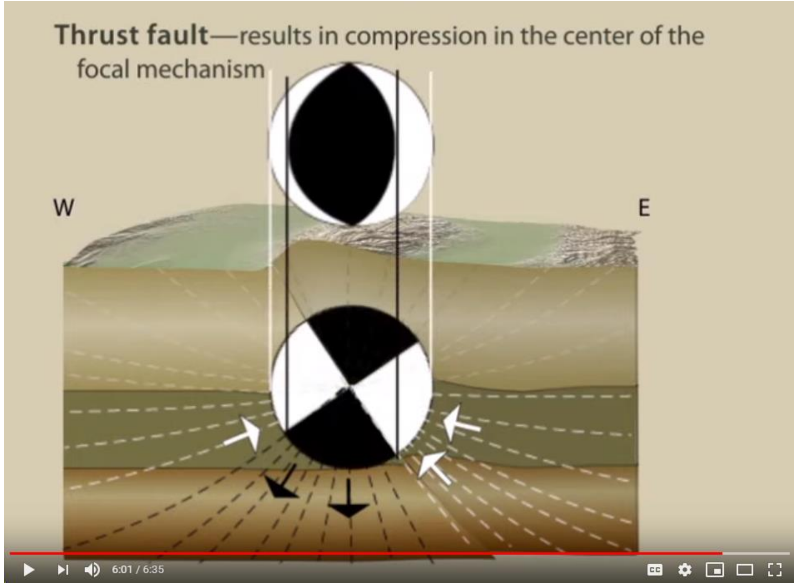




In Situ Stress Measurement Method
Indirect method – Focal Mechanism

- Reverse Fault (Thrust Fault)





In Situ Stress Measurement Method

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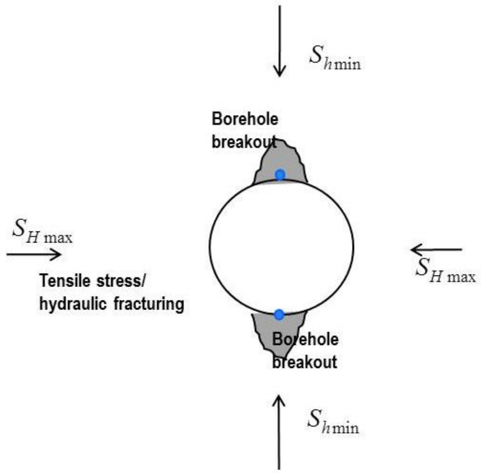
Table 1.2. *Summary of horizontal principal stress measurement methods*

Stress orientation	
Stress-induced wellbore breakouts	(Chapter 6)
Stress-induced tensile wall fractures	(Chapter 6)
Hydraulic fracture orientations	(Chapter 6)
Earthquake focal plane mechanisms	(Chapter 5)
Shear velocity anisotropy	(Chapter 8)
Relative stress magnitude	
Earthquake focal plane mechanisms	(Chapter 5)
Absolute stress magnitude	
Hydraulic fracturing/leak-off tests	(Chapter 7)
Modeling stress-induced wellbore breakouts	(Chapter 7, 8)
Modeling stress-induced tensile wall fractures	(Chapter 7, 8)
Modeling breakout rotations due to slip on faults	(Chapter 7)



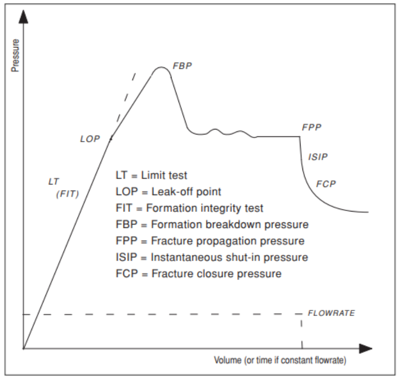


Figure 7.2. A schematic mini-frac or extended leak-off test showing pressure as a function of volume, or equivalently time (if the flow rate is constant). Modified after Gaarenstroom, Tromp *et al.* (1993). The significance of the various points indicated on the pressure record is discussed in the text.

