Rock Mechanics & Experiment
암석역학 및 실험

Lecture 8. In situ Stress in rock
Lecture 8. 암반의 초기응력 (현지응력)

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Outline

- Introduction
- Method of stress determination
  - Direct method
    - Flatjack method
    - Hydraulic fracturing test
    - USBM overcoring method
    - CSIRO (type) overcoring method
  - Indicator method
    - Borehole breakout
    - Other methods
- Presentation of in situ stress
- Worldwide in situ stress data

Introduction
Importance

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

Introduction

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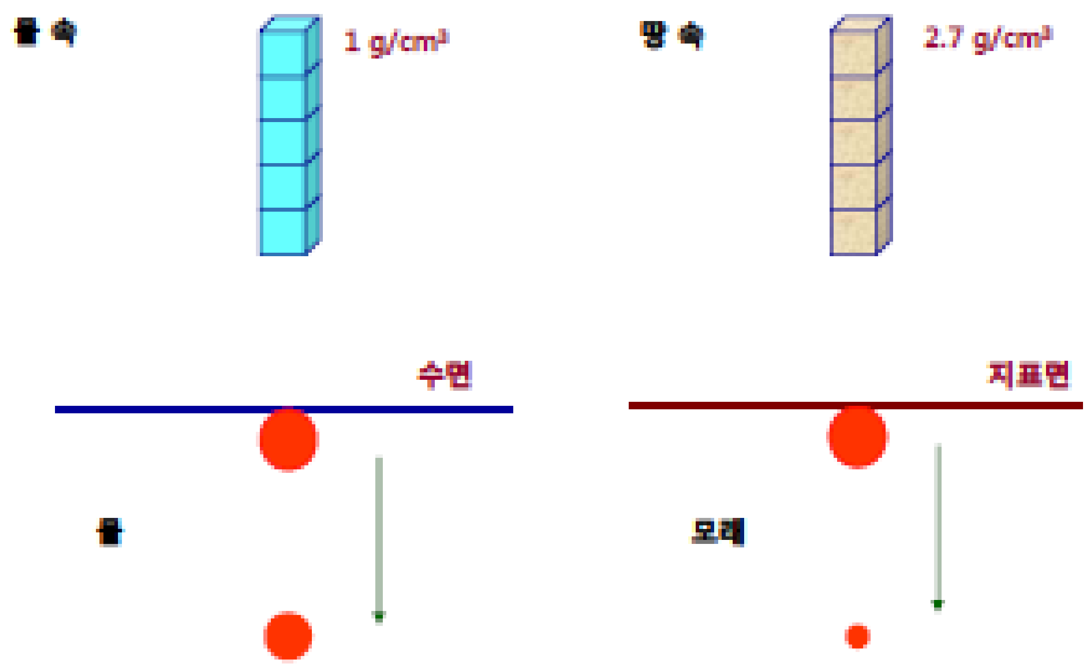
$$p = \rho g z = \text{밀도} \times \text{중력가속도} \times \text{심도}$$



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

전석원, 2008

Introduction
Prediction of in situ stress

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- Heim's rule
  - Assumption: no lateral deformation

Final In Situ stress at a given site
Presentation of in situ stress

- Principal stress is presented

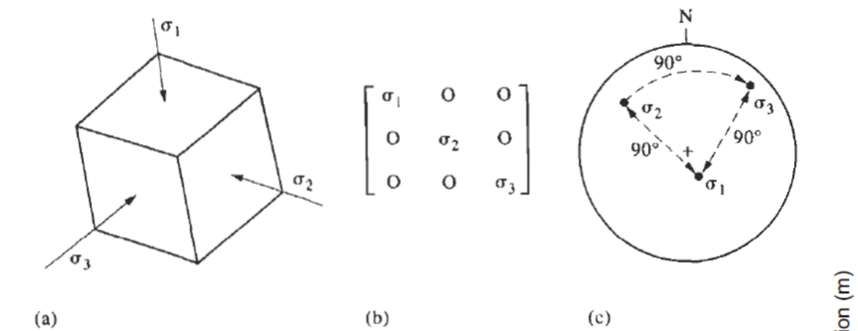
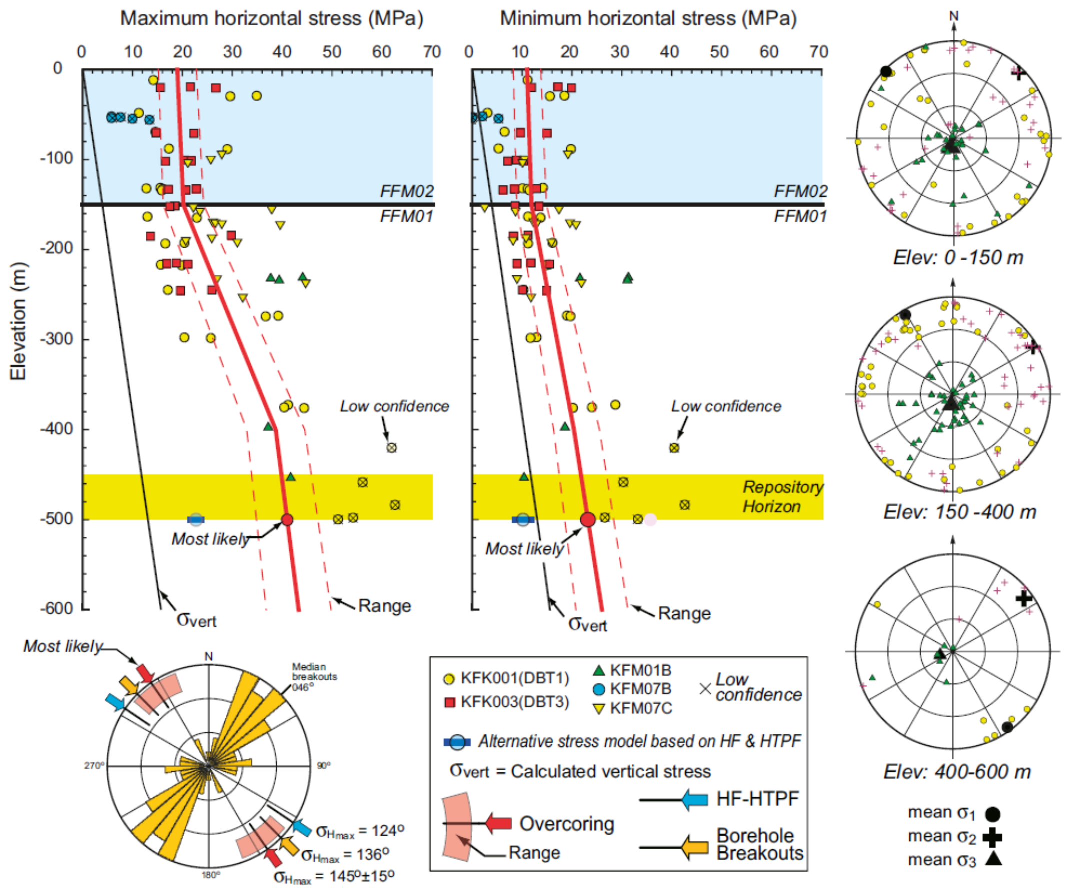


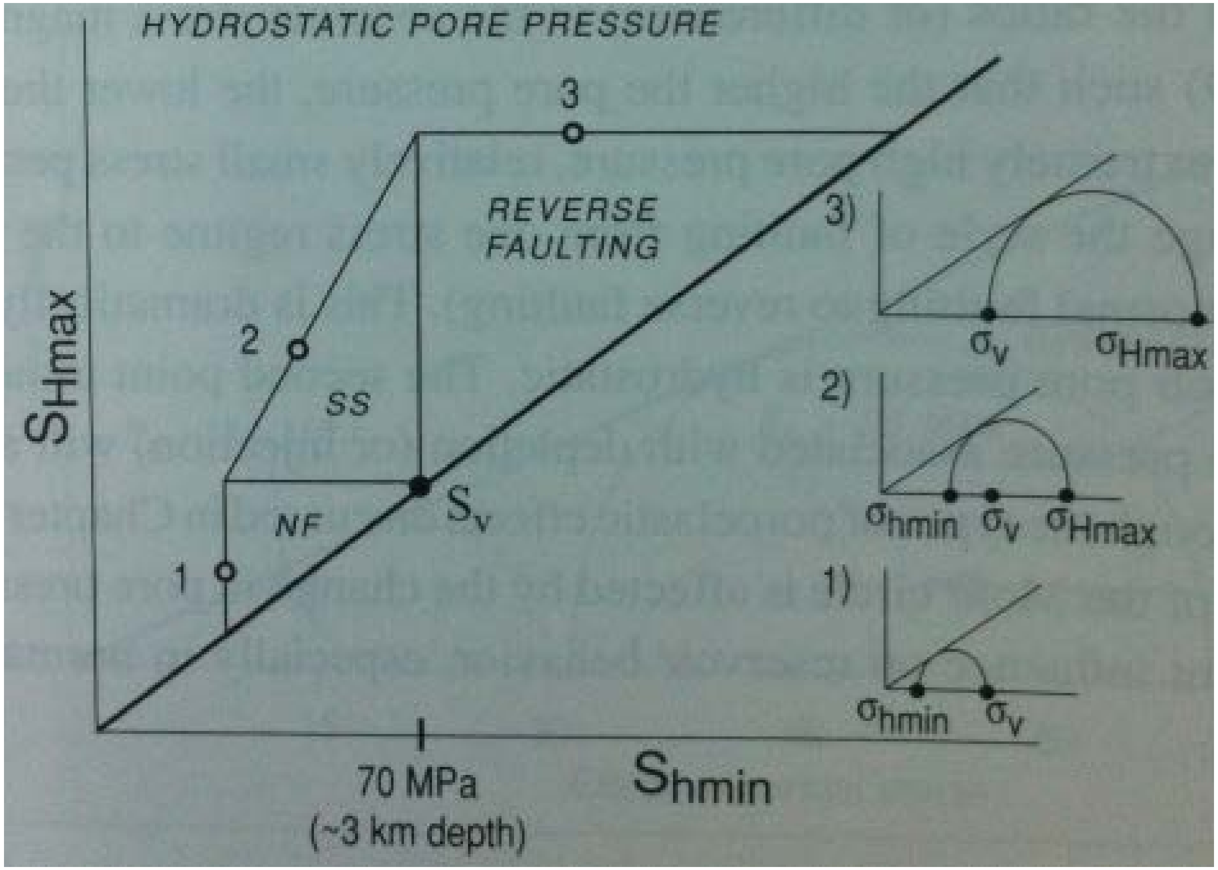
Figure 4.1 (a) Principal stresses acting on a small cube. (b) Principal stresses expressed in matrix form. (c) Principal stress orientations shown on a hemispherical projection.



Hudson & Harrison, 1997, Engineering Rock Mechanics, Elsevier

Final In Situ stress at a given site
Presentation of in situ stress

- Stress polygon



Final In Situ stress at a given site
Statistical analysis of stress state data

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- Averaging must be done in the same reference axis

Correct method for averaging two stress tensors

Two principal stress tensors resulting from stress measurement programmes are shown below and identified by the superscripts *a* and *b*:

$$\begin{bmatrix} \sigma_1^a & 0 & 0 \\ & \sigma_2^a & 0 \\ \text{Symm.} & & \sigma_3^a \end{bmatrix} \quad \begin{bmatrix} \sigma_1^b & 0 & 0 \\ & \sigma_2^b & 0 \\ \text{Symm.} & & \sigma_3^b \end{bmatrix}.$$

The principal stress components in these tensors will generally have different orientations. Before averaging can proceed, these must be transformed to a common set of reference axes, thus:

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

When averaged, these tensors give a subsequent tensor ,

$$\begin{bmatrix} (\sigma_{xx}^a + \sigma_{xx}^b)/2 & (\tau_{xy}^a + \tau_{xy}^b)/2 & (\tau_{xz}^a + \tau_{xz}^b)/2 \\ & (\sigma_{yy}^a + \sigma_{yy}^b)/2 & (\tau_{yz}^a + \tau_{yz}^b)/2 \\ \text{Symmetric} & & (\sigma_{zz}^a + \sigma_{zz}^b)/2 \end{bmatrix}$$

from which can be calculated the 'global' average principal stress tensor:

$$\begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{bmatrix}$$

together with the directions of the principal stresses.

