Where is the *Non-Linear* Rock Mechanics in the *Linear* Geomechanics of Gas Shales?

Nick Barton, NB&A, Oslo, Norway

www.nickbarton.com

WHY THIS LECTURE?

In other countries there is less space!

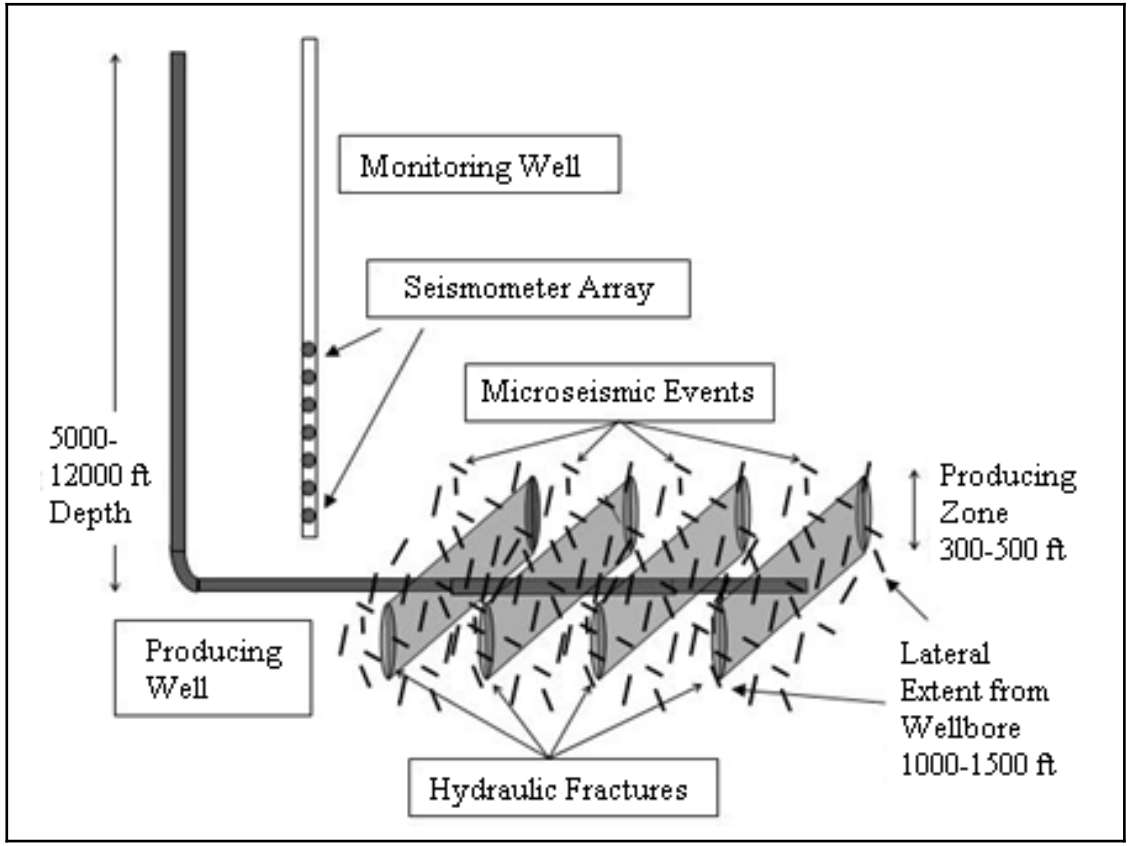
We may need improved *understanding, characterization, modelling,* to get optimal production *from far fewer wells.*

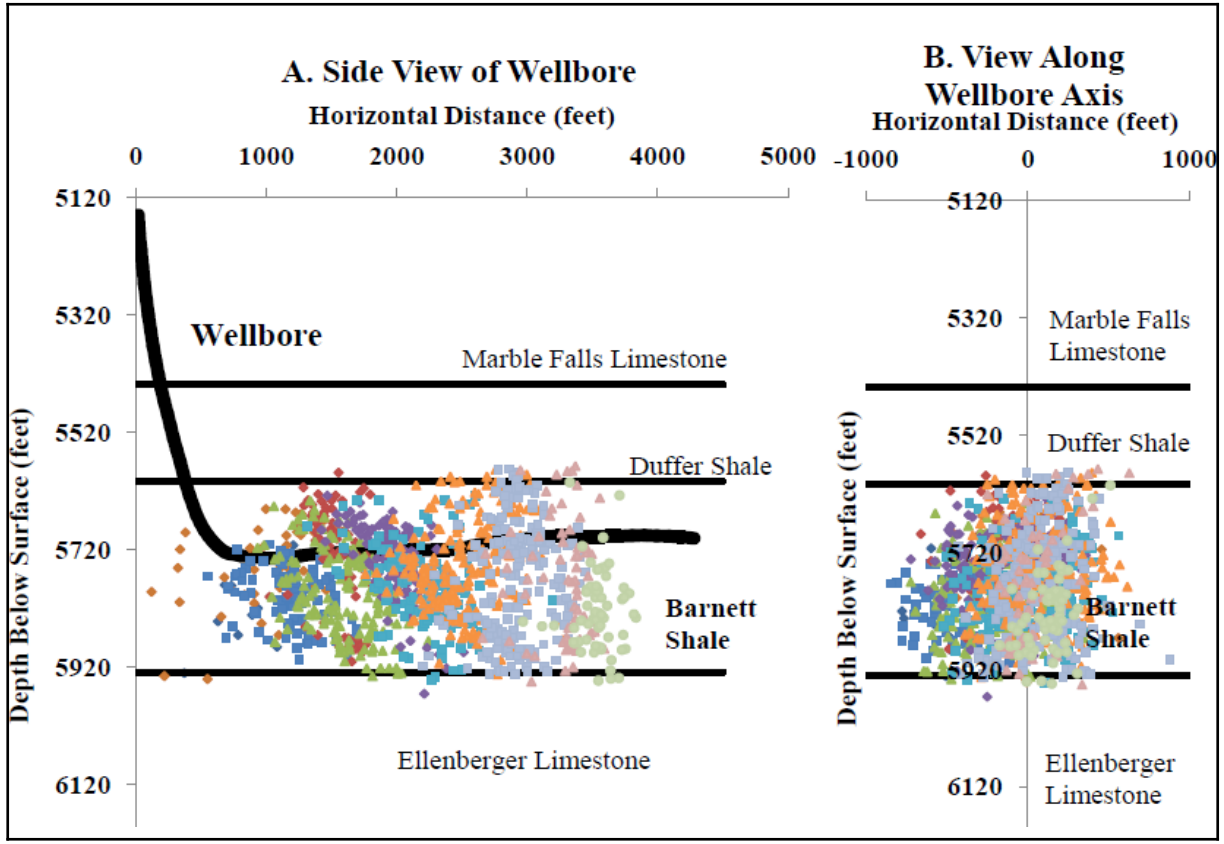
CONTENT of LECTURE

1. WHAT DO THE MICROSEISMIC DATA REPRESENT?
2. THE QUESTION IN THE TITLE: LINEAR OR NON-LINEAR (matrix, fractures)?
3. SUFFICIENT MATRIX STRENGTH AND SUFFICIENT MODULI ARE NEEDED
4. THE ROLE OF FRACTURE SHEAR DEFORMATION – AN INTRODUCTION
5. INPUT DATA NEEDED FOR NON-LINEAR SHEAR BEHAVIOUR: JRC, JCS, φr
6. STRESS-CLOSURE-PERMEABILITY IS THE *NEGATIVE* RESULT
7. SHEAR-DILATION-PERMEABILITY IS THE *POSITIVE* RESULT
8. DO SCALE EFFECTS IN SHEAR ASSIST LONGER PRODUCTION?
9. THE MOBILIZED ROUGHNESS CONCEPT
10. HYDRAULIC AND PHYSICAL APERTURES AND THEIR CONVERSION
11. CONCLUSIONS

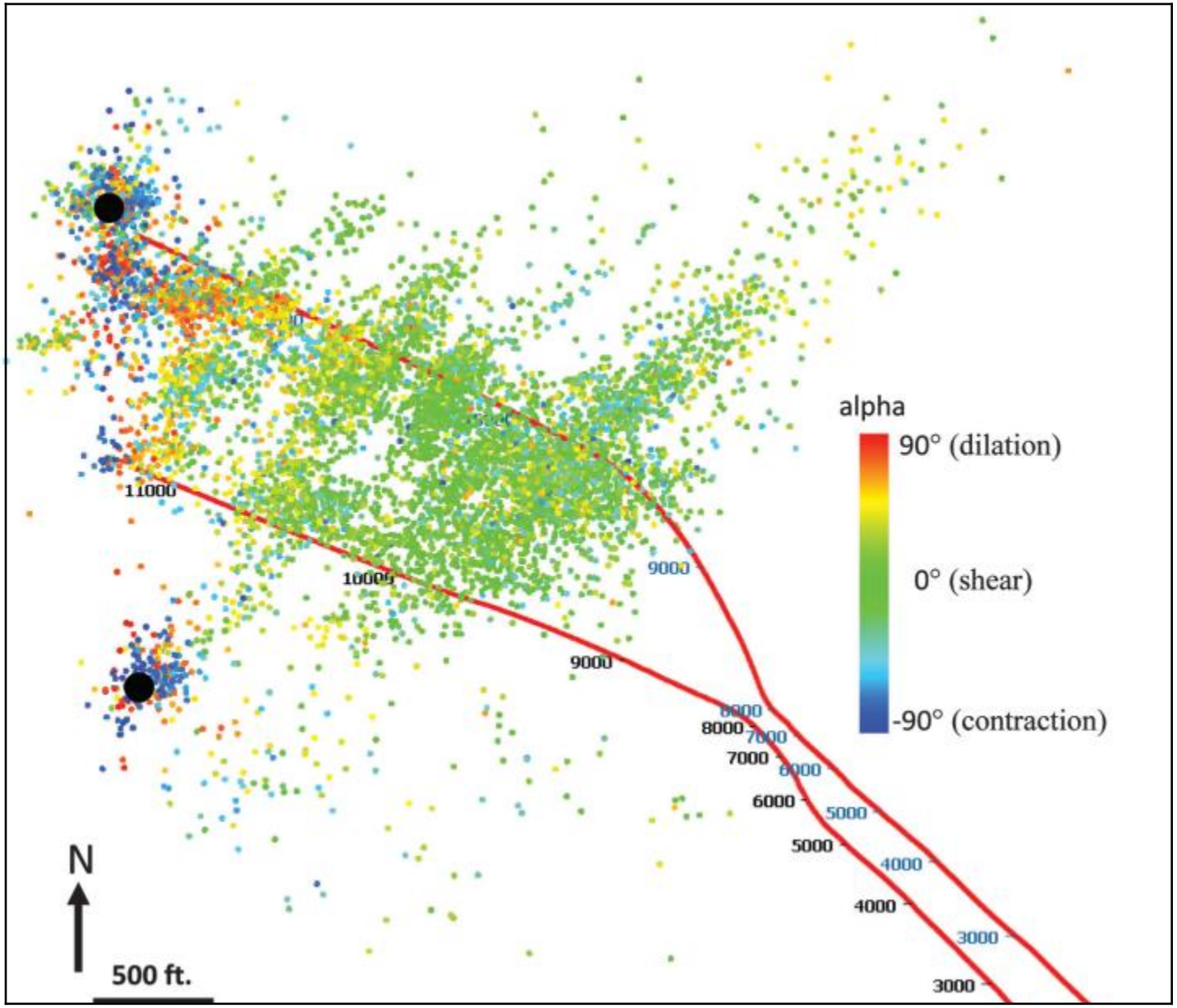
1. WHAT DO THE MICROSEISMIC DATA REPRESENT?

The ability to shear natural fractures beyond the peripheries of the ellipsoidally-propped region, in order to gain surface area, appears to be the key to maintenance of flow, is stated in King, 2010.





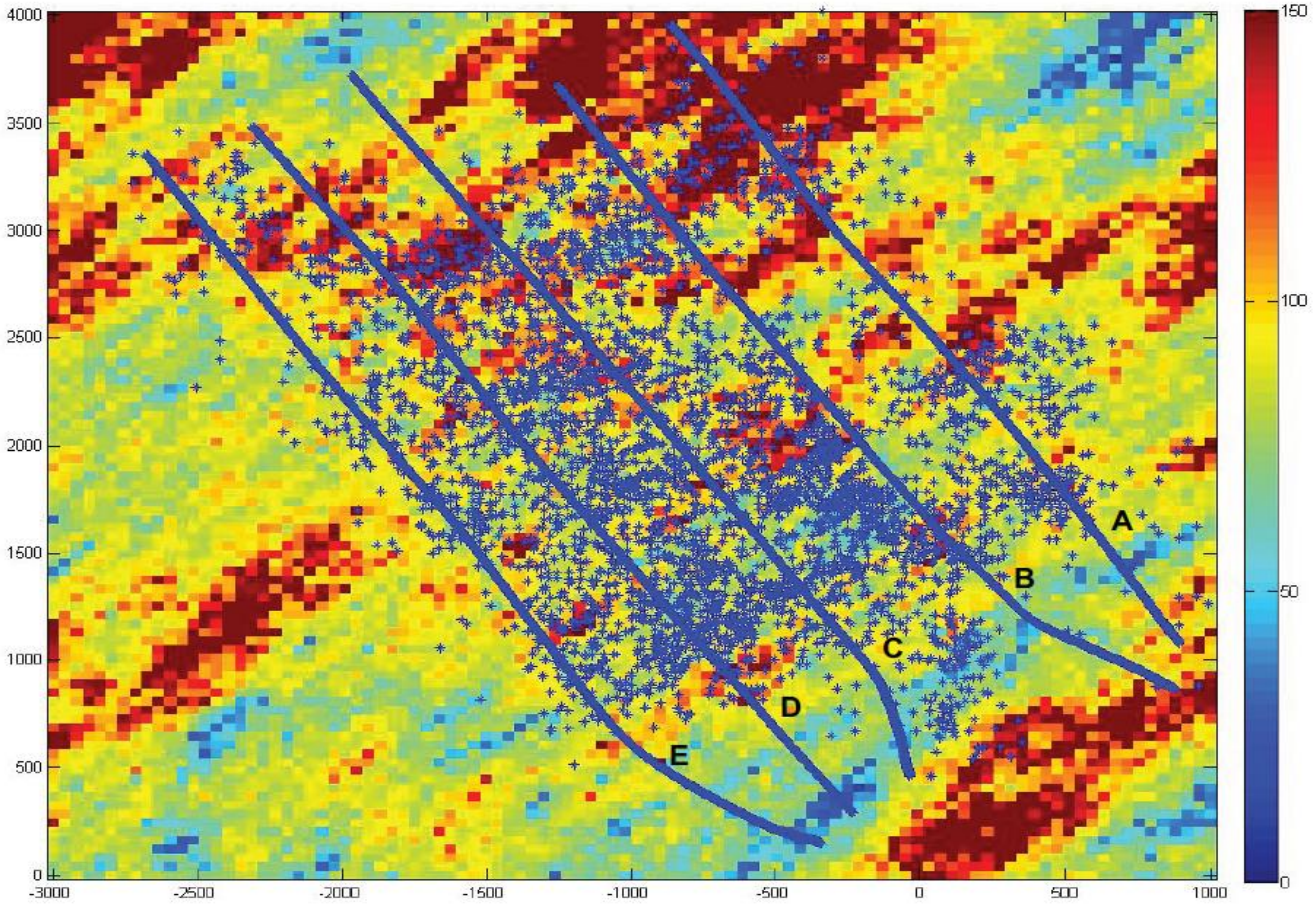
THE MICROSEISMIC EVENTS – WHAT DO THEY ACTUALLY REPRESENT? (Zoback et al. 2010)



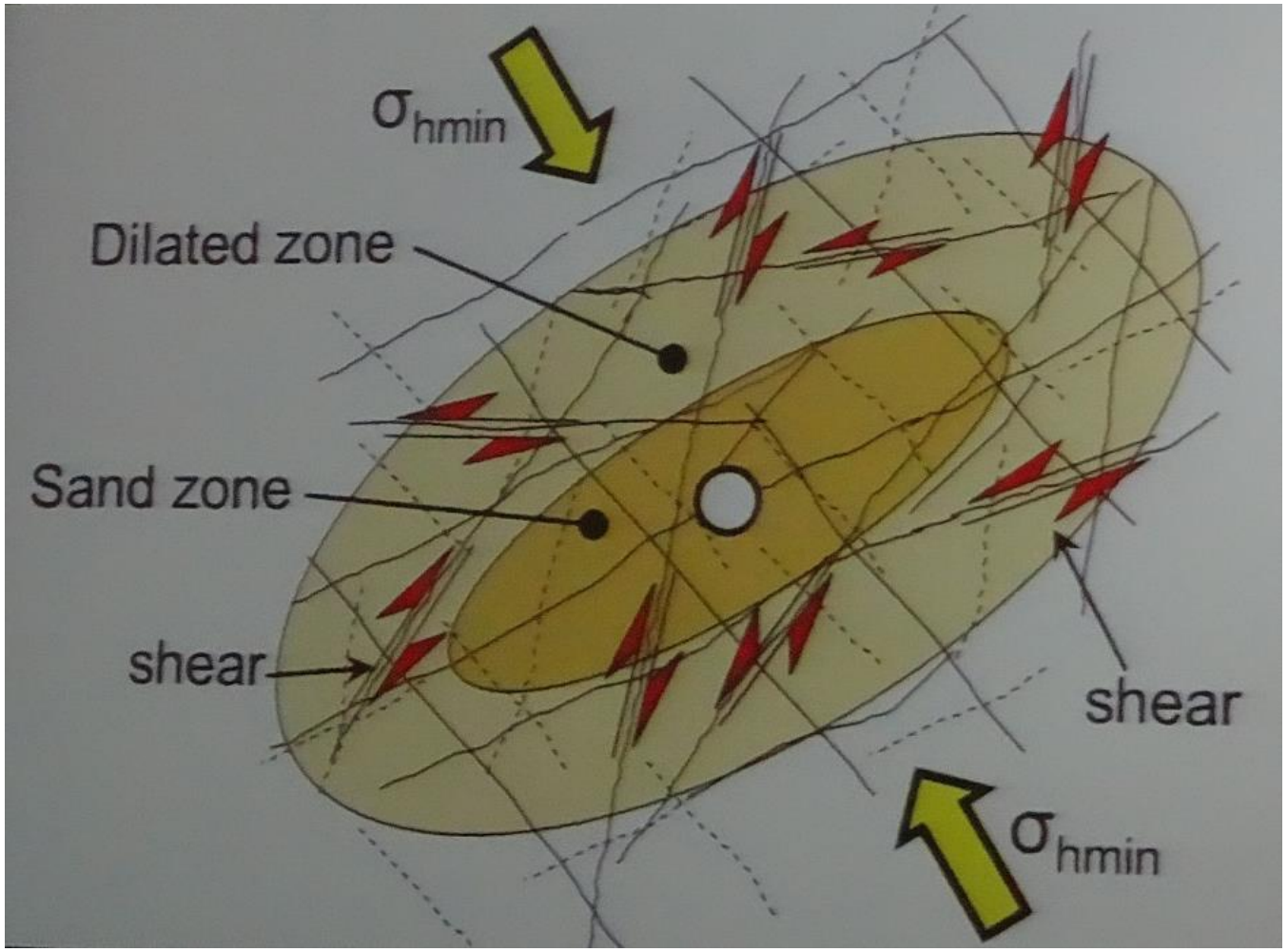
Barnett shale:
First stage fracturing, and a sophisticated interpretation of the microseismic. Conoco-Philips/Baker Hughes.