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Constraints of in situ stress
Stress Polygon

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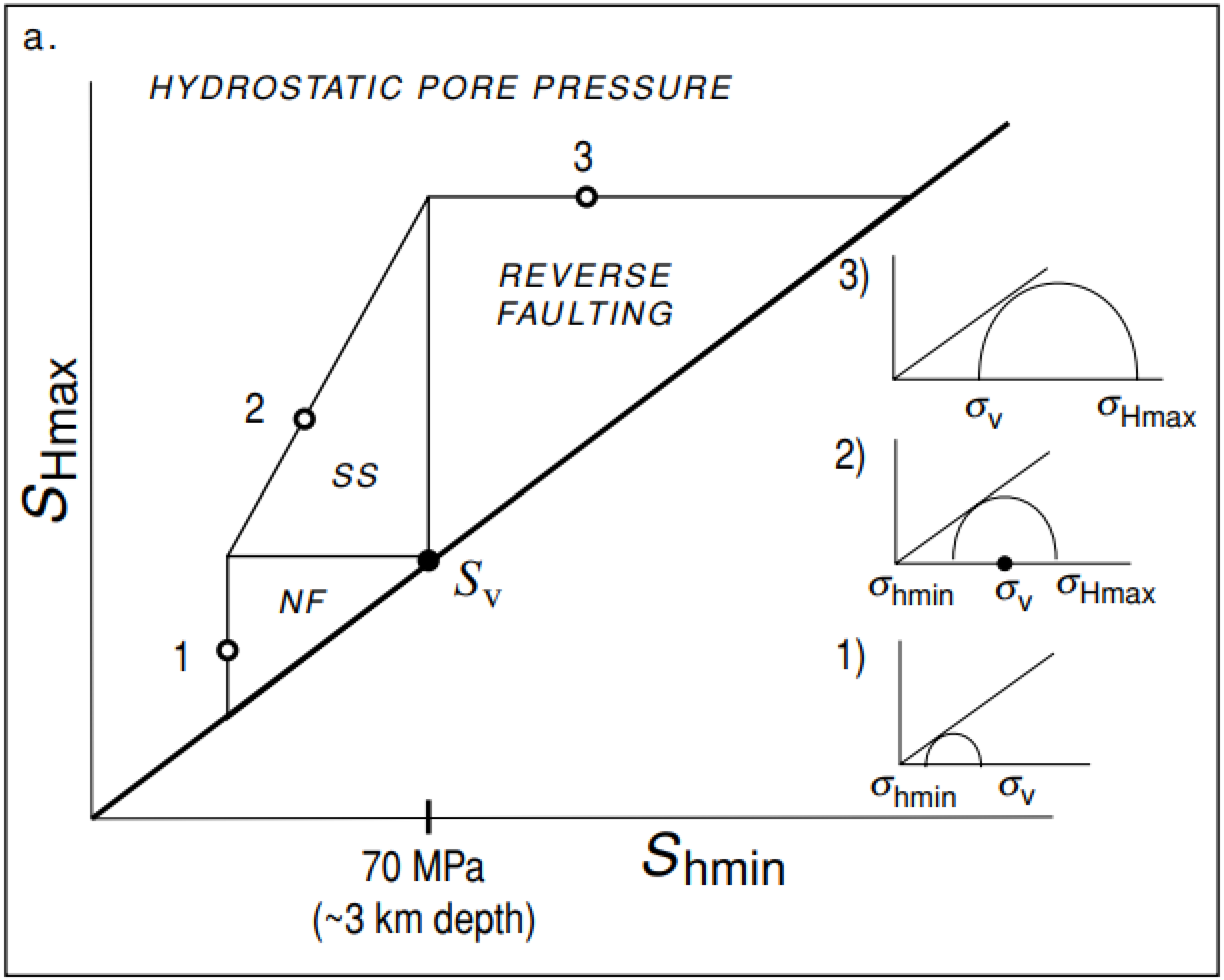
- Stress polygon – range of allowable stress magnitude