Hudson & Harrison, 1997, Engineering Rock Mechanics, Elsevier

Final In Situ stress at a given site
Integrated stress measurement

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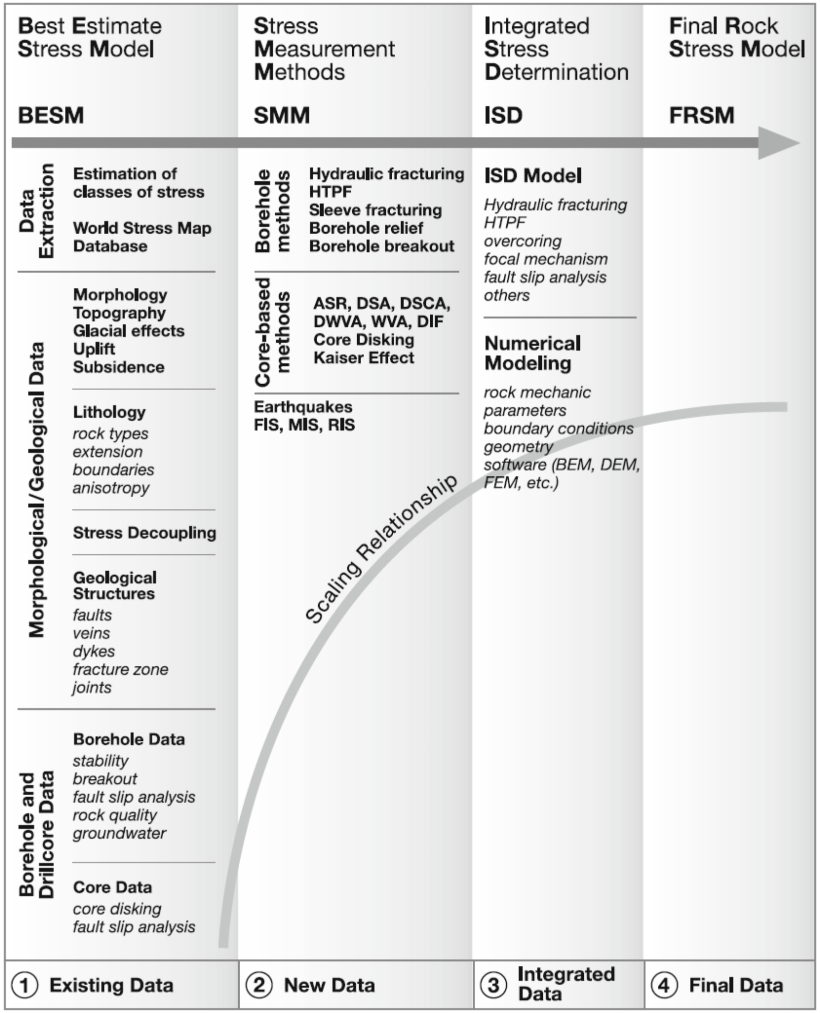
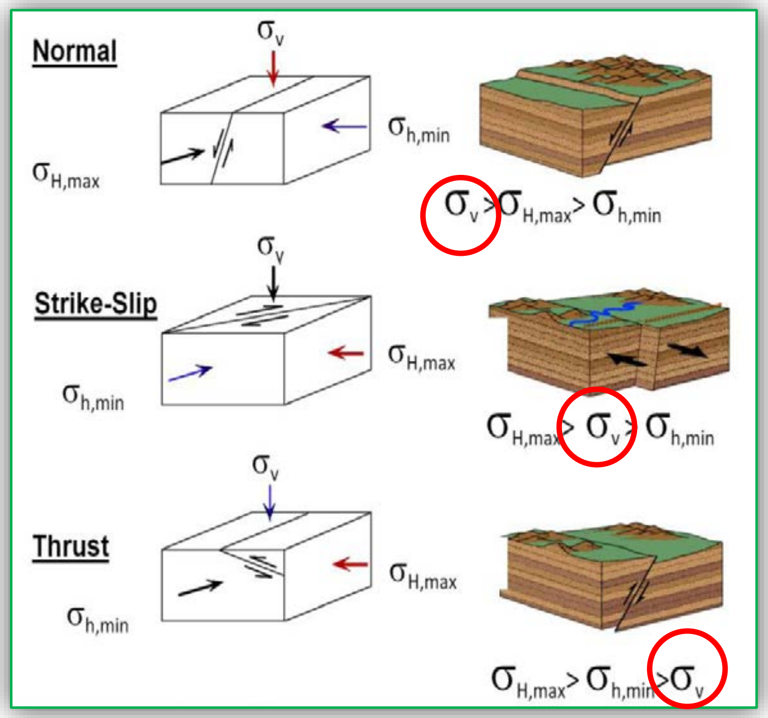
- Multiple methods are often needed



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

In Situ Stress
State of Stress

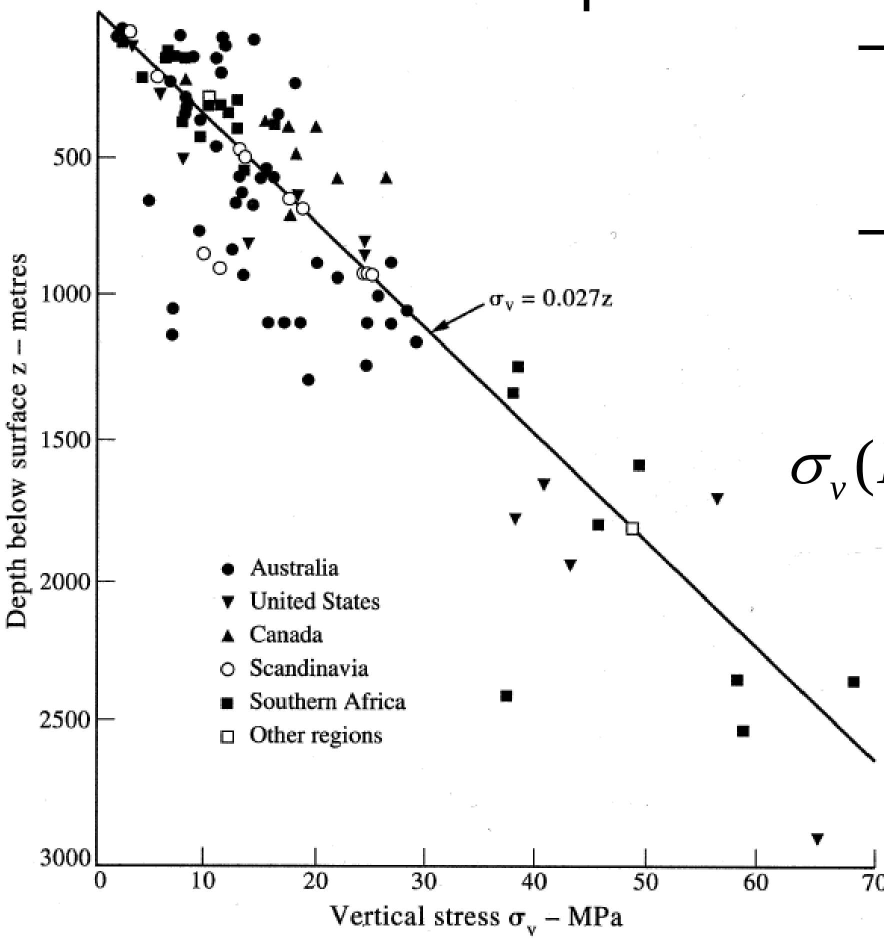
- Three types of stress regime
  - Normal fault stress regime
  - Strike-slip stress regime
  - Thrust fault stress regime



Itasca Consulting Group, 2011)

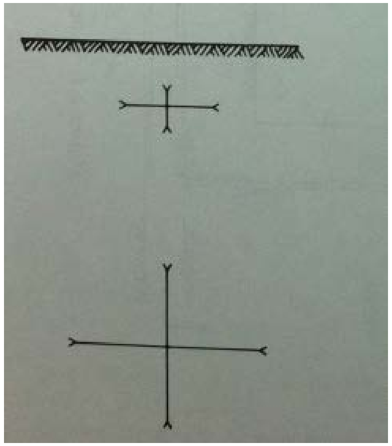
World wide in situ stress data
Magnitude of Vertical stress

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

World wide in situ stress data
Magnitude of Horizontal stress

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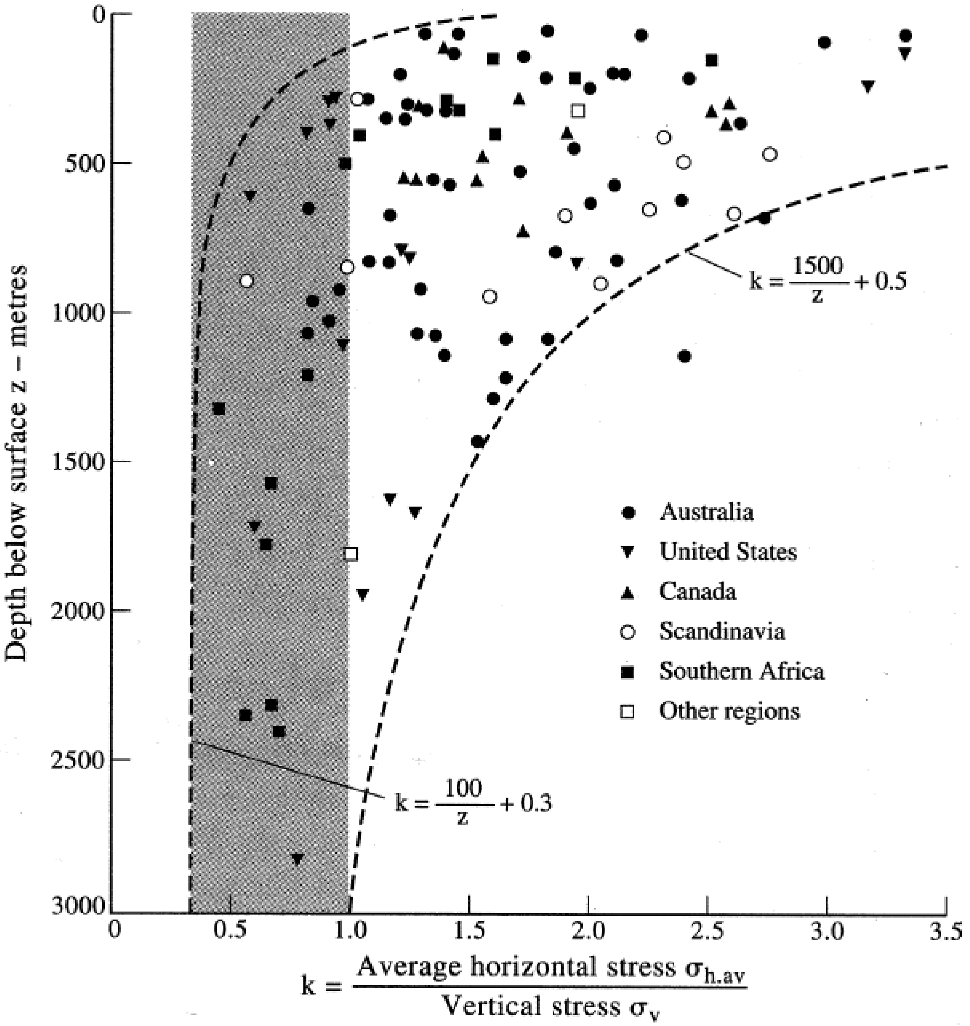
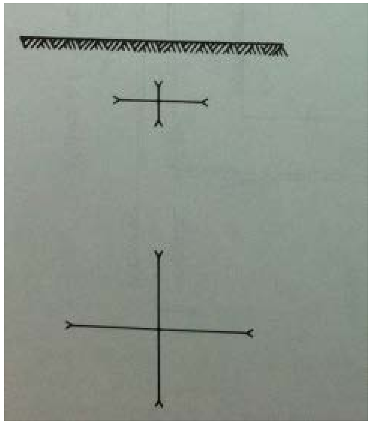