Geomechanics of hydraulic fracturing microseismicity: Part 1. Shear, hybrid, and tensile events. Busetti, Jiao, and Reches.

An interesting dependence of microseismic frequency-of-observation (+) and approx. clay content (from gamma-log plot). Aliyev and Wilson, referenced by Zoback et al., 2012.



CAN WE ASSUME (figuratively-speaking) THAT SOMETHING LIKE THIS MAY LIE BEHIND THE MOCROSEISMIC ACTIVITY? (DUSSEAULT, 2013)

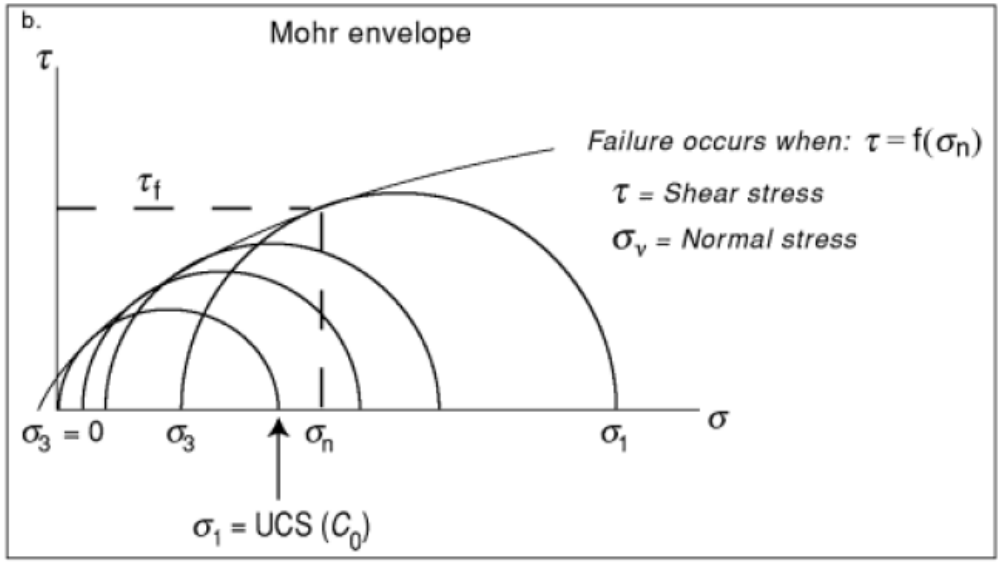


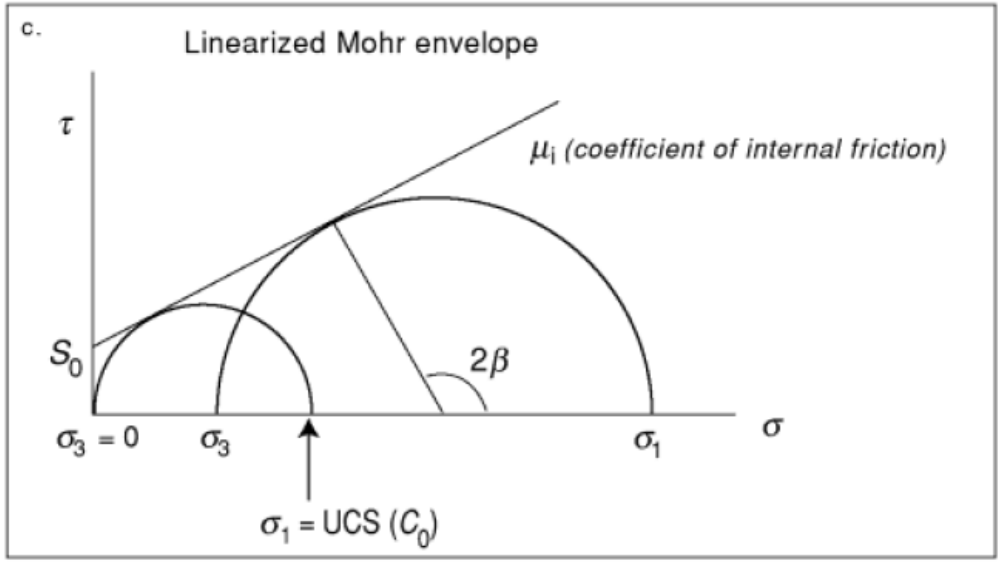
THE PROBLEM OF PRODUCTION FROM GAS SHALE WOULD SEEM TO BE VERY MUCH ROCK MECHANICS RELATED

DOES THE GEOMECHANICS SO FAR SEEN MAKE USE OF KNOWLEDGE ABOUT ROCK STRENGTH AND STIFFNESS BEHAVIOUR AND COUPLED (M-H) FRACTURE BEHAVIOUR?

IT SEEMS TO BE BASED ON OLD (LINEAR STRENGTH) CONCEPTS AS COMMONLY SEEN IN PRESENTATIONS IN GEOMECHANICS.

2. THE QUESTION IN THE TITLE: LINEAR OR NON-LINEAR? (matrix and fractures)

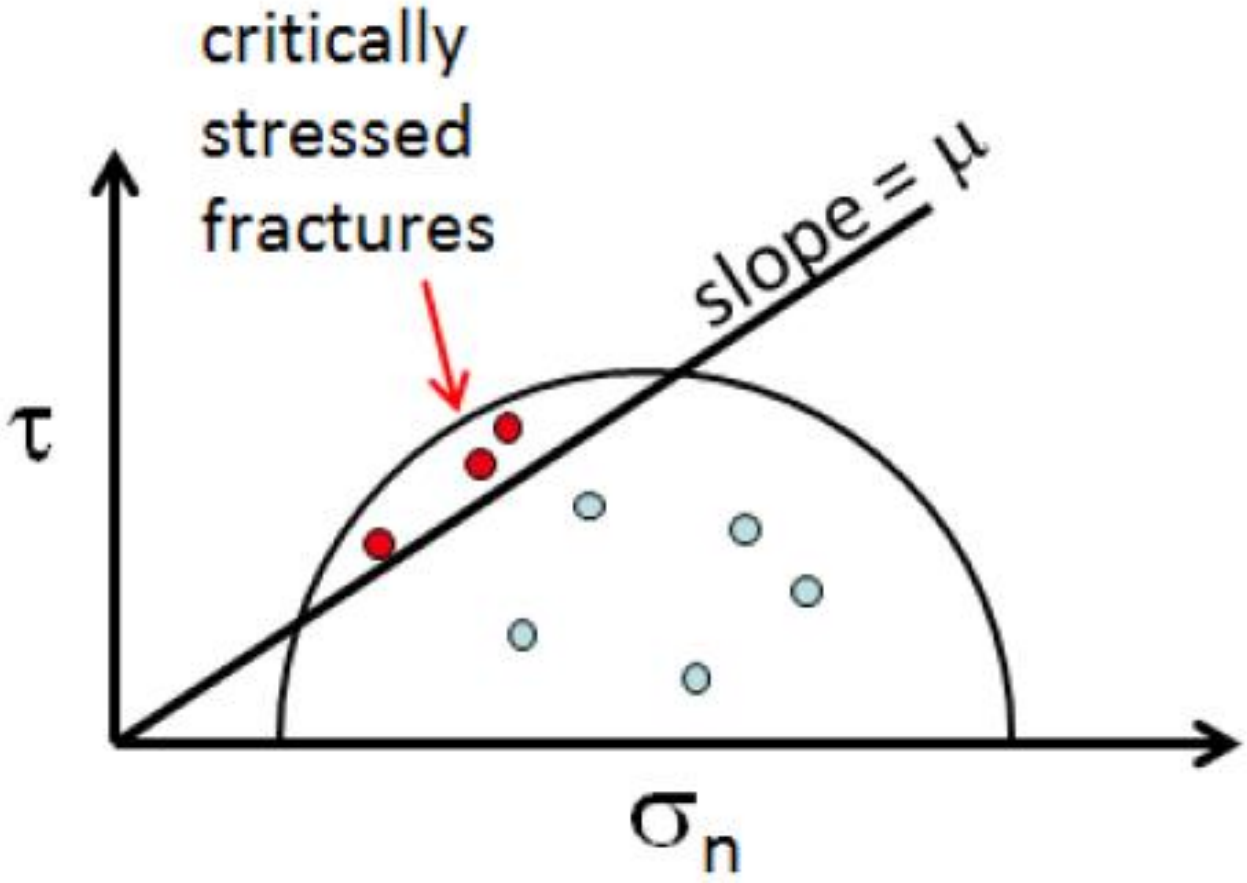




Mohr envelopes (are most often curved, for fitting to triaxial tests)

THE LINEARIZATION WHICH IS MOST FREQUENTLY USED IN GEOMECHANICS.

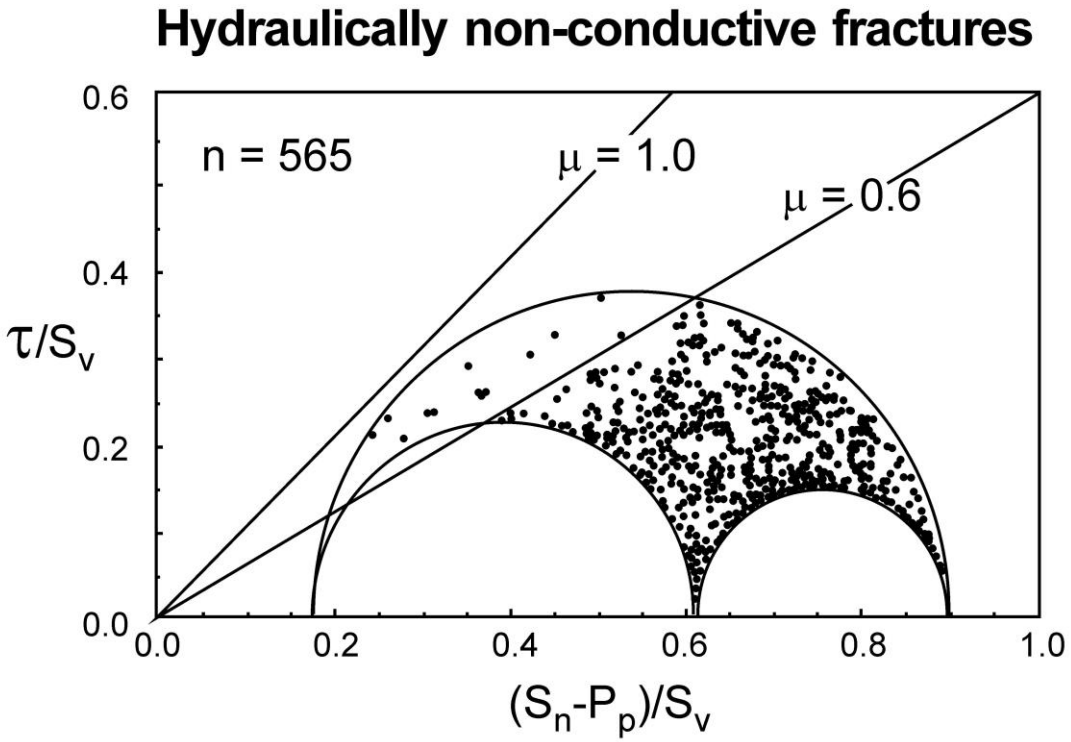
WHY? TO MAKE IT SIMPLER?



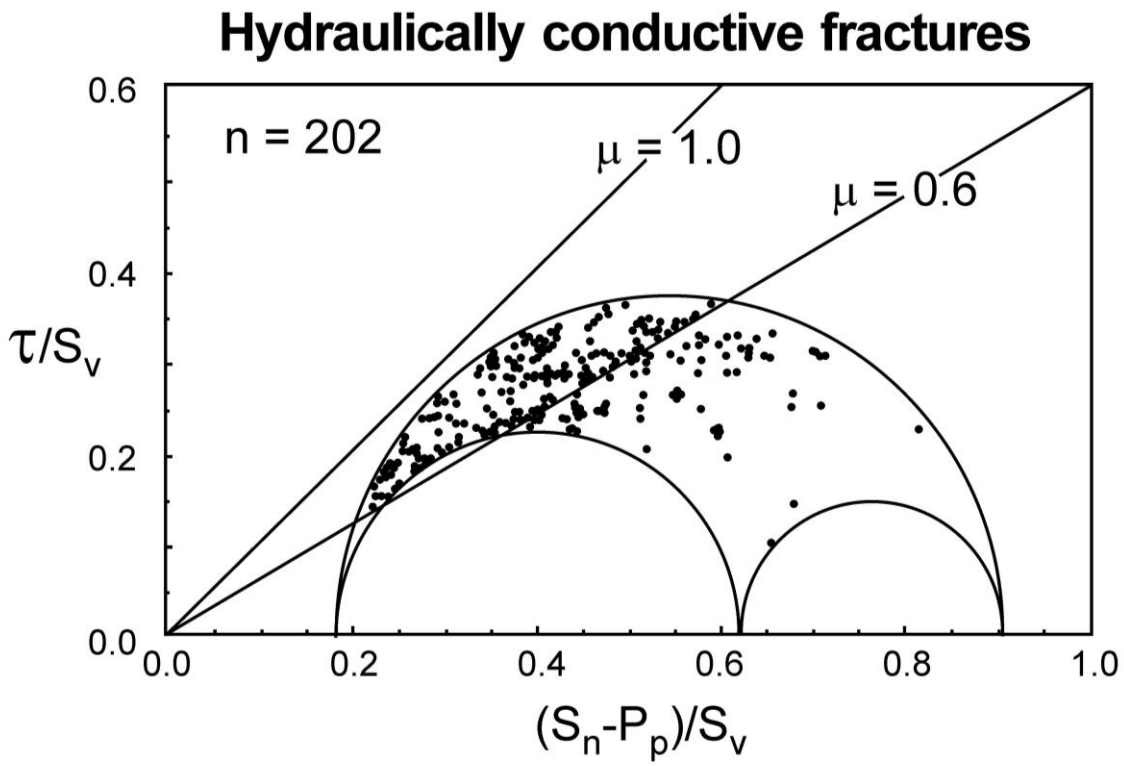
The 'CRITICALLY STRESSED FRACTURE' concept, as promoted by Stanford/following Byerlee, Zoback, C.Barton et al.

An illustration of the Stanford 'Model':

Below: Hydraulically conductive fractures
Note use of linear
'Byerlee friction coefficient',
as used in Stanford for many decades.

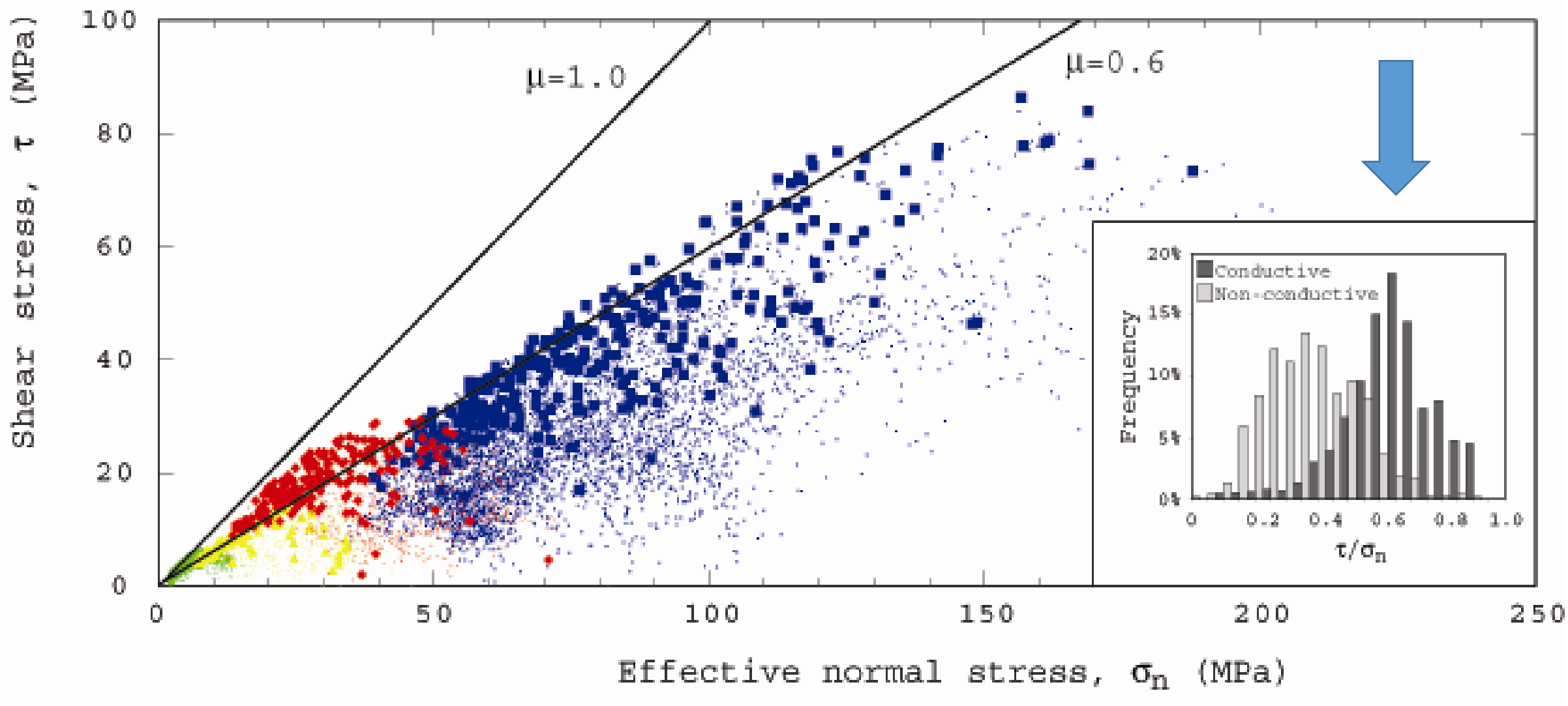


Above: Non-conductive fractures (fractures detected in crystalline-rock well-logs)



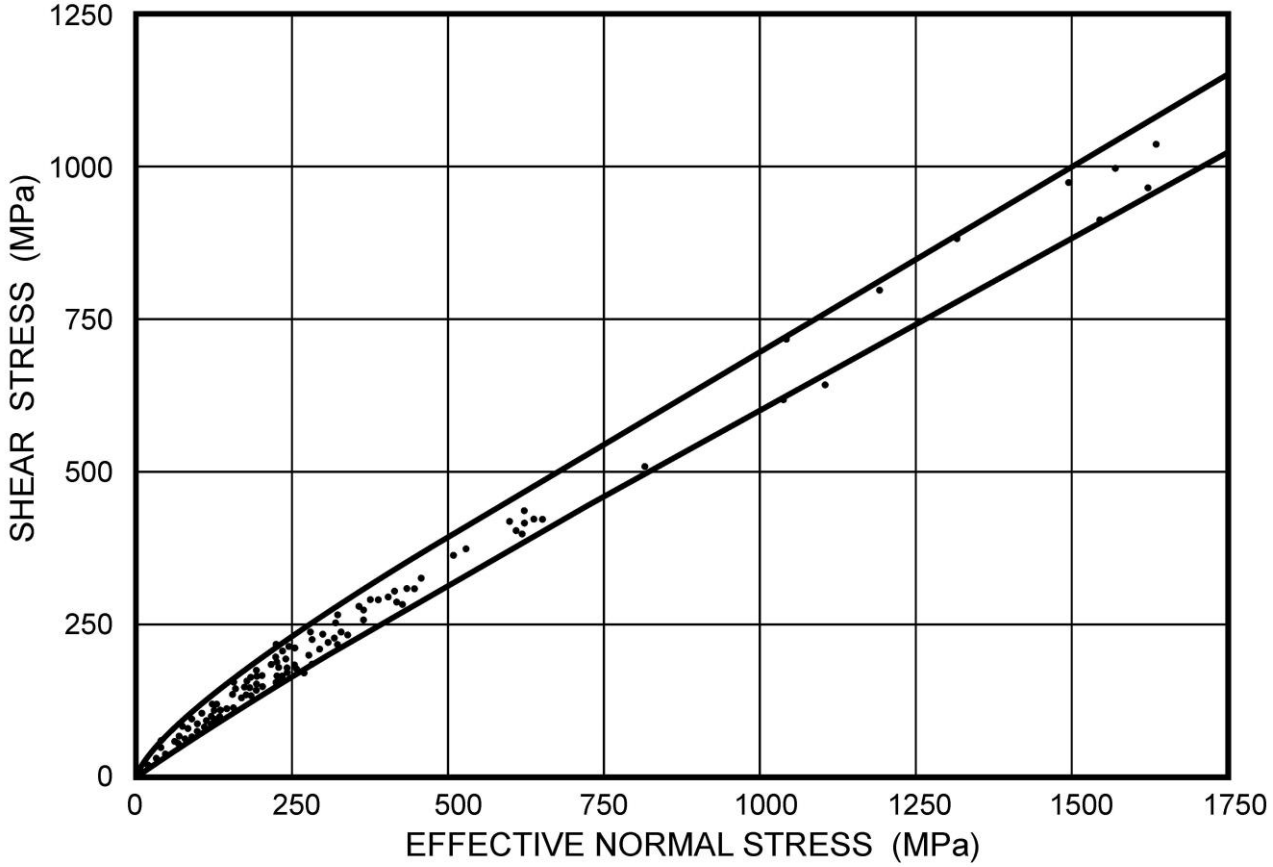
Conducting features are under greater shear stress. Note many values < 0.6.

