Stress in the Ground

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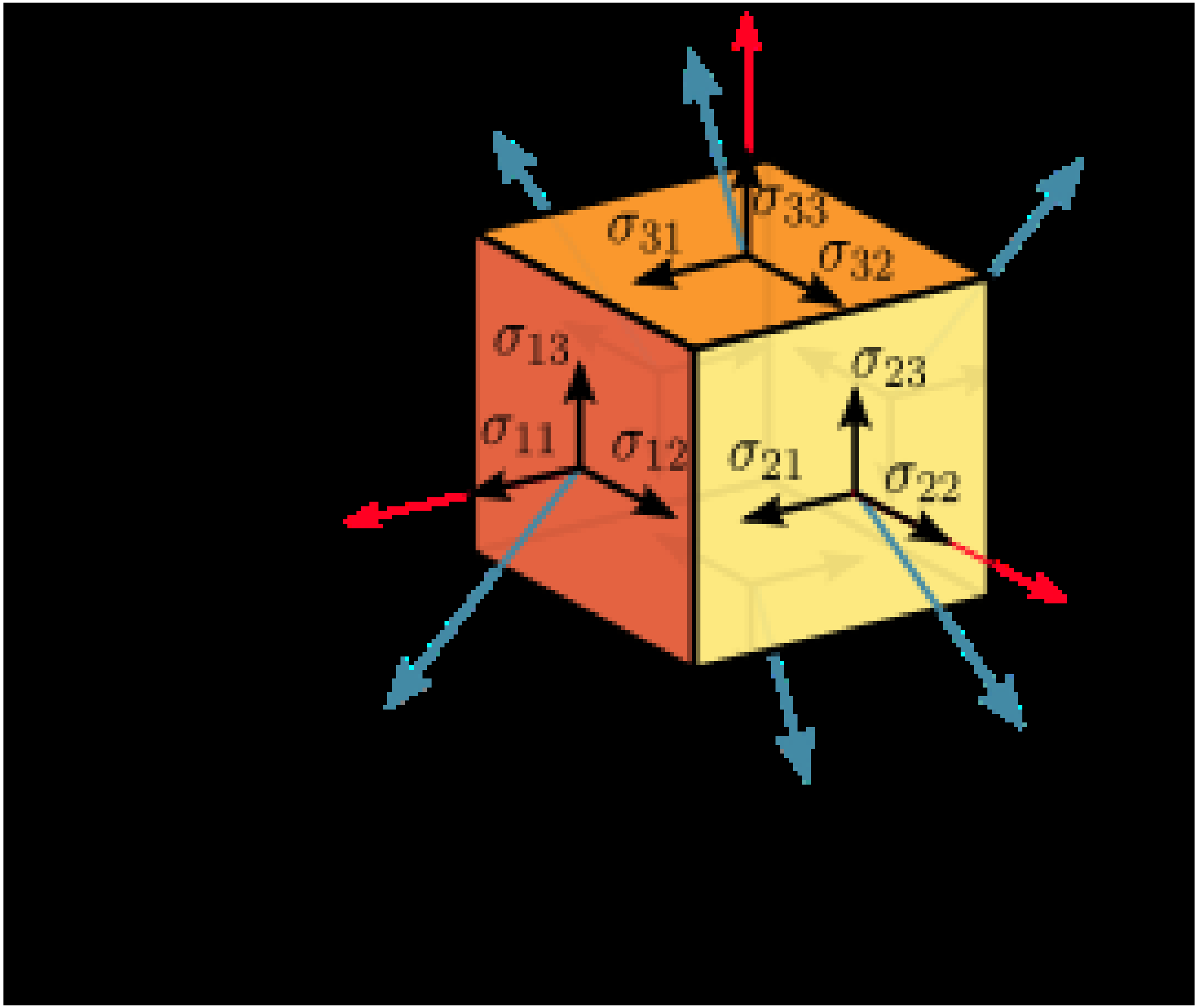
Eurock 2018 - 22 May

What is stress?



Stress is not Pressure

- Stress acts in directions and is described by a tensor

- Pressure acts in all directions and is a scalar quantity

Why does stress matter?

- If stress exceeds strength failure occurs

- If stress is too low failure may also occur

  Imagine a string of cotton reels

- Stress affects permeability of rock

  Especially in coals

Sedimentary Deposition

- Marine or lacustrine environment
- Usually low energy process
- Soil stress states exist

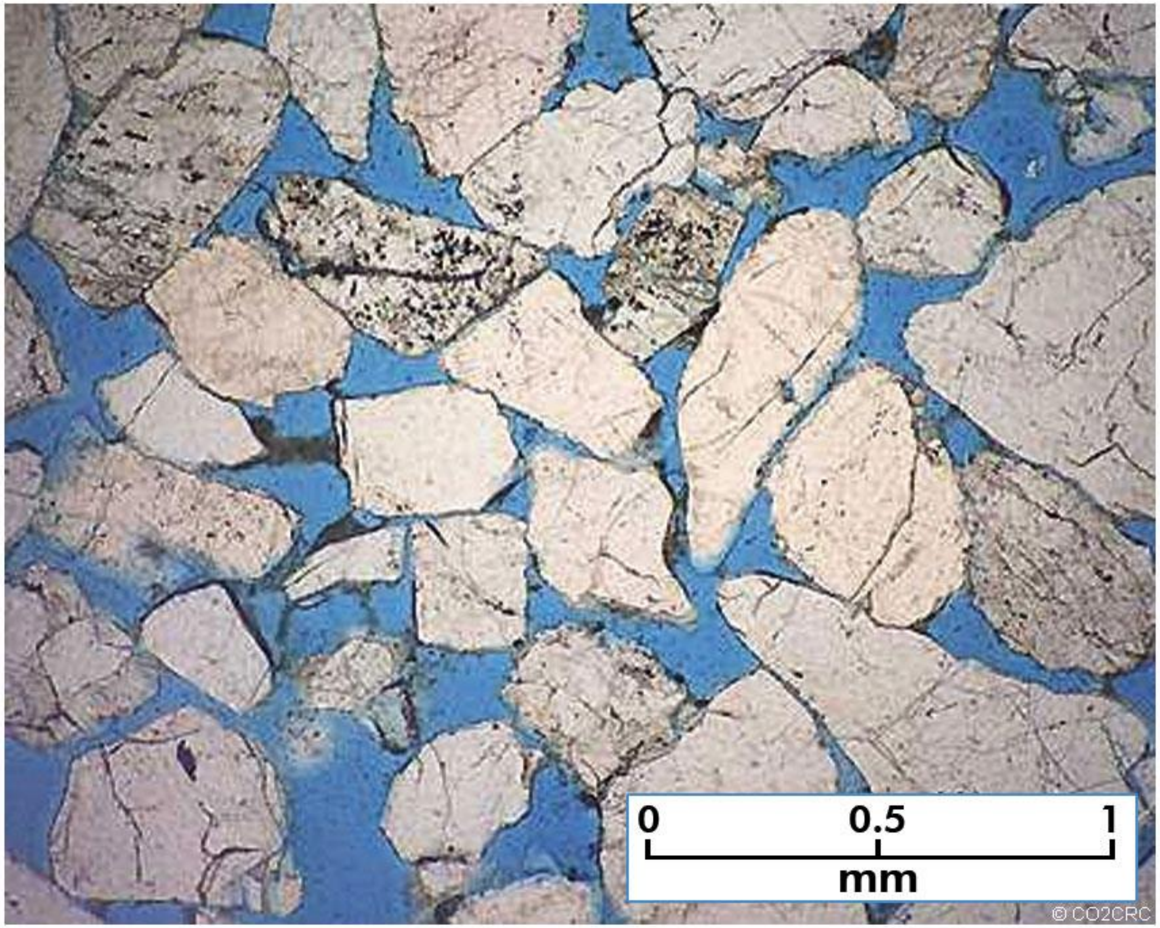
  - Consolidation – greatly assisted by earthquakes

  - Limits of active and passive states

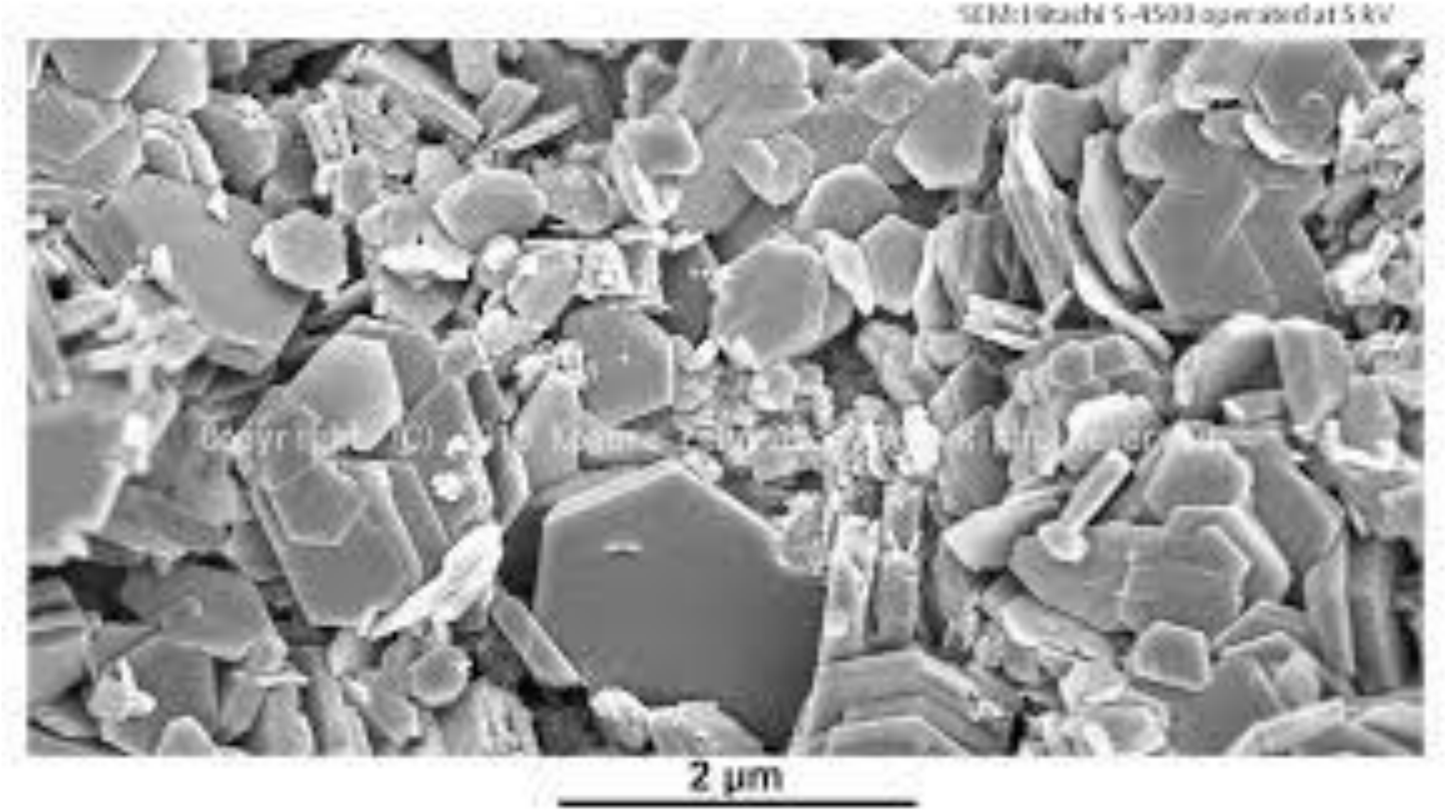
Effective Stress in a Soil

$$\sigma' = \sigma - P$$

Concept of effective stress holds with point contact – fluid acts on all surfaces



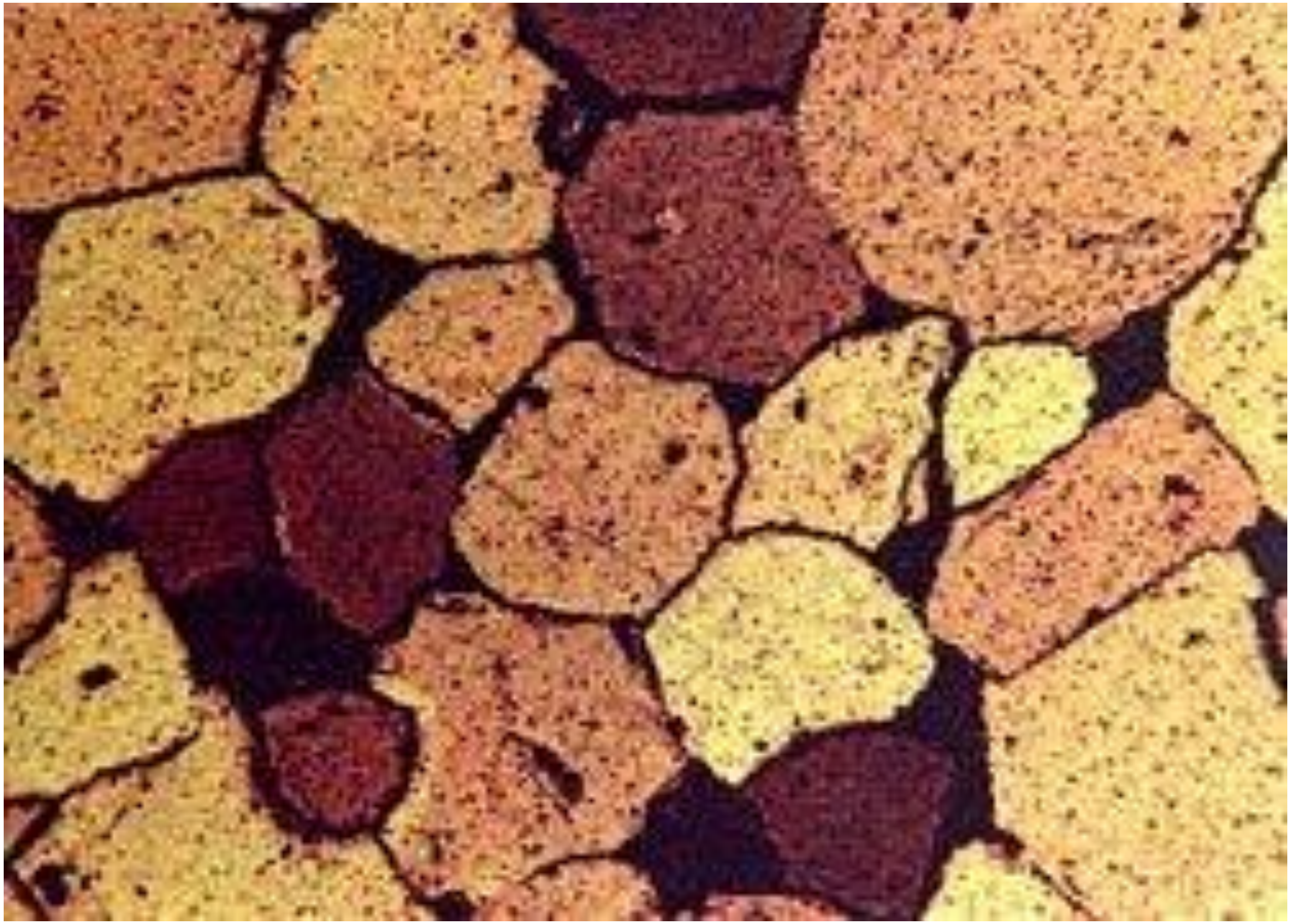
Effective stress also applies to clays



Lithification Occurs

- Cementation and crystal growth take place
- The soil becomes a rock with remaining soil stresses?
- With stiffer and more elastic properties

What happens if there is little void space?