- Horizontal components of insitu stress
- Average horizontal stress is usually 0.3 ~ 4.0 times of vertical stress
- High horizontal stress: tectonic stress, erosion, topography



Hudson & Harrison, 1997, Engineering Rock Mechanics, Elsevier

In Situ Stress
World stress map

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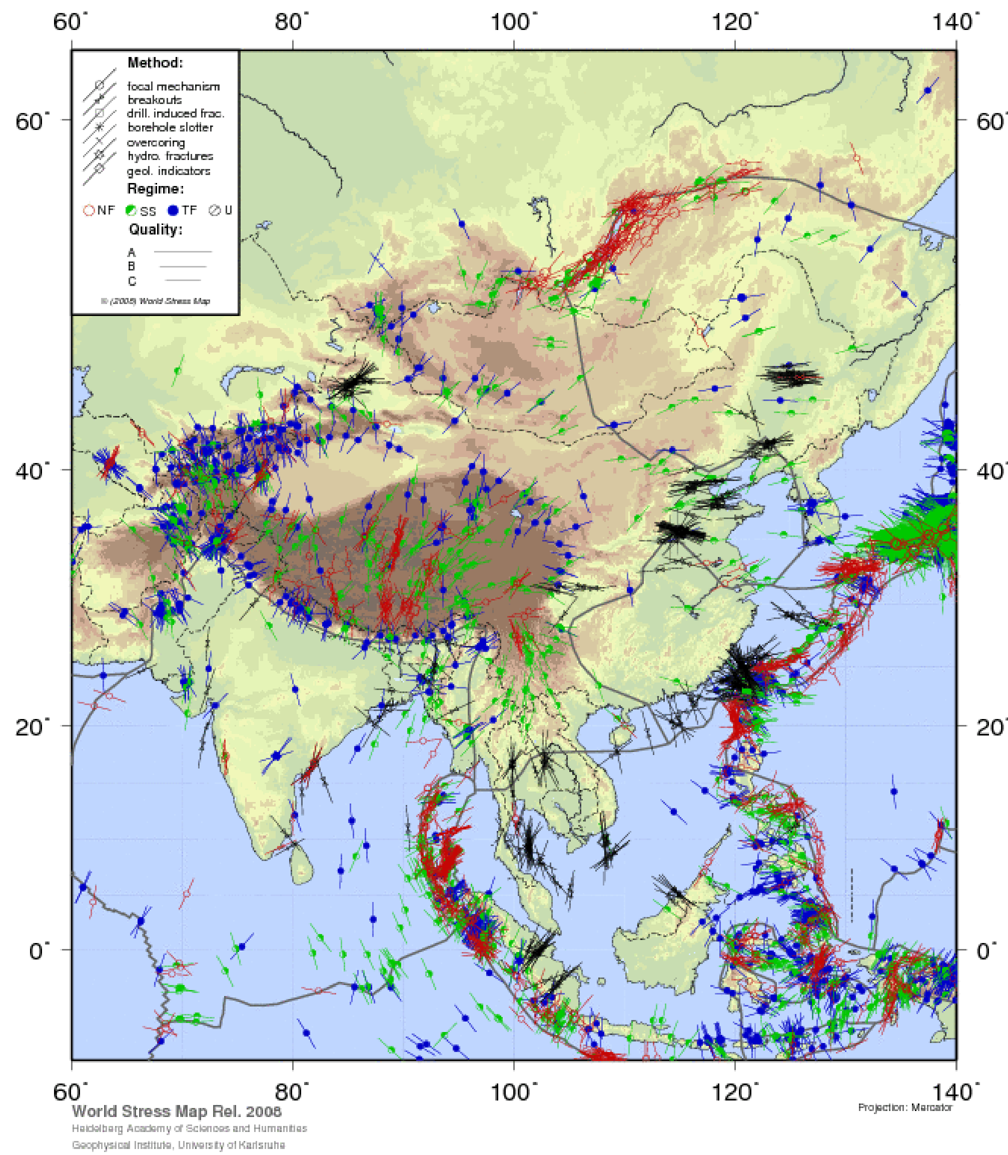
- http://dc-app3-14.gfz-potsdam.de/



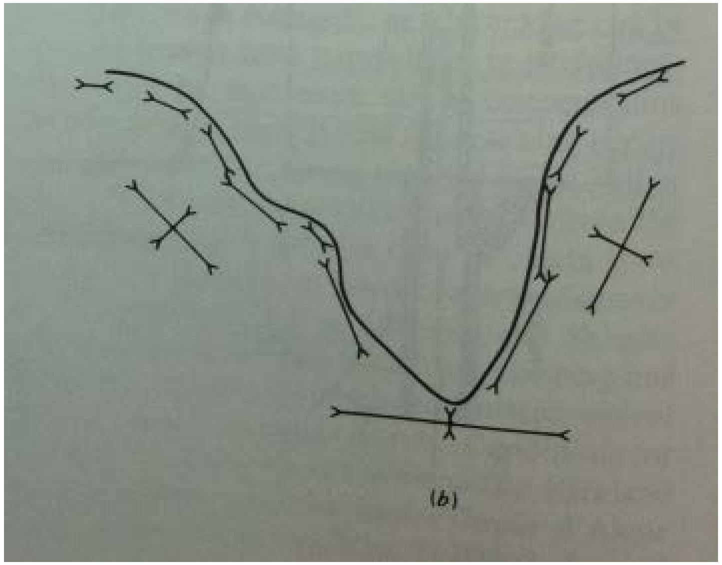
Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfeß, D. and Müller, B., The World Stress Map database release 2008 doi:10.1594/GFZ.WSM.Rel2008, 2008.

Factors affecting in situ stress measurement

- Erosion
- Tectonic activity
- topography
- Rock anisotropy
- Discontinuity

Factors affecting in situ stress measurement
Topography

- Topography



Goodman, 1989, Introduction to Rock Mechanics, Wiley

- Discontinuity

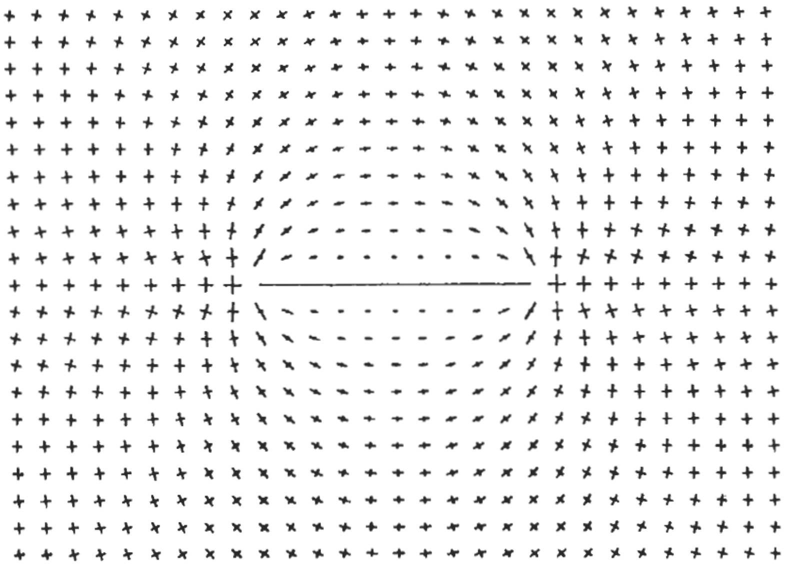
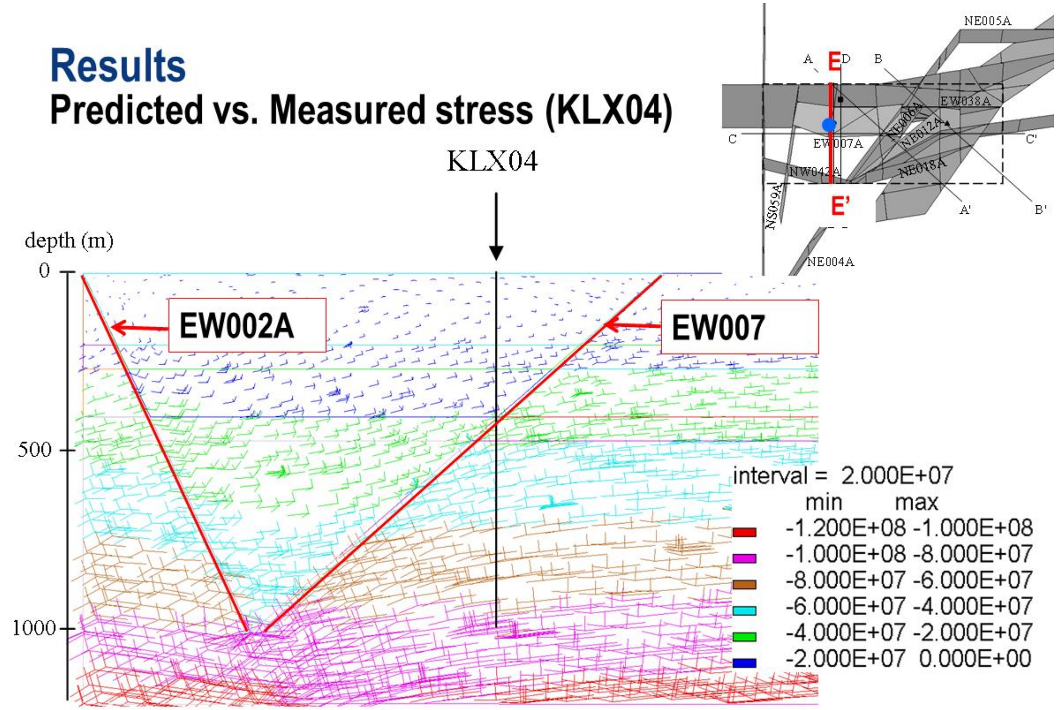


Figure 4.19 Example of the effect of a discontinuity on the near-field stress state, for an applied hydrostatic two-dimensional stress with the discontinuity having a modulus of 10% of the host rock (from Hyett, 1990). The crosses represent the magnitudes and directions of the principal stresses. Note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