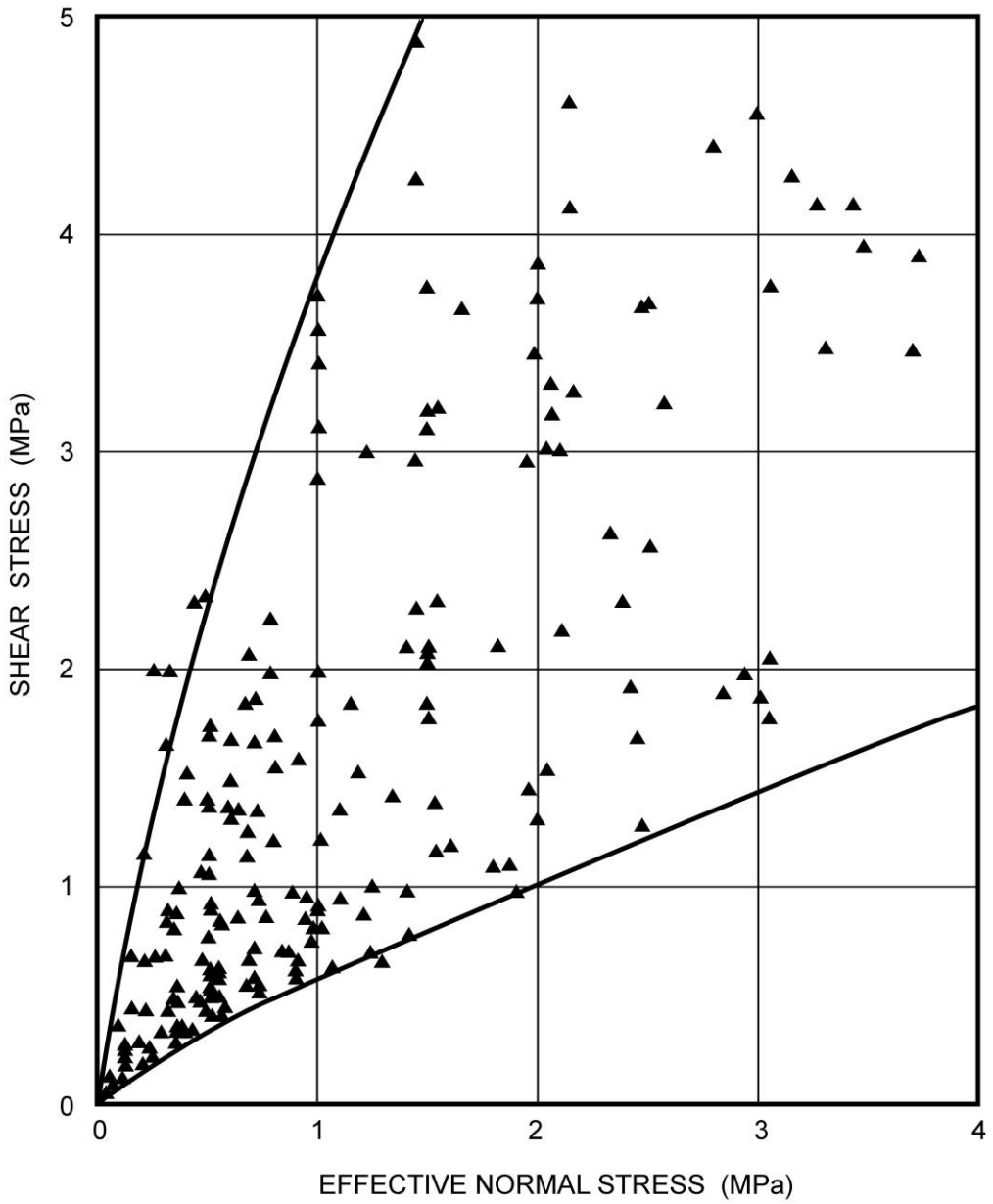
C. Barton et al., 1995, Townend and Zoback, 2000, Zoback and Townend, 2001



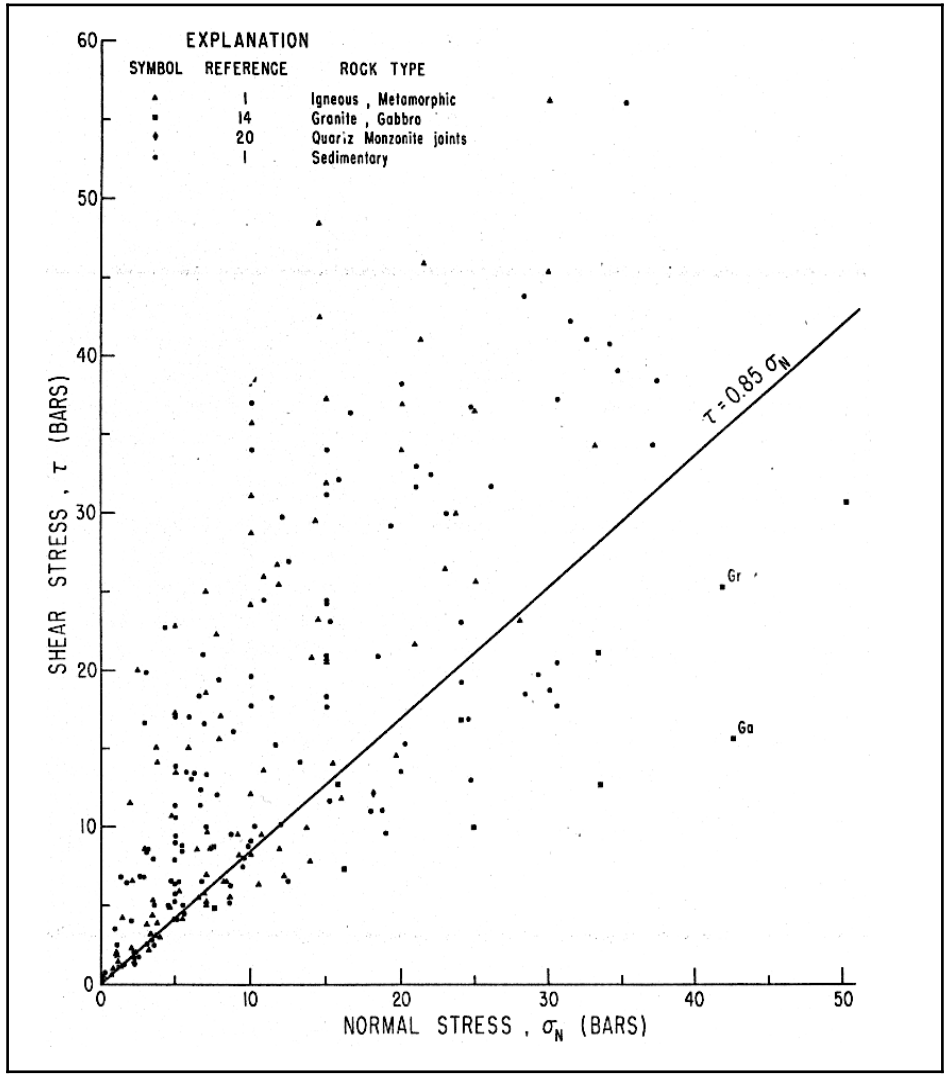
Shear strength of fractured (triaxial) miniature rock samples *and natural rock joints* at widely different stress levels (and sizes).

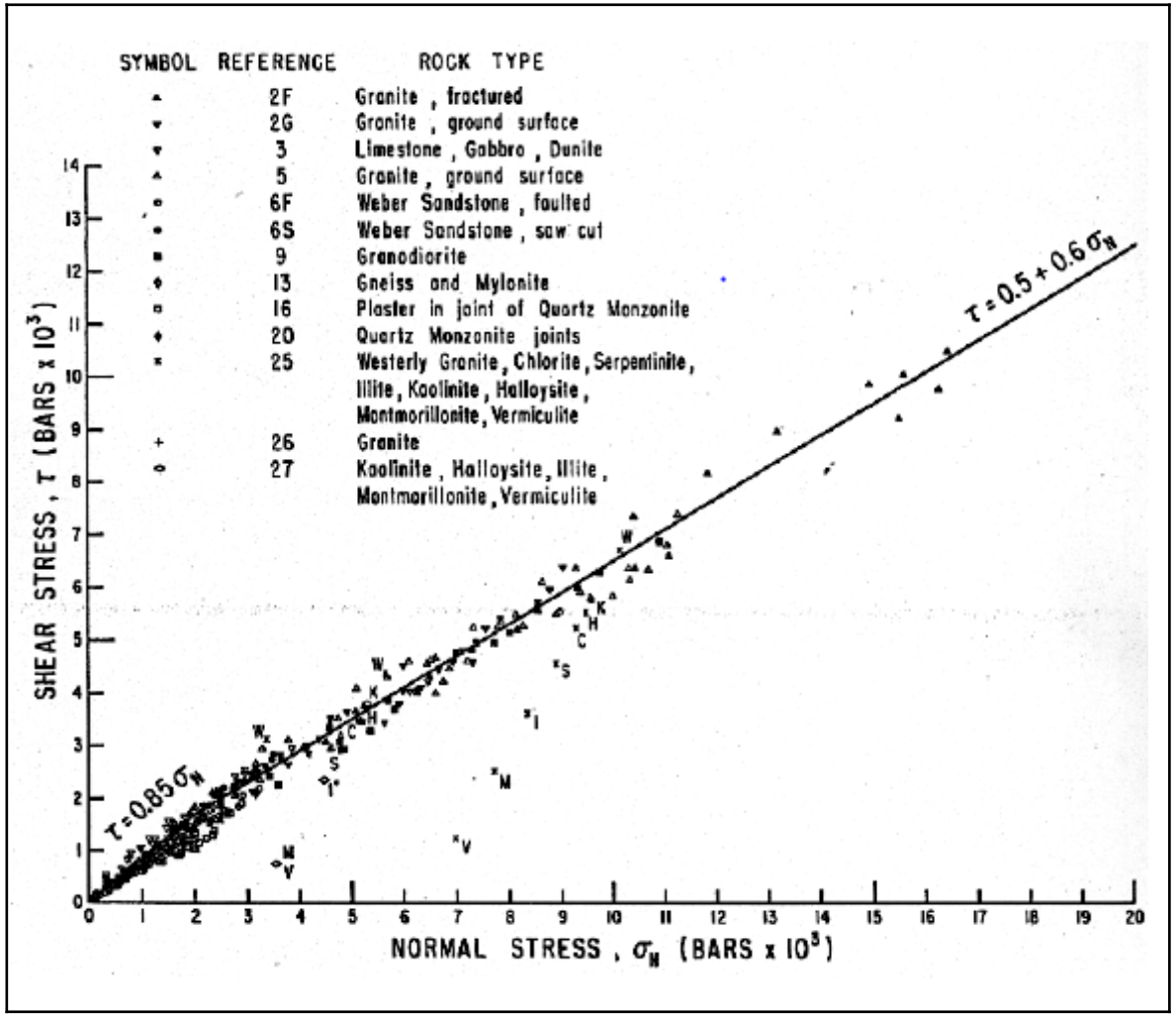
(Byerlee, 67, 68, 75 *and Barton, 1973, 1976*).





‘FRICTION OF ROCKS’, Byerlee, 1978. This short, widely referenced paper, is full of ‘surprising’ conclusions. It is unfortunate that ‘μ ≈ 0.85’ (one of Byerlee’s ‘laws’) is so influential in geomechanics. (ϕ ≈ 40.4° is *not very useful*). On the next screen we see why.





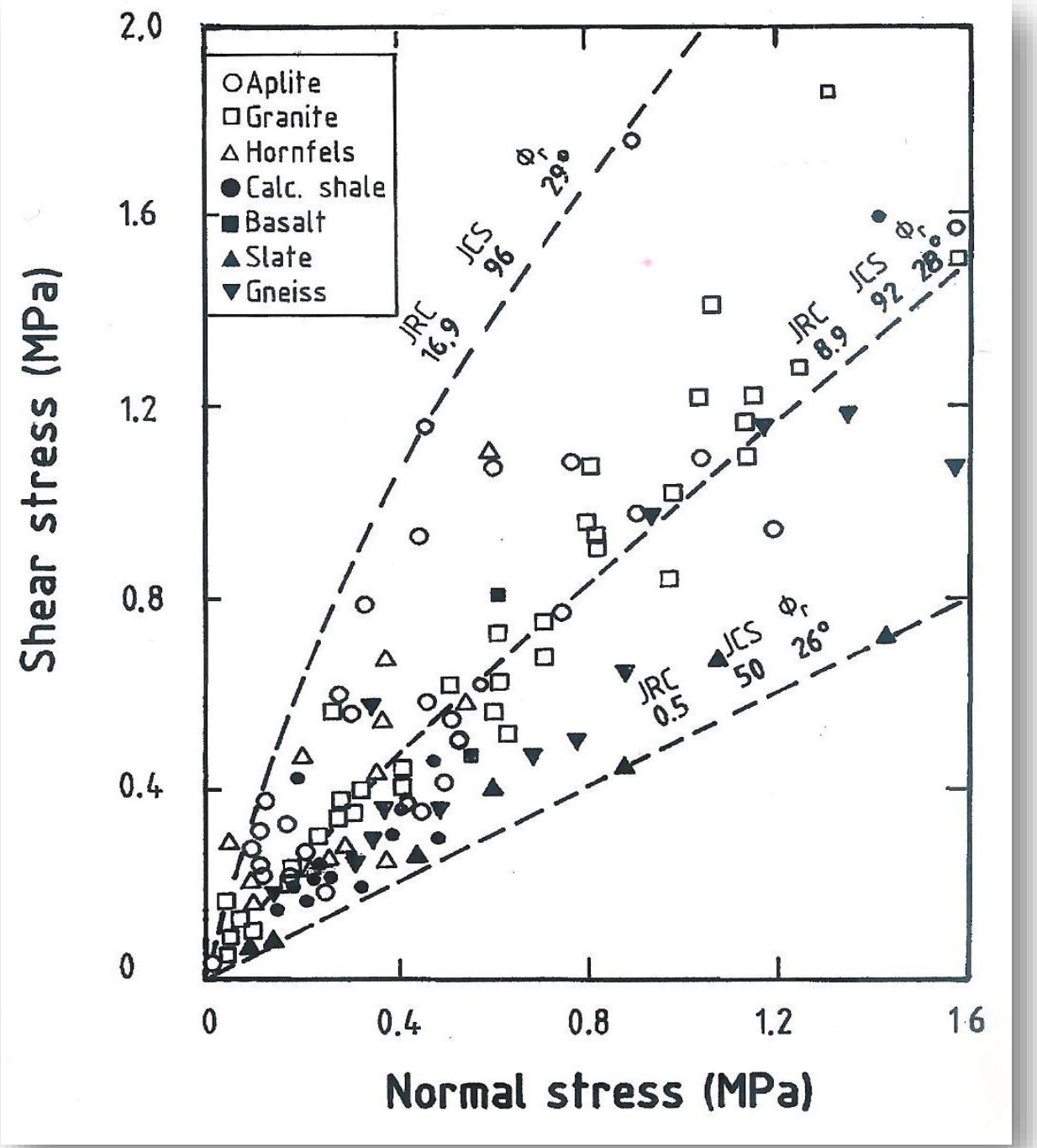
According to Byerlee, 1978:

'Barton (1976) has proposed that friction of rocks (sic) at low stresses can be approximated by the equation':

$$\tau = \sigma_n \tan\left[\mathrm{JRC}\log_{10}\left(\frac{\mathrm{JCS}}{\sigma_n}\right) + \phi_b\right]$$

'There are so many variable, whose precise value is uncertain, in the equation that its validity cannot be tested.' (sic). 'Rock types have little or no effect on friction'. (sic)!!