In rock the effective stress equation changes

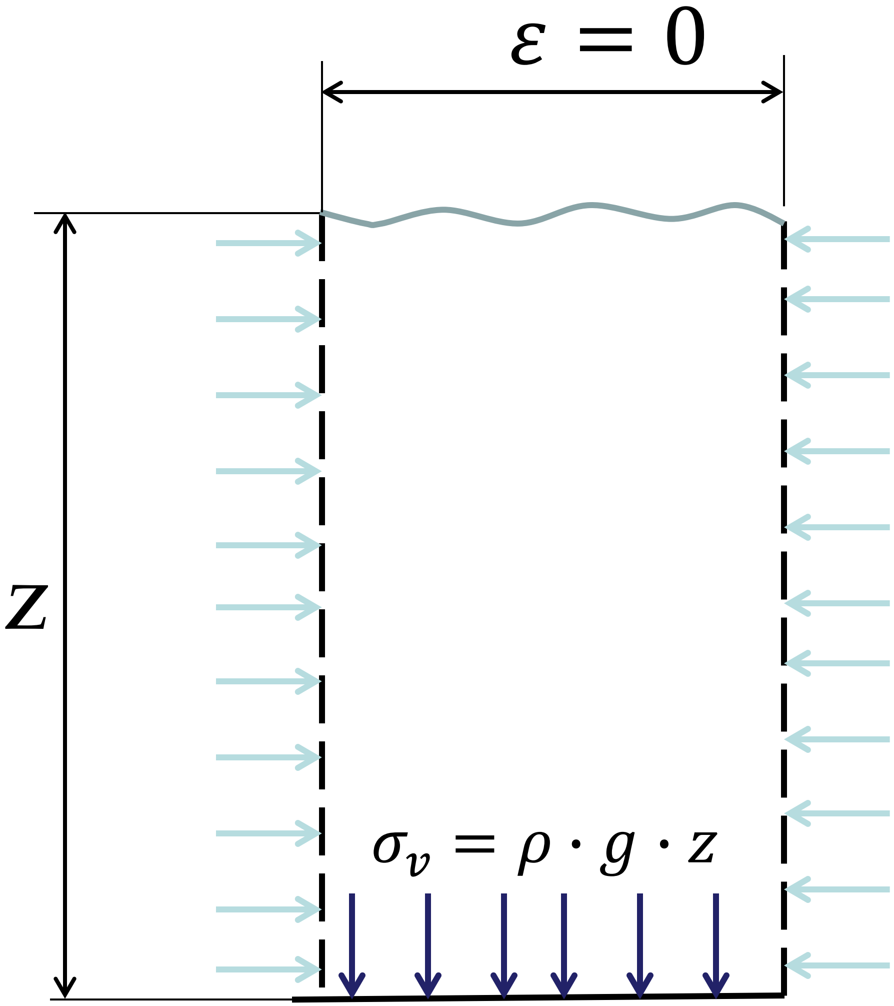
$$\sigma'_{ij} = \sigma_{ij} - \delta_{ij}\alpha_i P$$

σ'_{ii} = Principal effective stress

δ_{ij} = Kroneker delta

α_i= Biot's coefficient

P= Fluid pressure



Using this model

$$(\varepsilon = \frac{\Delta l}{l})$$

Rock as an Elastic Solid
- A big jump

- Vertical Effective Stress

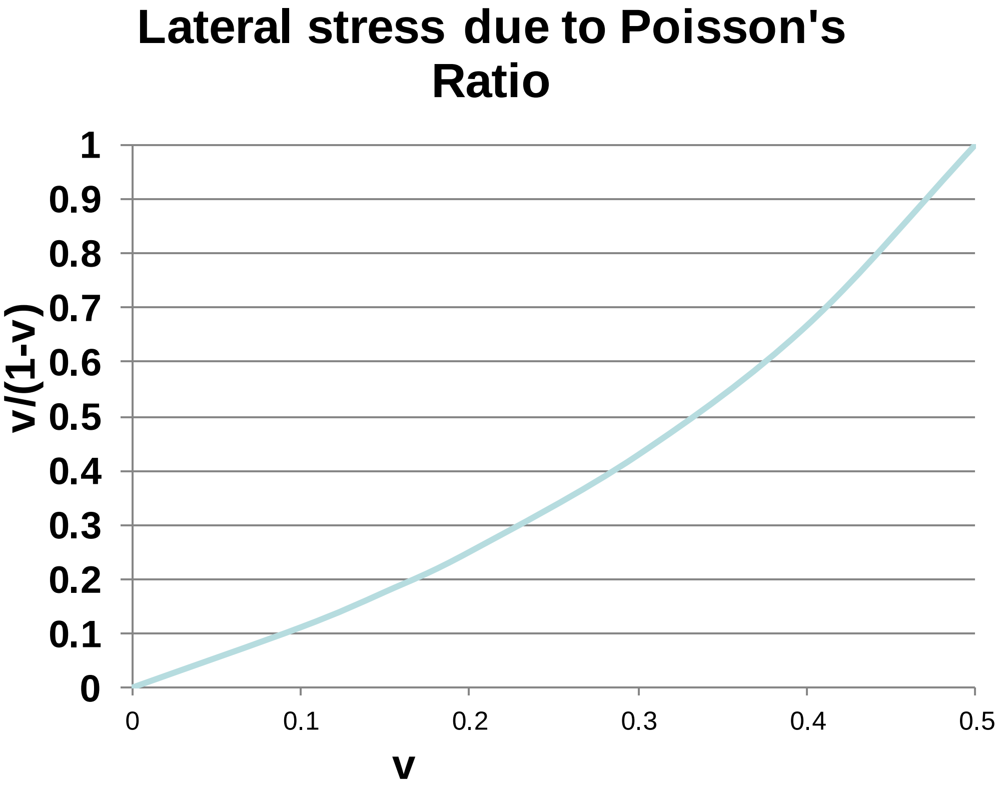
$$\sigma'_v = \rho g z - \alpha_v P$$

- Horizontal stress under zero lateral strain

$$\sigma'_h = \sigma'_v \left(\frac{v}{1-v}\right)$$

The Importance of Poisson's Ratio ν

- Lithostatic Horizontal stress
- $\sigma_h = \sigma_v \left(\frac{\nu}{1-\nu}\right)$



The fluid pressure is very important

- Fluid pressure can be at the minimum principal stress level

- More usually at hydrostatic level where it is related to groundwater

This indicates vertical connection

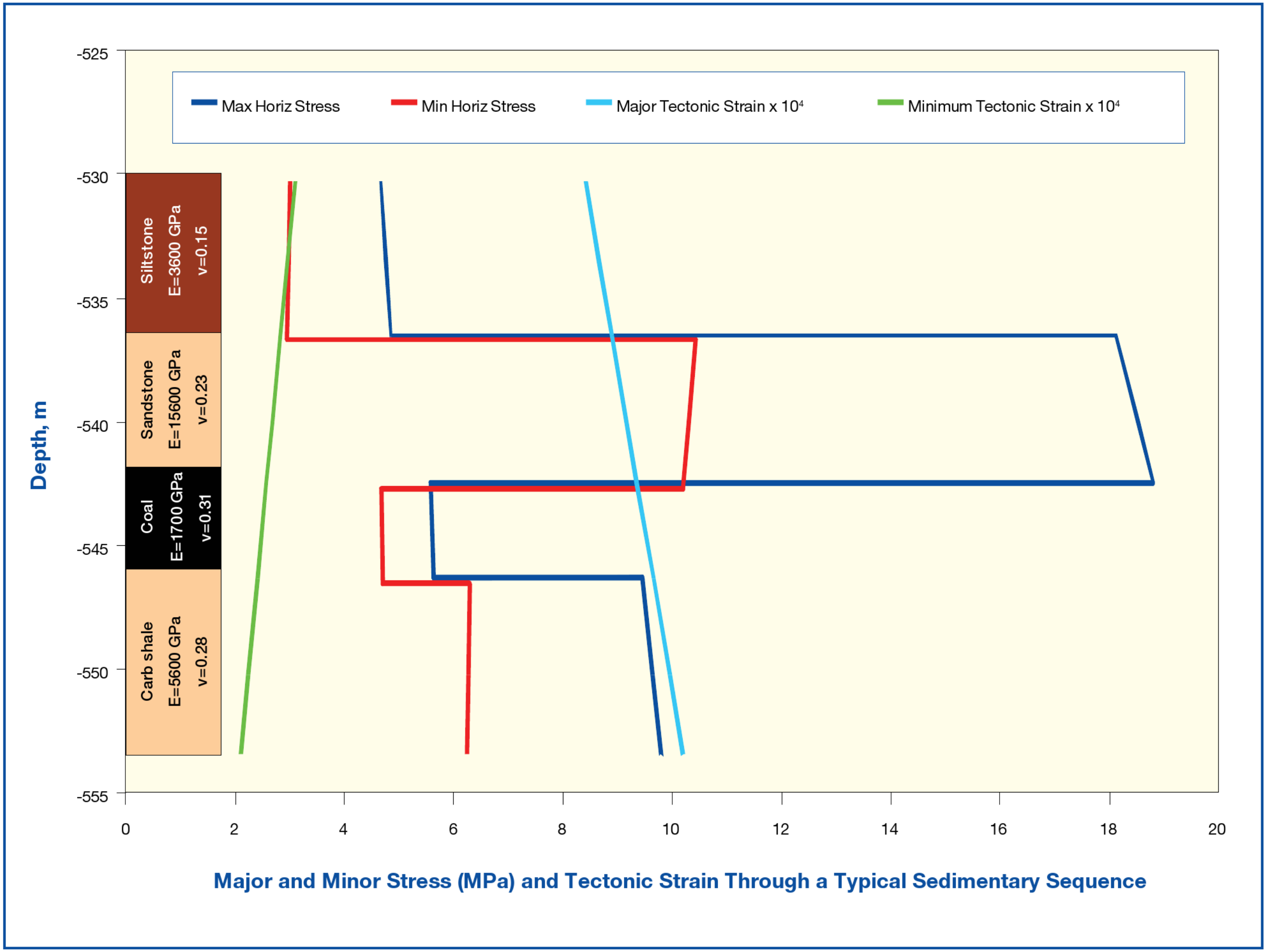
Let us consider stress in an environment where the lateral strain is not zero

- Lateral moment due to tectonic action
- Due to folds
  - Anticlines   Synclines   Monoclines
- The effects of overconsolidation, lithification, diagenesis, cooling and anything else!
- Call it TECTONIC STRAIN

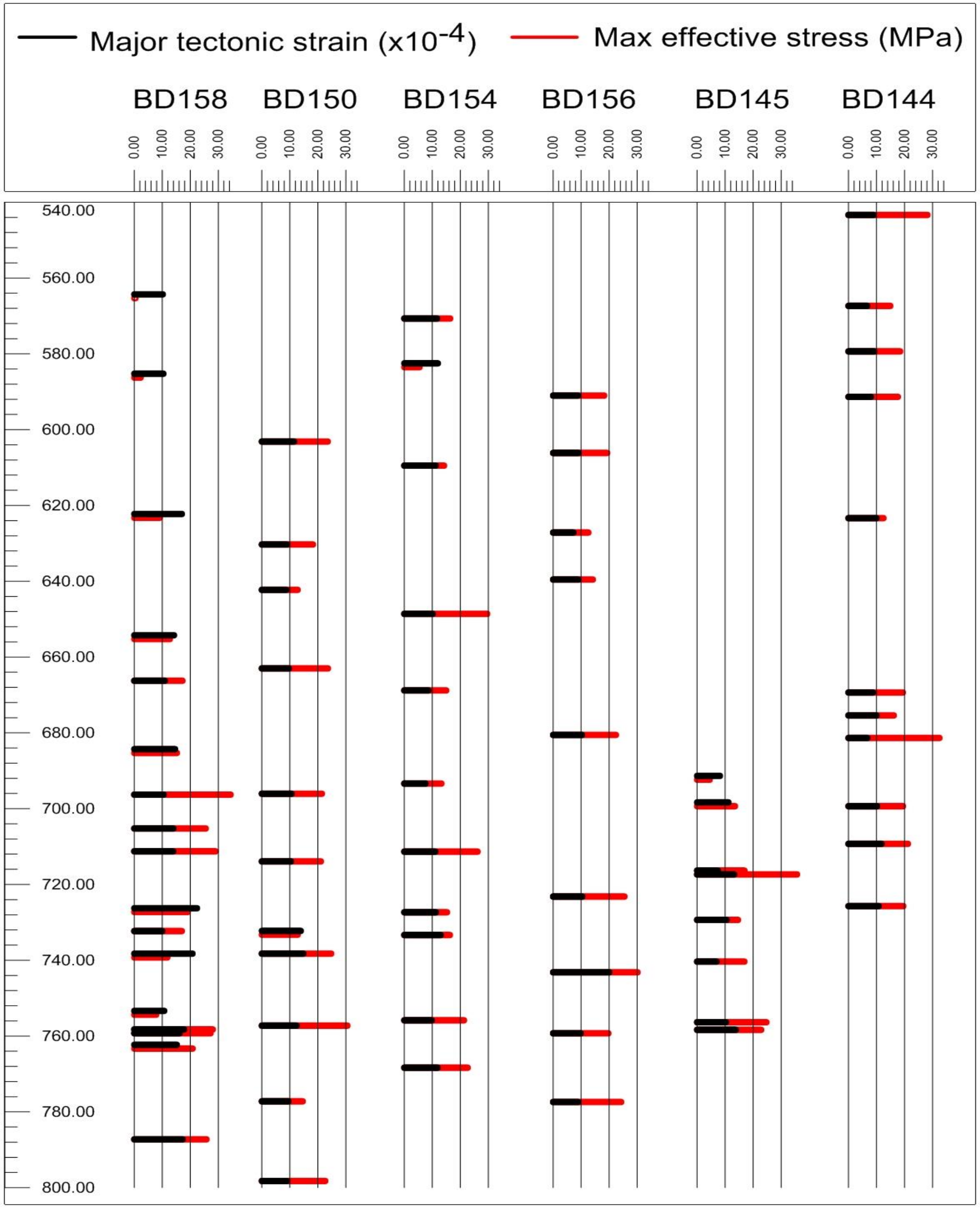
Tectonic Strain – when the lateral strain is not zero

- Sedimentary rocks have stiffness that varies layer by layer (or intrusion)
- Stresses vary with stiffness
- Tectonic strain is the strain that is required to develop the measured stress
- The general rule is that tectonic strains are fairly even through sedimentary sequences. There are exceptions!

Layered Sedimentary Strata with Varying Stiffness and Poisson's Ratio



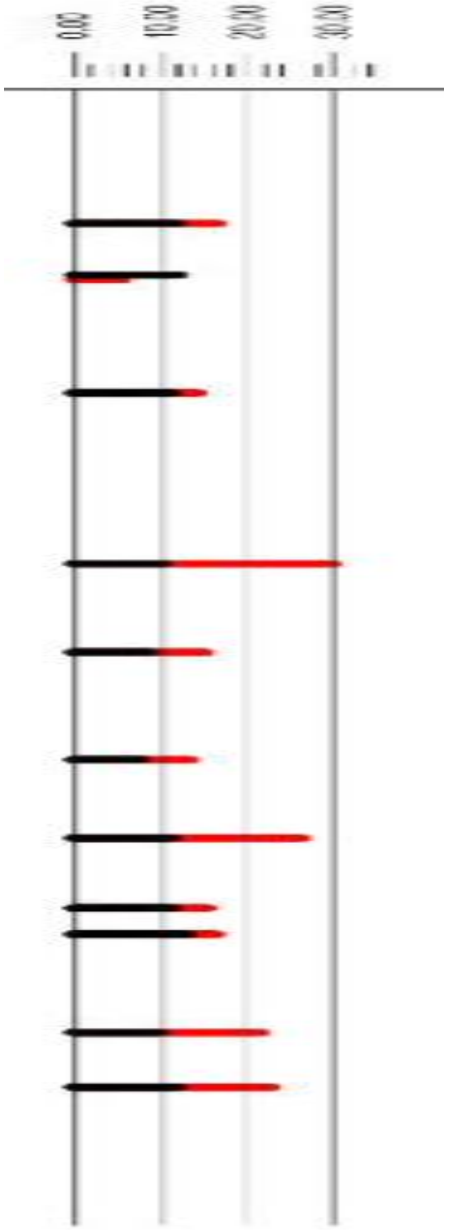
Major and Minor Stress (MPa) and Tectonic Strain Through a Typical Sedimentary Sequence



Queensland site

Stress ___

Tectonic strain______



Queensland Site

Stress ___

Tectonic strain______

Igneous Rocks

- Dykes and sills are indication of the stresses existing at the time of injection they are giant hydrofractures
- Igneous bodies cool and loose strain but may gain high surface stress with uneven cooling
- Stiff rocks attract much more stress with strain hence a stiff, strong rock may be highly stressed or de-stressed.