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

Methods of stress determination

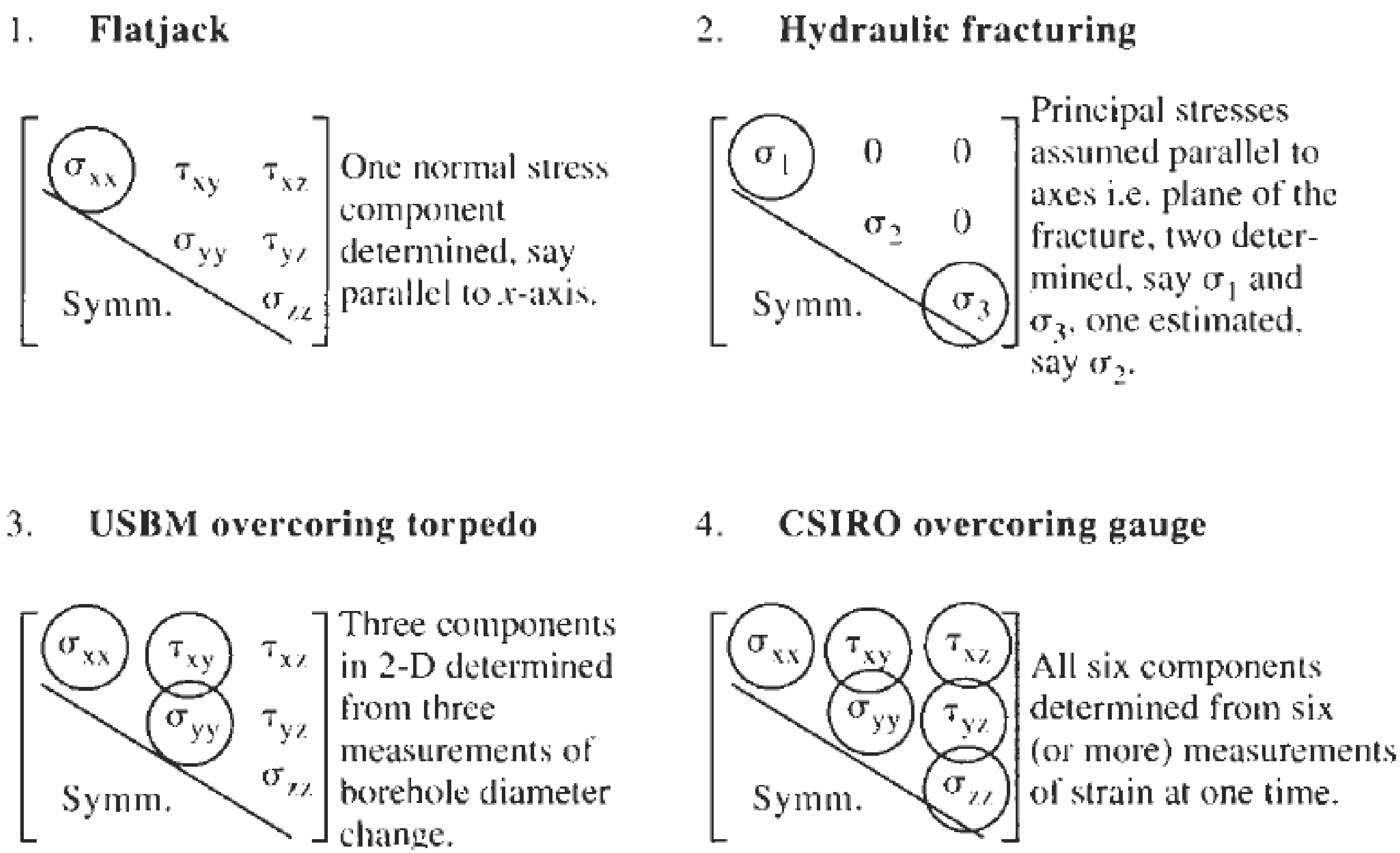
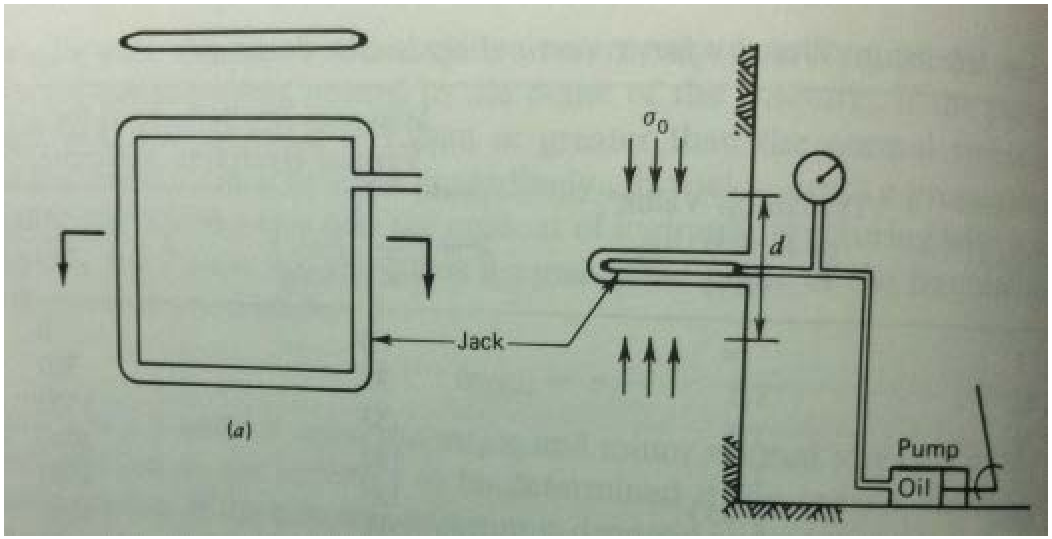


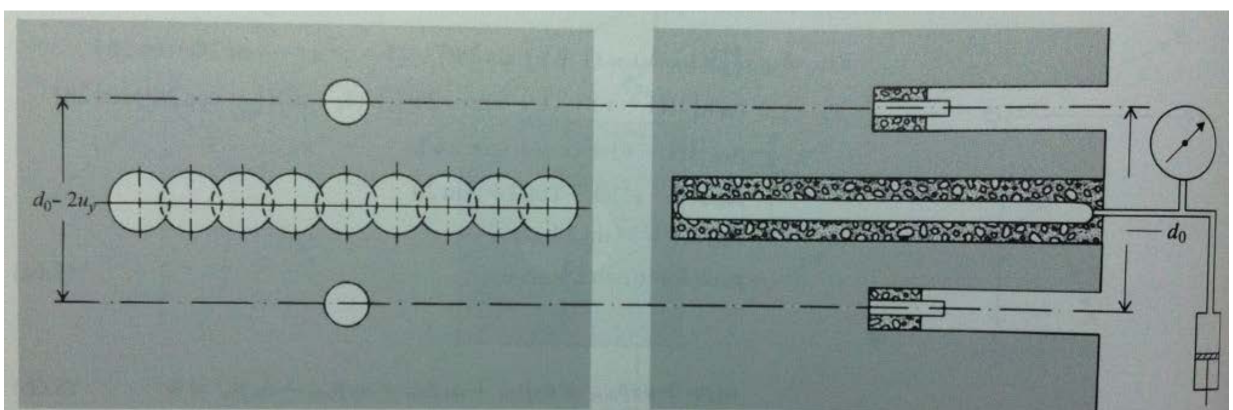
Figure 4.3 The four ISRM suggested methods for rock stress determination and their ability to determine the components of the stress tensor *with one application of the particular method.*

Hudson & Harrison, 1997, Engineering Rock Mechanics, Elsevier

Methods of stress determination
Flatjack method

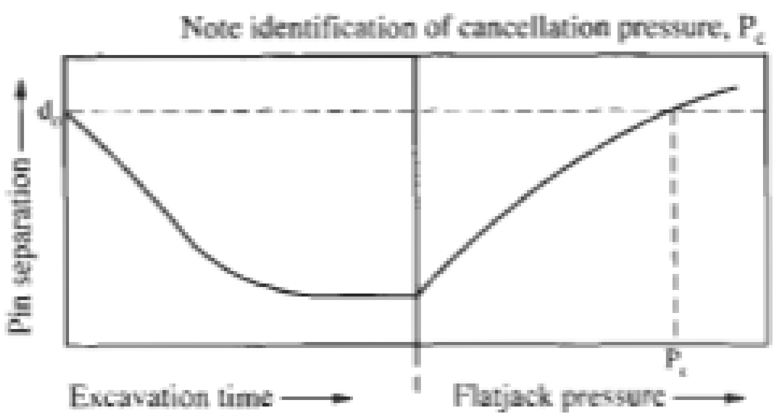
- Directly measure the tangential stress

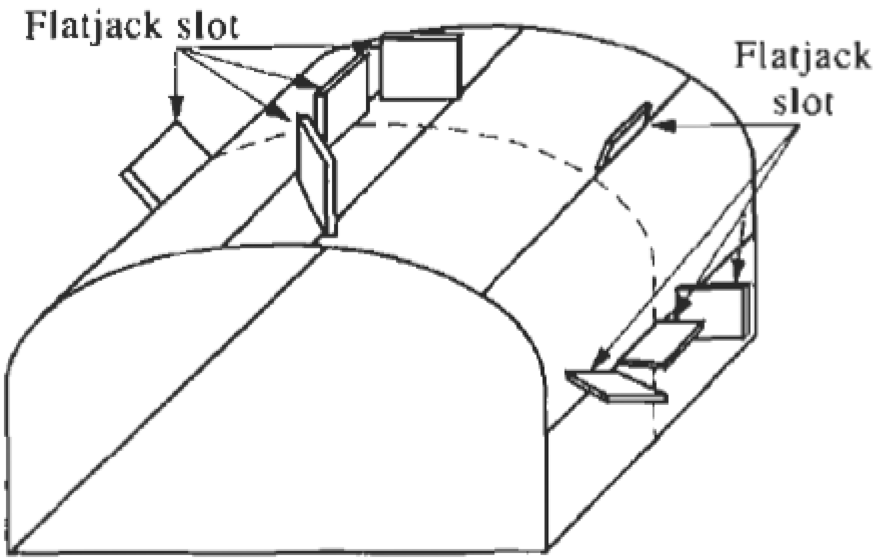




Brady & Brown, 2004, Rock Mechanics for underground mining, Kluwer Academic Publishers

Methods of stress determination
Flatjack method

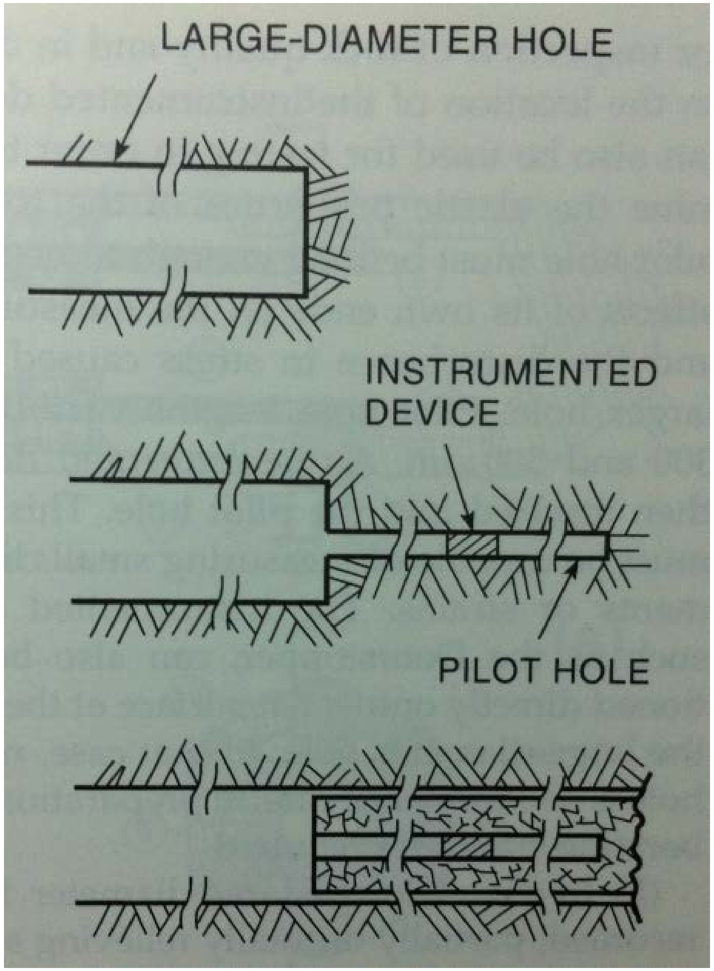


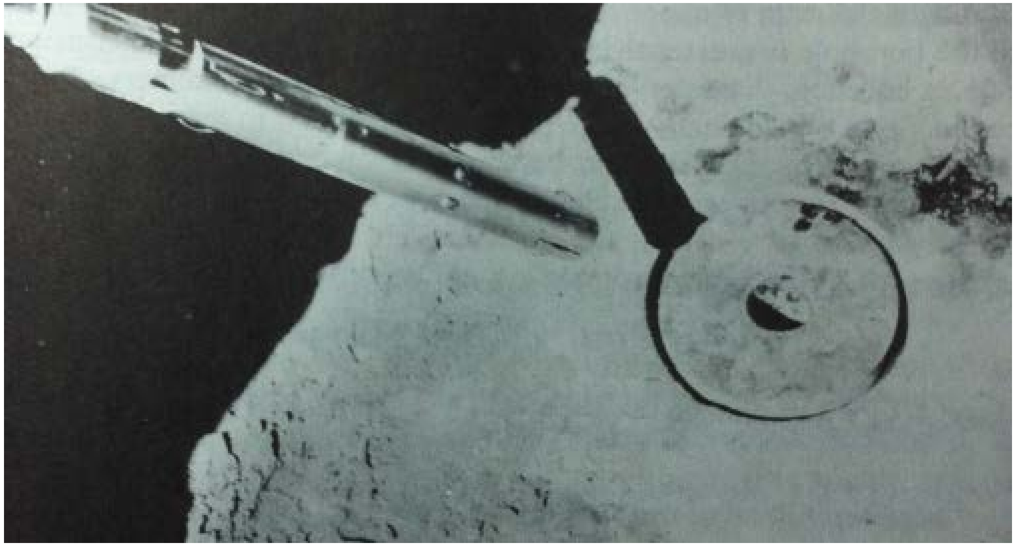


Hudson & Harrison, 1997, Engineering Rock Mechanics, Elsevier

Methods of stress determination
USBM overcoring method

- Typical overcoring procedure





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

Methods of stress determination
USBM overcoring method

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- USBM deformation gauge – at least three measurements are needed.