(Built-in-bias: Stanford: Byerlee, Zoback, generations of students, (US) oil companies: no JRC, JCS, ϕr discovered or referenced, despite widely referenced non-linear rock mechanics)



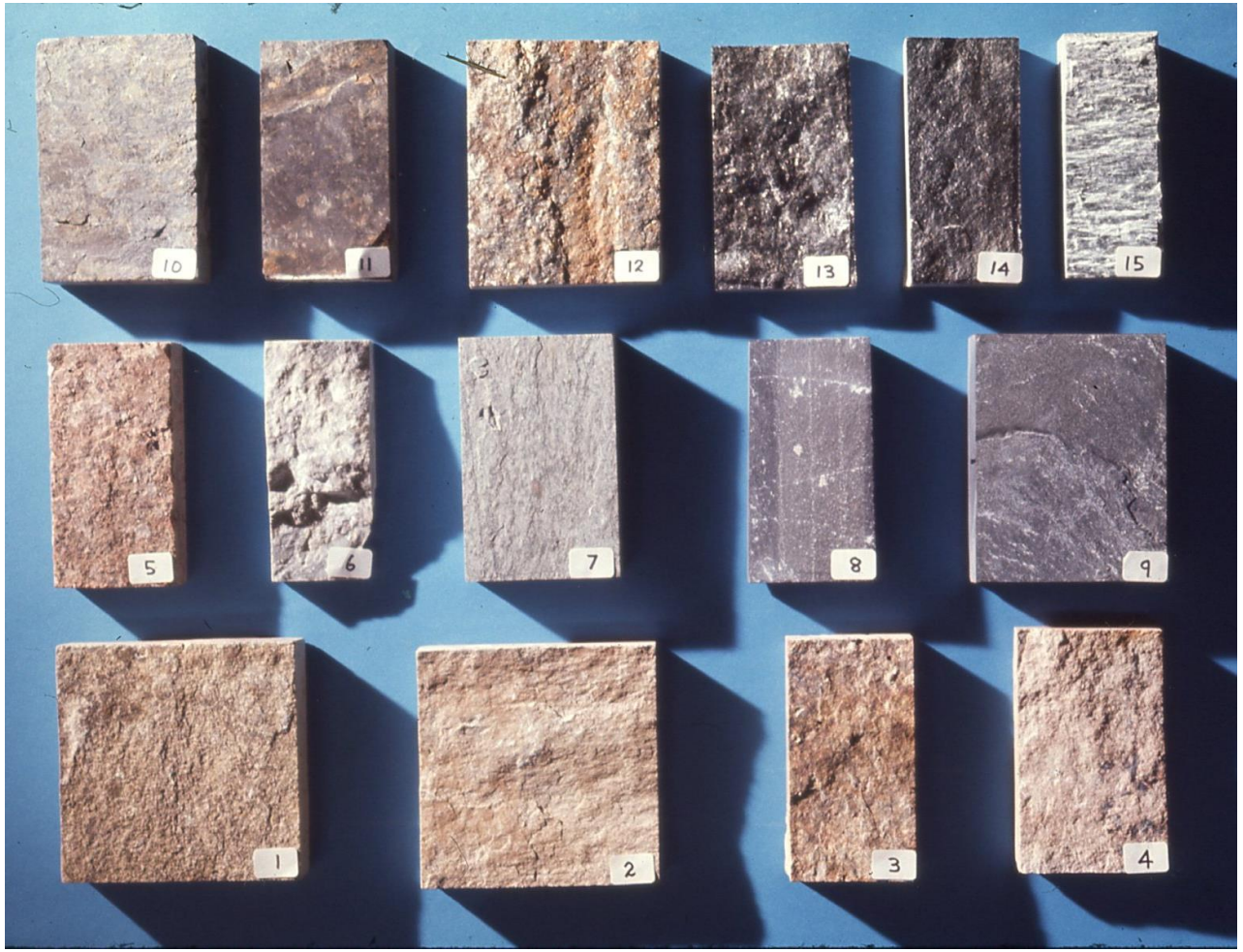
Validating what Byerlee (and maybe Zoback) assumed could not be validated. 130 rock-joint samples.

(Barton and Choubey 1977)

Three curved **peak shear strength** envelopes shown with JRC, JCS, ϕ_r

SOME OF THE 130 NATURAL JOINT SAMPLES (LOWER-HALF) SAWN FROM JOINTED BLOCKS OF ROCK.

(Barton and Choubey, 1977)

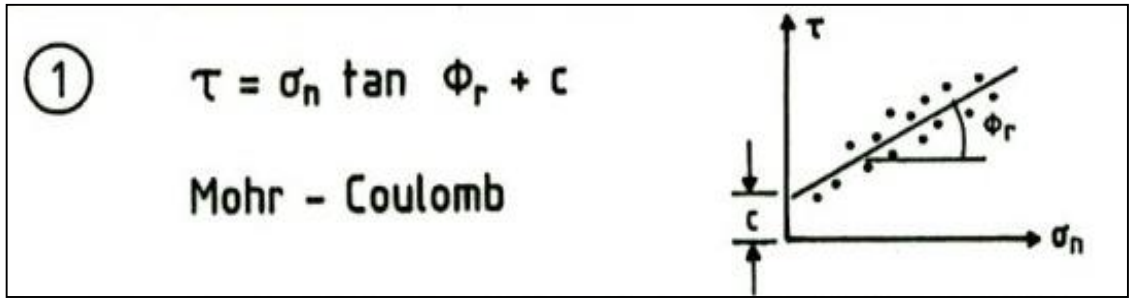


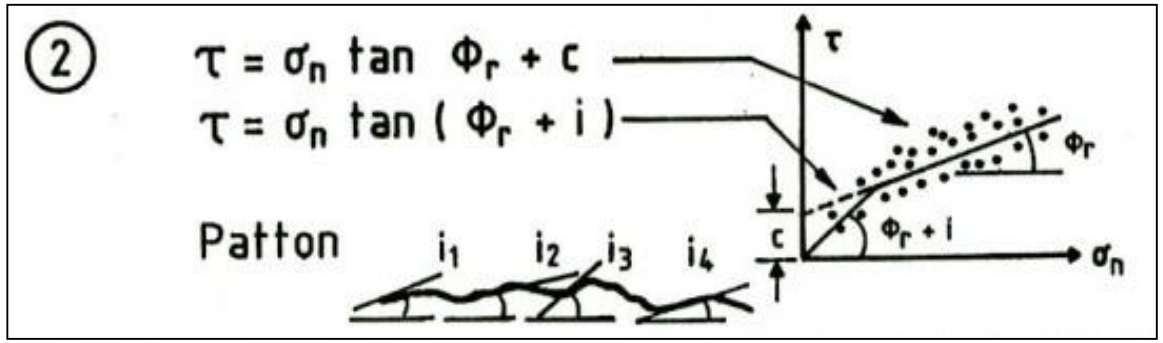
ACTUAL ROCK JOINTS – NOT STRESS-INDUCED SHEAR FRACTURES IN 'FINGER-SIZED' HIGH-PRESSURE (AND HIGH STRENGTH) TRIAXIAL SAMPLES…….

THE SOURCE OF BYERLEE'S 'constant μ',

***'rock type has little or no effect'* error.**

GEOMECHANICS SIMPLIFICATION (when expressed as μ = Byerlee 'law')

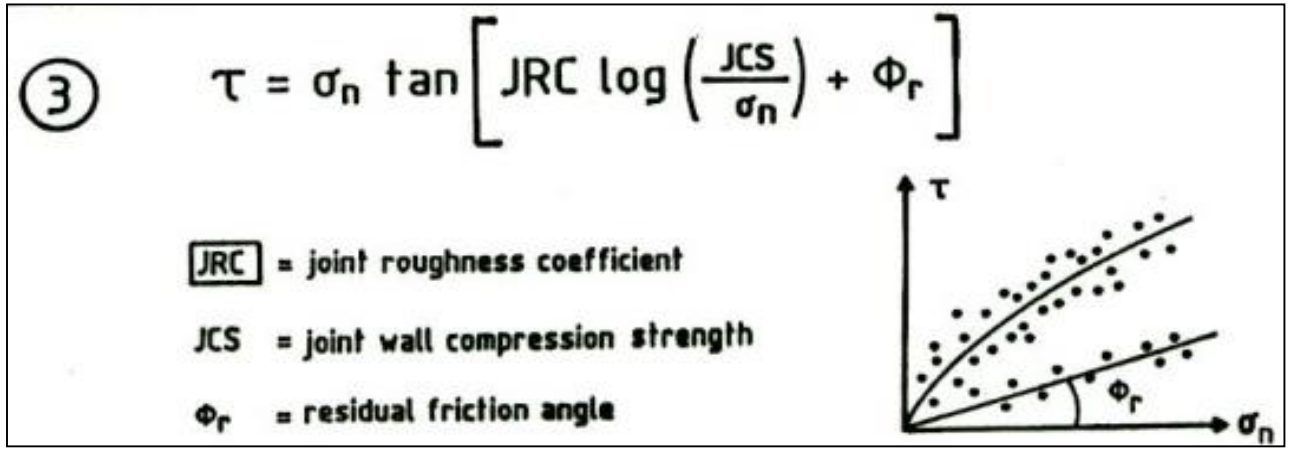


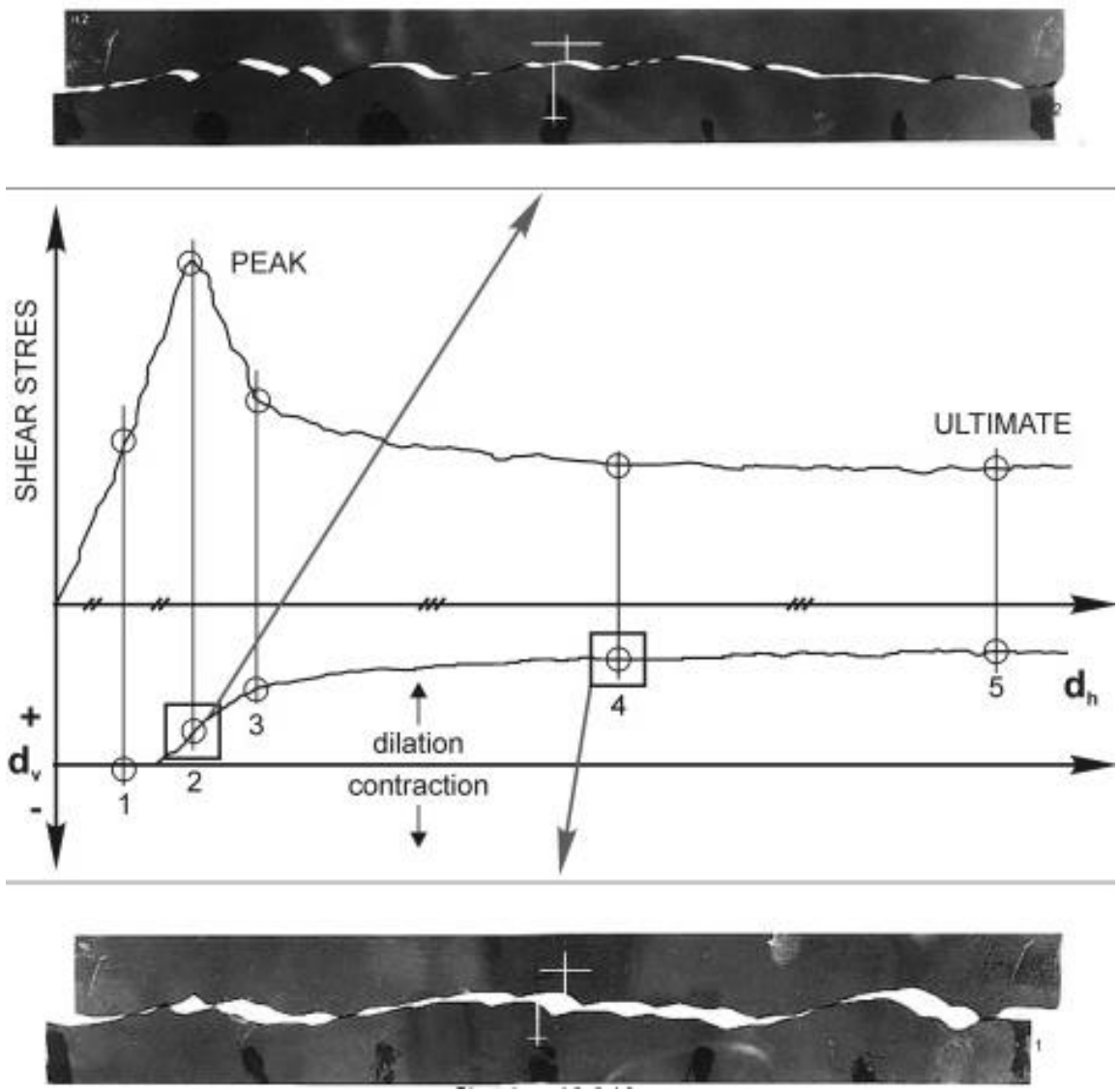


(Patton, 1966)

THE MORE ACCURATE NON-LINEAR EQUATION WIDELY USED IN ROCK MECHANICS

(Barton, 1967, 1971, 1973, 1977)





Shear-strength-displacement and dilation shown.

Replicas with very exaggerated tension-fracture roughness (Barton, 1973)

?? μ = 0.85, (0.6?) ??

How far does a single value of μ explain shale gas production?

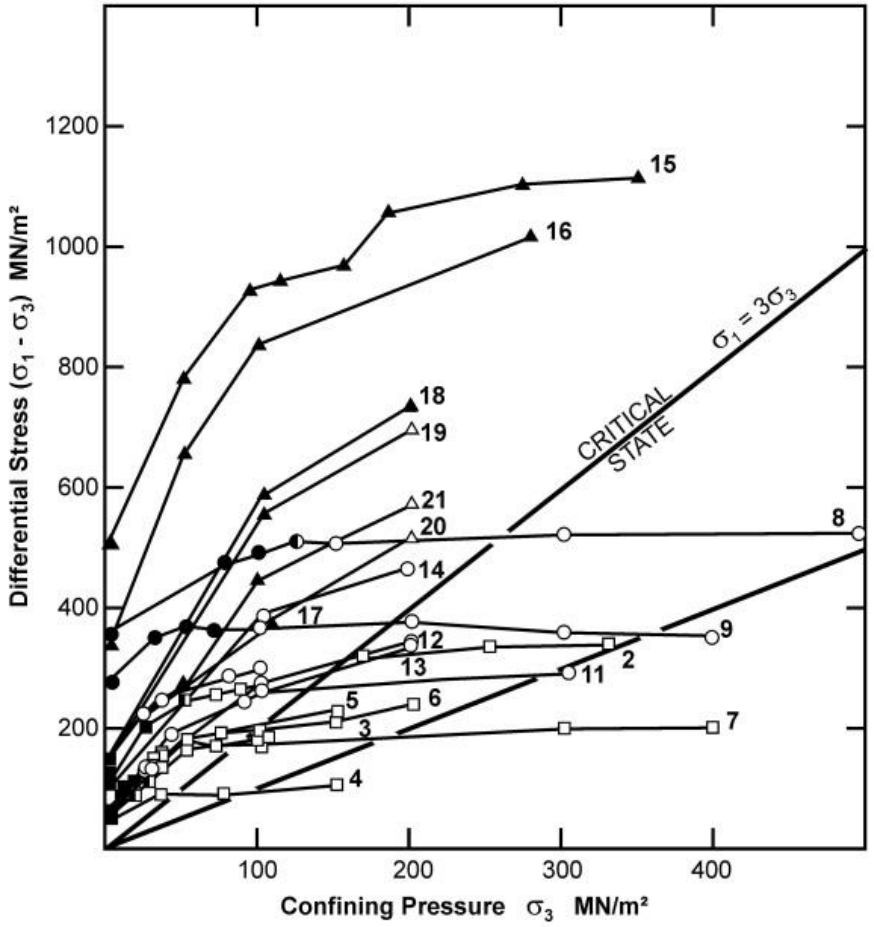
Petroleum geomechanics assumptions:

- Linear Mohr-Coulomb for the intact rock
- Linear Mohr-Coulomb (Byerlee μ) for the fractures
- *There is 'more to friction' than μ = 0.6, 0.85 etc. (such as pre-peak mobilization of friction, dilation, permeability, peak shear stiffness, post-peak loss of shear strength, etc.)*
- *Fracture apertures: e ≤ E (hydraulic < physical)*

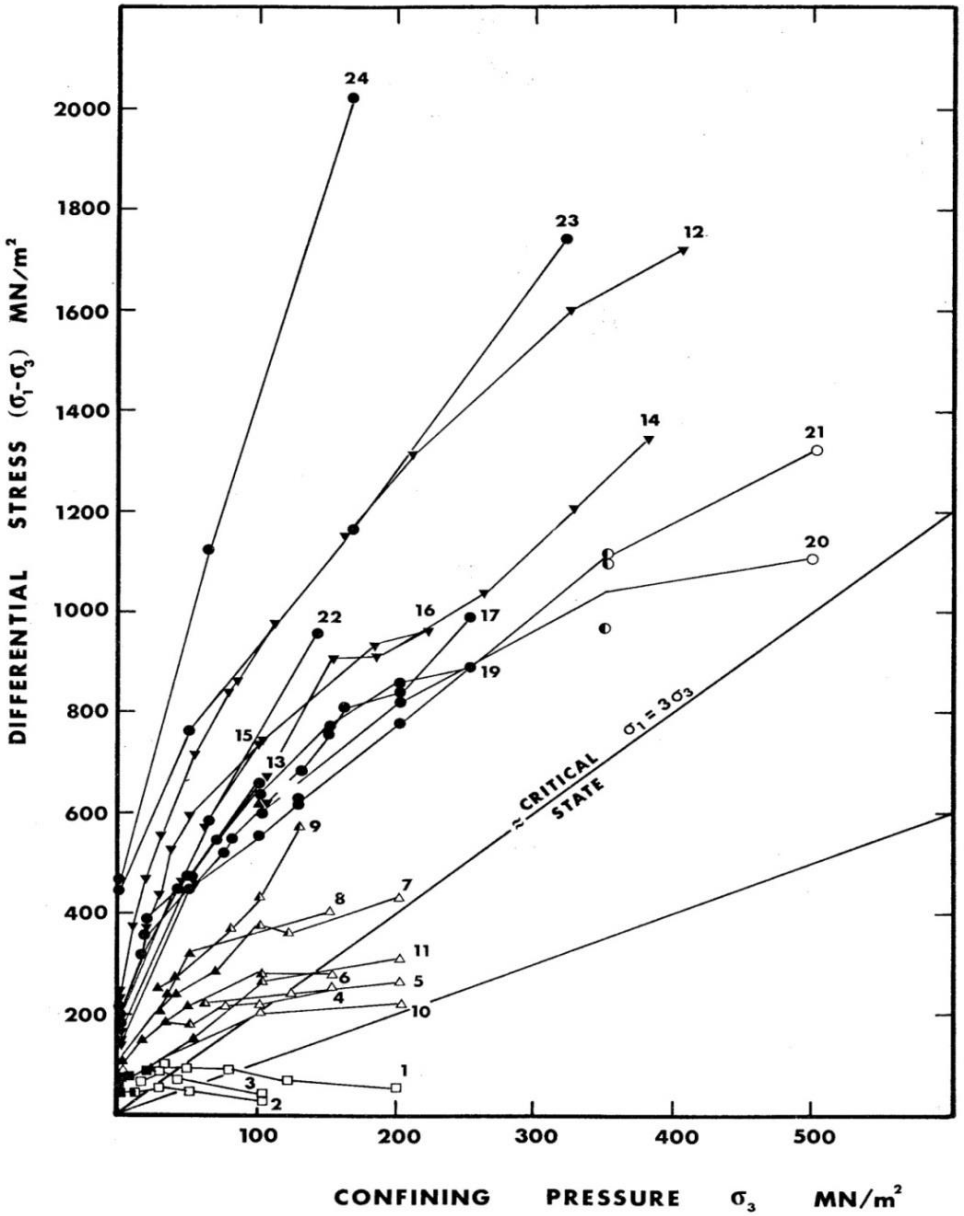
All the above lost to 'Geomechanics' as apparently practiced in the (US) oil-and-gas industry of 'unconventionals.' (Fractured reservoirs: > 60% of remaining world reserves!).