Poroelasitic Behaviour

- Strain in terms of effective stress
- $\Delta\varepsilon_i = \frac{1}{E_i}\Delta\sigma'_i - \frac{v_{ji}}{E_j}\Delta\sigma'_j - \frac{v_{ki}}{E_k}\Delta\sigma'_k$
- $\varepsilon_i = \frac{1}{E_i}(\Delta\sigma_i - \frac{v_{ji}}{E_j}\Delta\sigma_j - \frac{v_{ki}}{E_k}\Delta\sigma_k)$

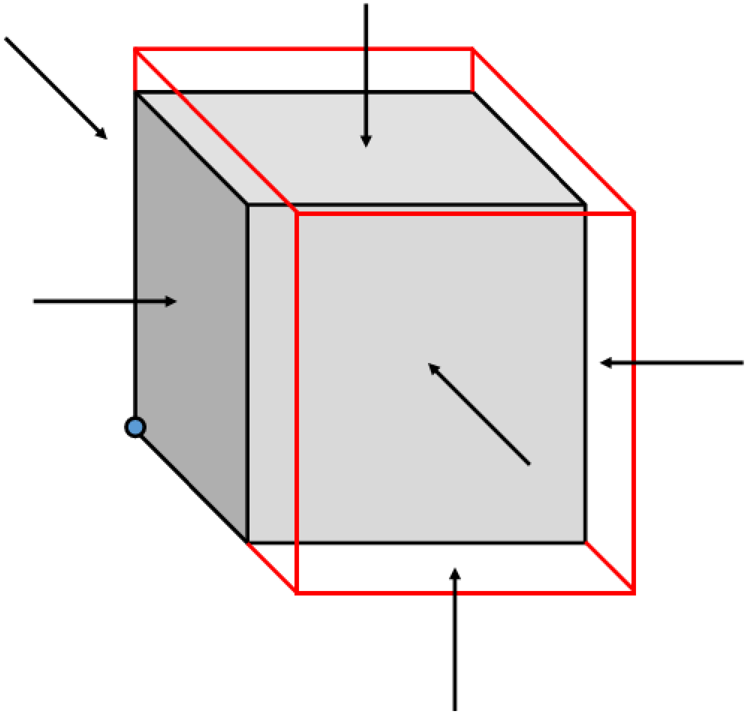
$$-\Delta P(\frac{1}{E_i}\alpha_i - \frac{v_{ji}}{E_j}\alpha_j - \frac{v_{ki}}{E_k}\alpha_k)$$

The Big Sponge

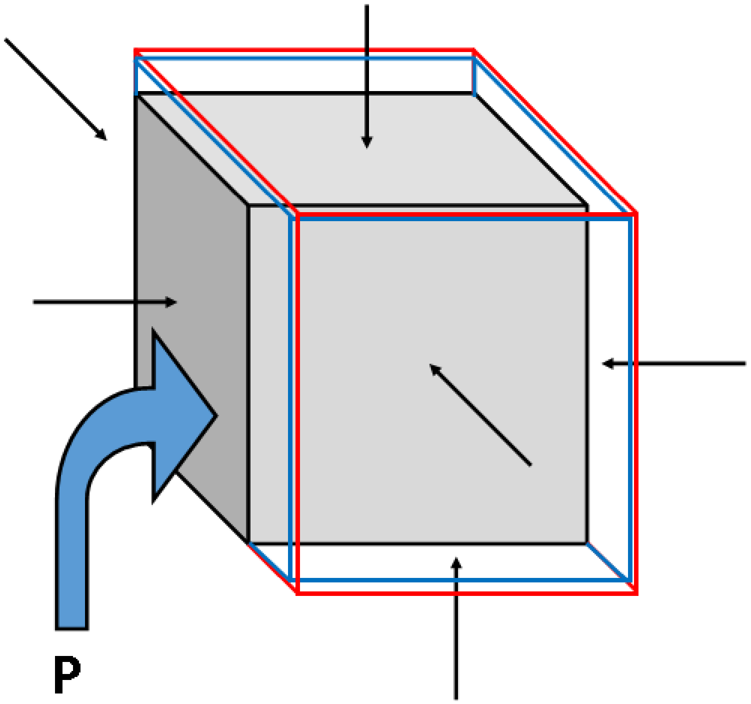
- The equations describe a block of rock that behaves as a sponge which expands with internal fluid pressure.

- Determining poroelastic coefficients requires measuring the elastic parameters and then injecting fluid into the specimen while monitoring strain.

Deformation under a unit stress



Recovery under unit fluid pressure Biot’s? Tensor



Effective Stress and a fracture

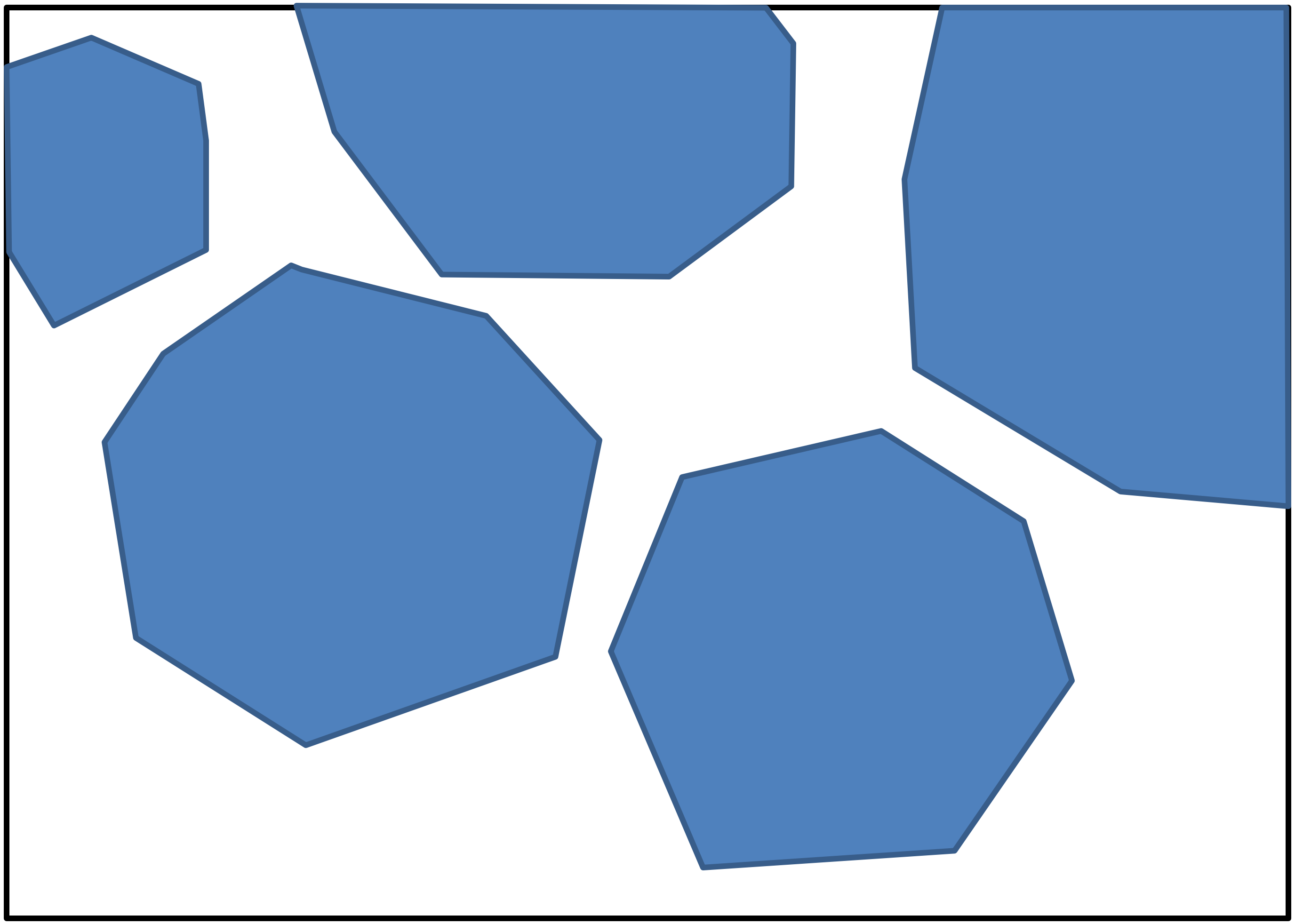
- The concept of effective stress only applies to the direction normal to the surface in question.

$$\sigma_n' = \sigma_n - \alpha P$$

Where	σ_n'	is the effective normal stress across a specific plane
	σ_n	is the total stress across the plane
	α	is Fracture area ratio
	P	is the fluid pressure

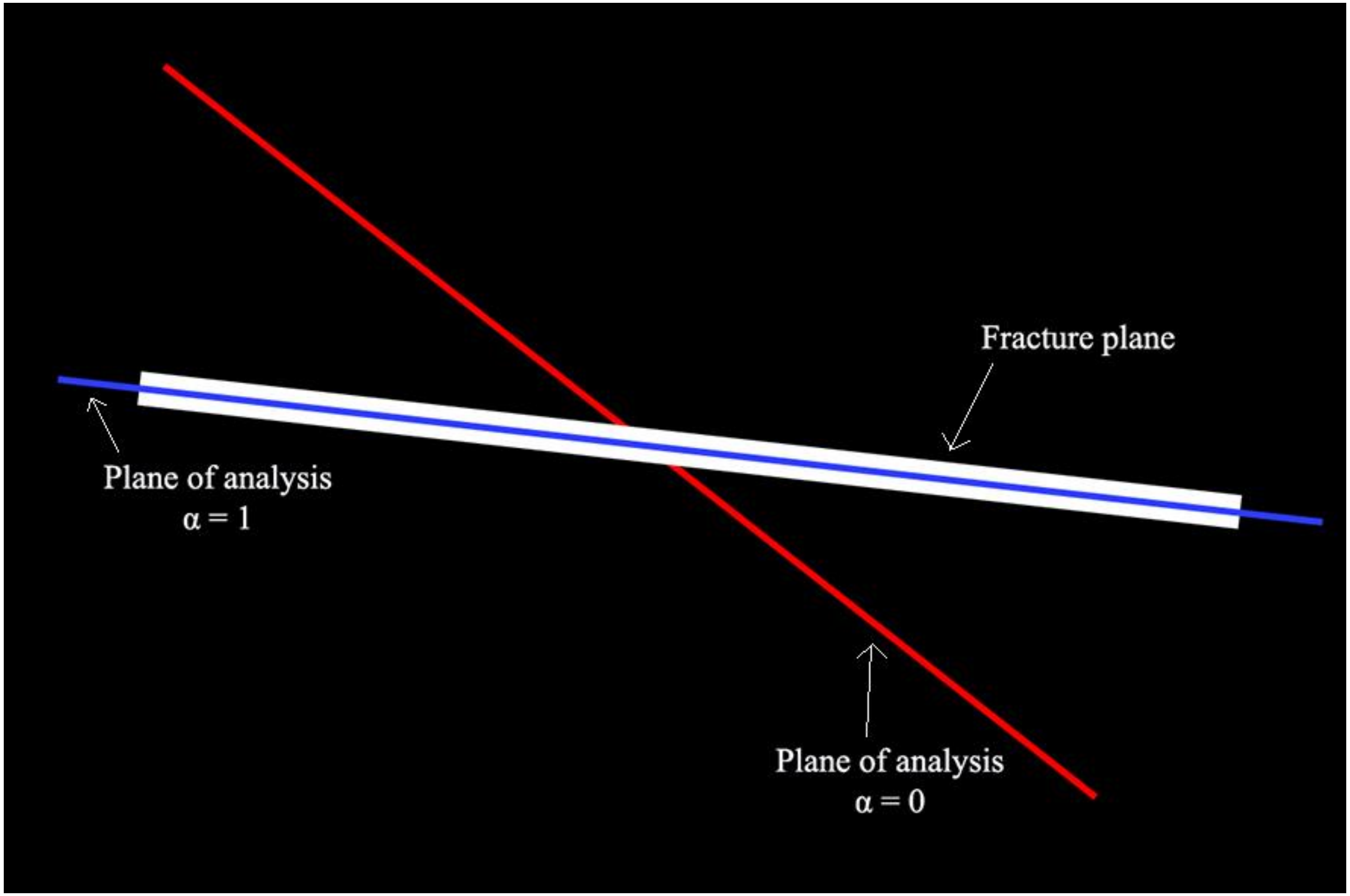
Effective stress in fractures

- Use the term fracture area ratio rather than Biot’s or poroelastic Coefficient

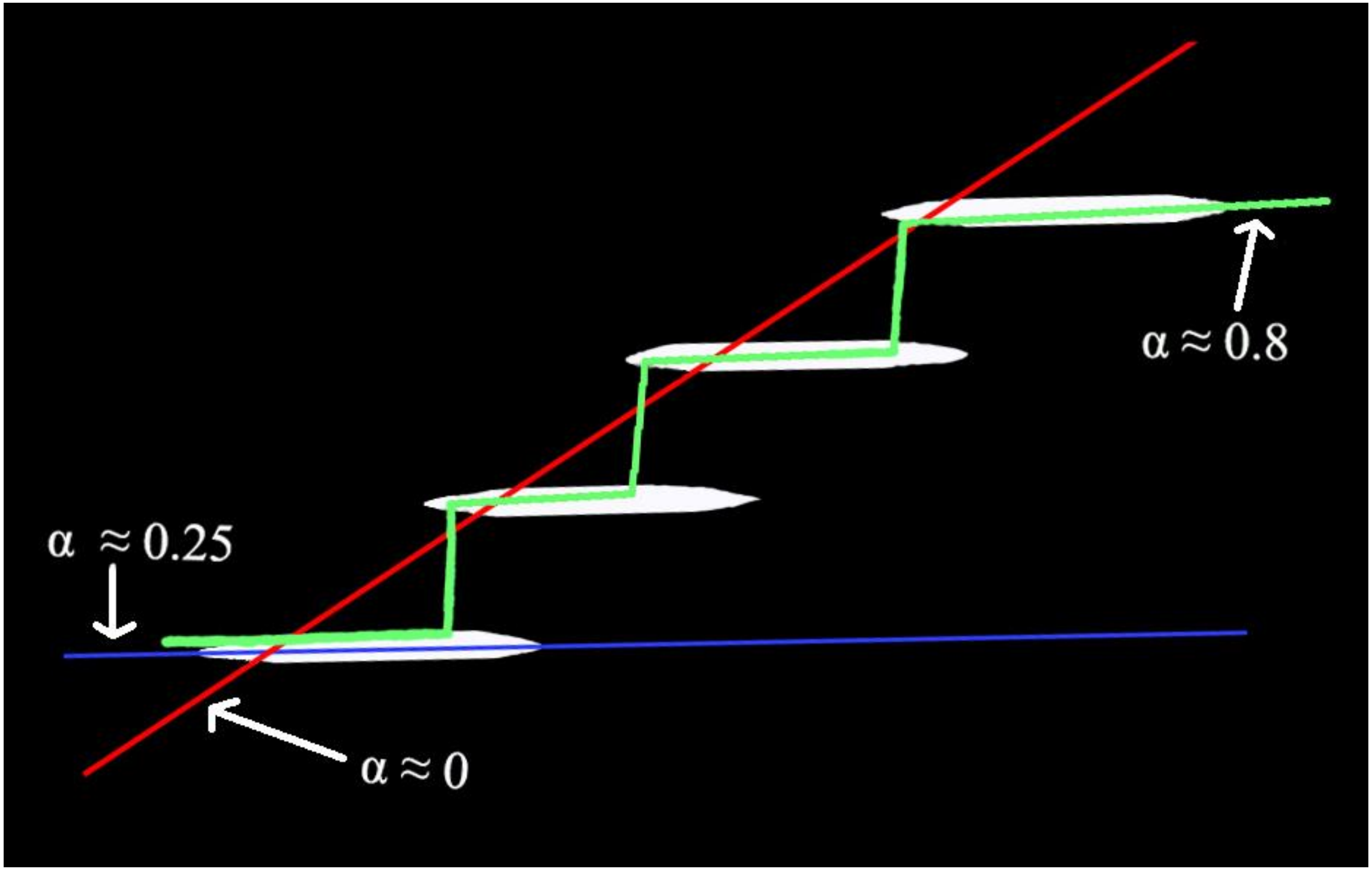


α= Blue Fractured Area/Total Area

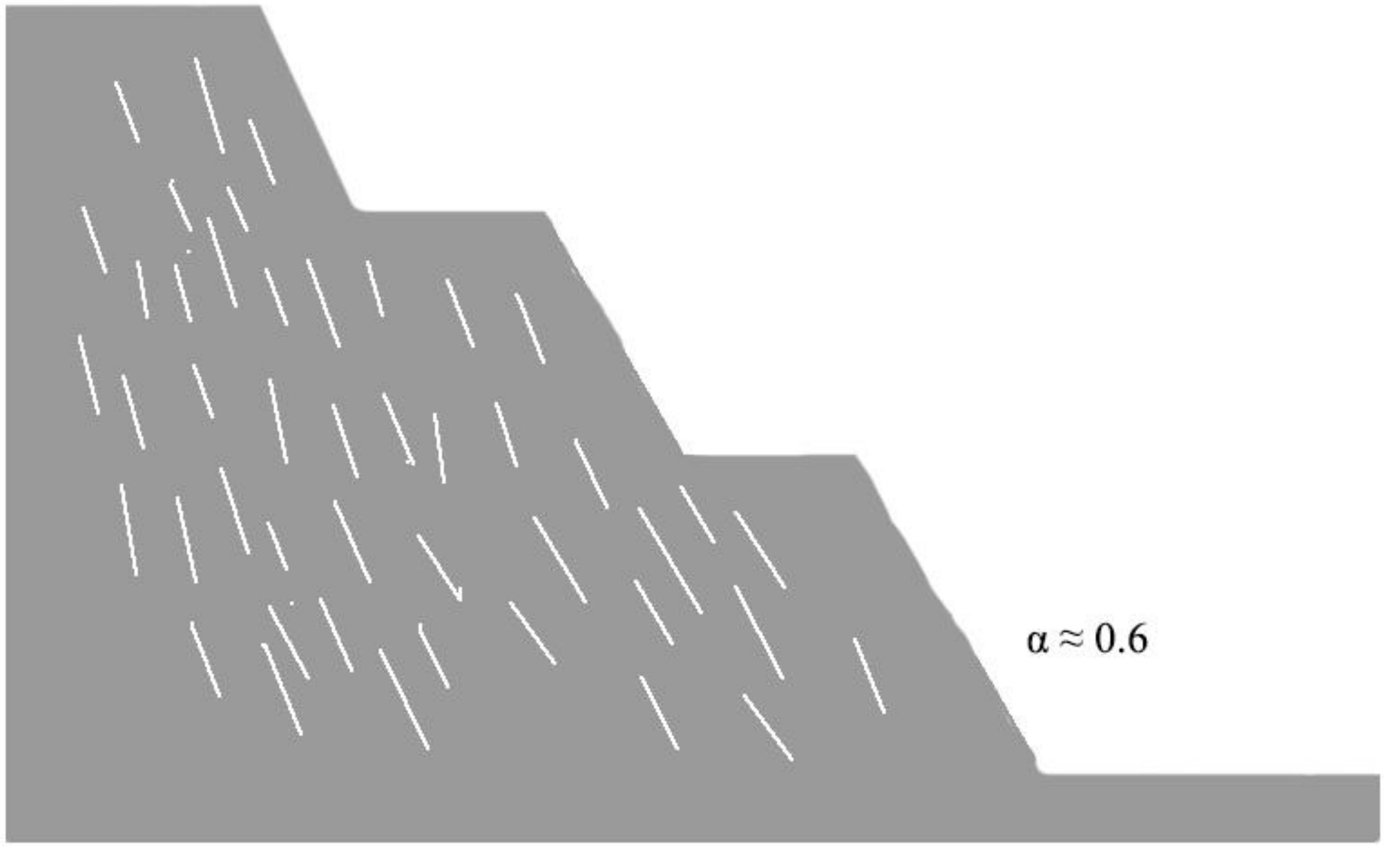
Consider a block of obsidian with a single fracture