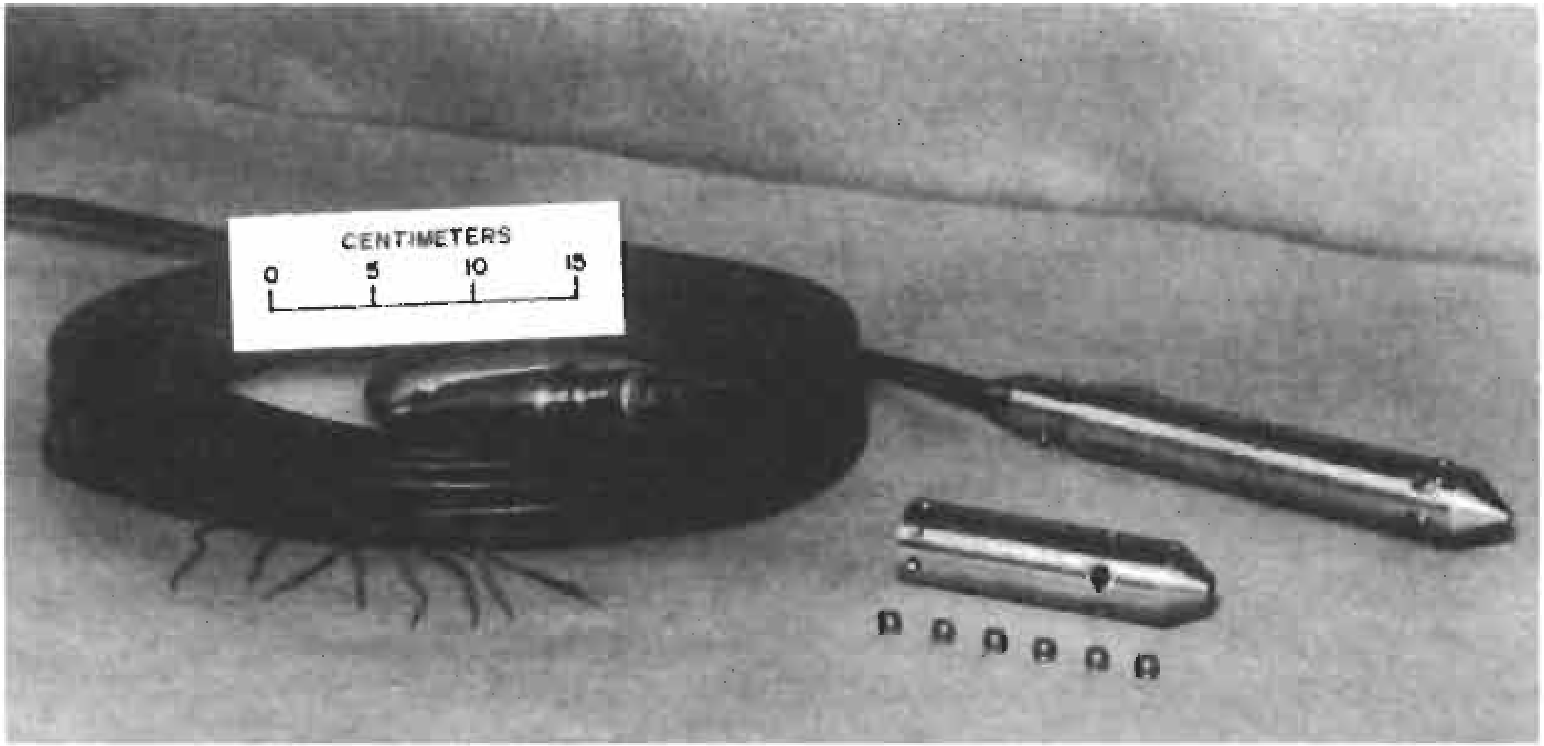


Figure 4.7 The USBM borehole deformation gauge.

Hudson & Harrison, 1997, Engineering Rock Mechanics, Elsevier

Methods of stress determination
USBM overcoring method

- Typical response curve

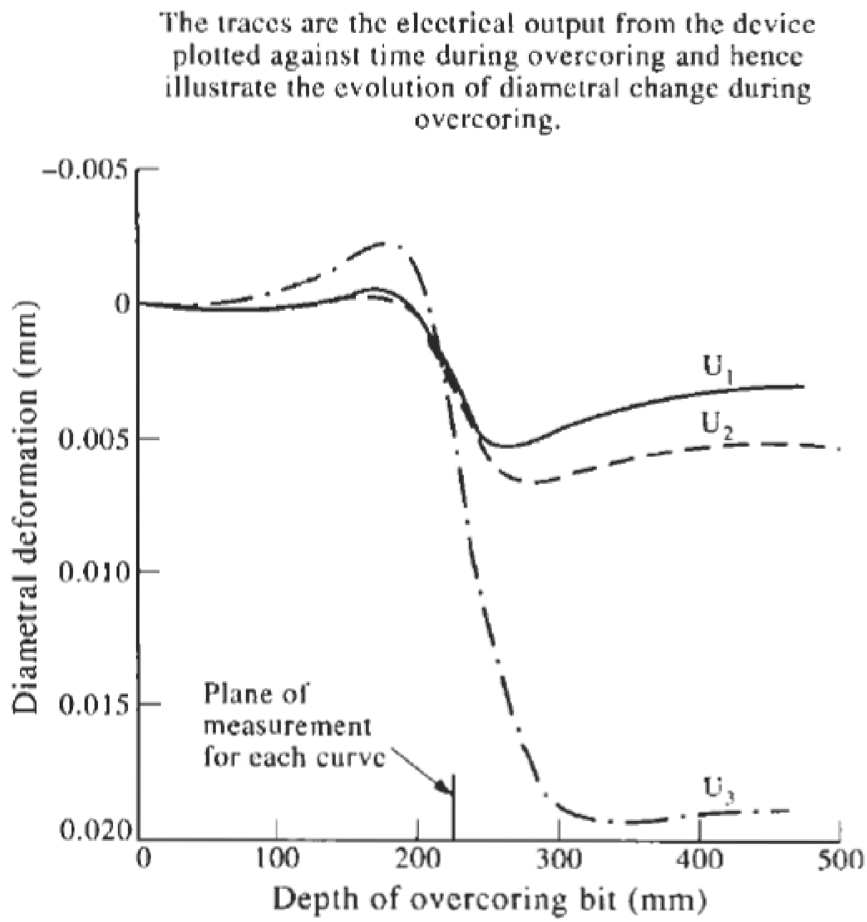
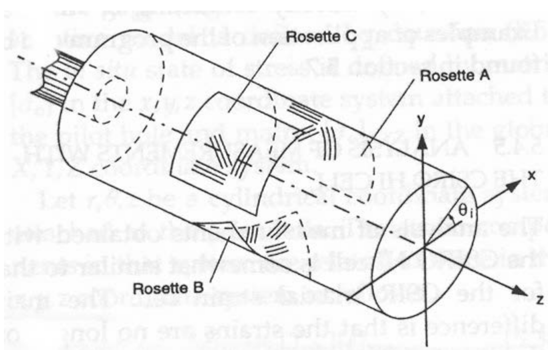


Figure 4.8 Data obtained during a USBM overcoring test.

Hudson & Harrison, 1997, Engineering Rock Mechanics, Elsevier

Methods of stress determination
CSIRO type overcoring method

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



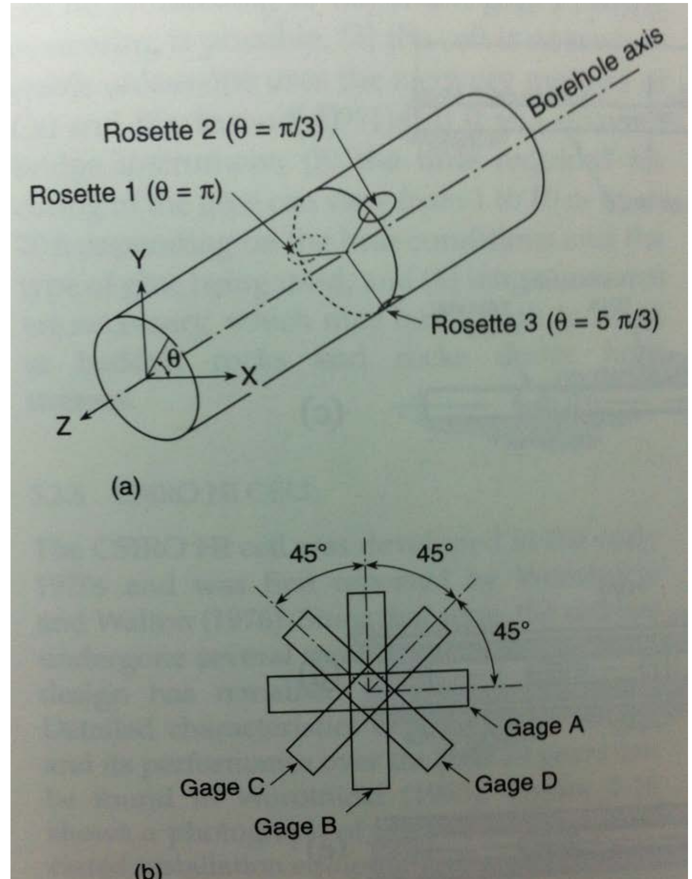
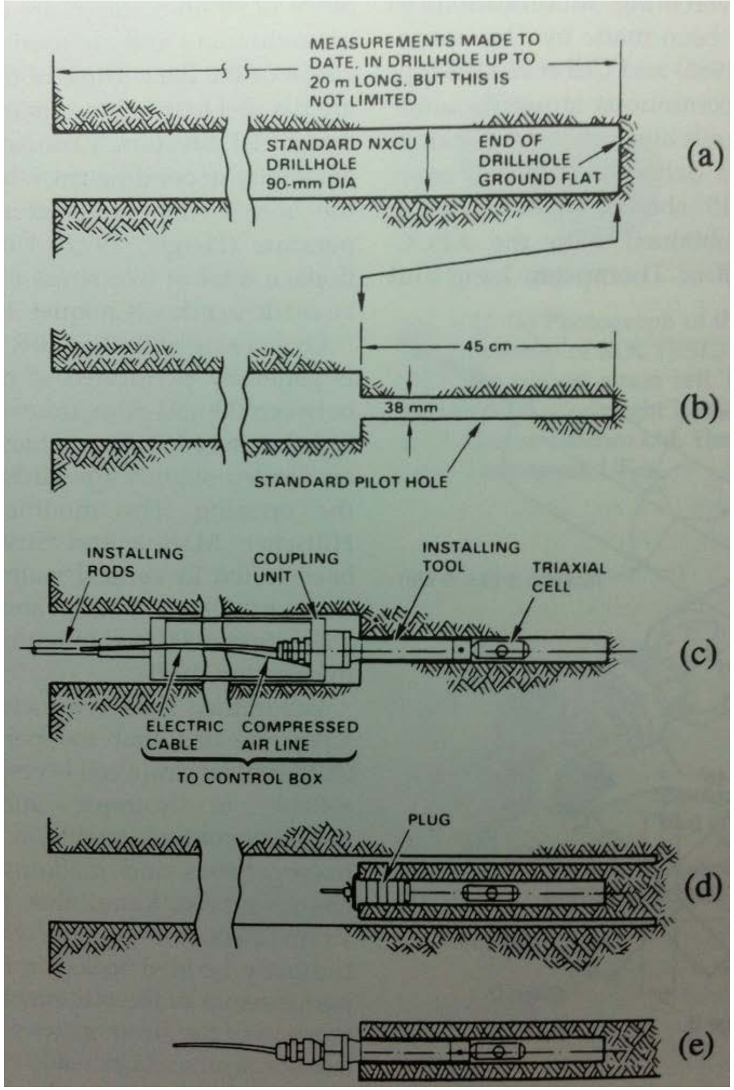
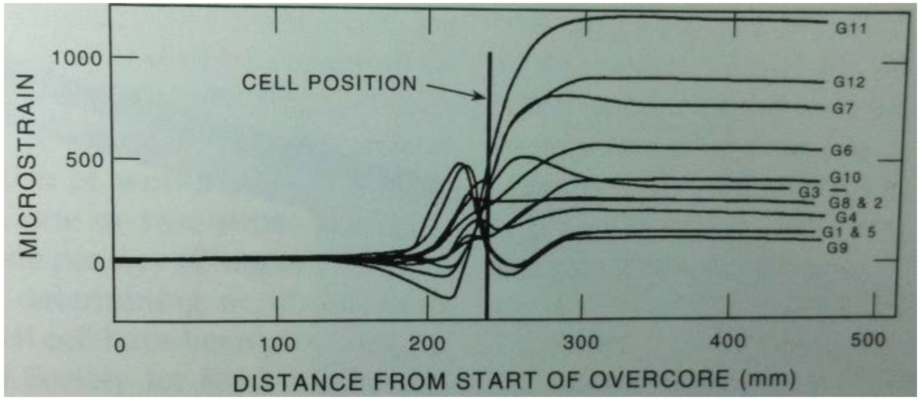