3. SUFFICIENT MATRIX STRENGTH AND SUFFICIENT MODULI ARE NEEDED

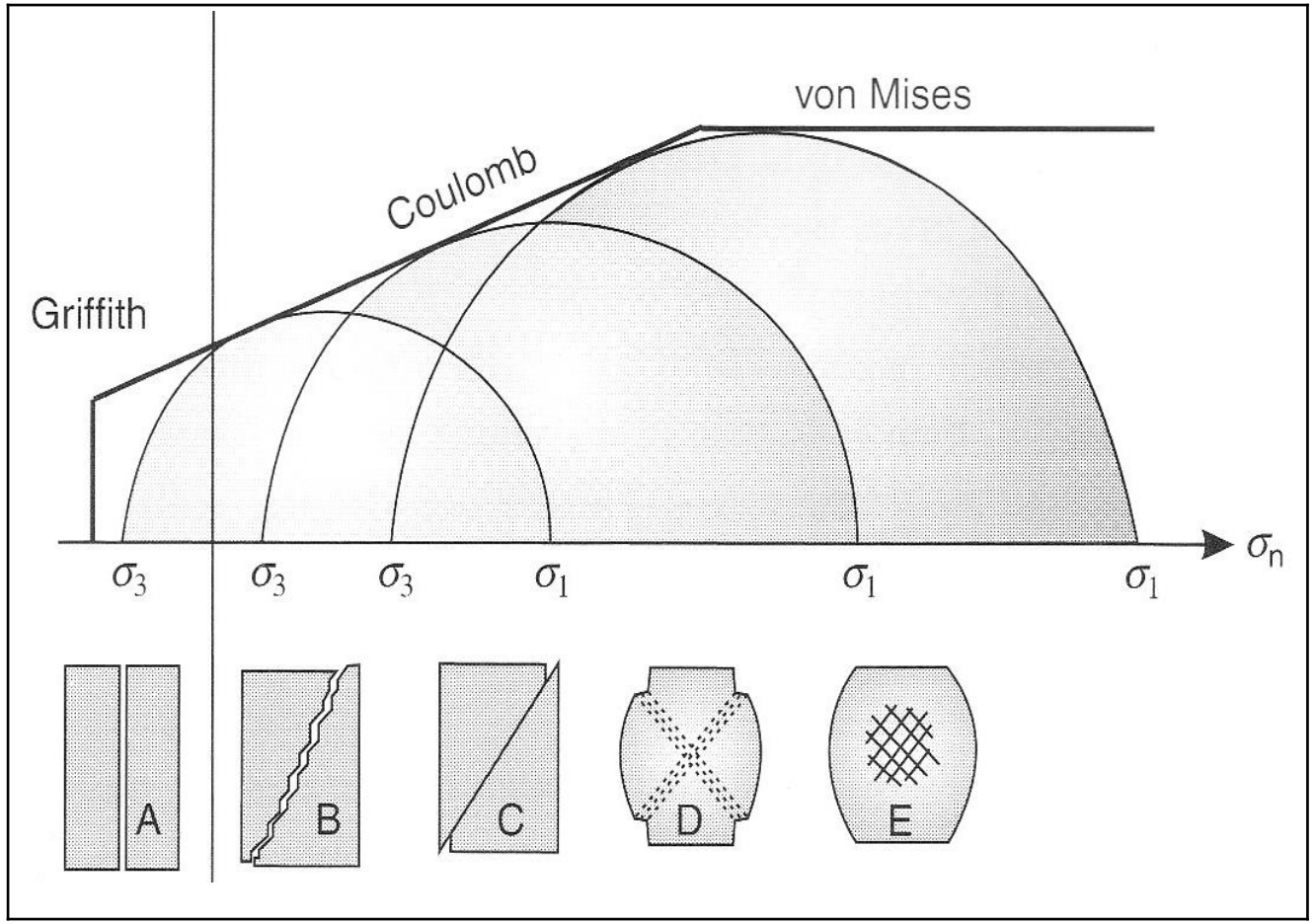
SOME OF THE EARLY EVIDENCE FOR NON-LINEARITY, BOTH AT HIGH AND LOW STRESS LEVELS



Dry carbonate rocks: Mogi 1964



Dry silicate rocks: Mogi 1964



IT MAY BE MISLEADING TO ASSUME LINEAR MOHR-COULOMB OVER DECADES OF STRESS.

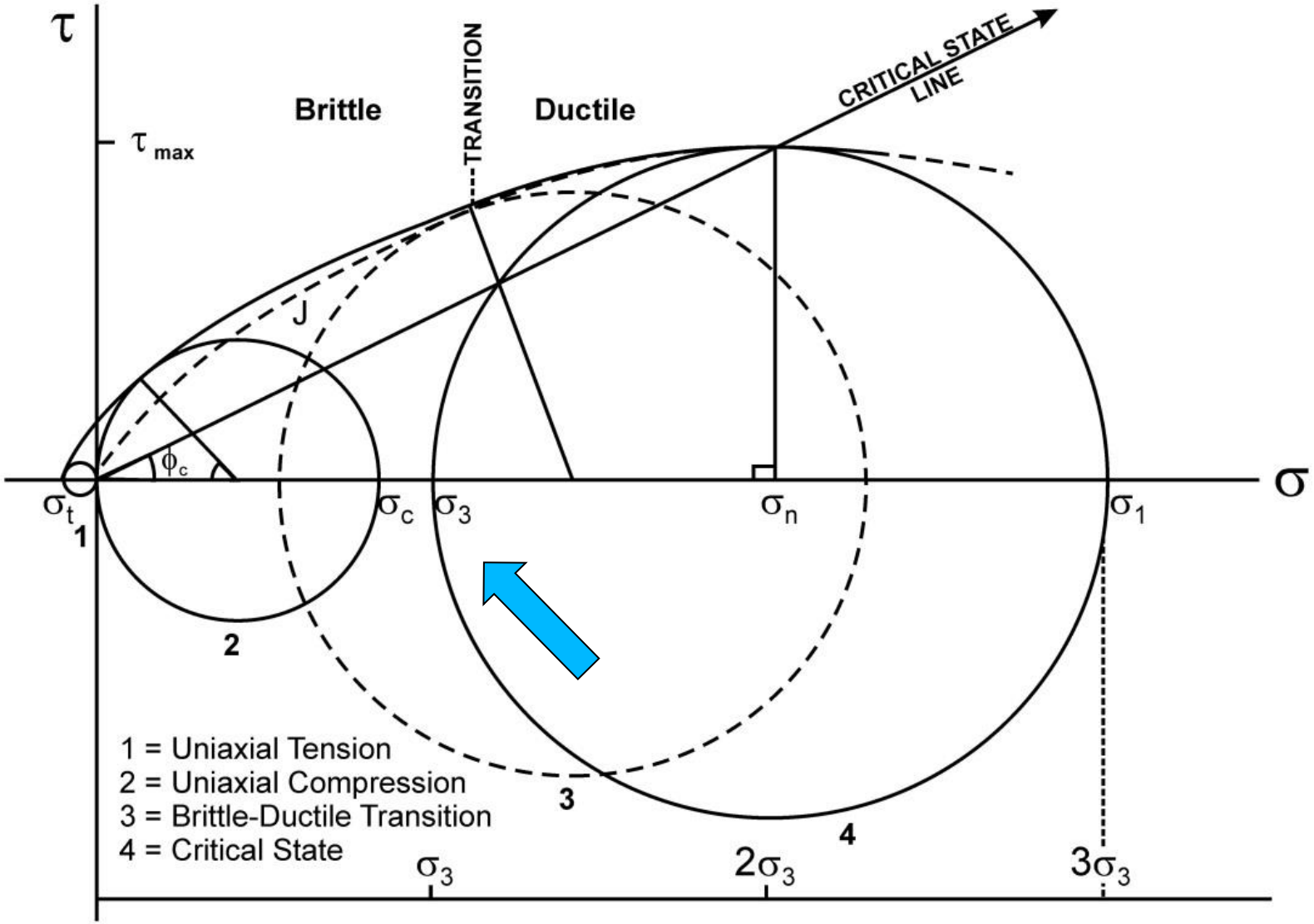
PRODUCTION MAY DECLINE RAPIDLY DUE TO OVER-STRESS (ductility of sheared 'island-asperities') caused by (TOO?) RAPID PRODUCTION.

The Singh-Raj-Singh criterion (see next screens) is a 'continuous' alternative to these classical criteria, based on a critical state suggestion.

(figure from Gudmundsson, 2011)

Critical state suggestion for rock (Barton, 1976)

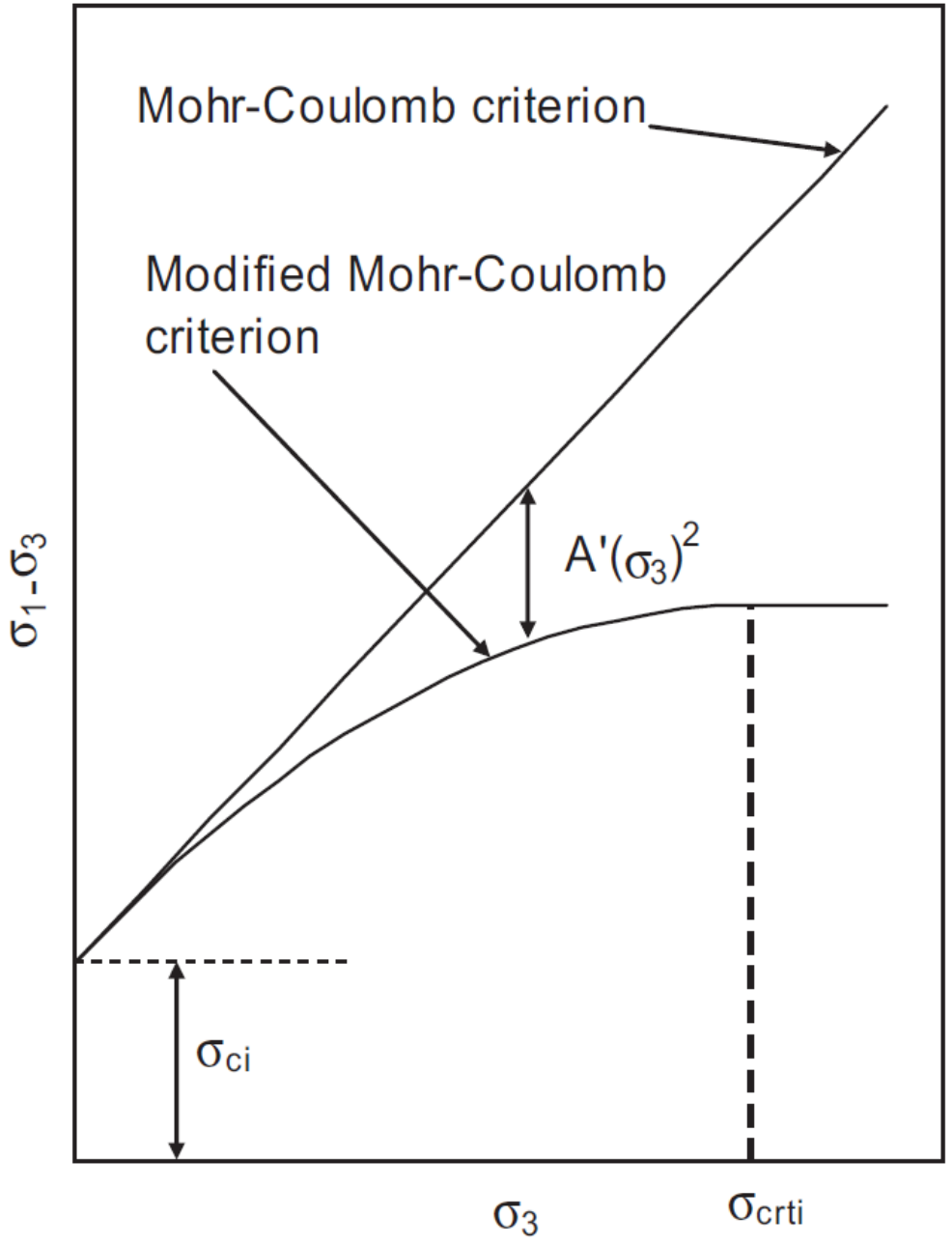
σ_1(max strength) = *3 x* σ_3(critical)

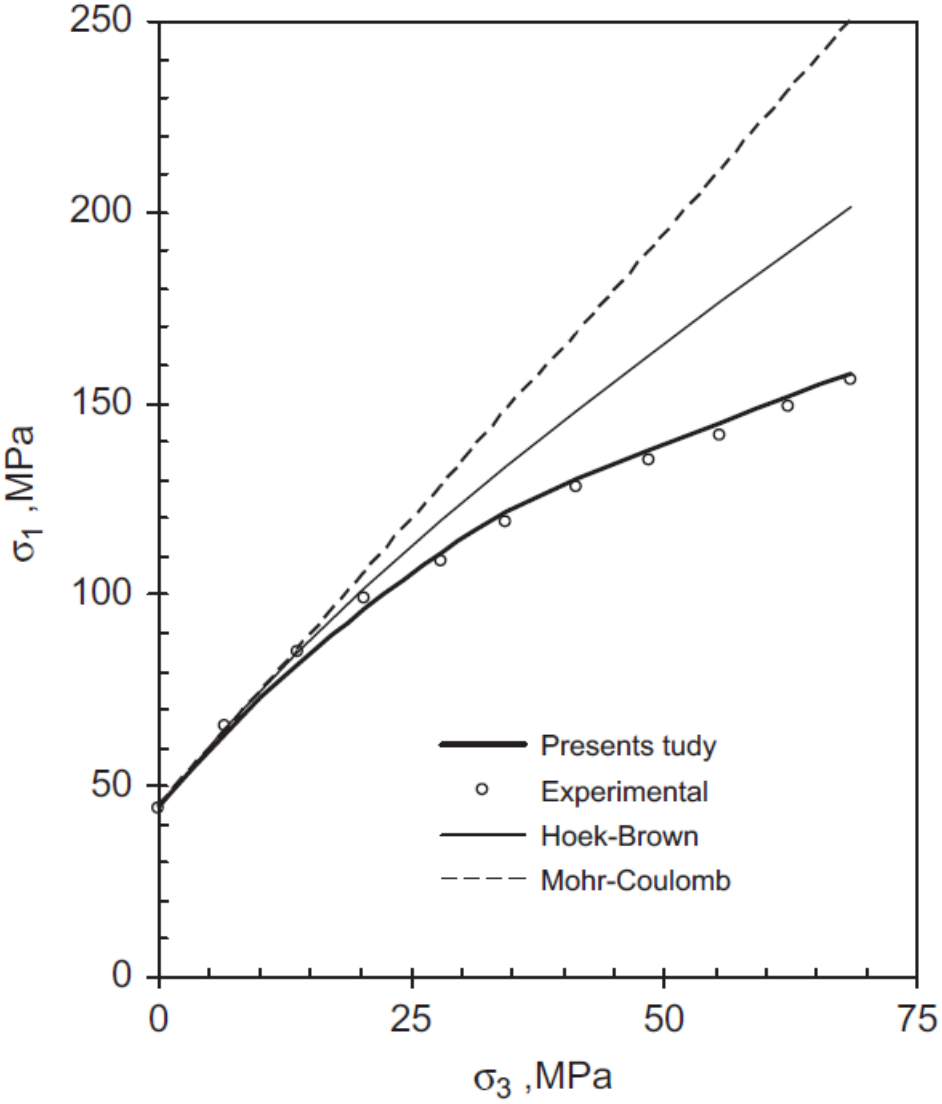


From a major review/analysis of test data, Singh et al. 2011 found that σ_3(critical) ≈ σ_c

From Singh et al. 2011

Left: **Objective** ***Right:*** **Example**





Contents lists available at ScienceDirect

International Journal of
Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Modified Mohr–Coulomb criterion for non-linear triaxial and polyaxial strength of intact rocks

Mahendra Singh *, Anil Raj, Bhawani Singh

Department of Civil Engineering, IIT Roorkee, Roorkee-247667, India

ARTICLE INFO

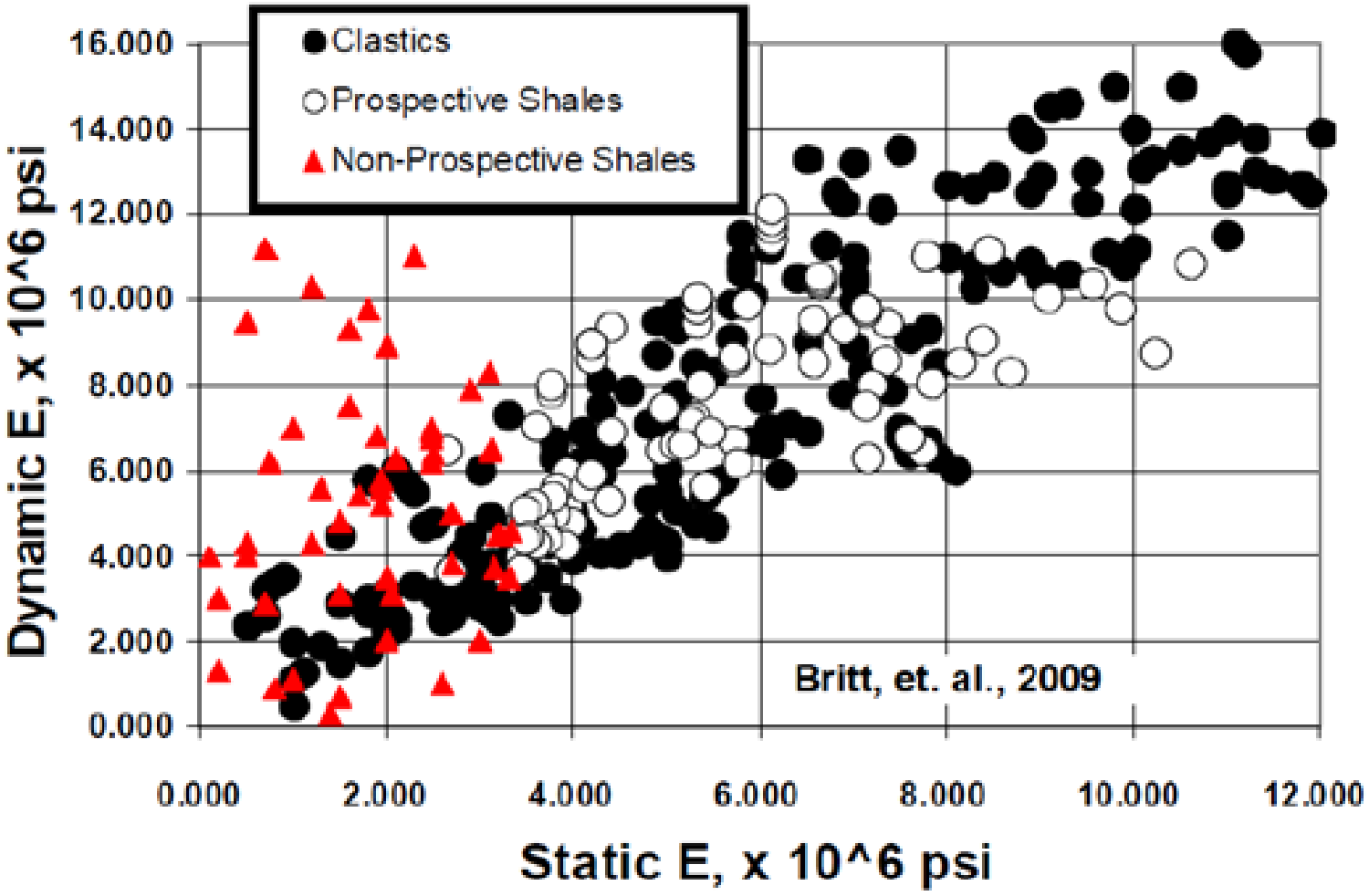
Article history:
Received 10 February 2010
Received in revised form
4 January 2011
Accepted 9 February 2011

Keywords:
Intact rock
Triaxial
Polyaxial
Strength
Criterion

ABSTRACT

Triaxial or polyaxial strength of rocks is required while analysing many civil and mining engineering structures in rocks. Mohr–Coulomb criterion is the most widely used strength criterion in rock engineering problems. In its present form the criterion suffers from two major limitations. Firstly, it represents the strength of rock as a linear function of confining pressure. Secondly, the effect of intermediate principal stress is not considered by this criterion. In the present study, this criterion is modified to take into account the non-linearity and effect of intermediate principal stress on strength behaviour. Barton's [1] critical state concept for rocks has been employed for this purpose. The applicability of the proposed simple non-linear triaxial and polyaxial strength criteria has been verified by applying them to experimental results for the intact isotropic rock material available from literature and comparing the prediction with the other popular criteria in vogue. The agreement has been found to be excellent. The applicability of the concept to jointed rocks will be discussed in separate publication.