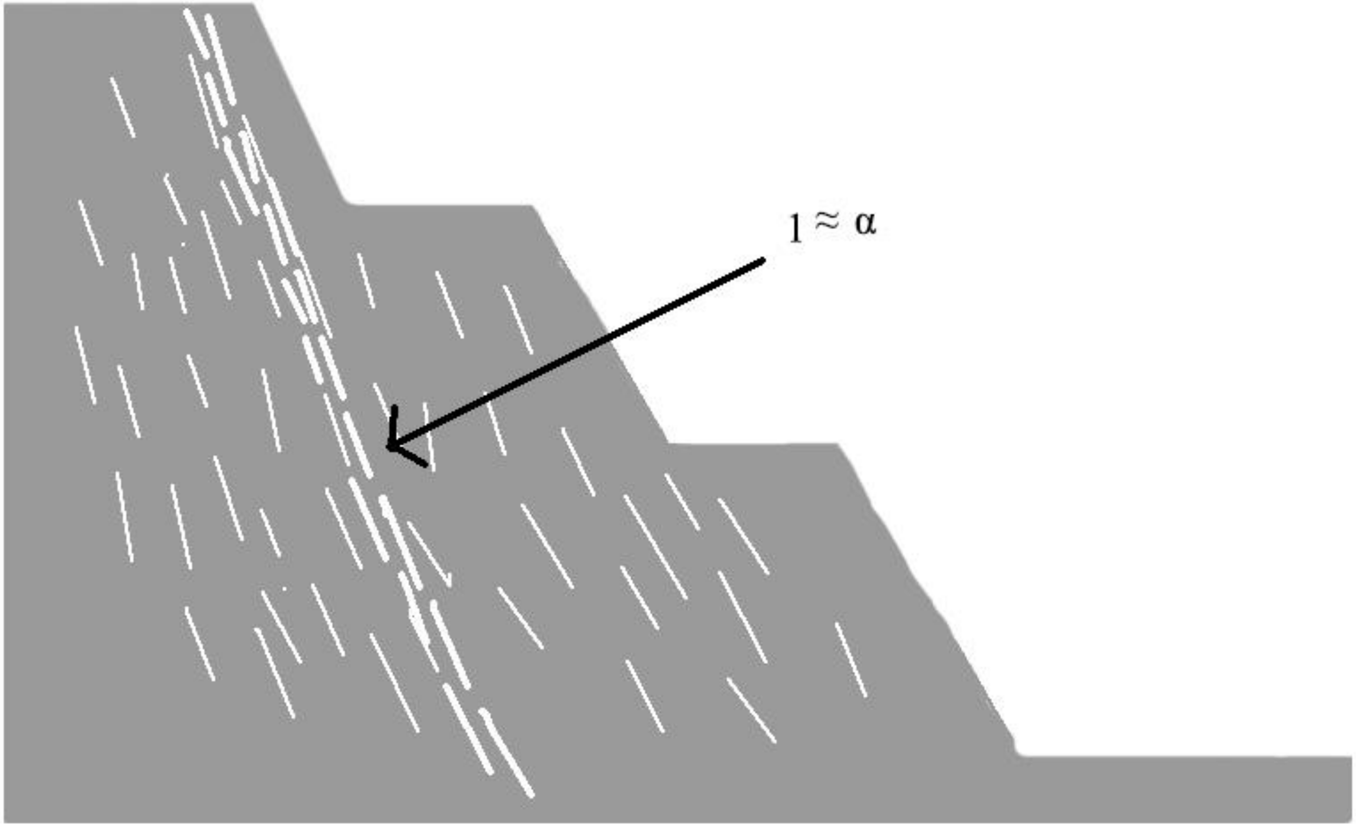
En Echelon Fractures



Slope with not fully connected fractures



Slope with fully developed fracture set



Fracture Area Ratio

- This is highly variable
- Is the fracture open or closed?
- What is the infill?
- Crystalline infill has a true poroelastic Biot’s coefficient = 0
- Consider talc in its original state Biot=0
- If disturbed does Biot =1?

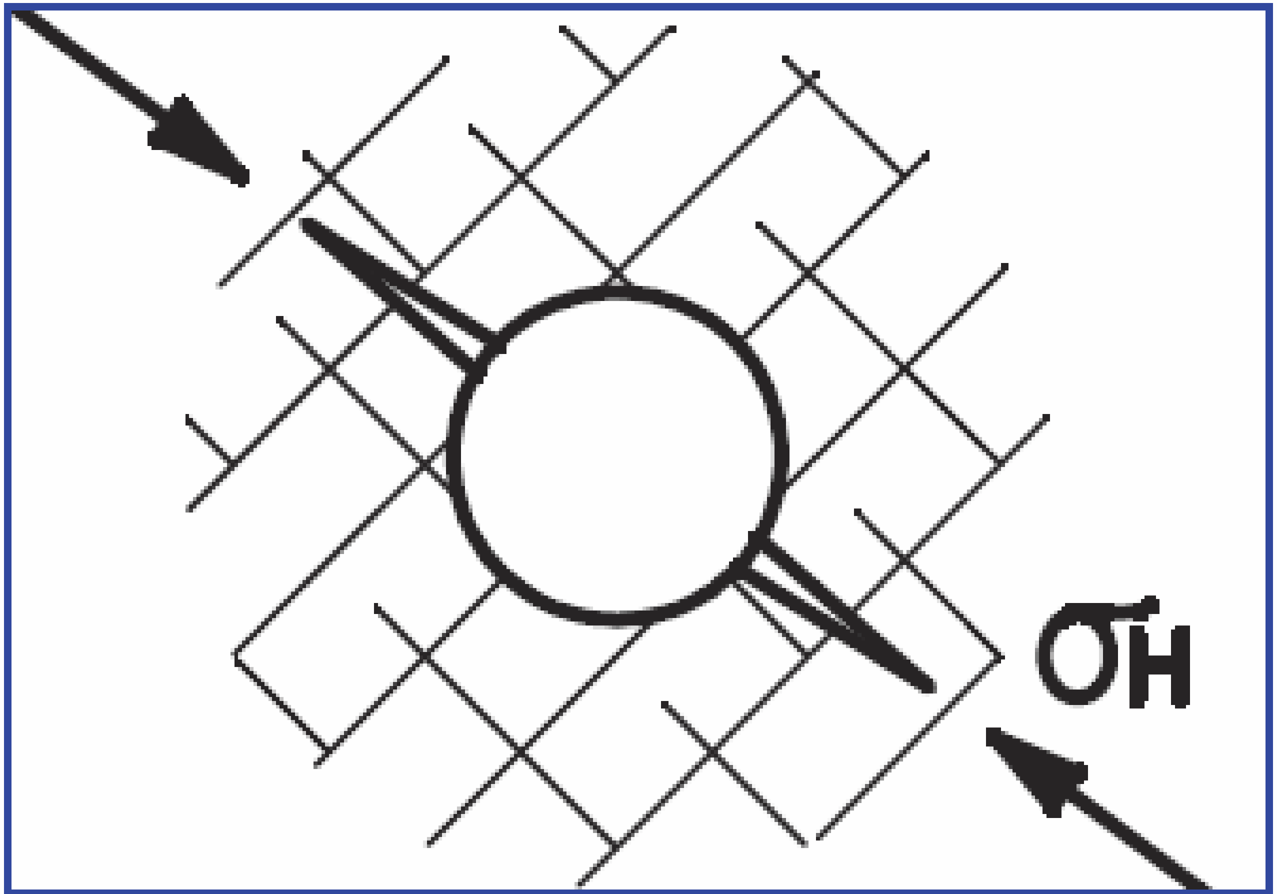
Failure due to changing effective stress

- Effective stress changes because of
- Varying fluid pressure
- Changing fracture system leads to changing Fracture Area Ratio

- This really means the fractures are developing and linking up

Stress Measurement in Rock

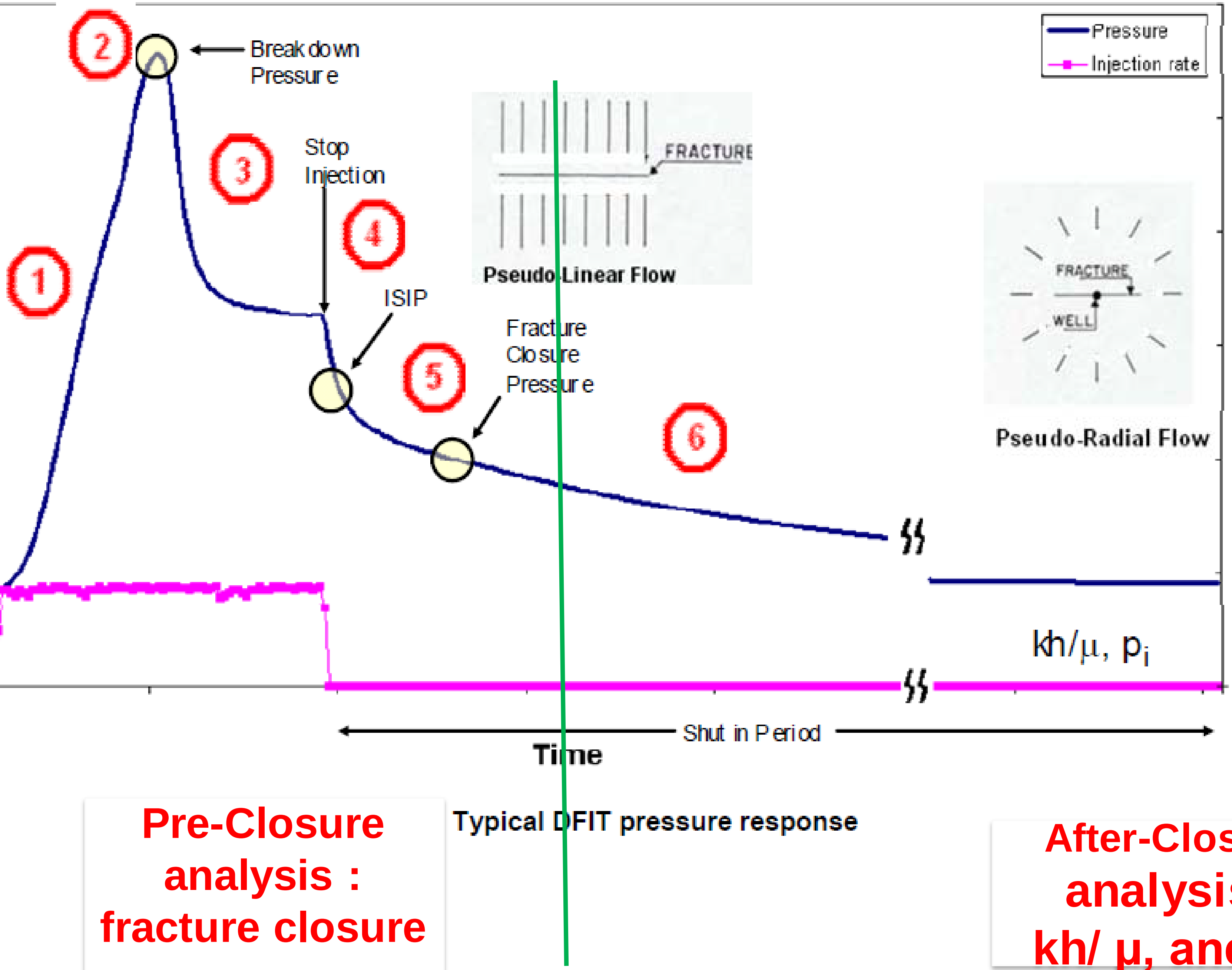
- Hydrofracture
- Borehole Breakout
- Overcoring
- Slot jacking
- Anelastic Recovery
  - Uncertain and difficult to achieve
- Kaiser Effect
  - Developed for metal does not work in rock



HYDROFRACTURE STRESS MEASUREMENT

Hydrofracture

- If minor stress is not coincident with hole axis then there is a problem
- Opening pressure flow rate dependent and dependent on openness of fracture – joint.
- By definition the pressure between the packer and borehole wall must be higher than the fluid pressure – hence the packers frequently induce failure.
- Requires highly skilled interpretation