Fig. 5.13 Position of the CSIR triaxial strain cell rosettes in (a) and strain gage configuration in (b). (After Van Heerden, 1976.)

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

Methods of stress determination
CSIRO type overcoring method





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

Methods of stress determination
CSIRO type overcoring method

Hudson & Harrison, 1997, Engineering Rock Mechanics, Elsevier

Methods of stress determination
CSIRO type overcoring method

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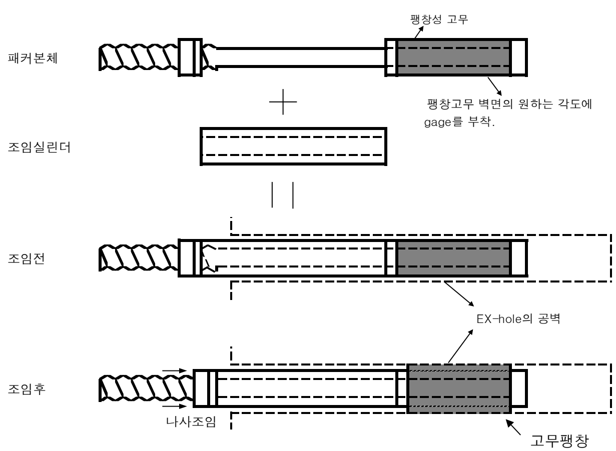
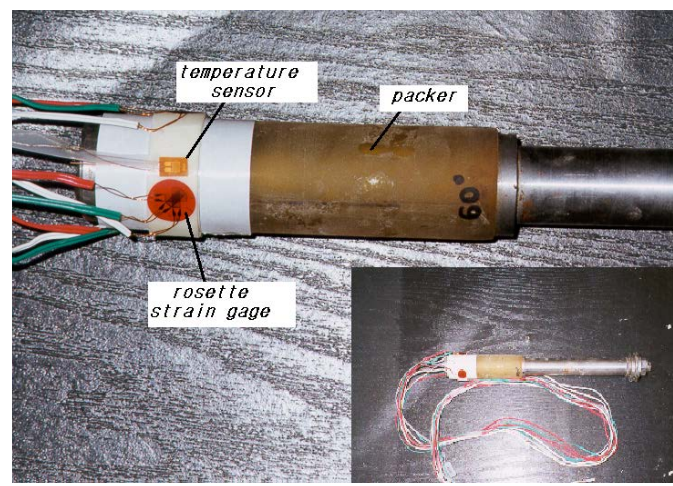
- Reproduction in the laboratory





Min KB, Lee CI, Choi HM, An experimental and numerical study of the in-situ stress measurement on transversely isotropic rock by overcoring method, In:Sugawara K et al (eds), 3rd International Symposium on Rock Stress - RS Kumamoto '03, Kumamoto, 2003, pp.189-195.

Methods of stress determination
Hydraulic Fracturing for stress determination

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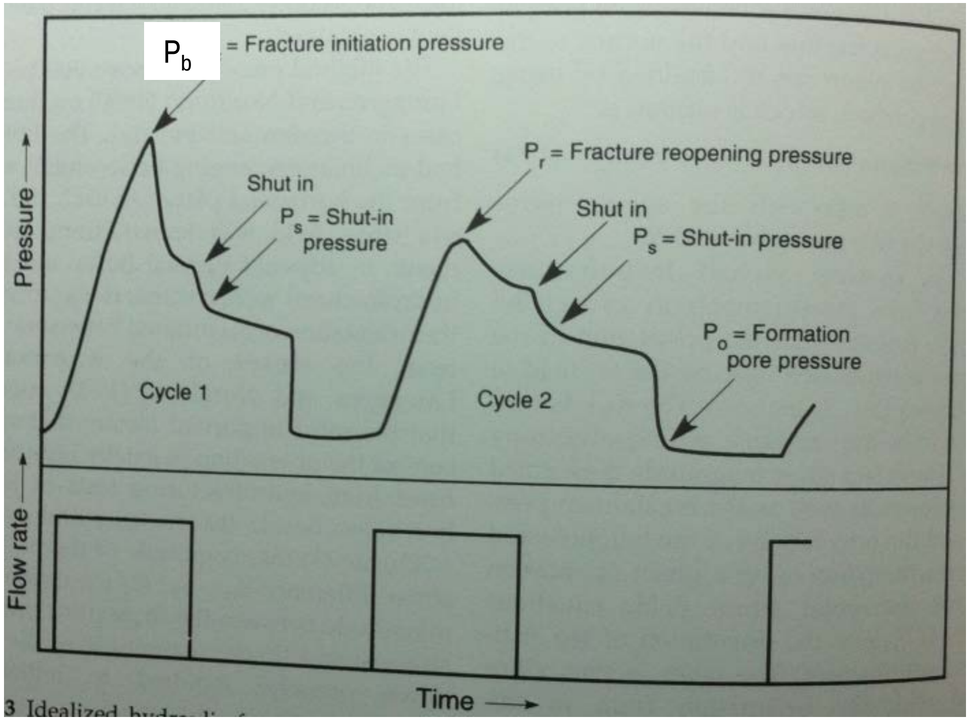
- Principle of stress measurement by hydraulic fracturing (magnitude & orientation)
  - Vertical stress is assumed
  - Knowledge of elastic constants is not needed

In open hole!

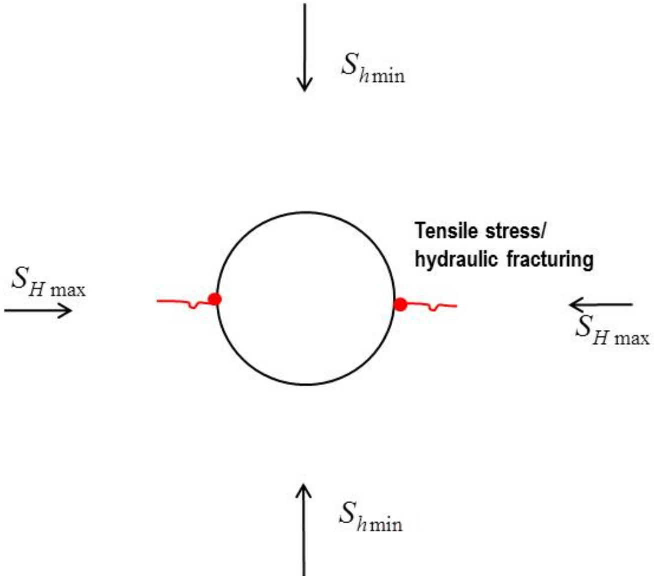
$$P_b = 3S_{h\min} - S_{H\max} + T_o$$

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

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



Flowrate-pressure responses



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

Methods of stress determination
Hydraulic Fracturing for stress determination

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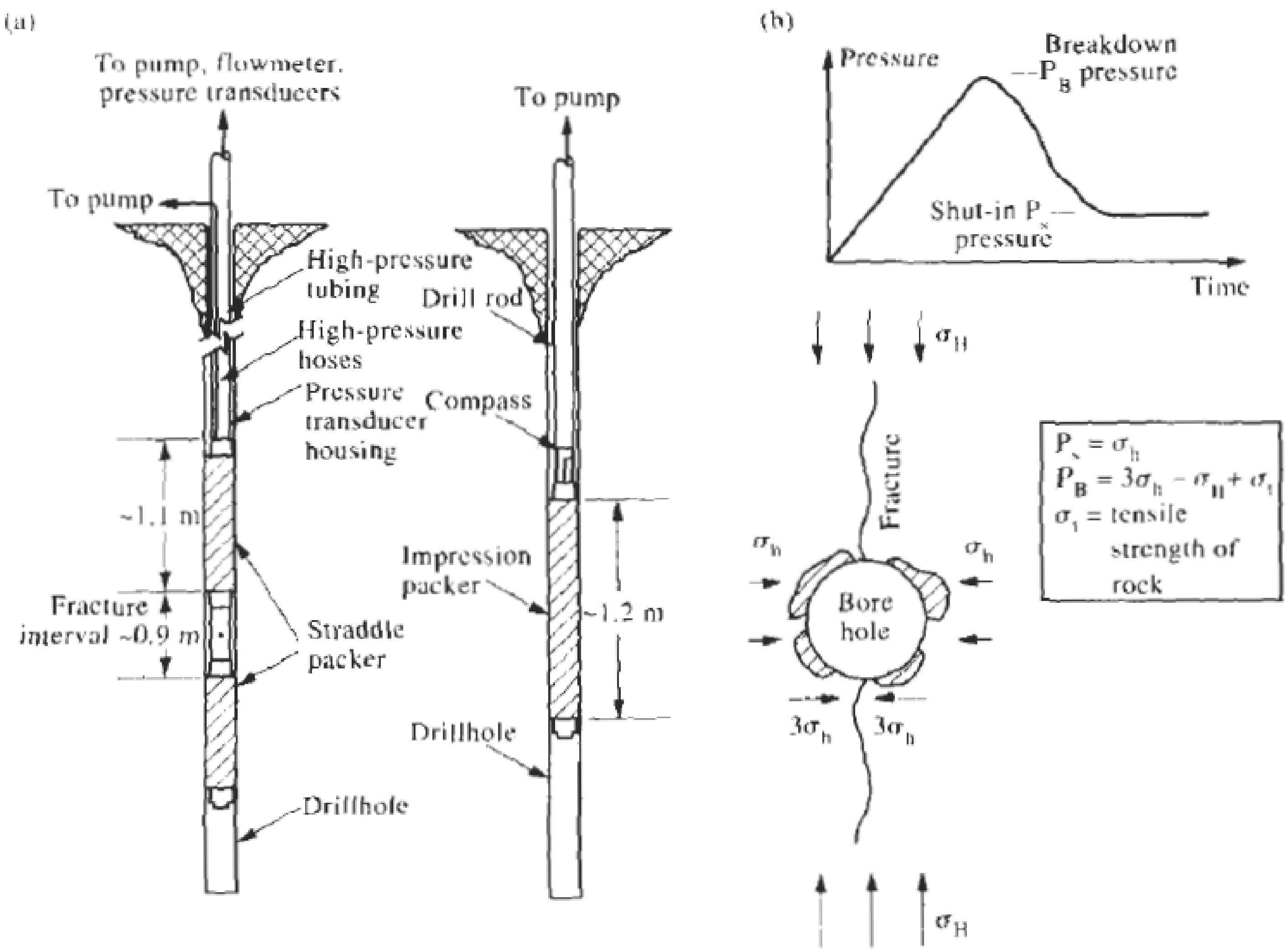

Figure 4.5 (a) The hydraulic fracturing system and (b) associated calculations (from *Suggested Methods for Rock Stress Determination*, Kim and Franklin, 1987).