FROM MAJOR REVIEW BY KING (2010) *Thirty years of gas shale fracturing: what we have learned? SPE 133456.* **VIABLE GAS SHALES NEED SUFFICIENT MODULI:**



The Geomechanics of a Shale Play: What Makes a Shale Prospective.

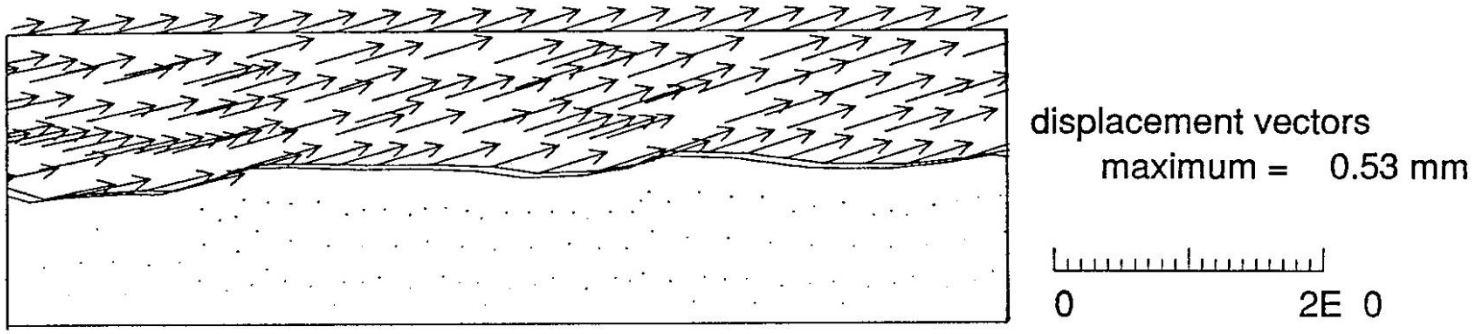
(Britt and Schoeffler, 2009)

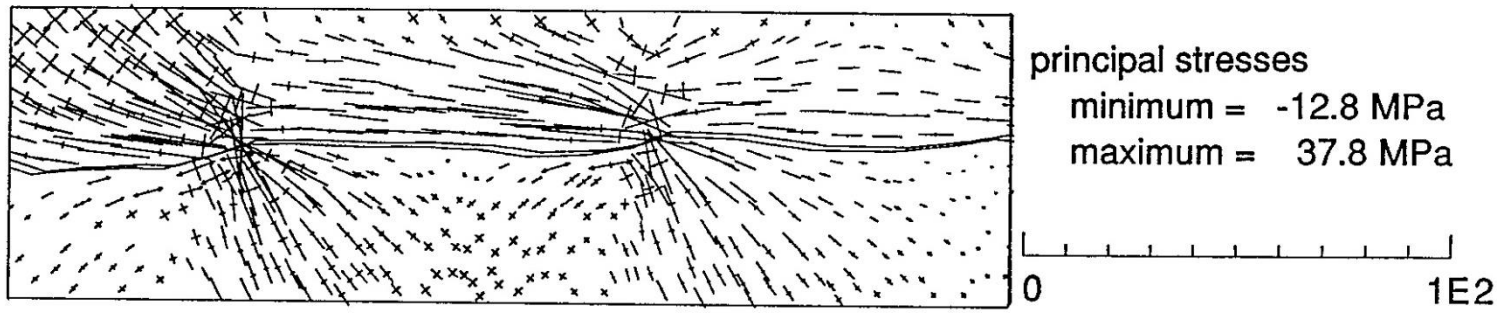
as referenced by King, 2010).

VALUES OF STATIC MODULUS NEED TO BE e.g. >20-25 GPa.

PROSPECTIVE SHALES TEND TO BE BRITTLE WITH THE *STATIC YOUNG'S MODULUS* GENERALLY IN EXCESS OF 3.5 X 10^6 PSI. (> 24 GPa). OF COURSE THIS BRITTLENESS IS RELATED TO THE LACK OF CLAY CONSTITUENTS THAT MAKE UP THESE ROCKS.

(Britt and Schoeffler, 2009)





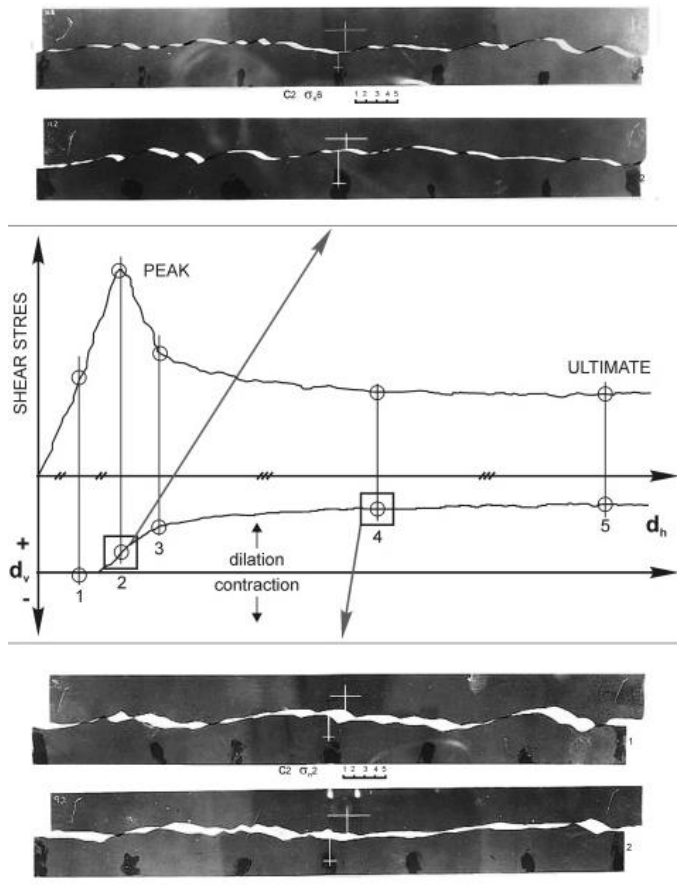
Both **shear strengths and moduli** will be put to the test at the more highly stressed asperity contacts.

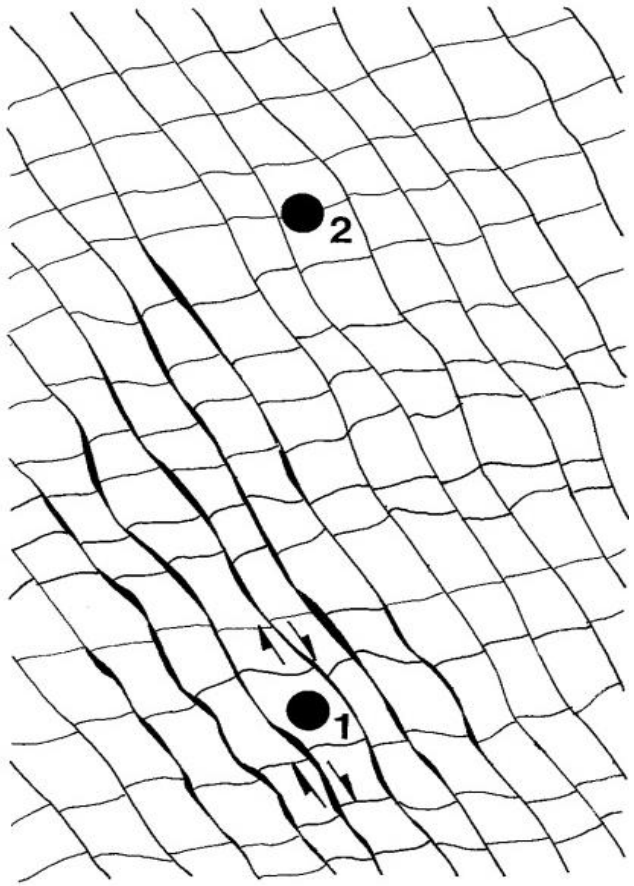
(Prof. Guttierez, former NGI colleague) pers. comm.)

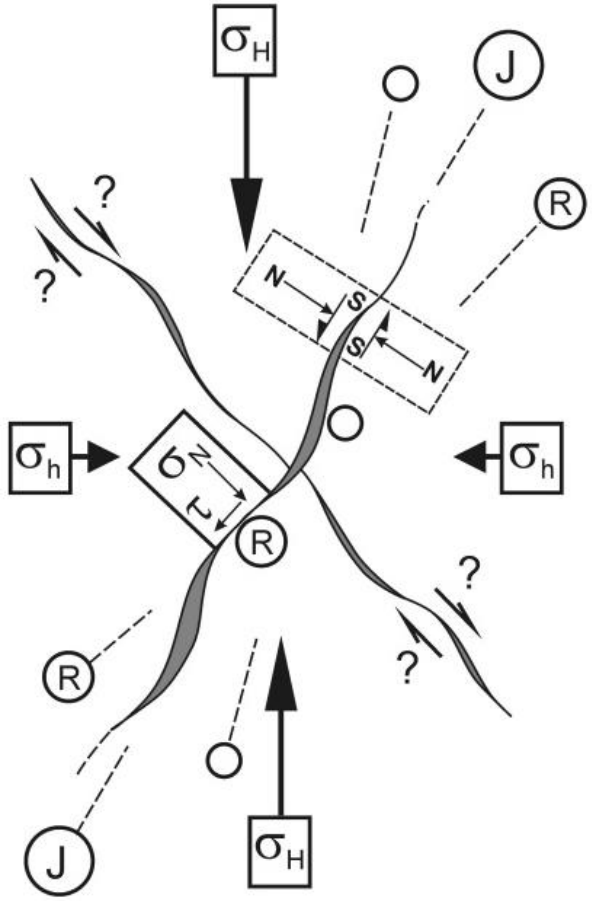
The difficulty of shear testing fractures in shale means that relevant index properties JRC, JCS, ϕr are extra useful for modelling the likely behaviour, and will be found to give much 'richer' behaviour than a single μ.

4. THE ROLE OF FRACTURE SHEAR DEFORMATION – AN INTRODUCTION

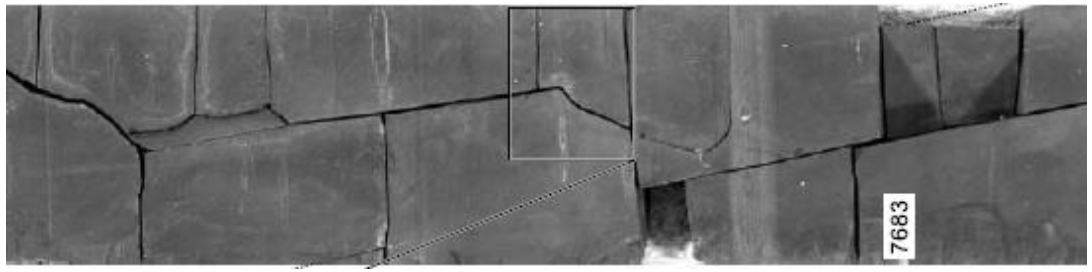
FRACTURE SHEARING, DILATION, APERTURE CHANGE, Δ-PERMEABILITY ARE WELL-KNOWN PHENOMENA IN ROCK MECHANICS (Barton, 1967/1973, 1981, and 2006)







Joints or natural fractures **in gas-shales seem typically to be quite planar.** ***Jr = 1 to 1.5,*** **and also** ***JRC = 0 to 4*** **are probably typical.**



However these 40-year-old (1973, 1974) and widely-used rock engineering terms Jr and JRC are never (?) seen in petroleum geomechanics presentations.

AN ANALYSIS OF THE MINERALOGY INDICATES THAT SHALE PLAYS ARE MADE UP OF MOSTLY SILICA AND CARBONATE MATERIAL AND HAVE FEW CLAY CONSTITUENTS. IN OTHER WORDS, THE *PROSPECTIVE* SHALE'S ARE ACTUALLY FINE-GRAINED CLASTICS AND NOT SHALE!

(Britt and Schoeffler, 2009)

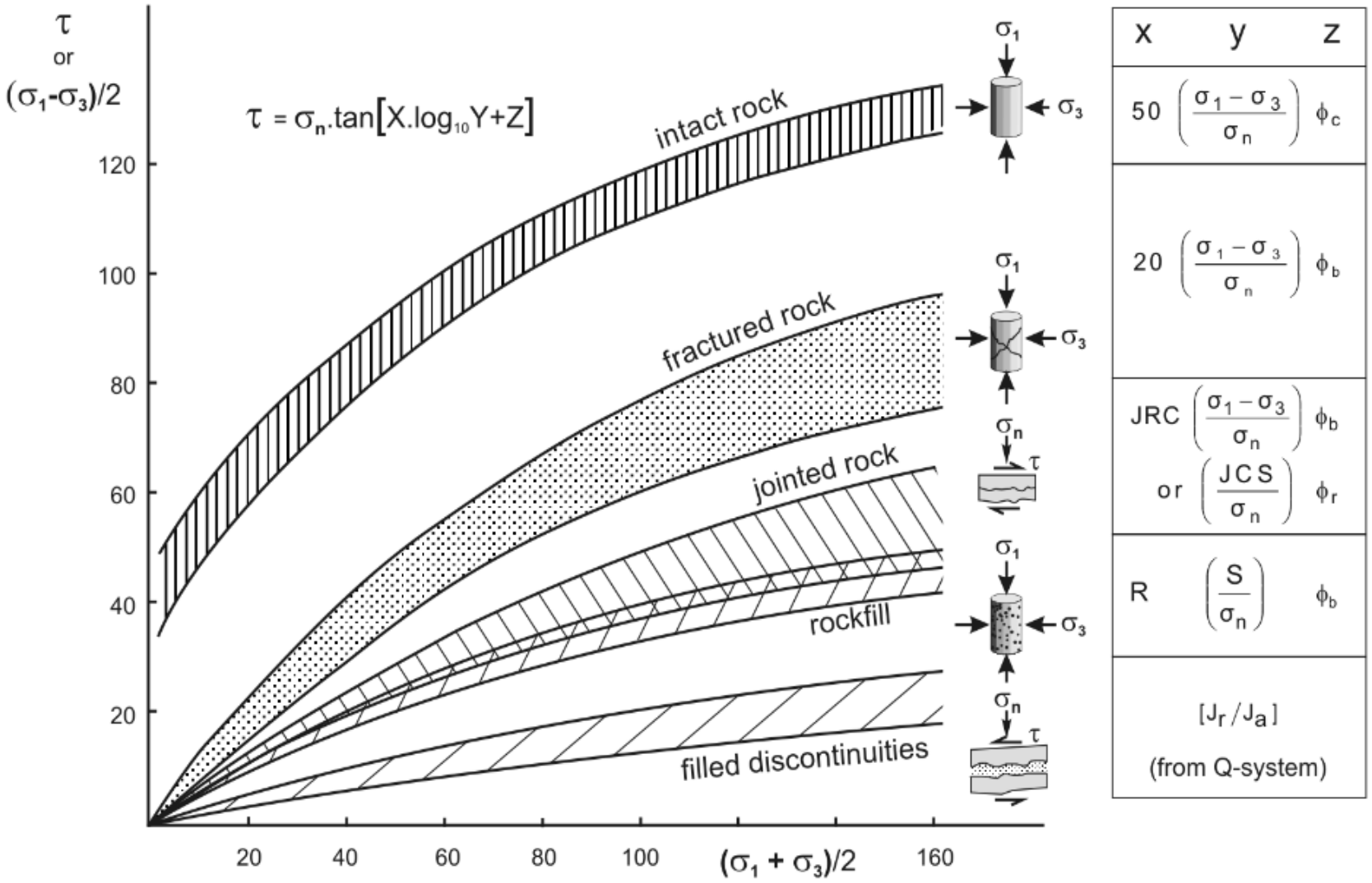
KIMMERIDGE BAY ‘SHALES’ (Dorset, S. England) –

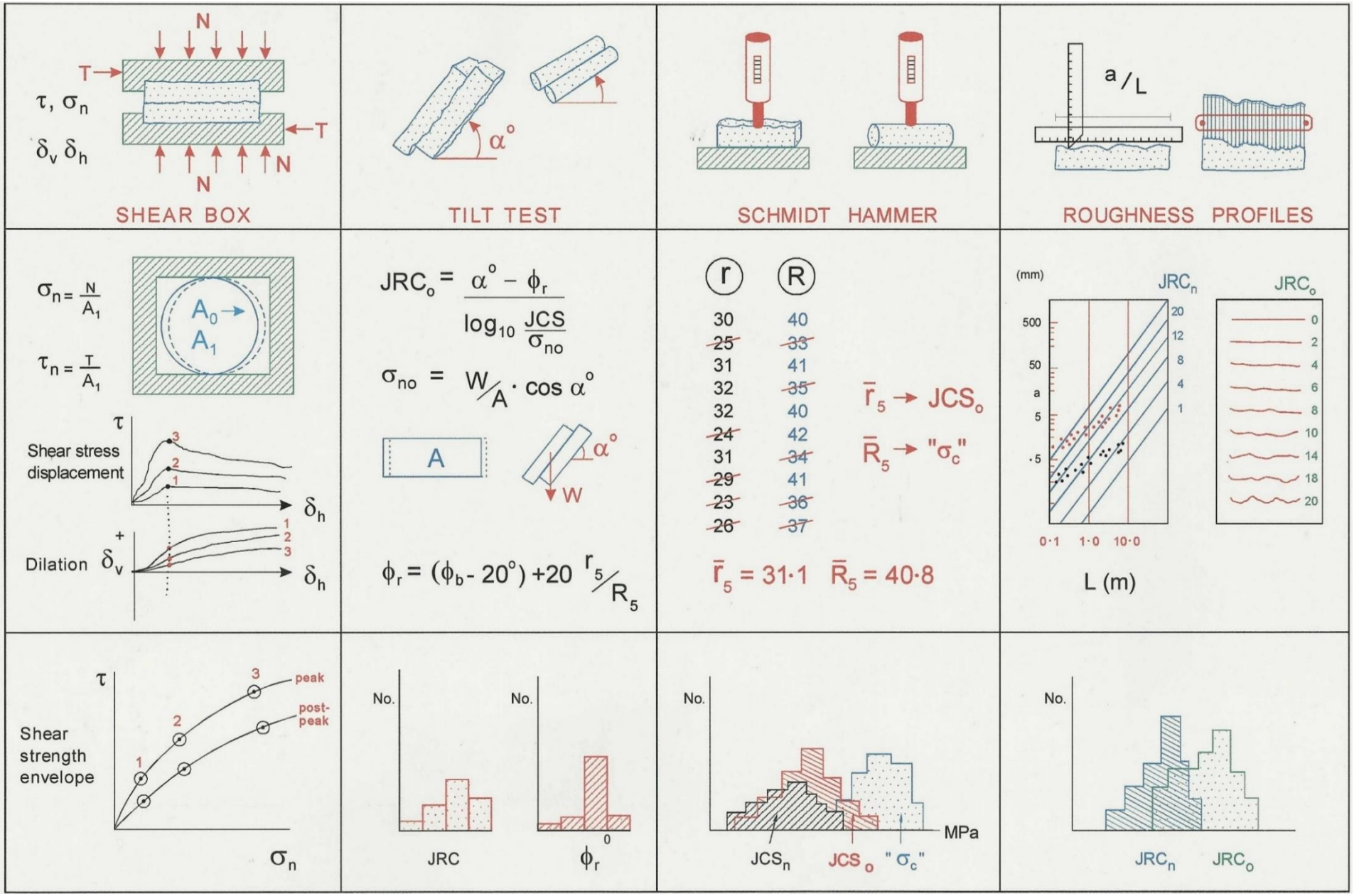
THE SOURCE ROCKS FOR THE NORTH SEA PETROLEUM