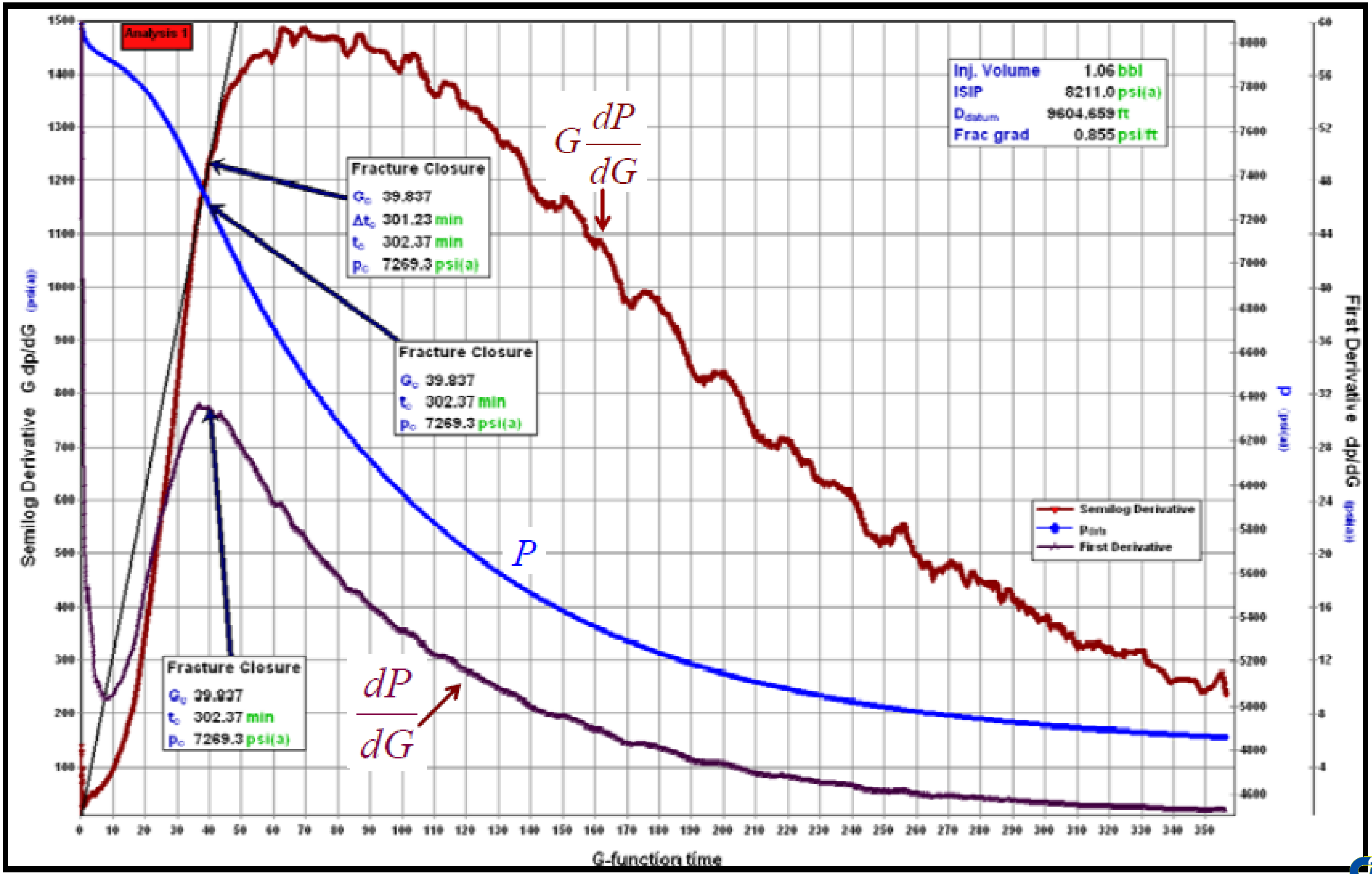


Typical DFIT pressure response

Pre-Closure analysis : fracture closure pressure

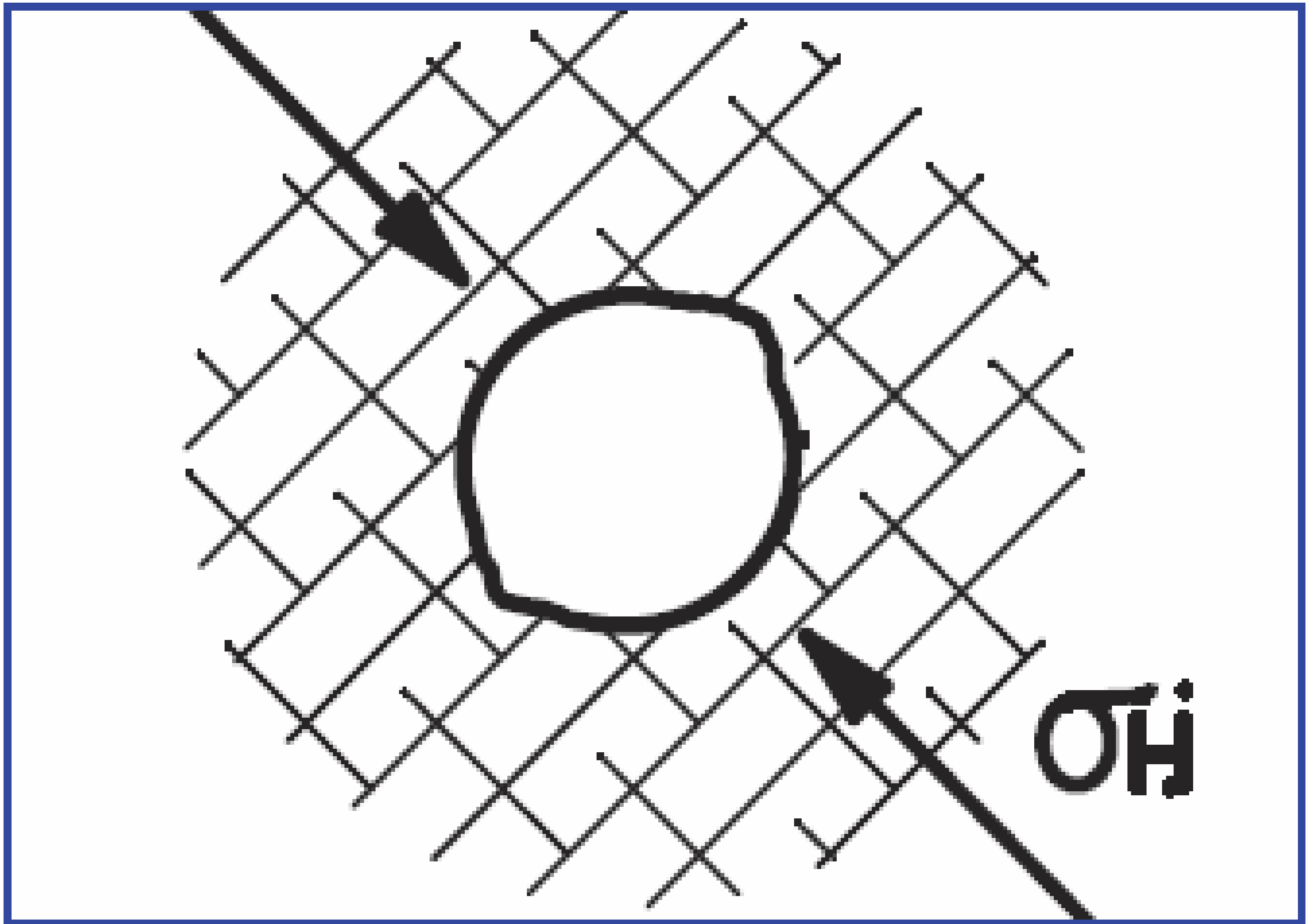
After-Closure analysis : kh/ μ, and Pi

G-Function plot



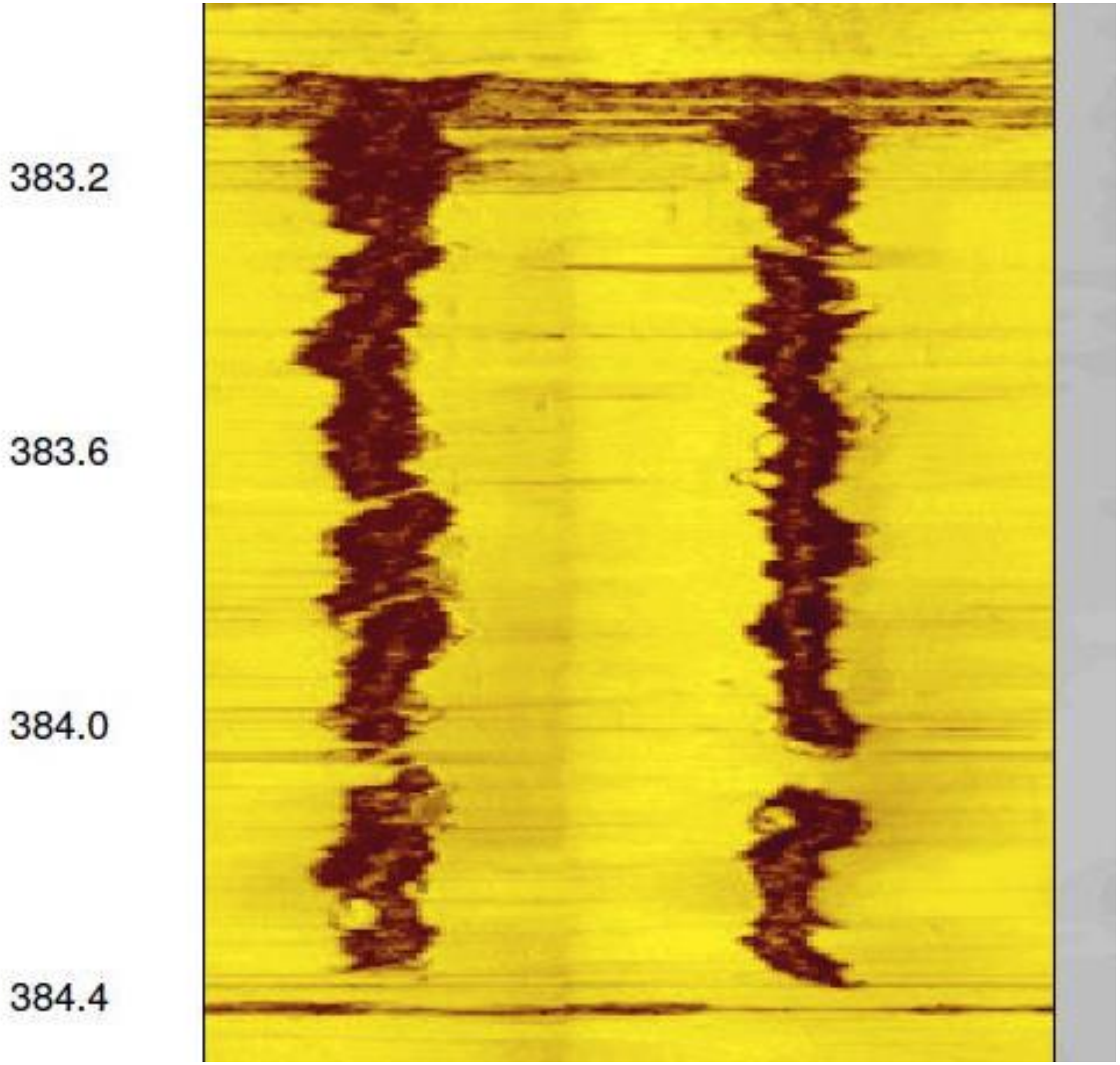
Hydrofracturing can be useful

- To establish a minimum stress from closure
- As part of diagnostic fracture injection testing when the closure phase is also used for permeability measurement
- To determine in-situ fluid pressure at the end of leak-off period
- To determine normal stress across a joint
- To measure stress in a hole that has been drilled



BOREHOLE BREAKOUT

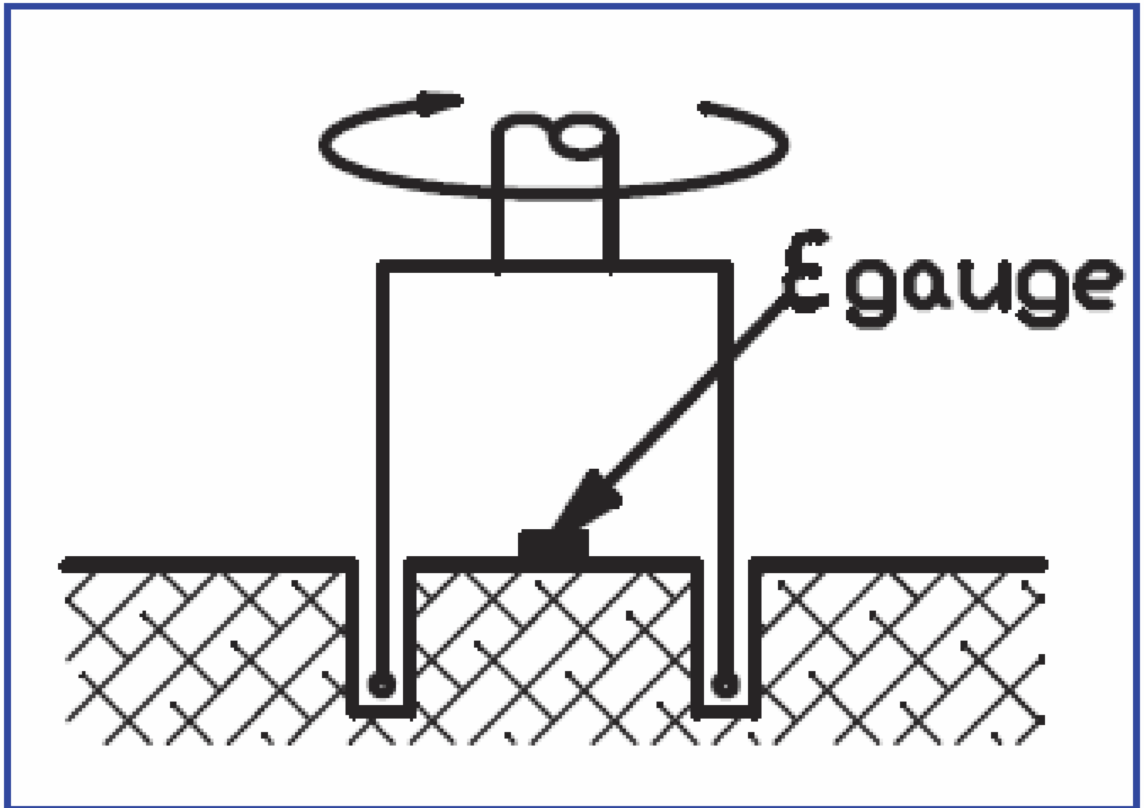
Acoustic scan showing breakout



Borehole Breakout

- Primarily Biaxial stress direction indicator
- May be analysed for major stress value if you know the UCS of the rock and the minimum stress (from hydrofracture closure)
- Relations between sonic logs and UCS not adequately reliable for quantitative analysis of breakout

Surface Overcoring



SURFACE OVERCORING

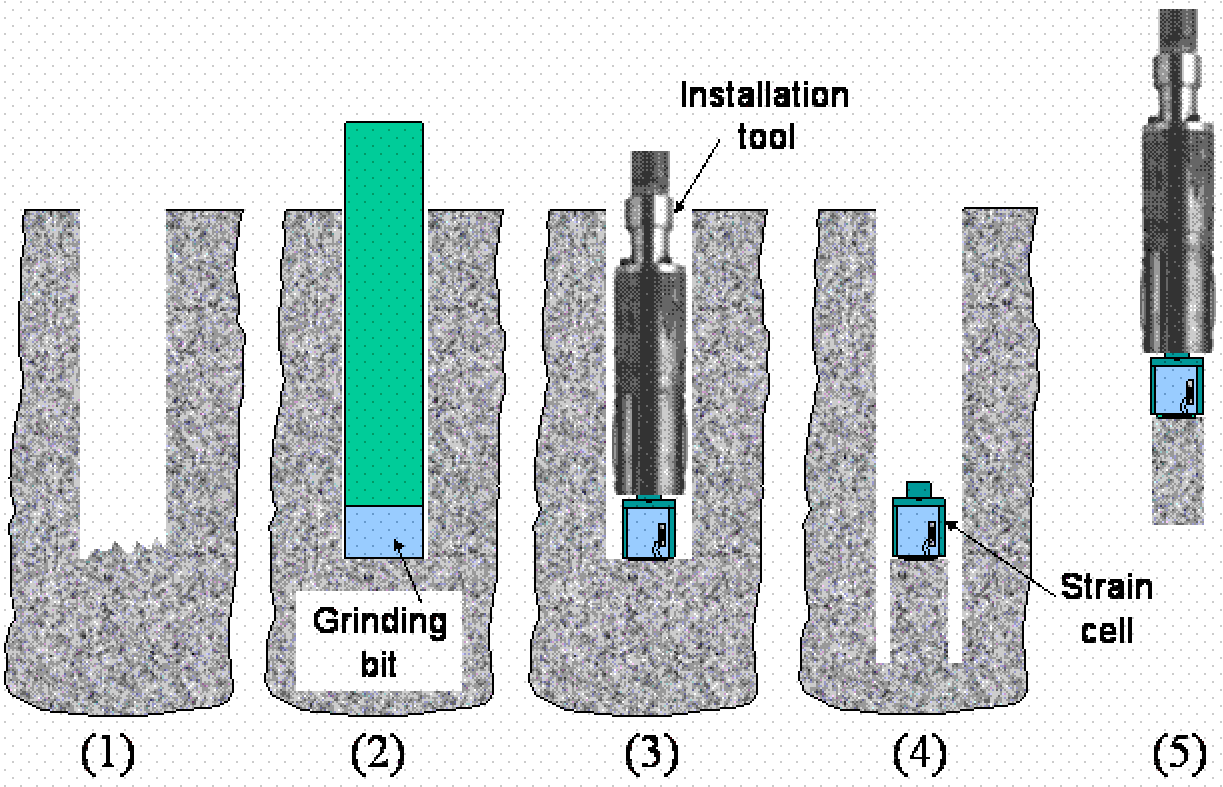
Overcoring

- Most convenient indirect system
- Requires, elastic though not necessarily linearly elastic response for analysis
- This means that failure of the borehole wall is a problem, i.e. if major stress is 1/3 to 1/2 of UCS breakout may occur