Hudson & Harrison, 1997, Engineering Rock Mechanics, Elsevier

Methods of stress determination
Hydraulic Fracturing for stress determination

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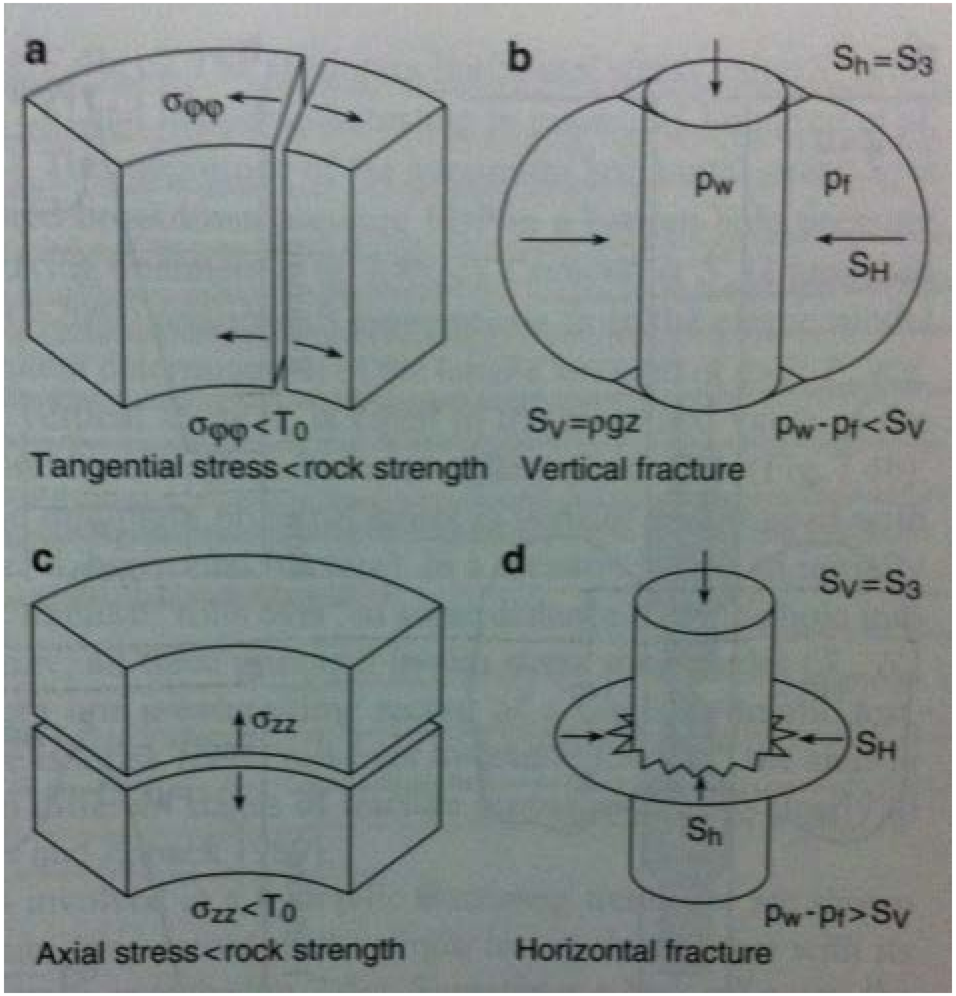
- Vertical fracture vs. horizontal fracture (in vertical hole)



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

Methods of stress determination
Hydraulic Fracturing for stress determination

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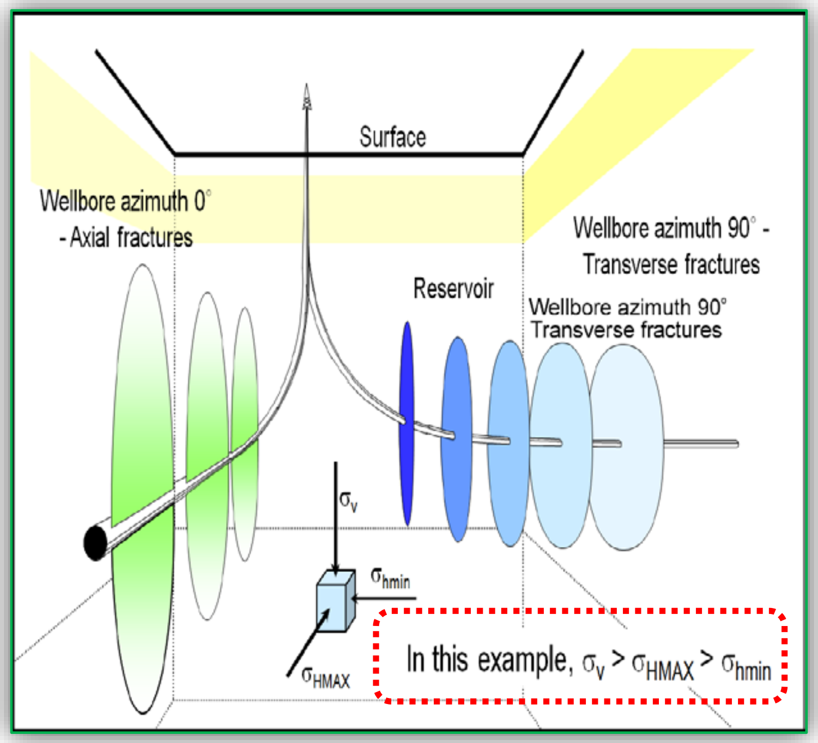
- 'Hydraulic fracturing' is used slightly differently in the industry
  - Hydraulic fracturing for stress measurement: axial fractures <1 m, vertical hole
  - Hydraulic fracturing for shale gas or other petroleum/geothermal engineereing: perforation used, transverse fractures > 100 m, usually horizontal hole (petroleum), ? (geothermal)



Hydraulic fracturing for shale gas production

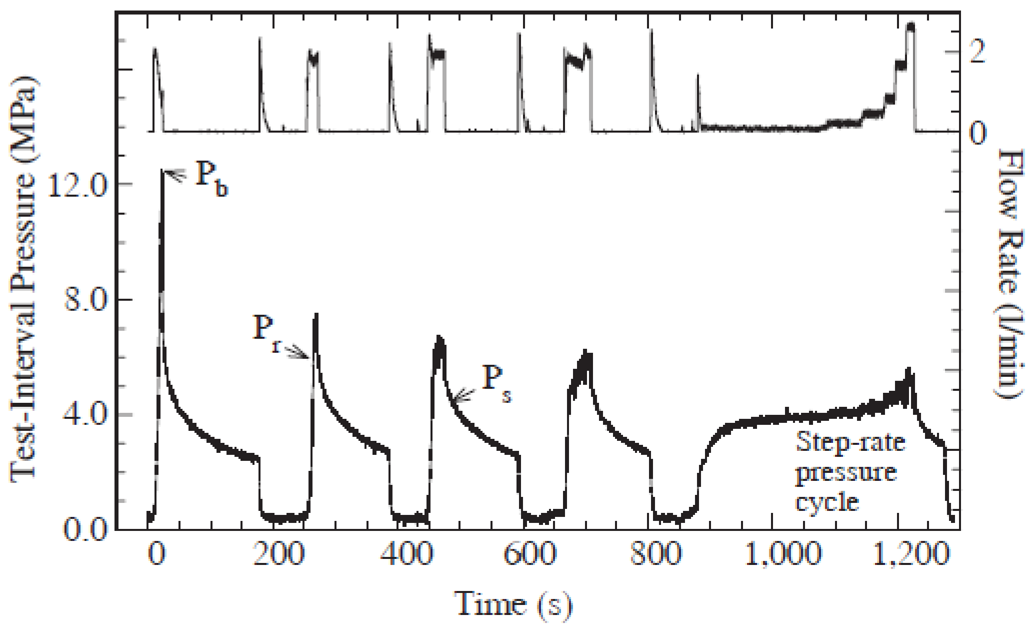
- 초기응력의 상태가 수압파쇄 균열의 방향을 "결정"

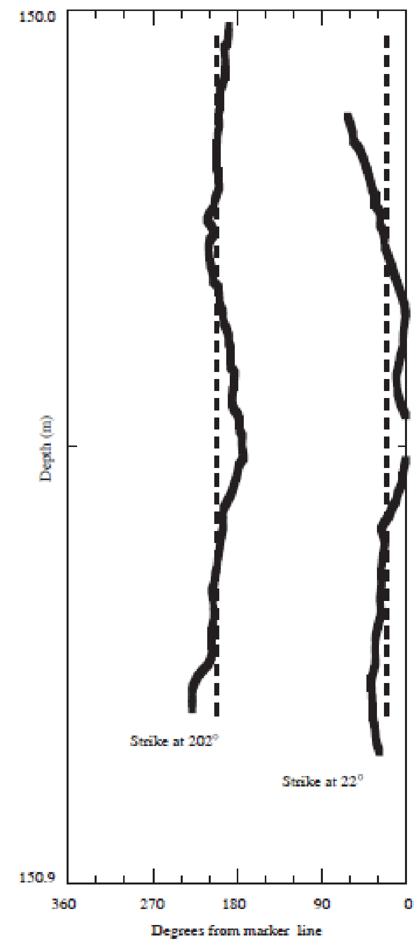
- 최소수평주응력 방향으로 수평정 시추 필요.

(MA Dusseault, 2011)

Methods of stress determination
Hydraulic Fracturing for stress determination

- Actual records





Actual impression packer record
(Haimson & Cornet, 2003)

Methods of stress determination
Indirect method

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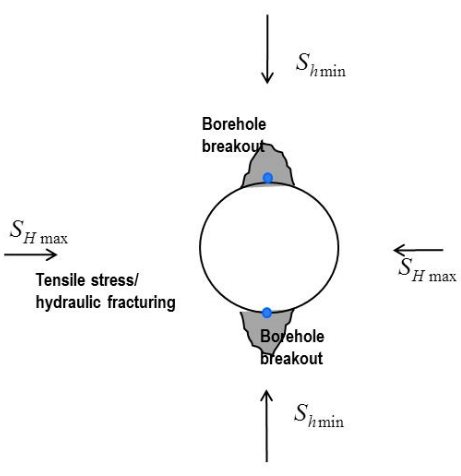
- Borehole breakout
- Anelastic Strain Recovery (ASR)
- Kaiser effect:
- Core disking
- Focal mechanism

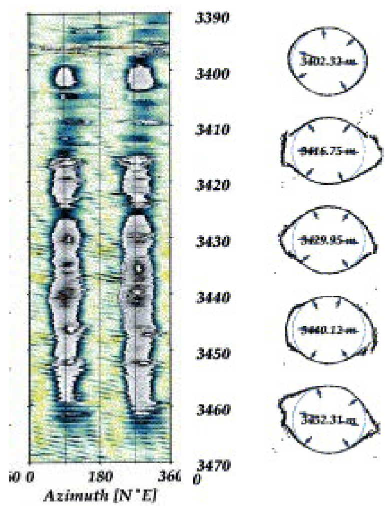
Methods of stress determination
Indirect method

- 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)

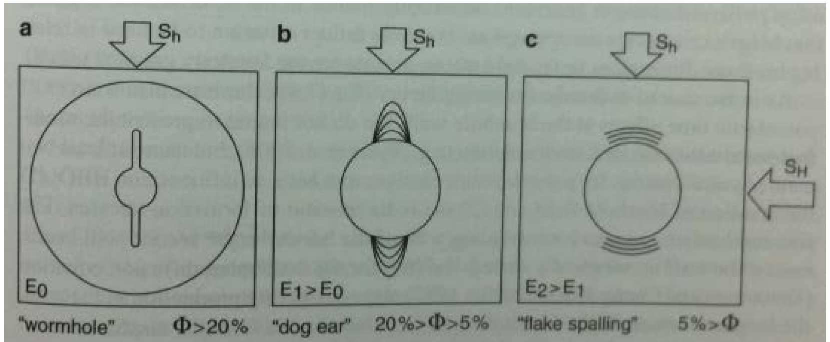


Fig. 7.12 Schematic final shape of borehole breakouts in a sand production with wormholes, b dog-ear breakouts in sandstone, and c flake-spalling process in dolerite or granite

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

Methods of stress determination
Indirect method

- 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.