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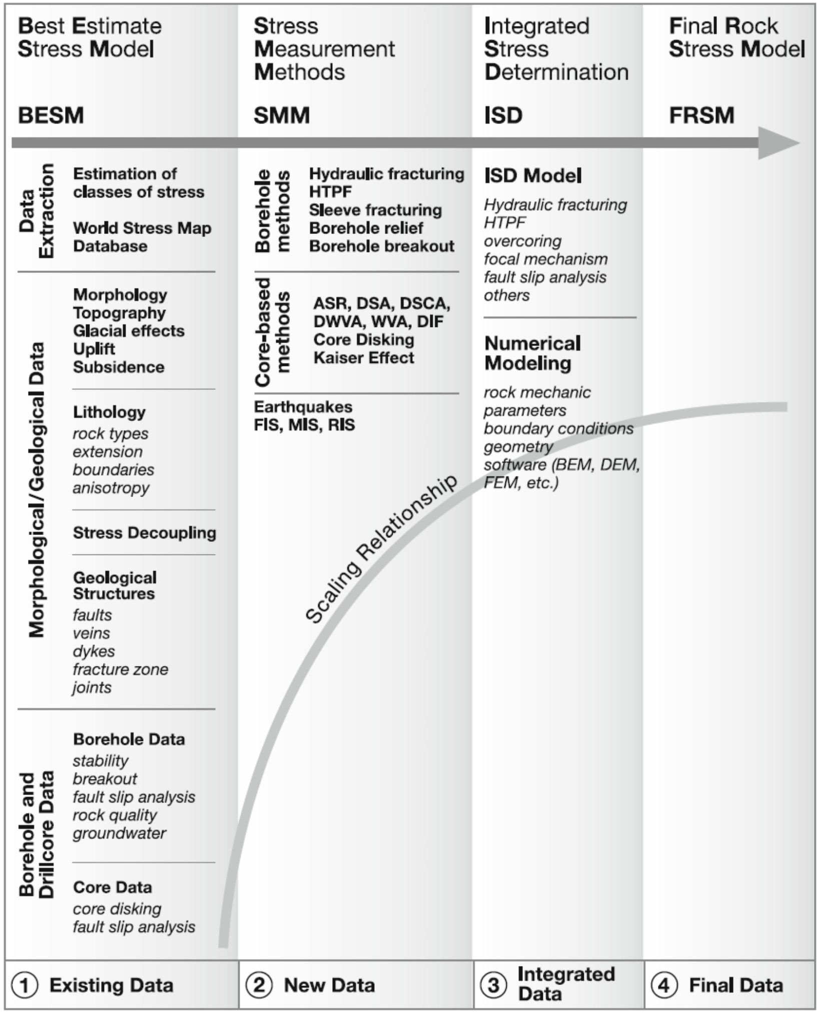
In Situ Stress Measurement Method
Integrated stress measurement

- Multiple methods are often needed



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World wide in situ stress data
World stress map