(incorporates some beds of dolomite)

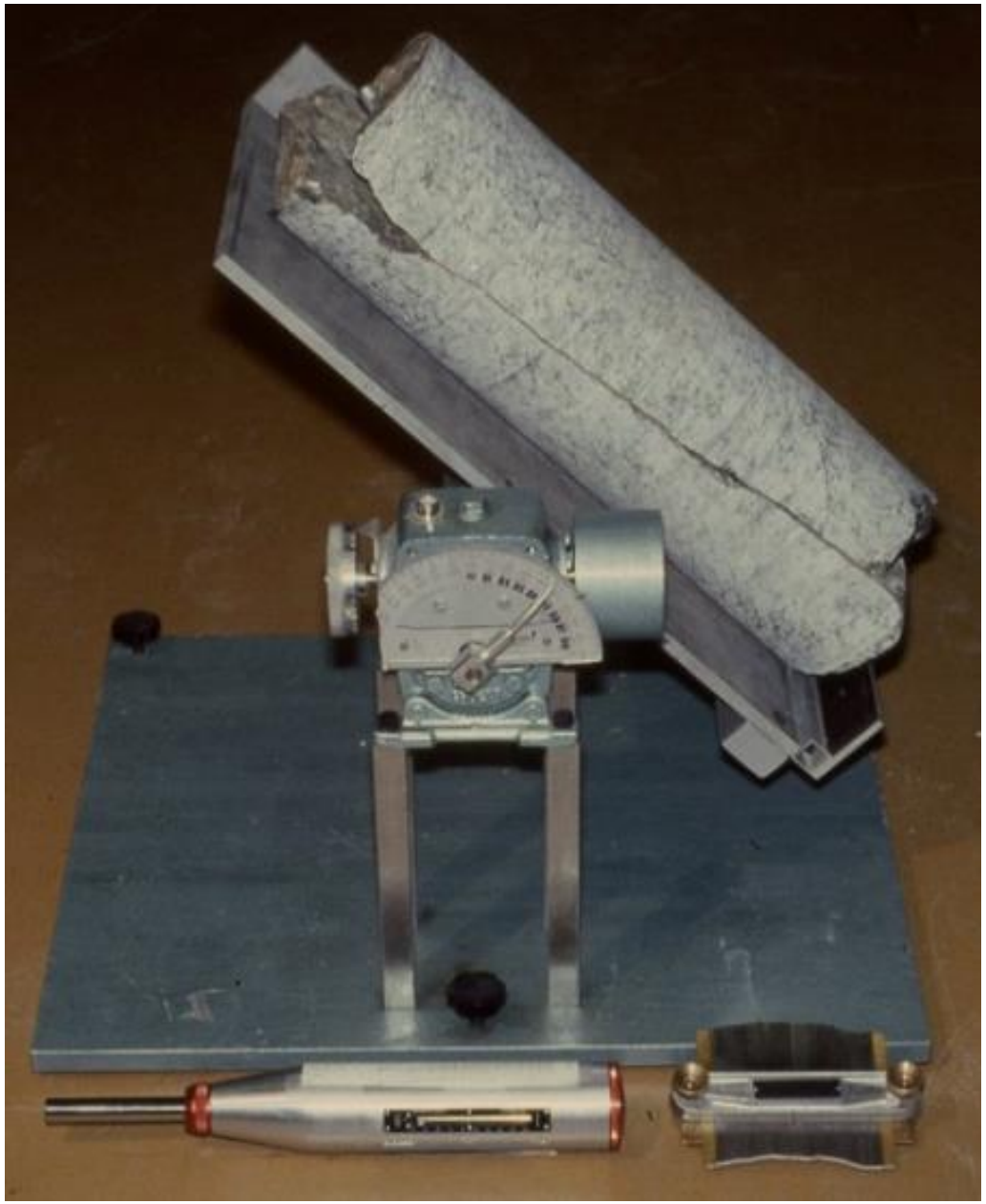
5. INPUT DATA NEEDED FOR NON-LINEAR SHEAR BEHAVIOUR: JRC, JCS, ϕr

THE NON-LINEAR REALITY – IF A LARGE RANGE OF STRESS IS INVOLVED (e.g. AS IN MINING AND PARTICULARLY IN PETROLEUM ENGINEERING) (Barton 1976, 2006)

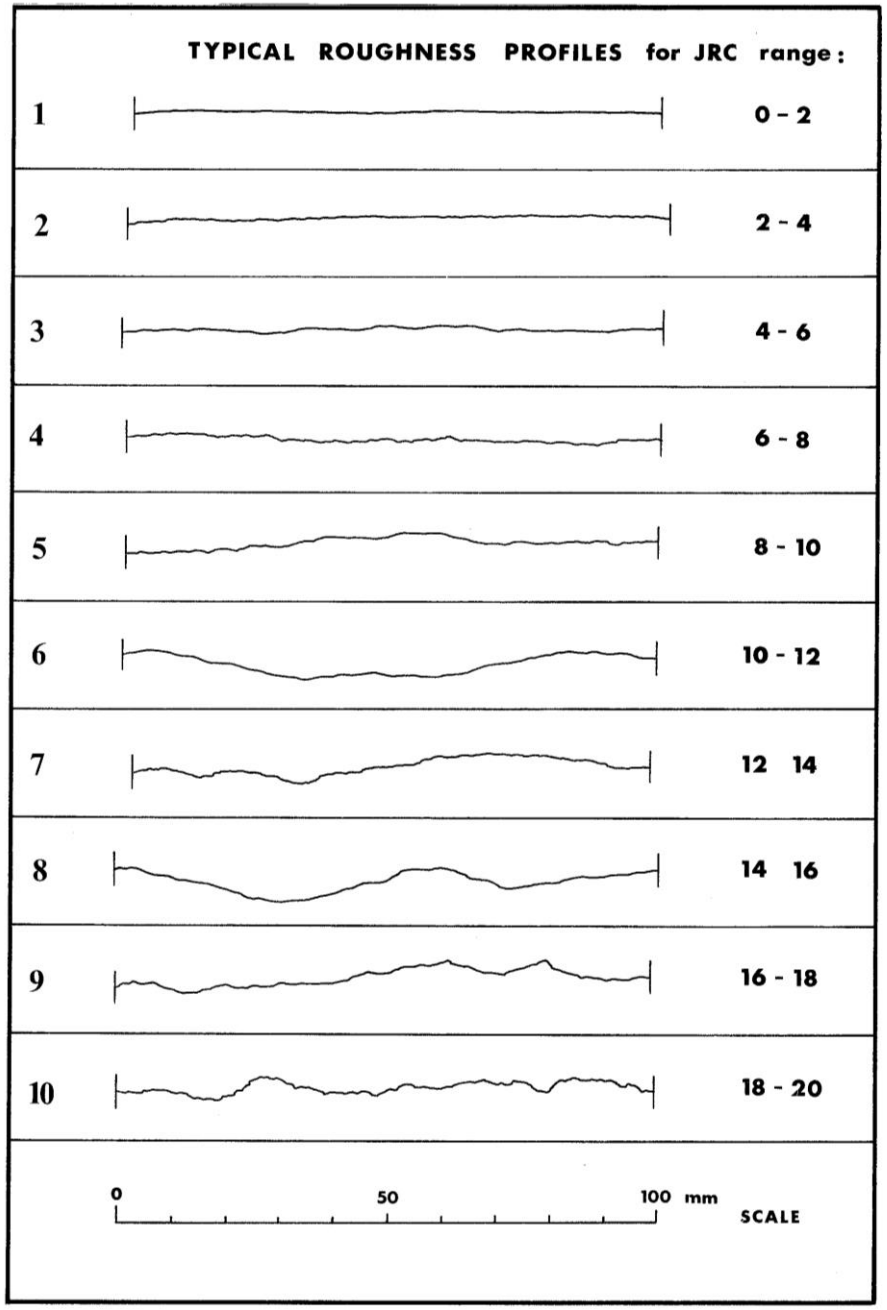




SHEAR BOX AND INDEX TESTING OF ROCK JOINTS (or FRACTURES)



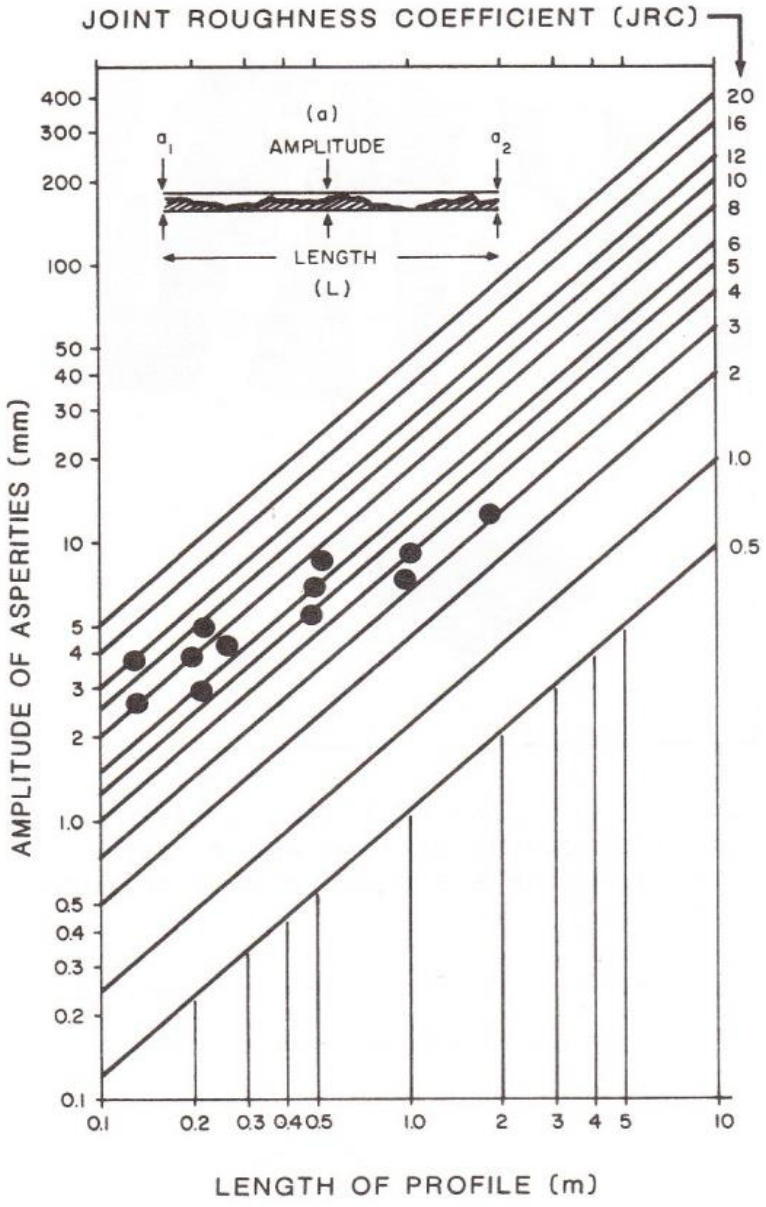
HOLROYD



SIMPLE SCALE OF ROUGHNESS JRC:

1. for improved communication
2. for modelling behaviour (shear strength, dilation, permeability-change).

(Barton and Choubey, 1977, Barton et al. 1985)



The 'a/L' method for scaling block-size effects (pavement analogues, cliff exposures)

JRC Profiling major-joint MJ-67 in limestones.

Karun IV, 240 m double-curvature arch dam, Iran.

This technique could be used on analogue pavements, cliff exposures etc.

Schmidt hammer for determining ***JCS*** (use mean of top 50% of results).

Samples must be clamped to a heavy base, and placed on a smooth concrete floor.

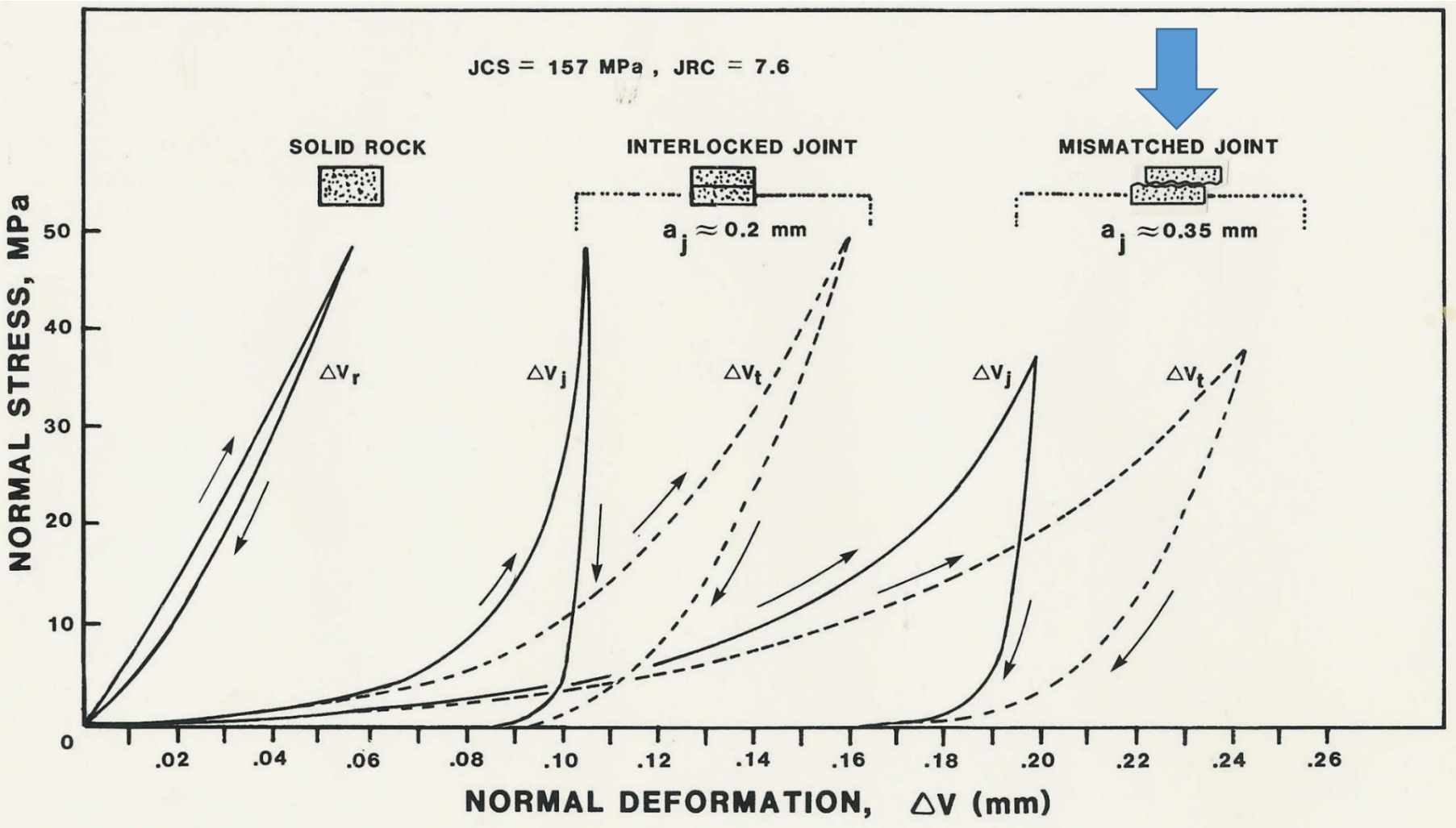
JCS < UCS

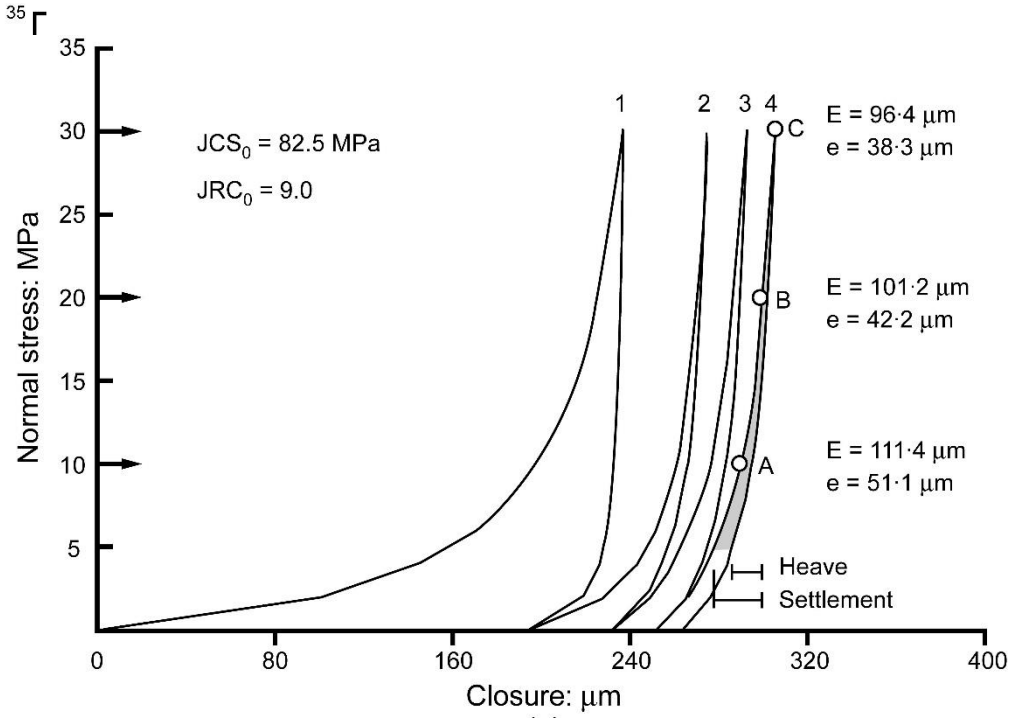
(UCS in all the ‘islands’ not eroded by the waves)