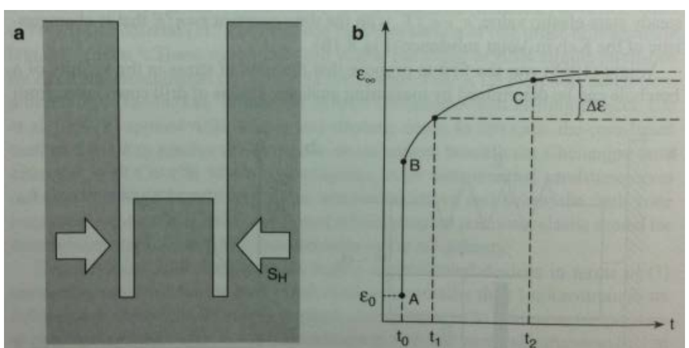
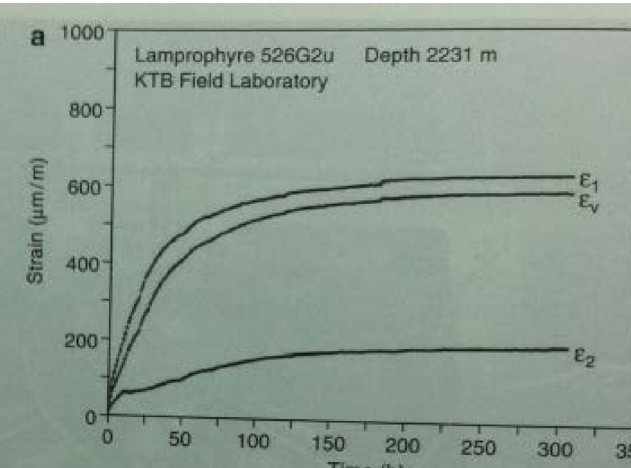


Fig. 8.2 In-situ drilling of core material (**a**) and instantaneous (elastic) plus time-dependent (anelastic) behaviour of the rock core (**b**) (modified after Teufel 1983). Time of in-situ coring is t_0, while $t_2 - t_1$ is the time interval for ASR measurements

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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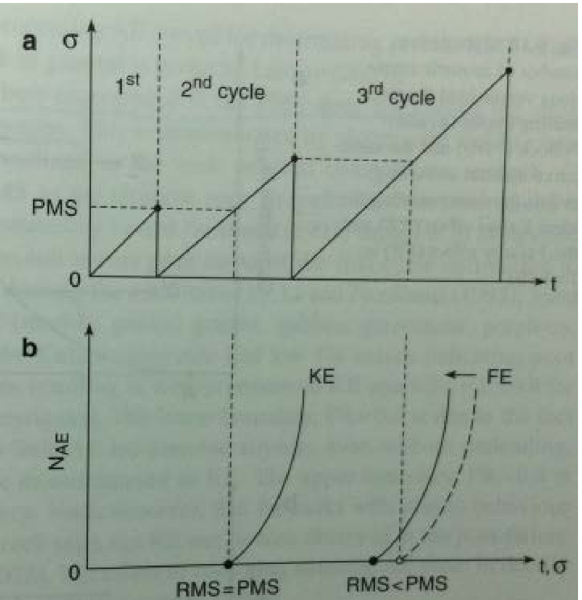
Methods of stress determination
Indirect method

- Kaiser effect
  - phenomenon that a material under stress emits acoustic emissions only after the previous maximum stress is reached.
  - Joseph Kaiser (1950)

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)



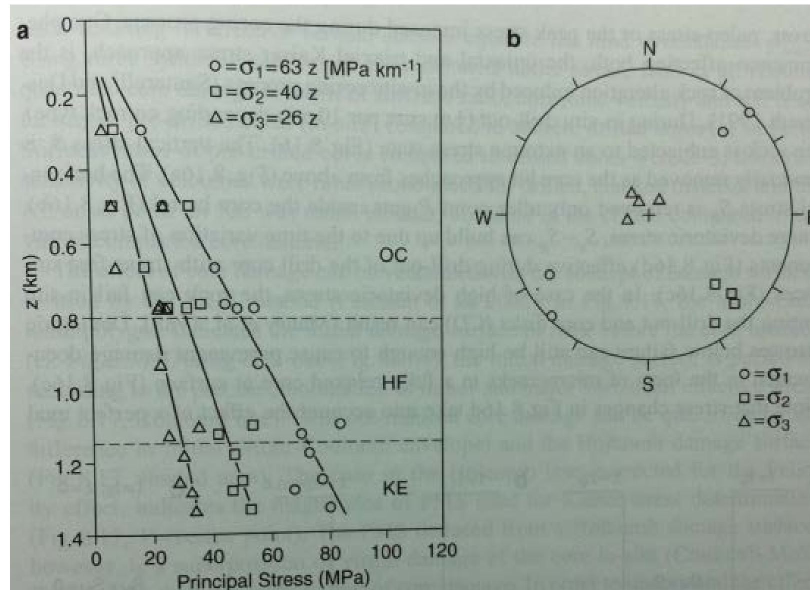


Fig. 8.15 In-situ stress estimates in the Perseverance nickel mine, Western Australia. **a** Stress magnitudes from overcoring (*OC*), hydraulic fracturing (*HF*) and AE onset (*KE*) versus depth. **b** Orientations of in-situ stresses for the four KE stress data from **a** at a depth ranging from 1175 to 1330 m (after Villaescusa et al. 2006)

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

Methods of stress determination
Indirect method

- 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

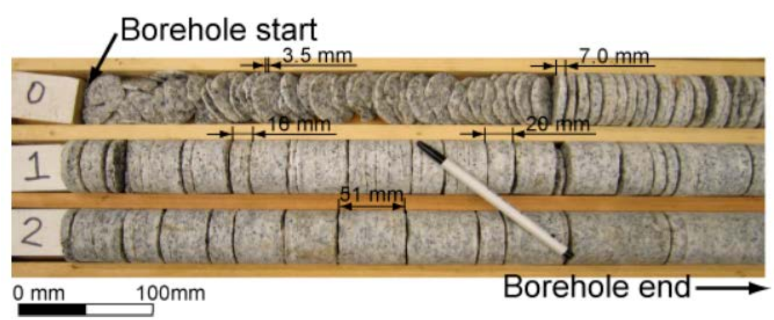
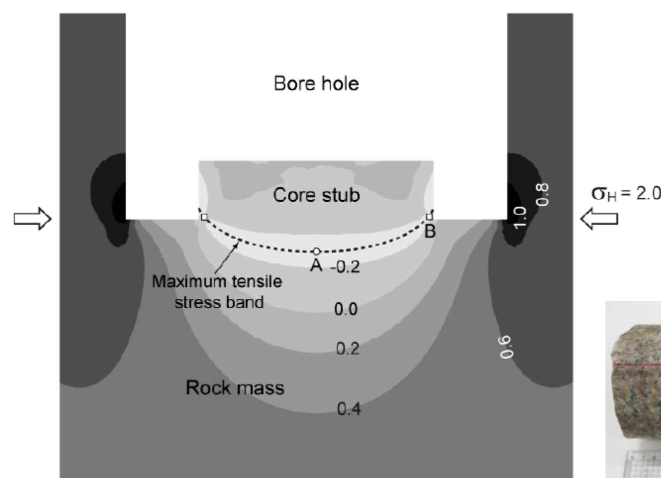
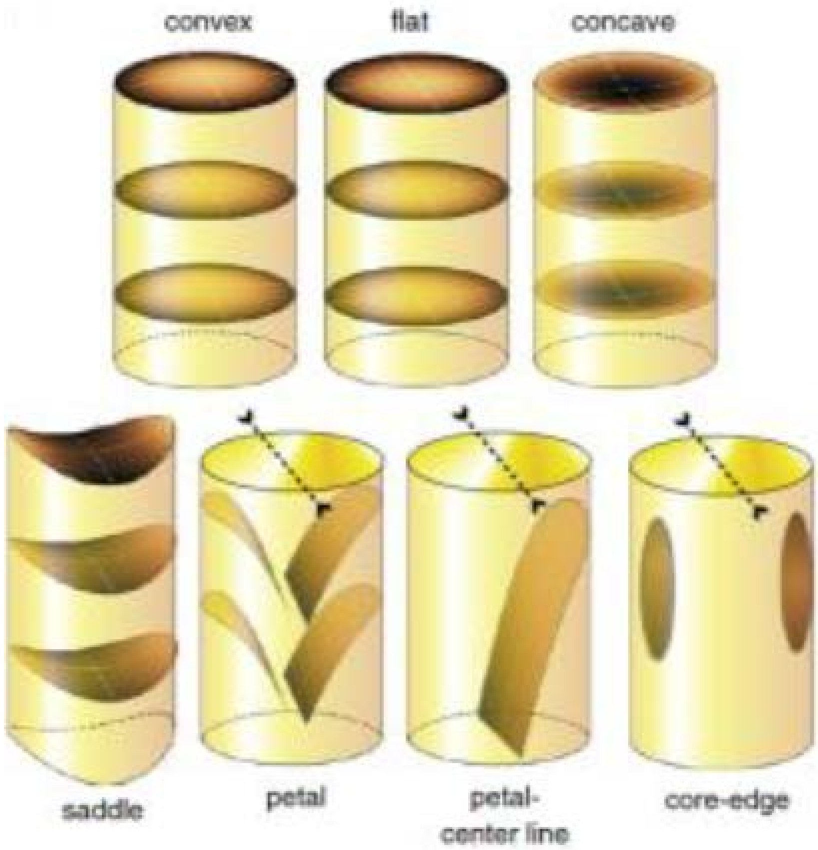


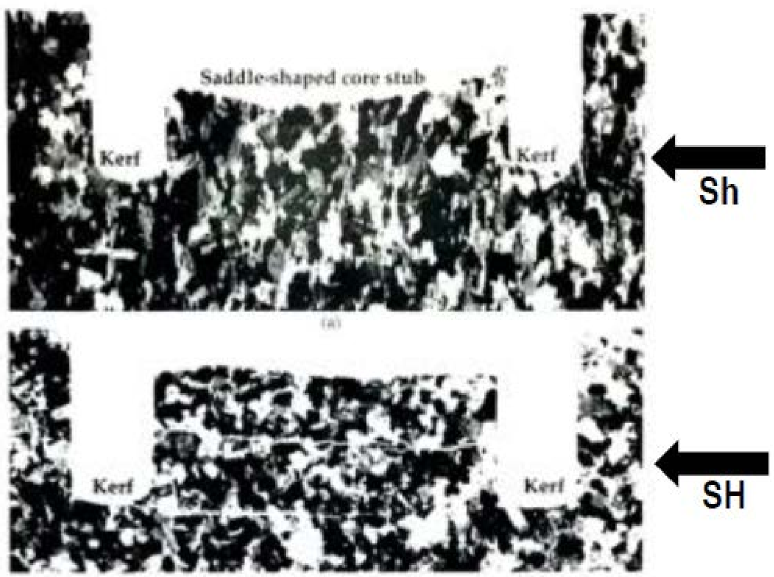
Fig. 1. Typical core disking observed in 75-mm-diameter boreholes drilled from tunnels at the 420-m depth Level of AECL's Underground Research Laboratory.



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

Methods of stress determination
Indirect method





Kim H (2016) presentation material.