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Method

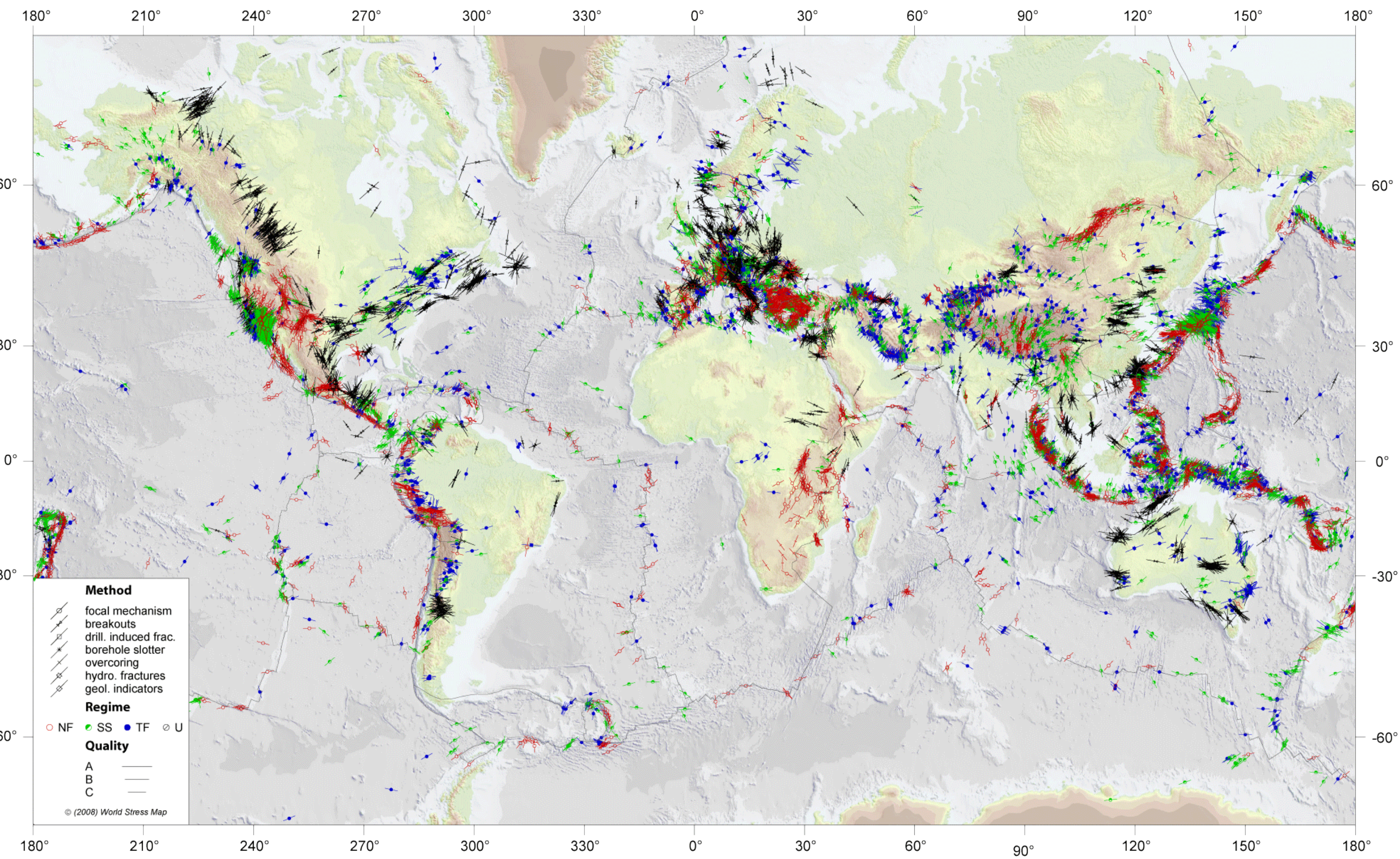
focal mechanism
breakouts
drill. induced frac.
borehole slotter
overcoring
hydro. fractures
geol. indicators

Regime

NF SS TF U

Quality

A
B
C



http://www.world-stress-map.org/

Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfeß, D. and Müller, B., The World Stress Map database release 2008 doi:10.1594/GFZ.WSM.Rel2008, 2008.