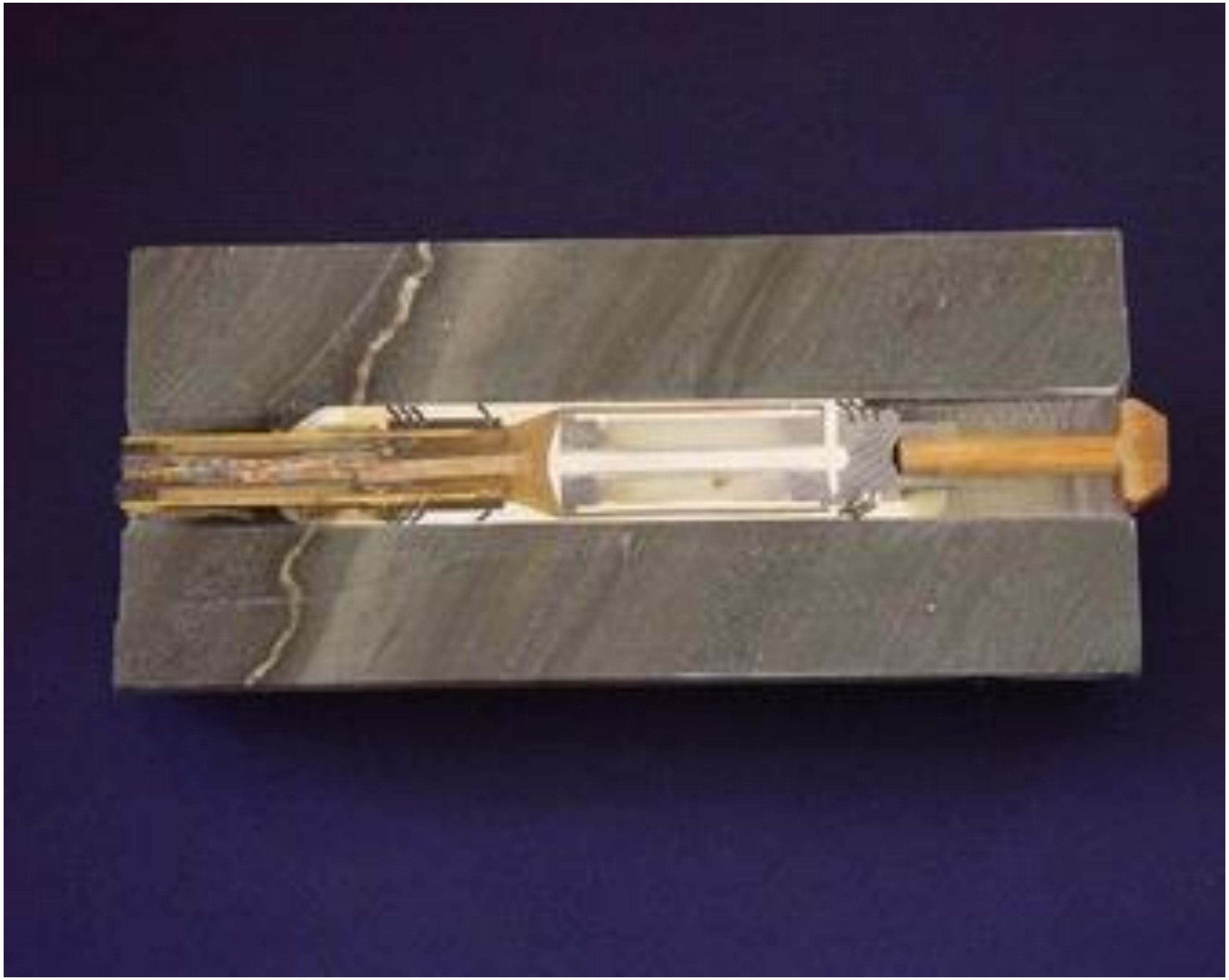
Overcore devices

- Glued devices – all give poor reliability in wet holes
  - Doorstoppers
  - Leeman Triaxial Cell - ANZSI cell
  - CSIRO HI Cell - Borre Probe
  - Cone cell
- Mechanical Devices
  - USBM deformation gauge
  - Sigra IST tool

Doorstopper



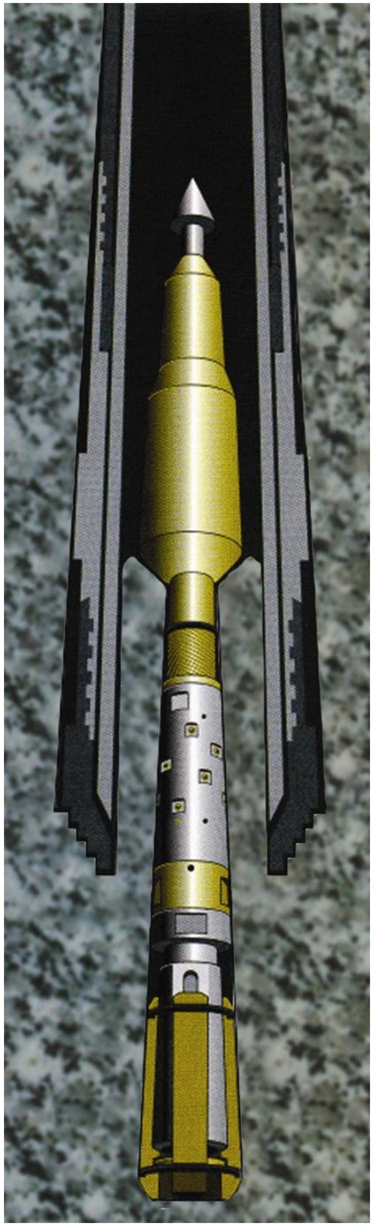
CSIRO HI Cell



Cone Cell

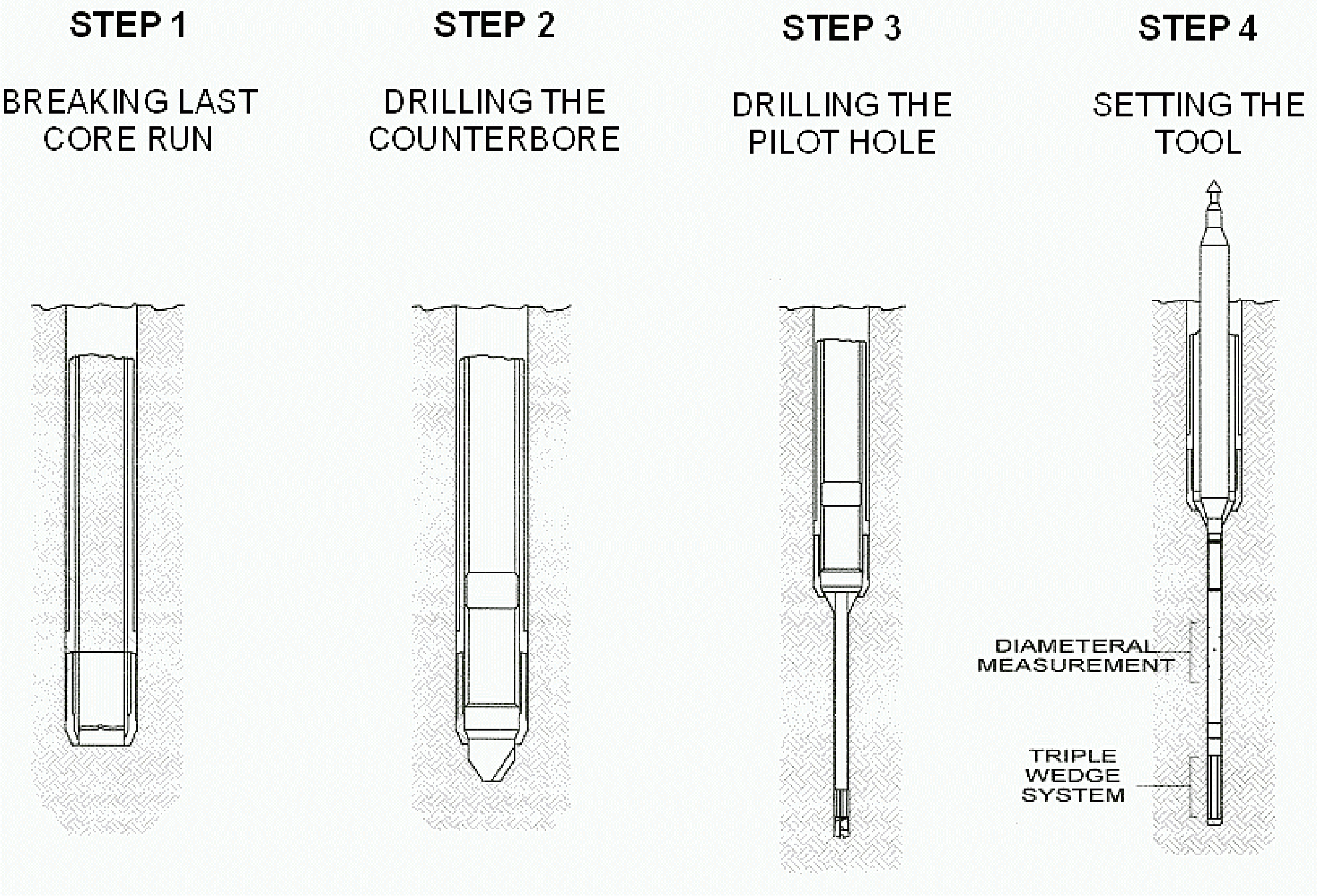
Sigra IST system

- Quick biaxial overcore system
  - 100 m hole overcore in 1 ½ hours
  - 500 m hole overcore in 3 hours
  - 800 m hole overcore in 4 hours
- Used primarily with HQ wireline coring system
- Mostly used in vertical holes
- Capable of operation to 1500 m vertical depth