World wide in situ stress data
World stress map

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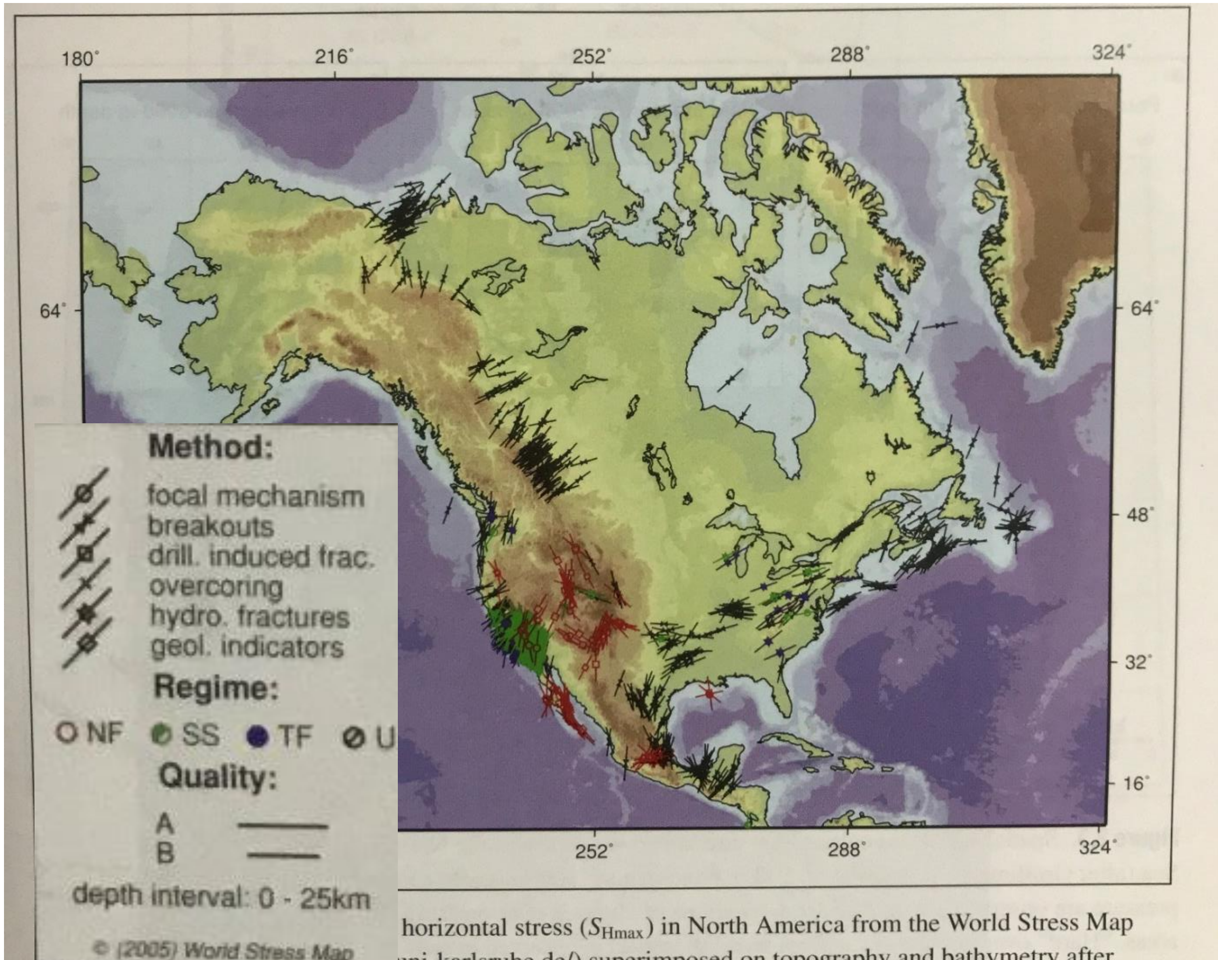

… horizontal stress (S_{Hmax}) in North America from the World Stress Map (…uni-karlsruhe.de/) superimposed on topography and bathymetry after Zoback and Zoback (1980, 1989, 1991). Only A and B quality data are shown. Data points characteristic of normal faulting are shown in red, strike-slip areas are shown in green, reverse faulting areas are shown in blue and indicators with unknown relative stress magnitudes are shown in black.

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World wide in situ stress data
World stress map