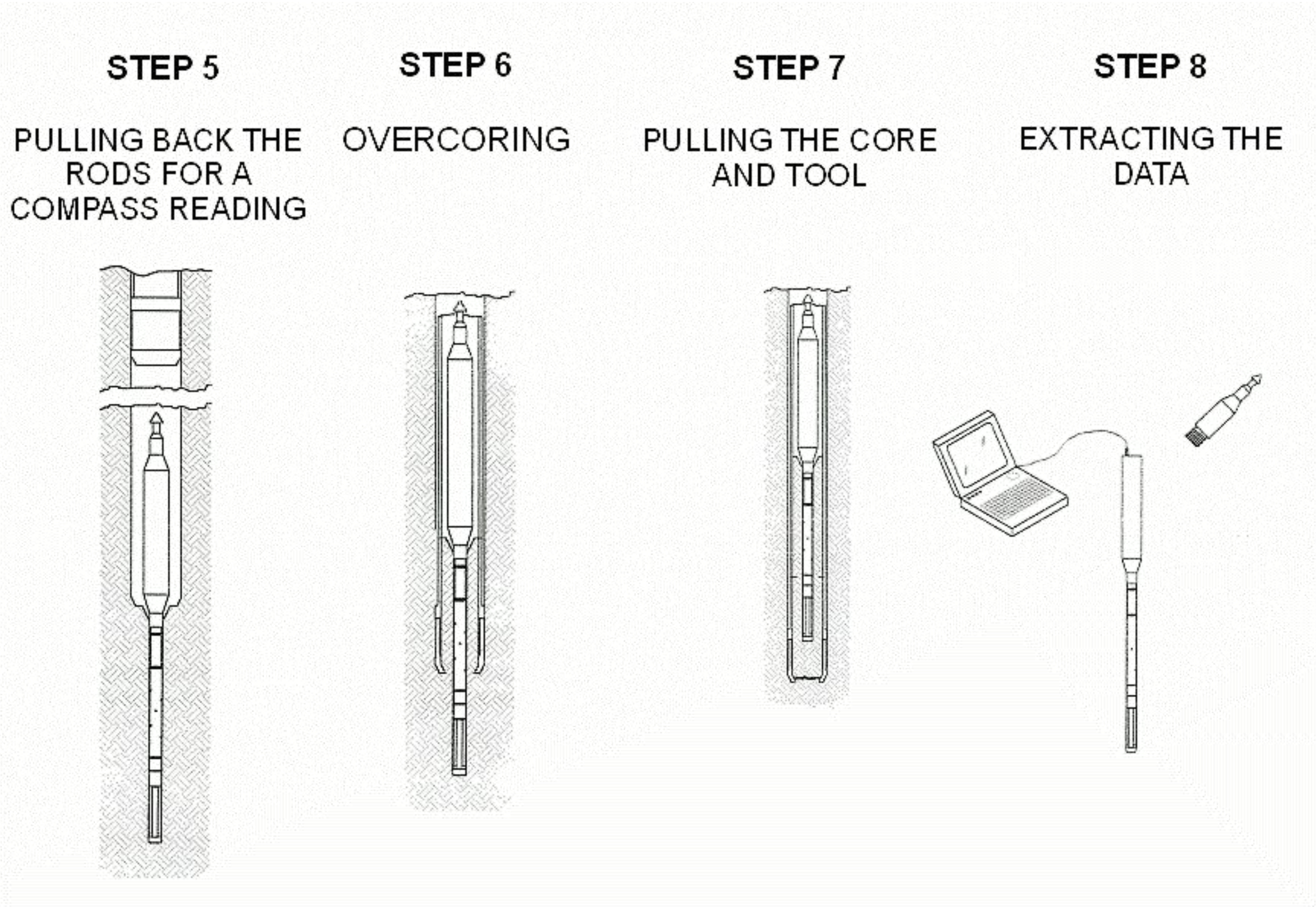


Sigra Stress Measurement Tool

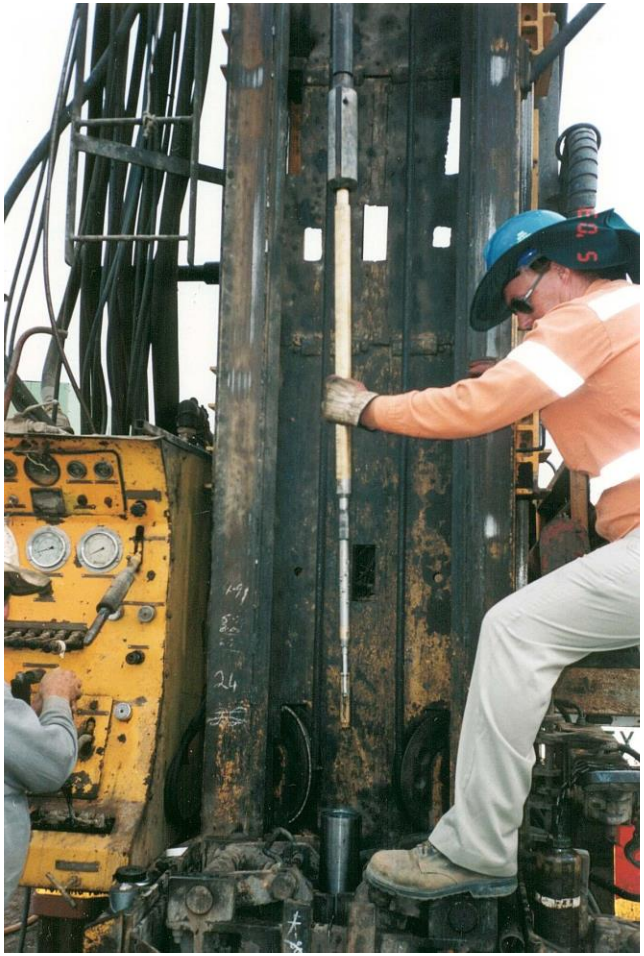
In-Situ Stress Measurement Tool



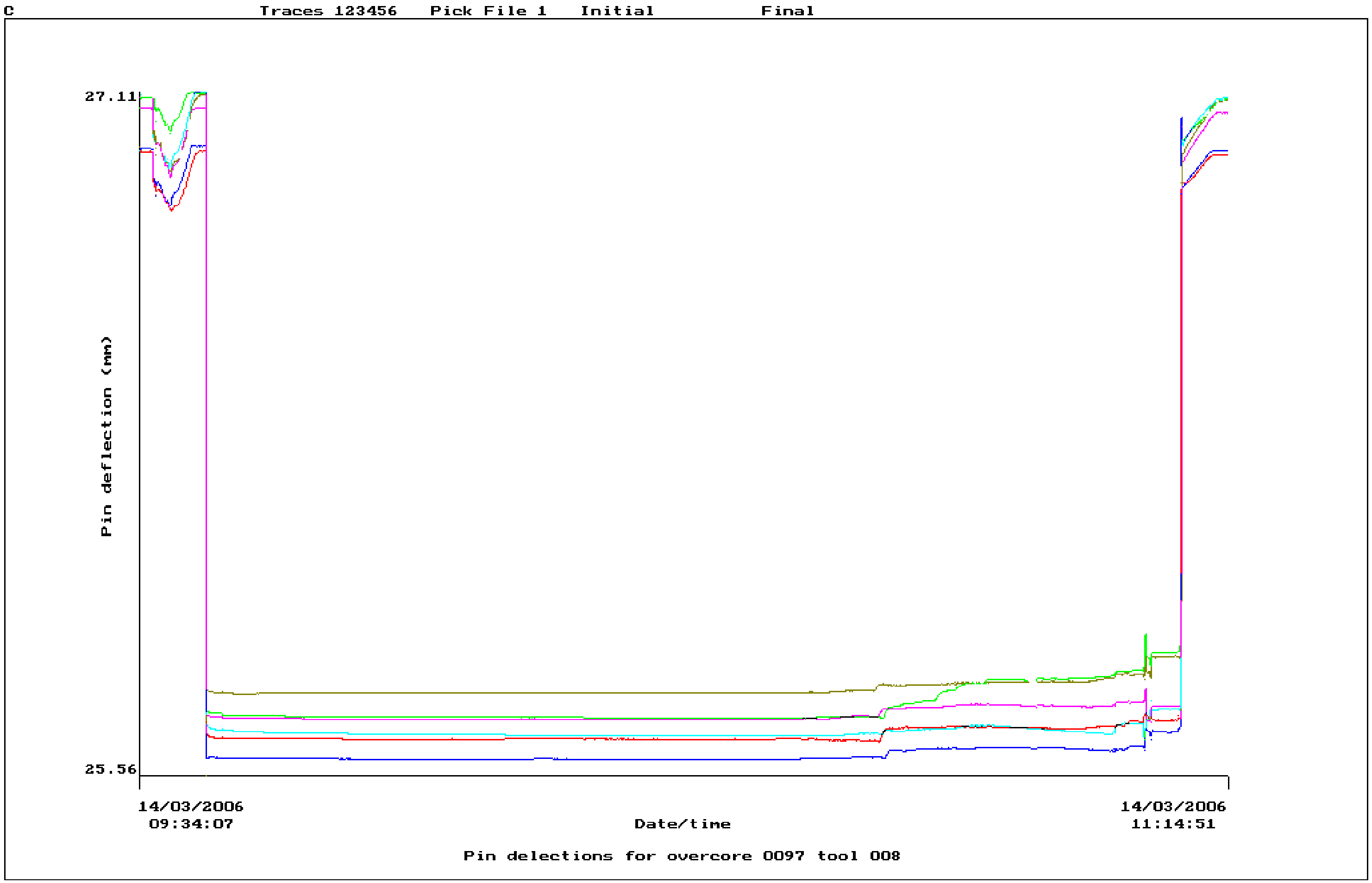
IN-SITU STRESS MEASUREMENT TOOL



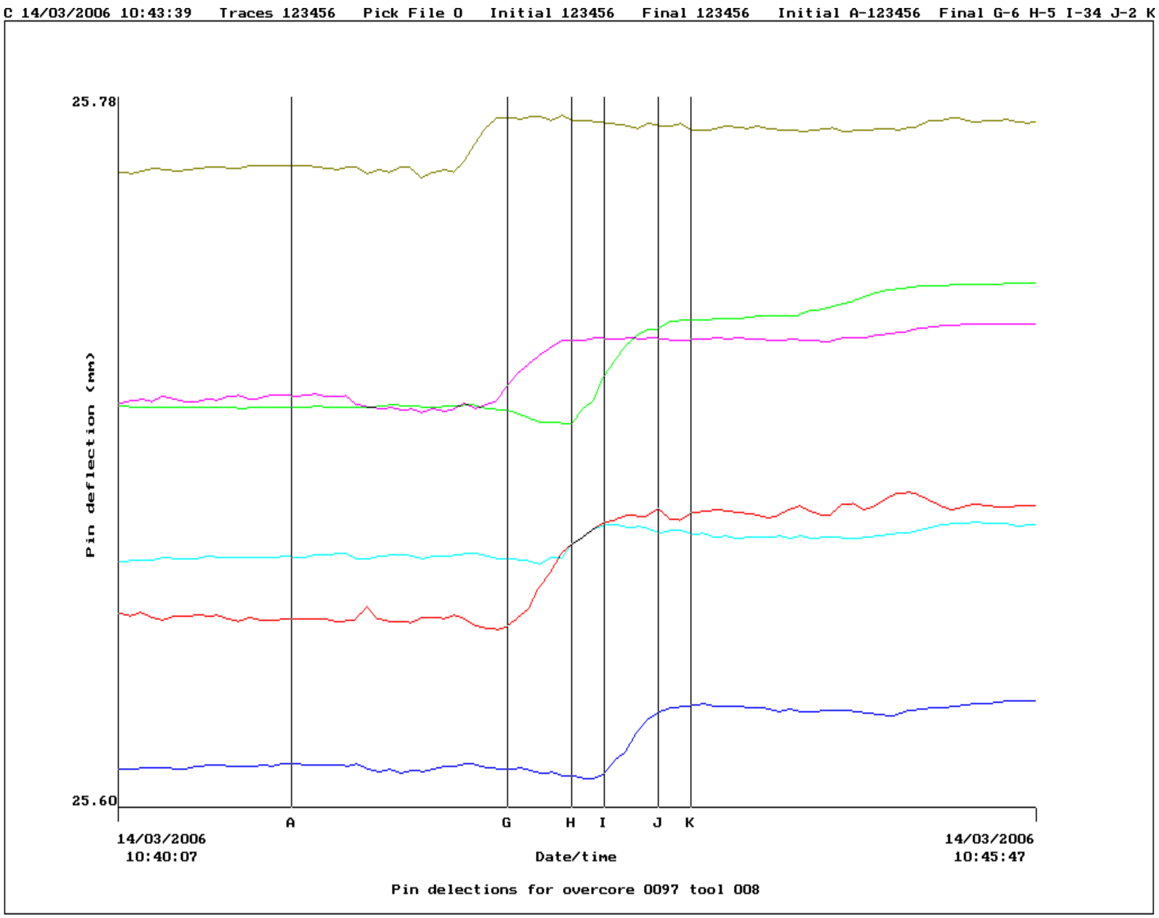
IST TOOL



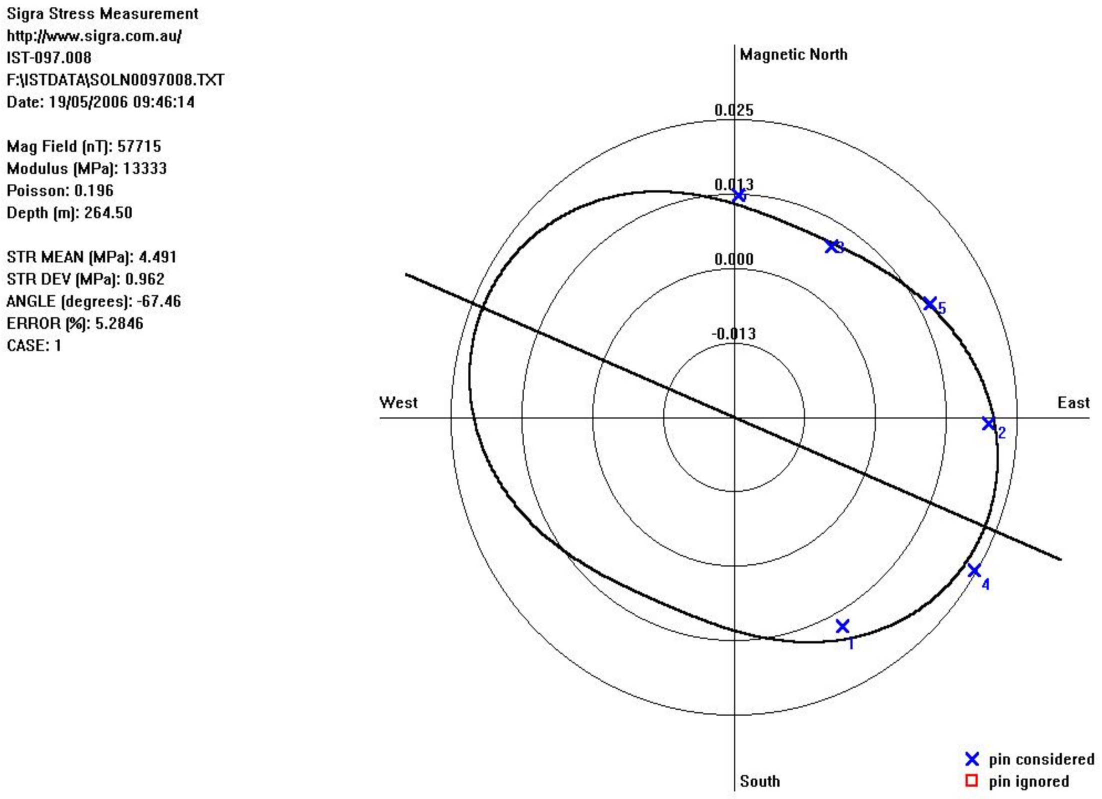
IST – TOTAL DEFORMATION



IST – OVERCORE DEFORMATION



IST RADIAL DEFORMATION & BEST THEORETICAL FIT



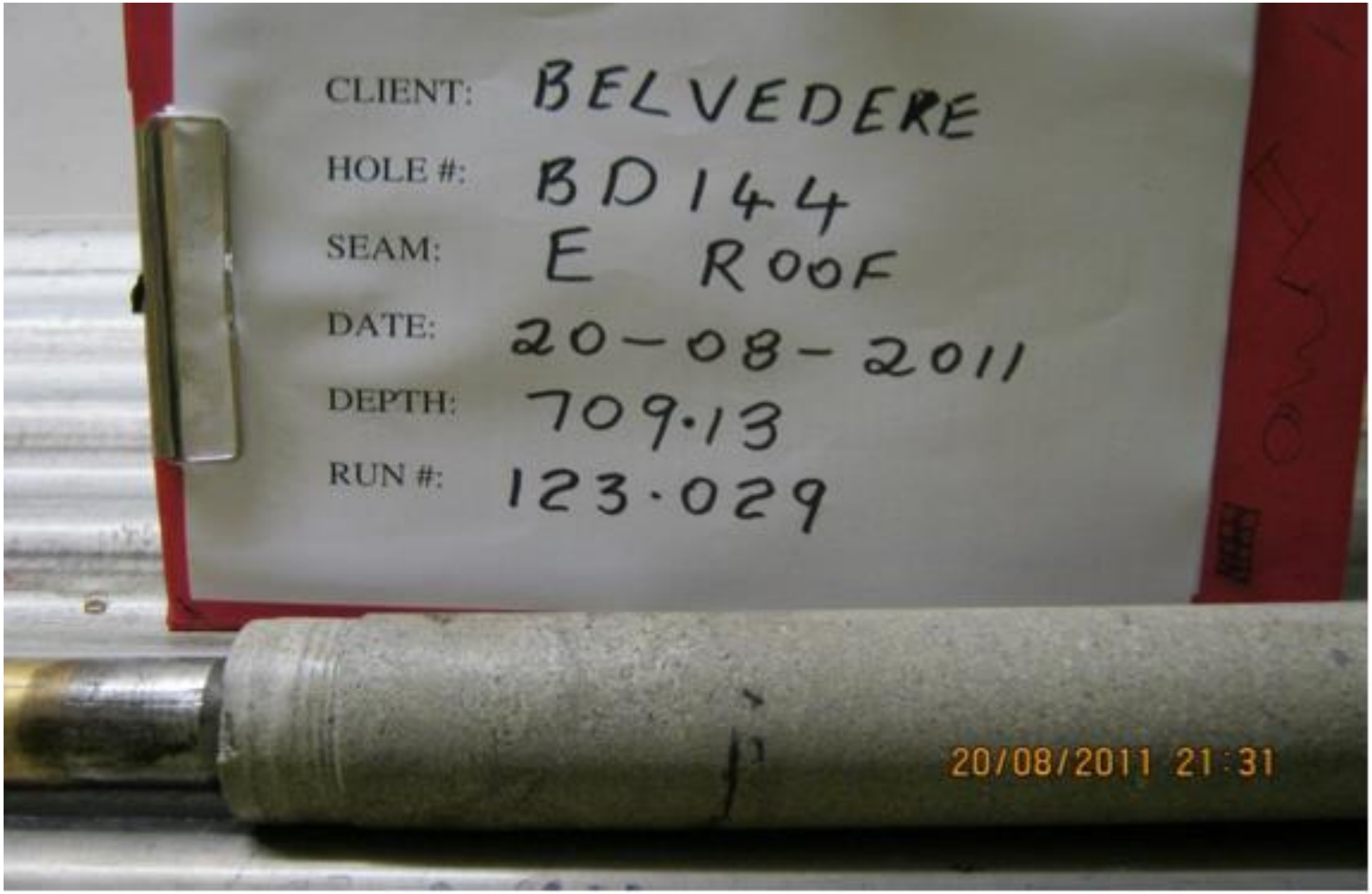
Sigra Stress Measurement
http://www.sigra.com.au/
IST-097.008
F:\ISTDATA\SOLN0097008.TXT
Date: 19/05/2006 09:46:14

Mag Field (nT): 57715
Modulus (MPa): 13333
Poisson: 0.196
Depth (m): 264.50

STR MEAN (MPa): 4.491
STR DEV (MPa): 0.962
ANGLE (degrees): -67.46
ERROR (%): 5.2846
CASE: 1

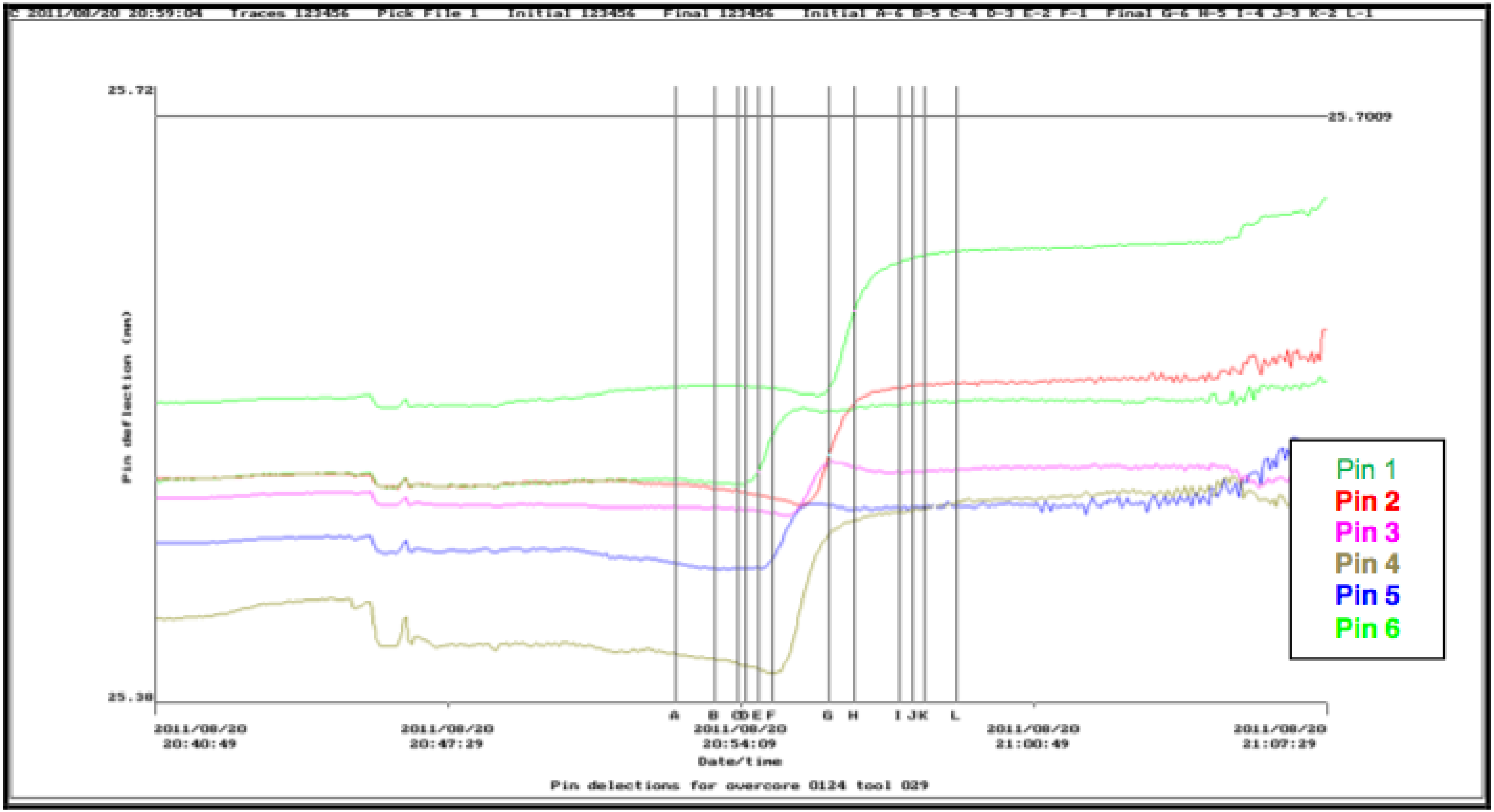
Combinations of Solution

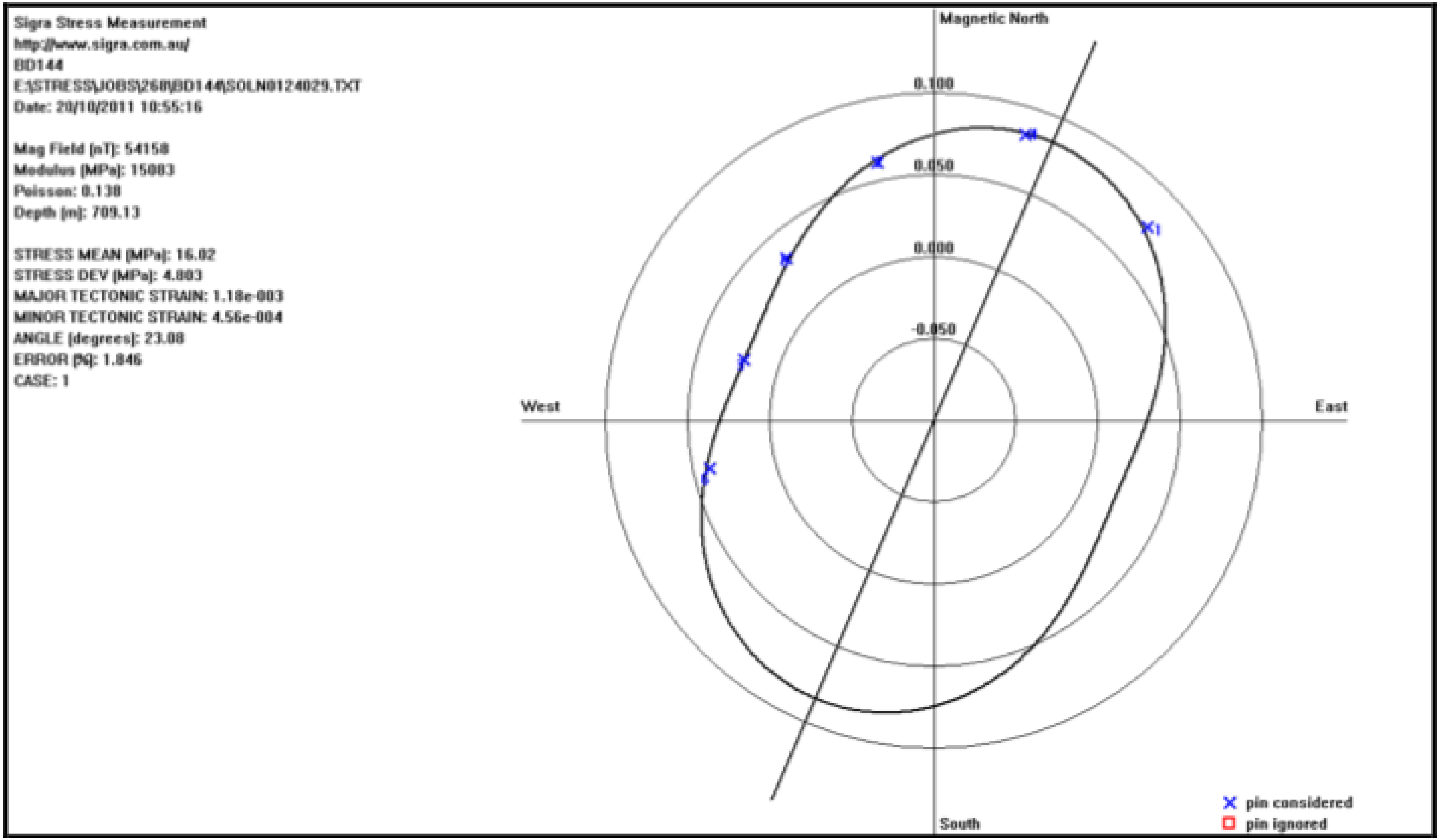
- 1 x 6 pin pair set solution
- 6 x 5 pin pair set solution
- 15 x 4 pin pair set solution
- 20 x 3 pin pair set solution – do not use as no redundancy
- Can handle minor breakout or fracture problems – just ignore pin result



CLIENT: BELVEDERE
HOLE #: BD144
SEAM: E ROOF
DATE: 20-08-2011
DEPTH: 709.13
RUN #: 123.029

20/08/2011 21:31


C 2011/08/20 20:59:04 Traces 123456 Pick File 1 Initial 123456 Final 123456 Initial A=6 B=5 C=4 D=3 E=2 F=1 Final G=6 H=5 I=4 J=3 K=2 L=1
25.72
25.7009
25.38
Pin deflection (mm)
A B CD E F G H I JK L
2011/08/20 20:40:49
2011/08/20 20:47:29
2011/08/20 20:54:09
2011/08/20 21:00:49
2011/08/20 21:07:29
Date/time
Pin delections for overcore 0124 tool 029
Pin 1
Pin 2
Pin 3
Pin 4
Pin 5
Pin 6



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Sigra Stress Measurement
http://www.sigra.com.au/
BD144
E:\STRESS\JOBS\268\BD144\SOLN0124029.TXT
Date: 20/10/2011 10:55:16

Mag Field (nT): 54158
Modulus (MPa): 15003
Poisson: 0.138
Depth (m): 709.13

STRESS MEAN (MPa): 16.02
STRESS DEV (MPa): 4.803
MAJOR TECTONIC STRAIN: 1.18e-003
MINOR TECTONIC STRAIN: 4.56e-004
ANGLE (degrees): 23.08
ERROR (%): 1.846
CASE: 1
```

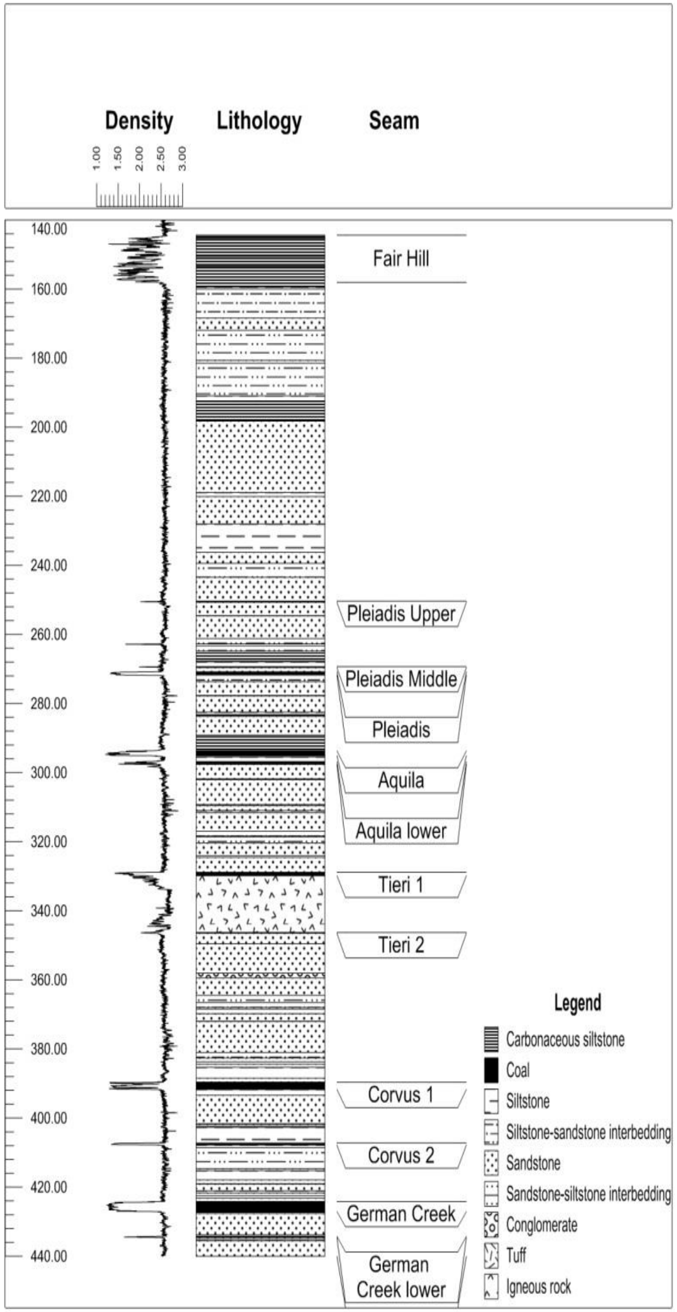
Hole Reference	BD144	
Sigra In-situ Stress Test (IST) Reference	124.029	
Date of Test	20 Aug 2011	
Material Description	Sandstone	
Depth of Run	709.13	m
Young's Modulus	15,083	MPa
Poisson's Ratio	0.14	
Unconfined Compressive Strength, UCS	74.60	MPa
Mean Effective Stress	16.02	MPa
Deviatoric Stress	4.80	MPa
Angle of Principal Effective Stress	23.08	Degrees from Magnetic North
RMS Error	1.80	%
Maximum Principal Effective Stress	20.82	MPa
Minimum Principal Effective Stress	11.22	MPa
Ratio of Maximum Effective Stress over UCS	0.28	
Horizontal Effective Stress due to Self-weight	1.70	MPa
Maximum Tectonic Stress	19.12	MPa
Minimum Tectonic Stress	9.51	MPa
Maximum Tectonic Strain	1.18E-03	
Minimum Tectonic Strain	4.56E-04	

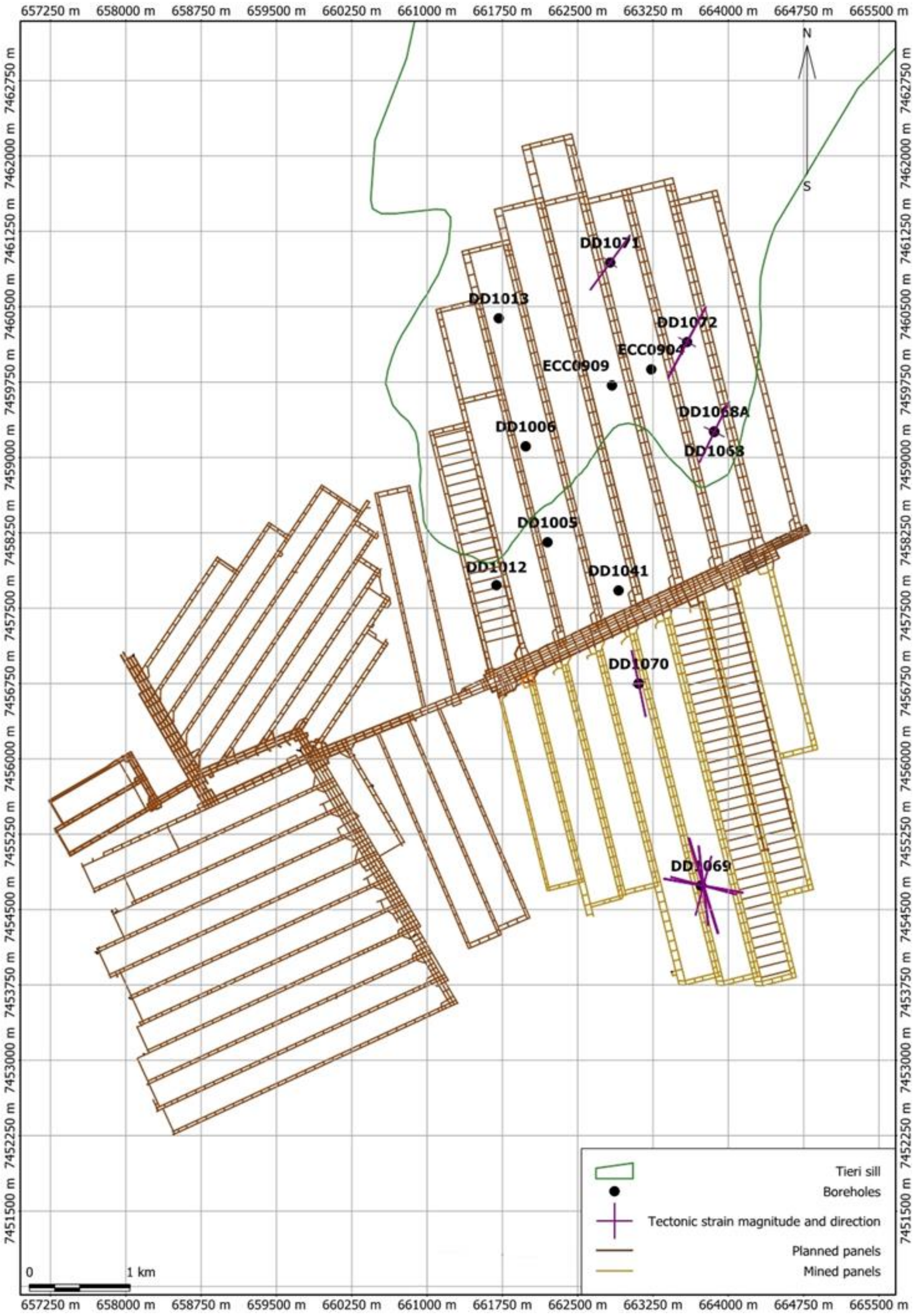
Used in multiple rock types

- Very weak rock with UCS of 4 MPa – Crinum Colliery

- Very hard rock with UCS of 280 MPa and stiffness of 80 GPa at Burdekin Falls Dam Spillway

Sedimentary sequence at Grasstree Mine German Creek seam mined first below Aquila seam

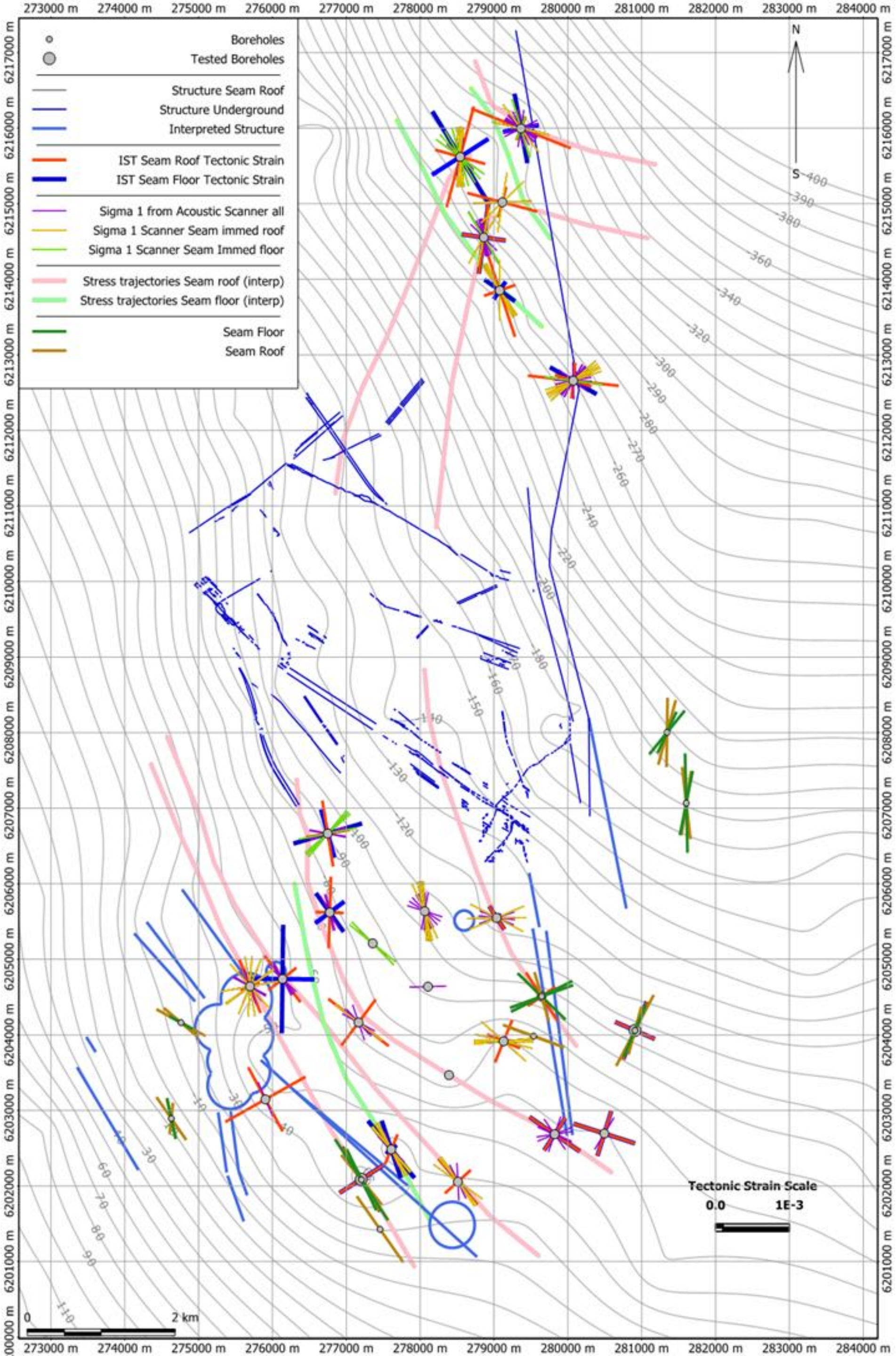




Grasstree mine tectonic strains of unmined area in north and above mined area to south where stresses are aligned with the longwall block

Grasstree Conclusions

- Even tectonic strains throughout sequence in unmined areas
- Similar apparent tectonic strains 120 m above goaf of German Creek seam but re-orientated
- Mid panel – in line with longwall panel
- Over top of pillars - variable



Illawarra Site Complex stress distribution and rotation of direction

Illawarra Site

- Original NE-SW stress orientation
- Very complex stress distribution
  - Required IST, borehole breakout & seismic to understand
- Principal stress directions rotated up to 90 degrees
  - Due to reverse and slip strike faulting relieving stress
  - Frequent reverse faulting leading to in-seam shears