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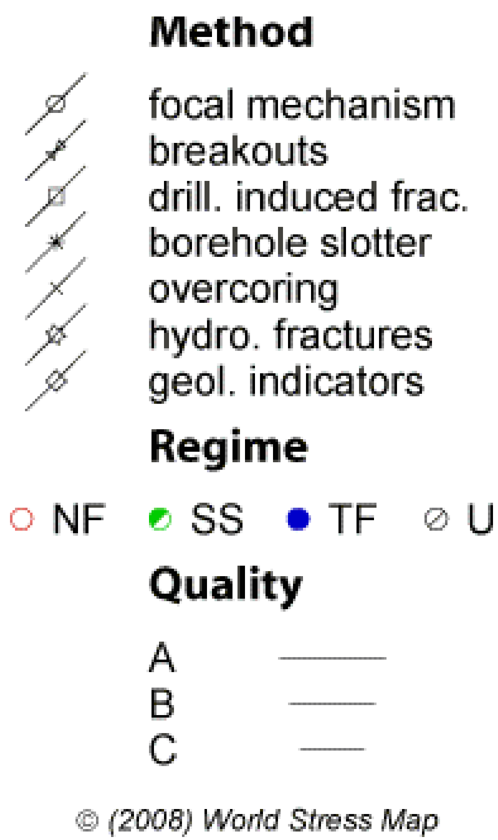
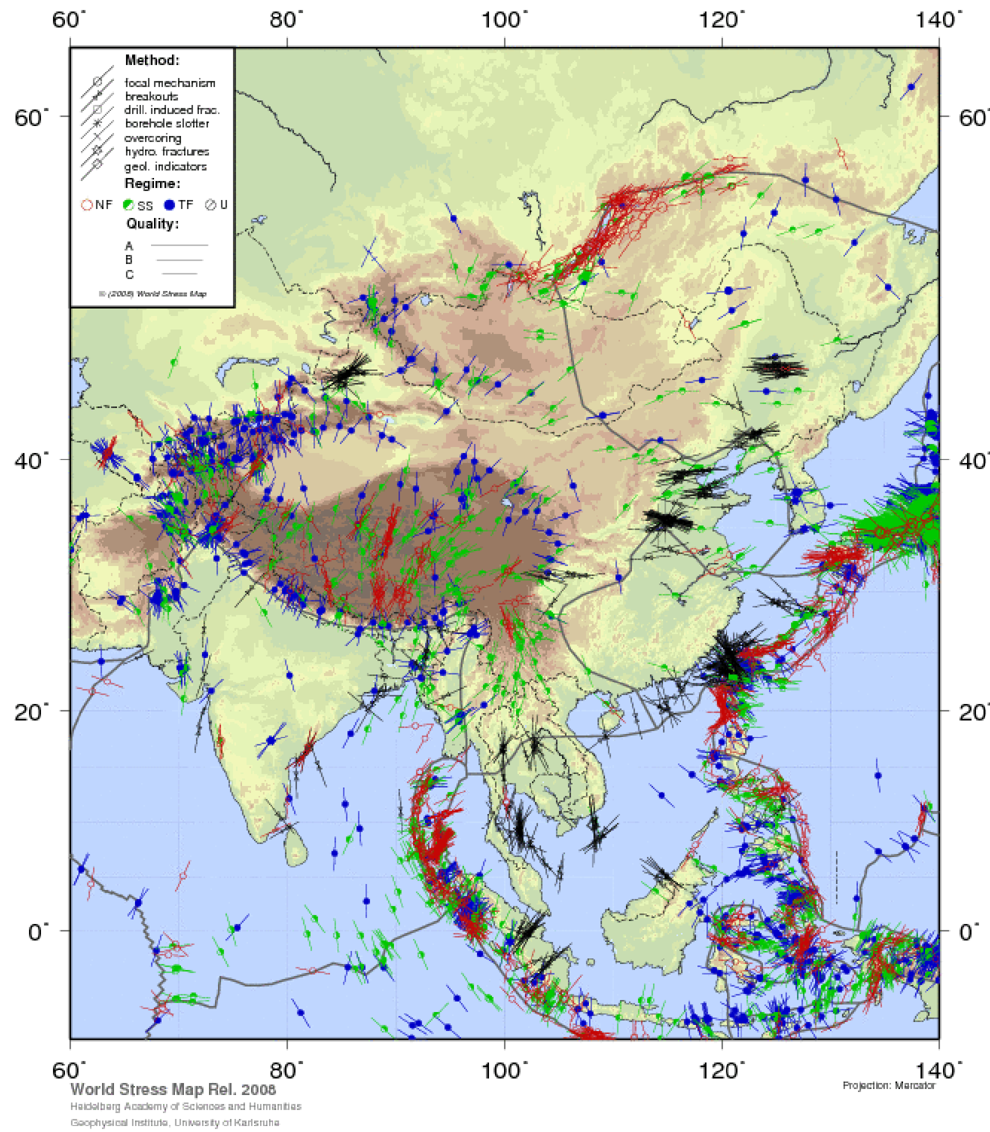
- http://www.world-stress-map.org/





Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfeß, D. and Müller, B., The World Stress Map database release 2008 doi:10.1594/GFZ.WSM.Rel2008, 2008.

Summary
Content of the course

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- Understand the importance of in situ stress for geomechanics
- Nature of in situ stress measurement;
- Direct method
  - Flatjack method
  - USBM overcoring method
  - CSIRO (type) overcoring method
  - Hydraulic fracturing method (mini-frac or micro-frac)
- Indicator method (indirect method)
  - Borehole breakout
  - Anelastic Strain Recovery (ASR)
  - Kaiser effect
  - Core disking
  - Focal Mechanism of earthquake
- Estimation
  - World Stress
  - Integrated method