Dolomite bed in Kimmeridge ‘shales’, Dorset, UK

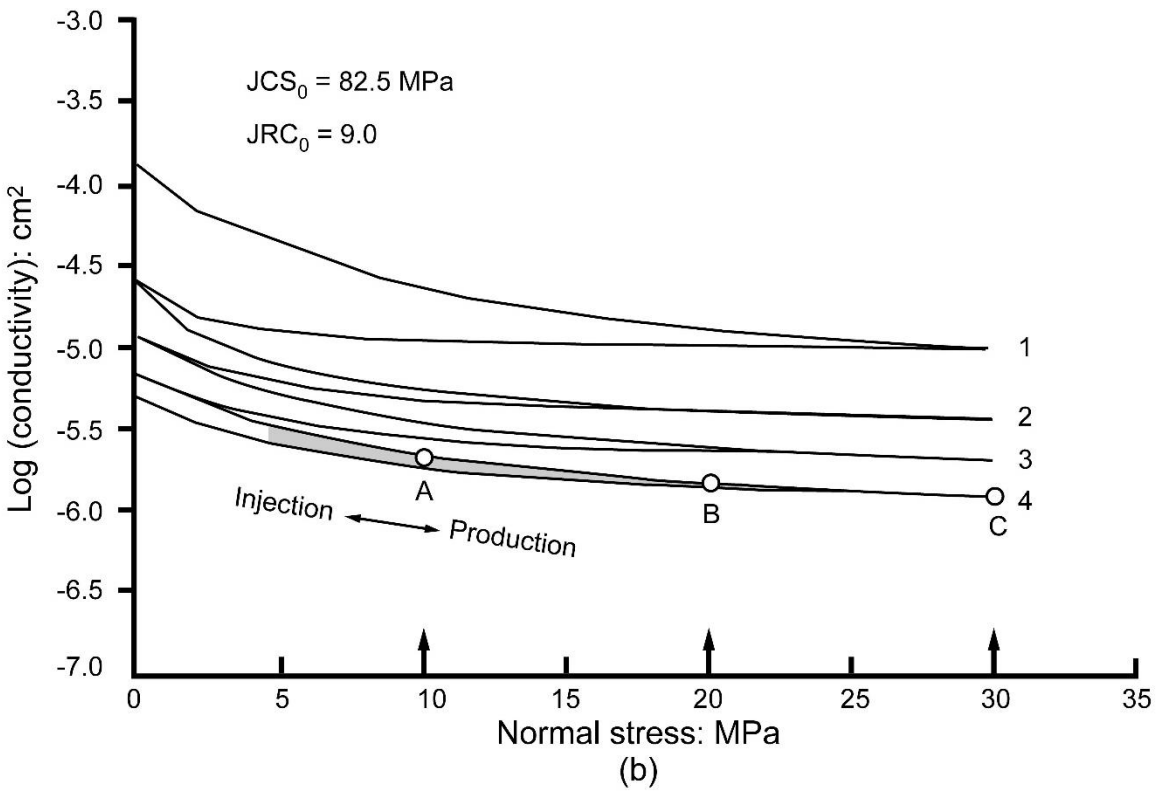
6. STRESS-CLOSURE-PERMEABILITY IS THE *NEGATIVE* RESULT

STRESS-CLOSURE OF INTERLOCKED AND SHEARED FRACTURES: REDUCED ***NORMAL-STIFFNESS*** IS PROOF OF RAISED STRESS LEVELS AT ASPERITIES (THEREFORE NON-LINEAR STRENGTH, MODULI, ARE IMPORTANT) (Bandis et al. 1983)

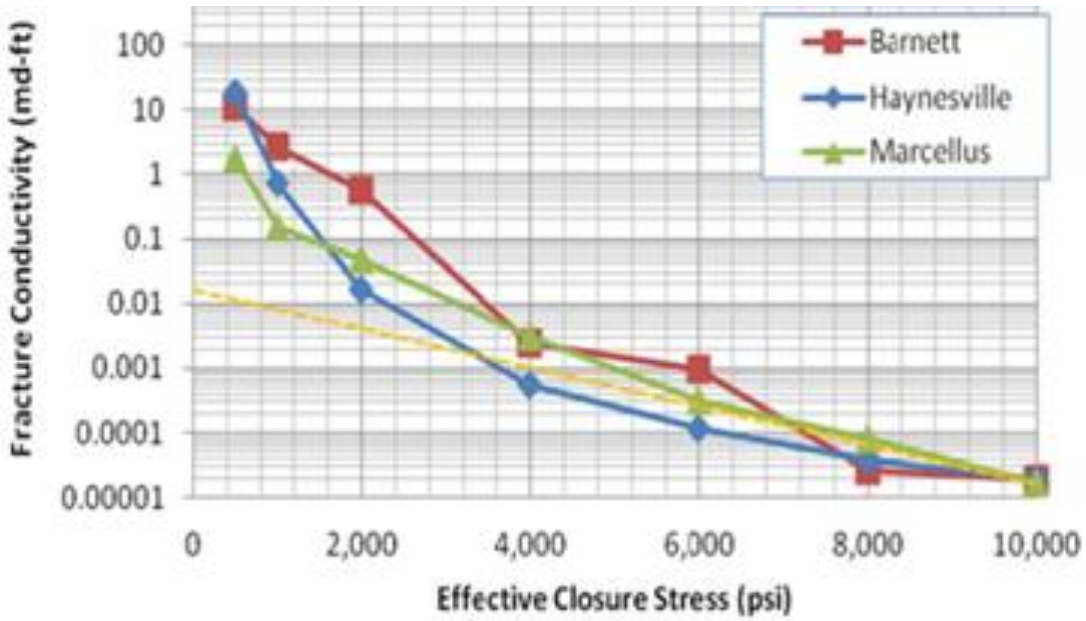




BB-modelling of stress-closure, with JRC and JCS as input. (Assume 4th cycle similar to in situ – undisturbed).

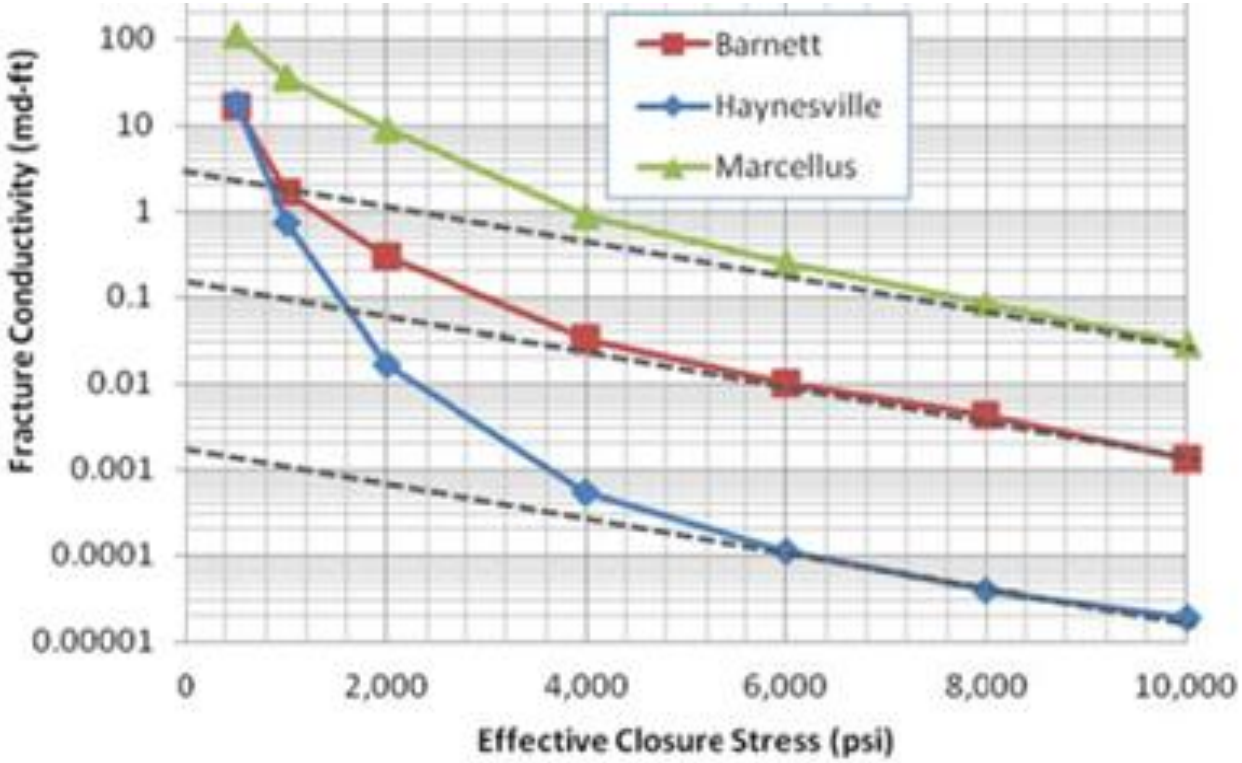


(Input data from G-tunnel welded-tuff, Nevada Test Site. Barton, Bandis, Bakhtar, 1985). *Imaginary reservoir water-flood application.*



High pressure 'fracture' conductivity tests conducted (top): in ***saw-cut*** samples and (bottom) in ***1 mm displaced-before-loading*** tension fractures.

Ghassemi and Suarez-Revera, 2012.



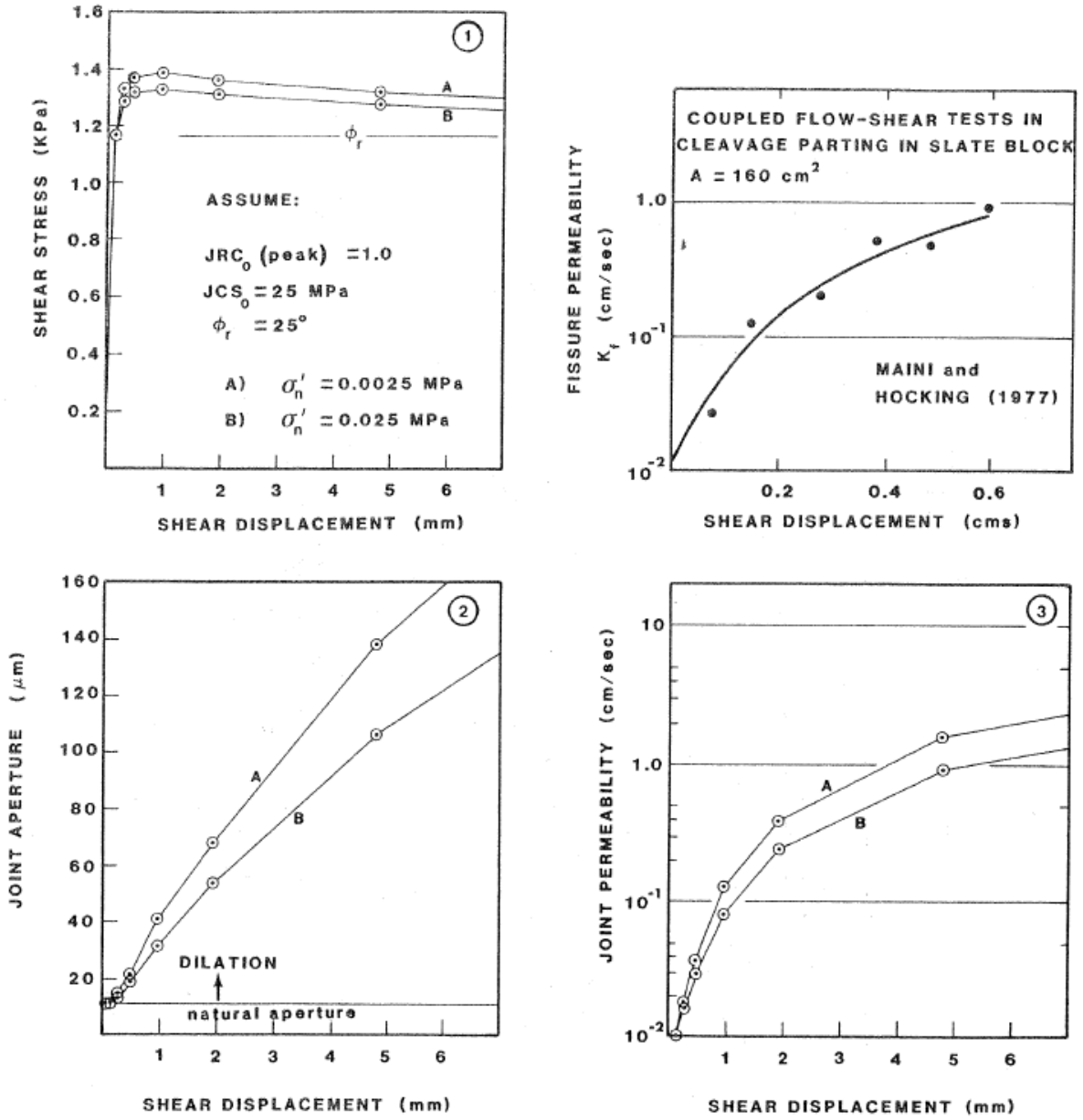
The dotted lines show two decades of conductivity reduction over the increment of 69 MPa (10,000 psi) closure stress.

Note that naturally fractured shale samples were not used in these studies, so maybe somewhat different results compared to CSFT (coupled shear-flow tests) with natural samples.

7. SHEAR-DILATION-PERMEABILITY IS THE *POSITIVE* RESULT

START WITH SOME EXAGGERATED ROUGHNESS

Lack of planarity means dilation, higher local stresses and permeability increase. (Damage and gouge production may partly hinder flow).

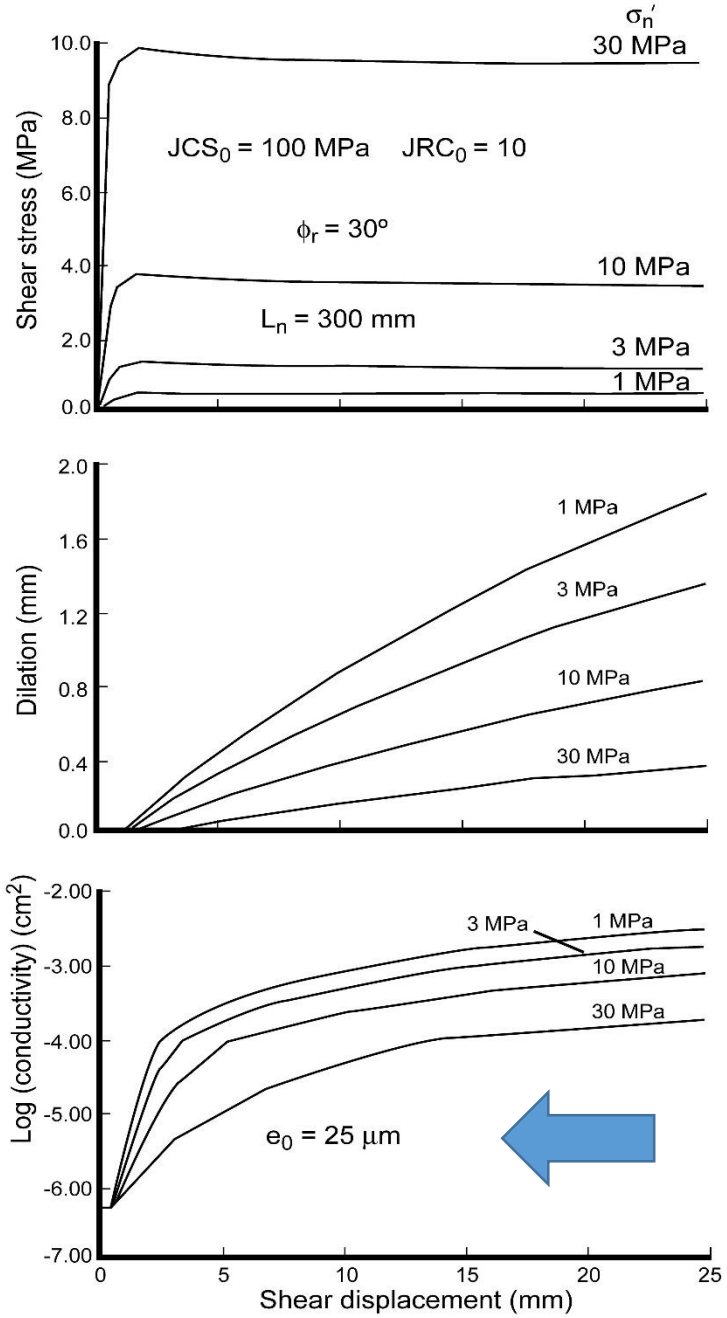


MAYBE THE FIRST CSFT (coupled shear flow test), by Maini 1972.

A shear-under-*self-weight*-with-*flow-measurement* on cleavage planes in *slate.*

Attempts to predict the shear strength and dilation, and to predict/match the permeability increase.

(Barton, 1982)



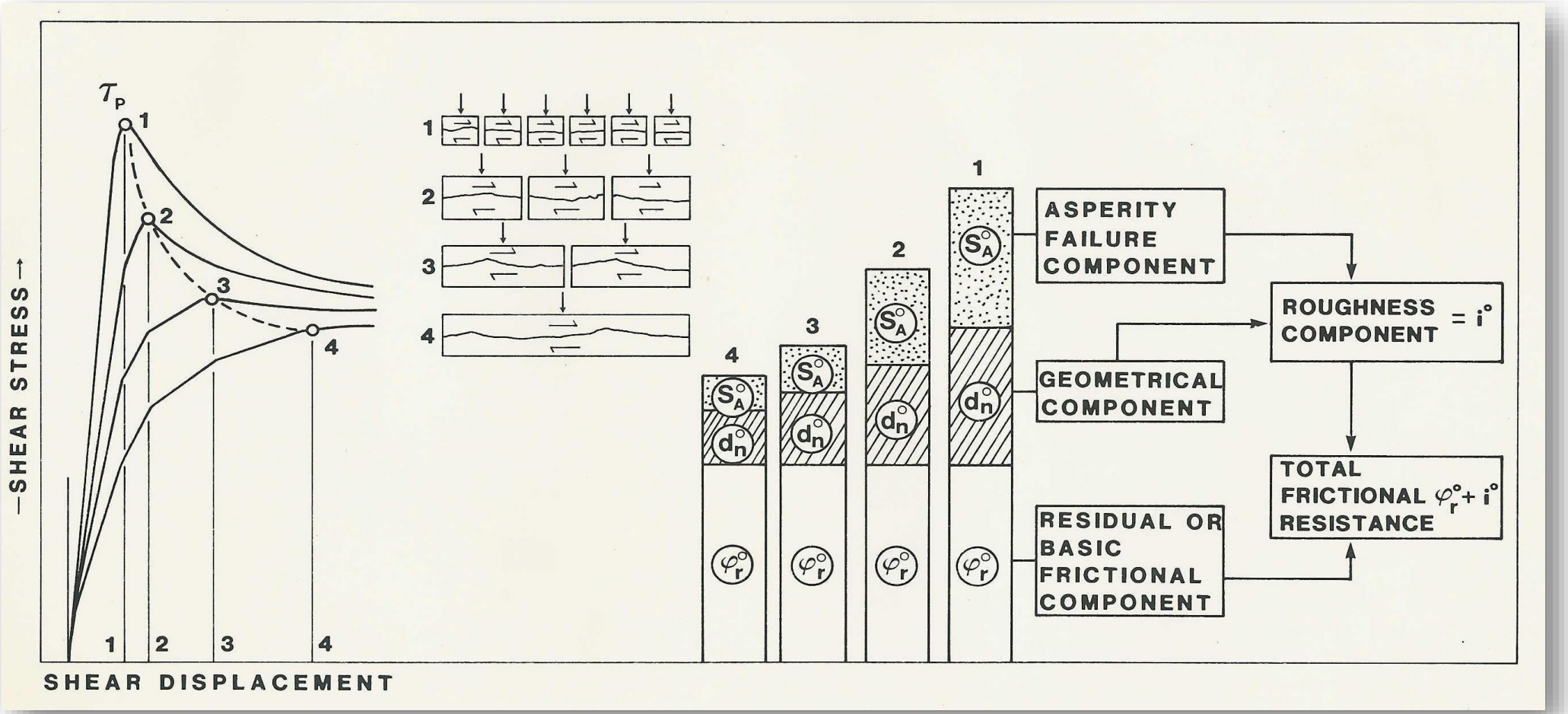
Example of BB-modelling of shear-dilation-conductivity coupling.

Imaginary input data (JRC, JCS, ϕ_r) and effective normal stresses of 1, 3, 10 and 30 MPa. (Block-size L_n = 0.3 m)

Note the assumed 'common' starting point of e = 25 µm (hydraulic aperture). This converts from the physical aperture E using JRC (see later). Δk = 2 to 3 orders of magnitude from 20mm of shearing.

(Barton and Bakhtar, 1983)

8. DO SCALE EFFECTS IN SHEAR ASSIST LONGER PRODUCTION?



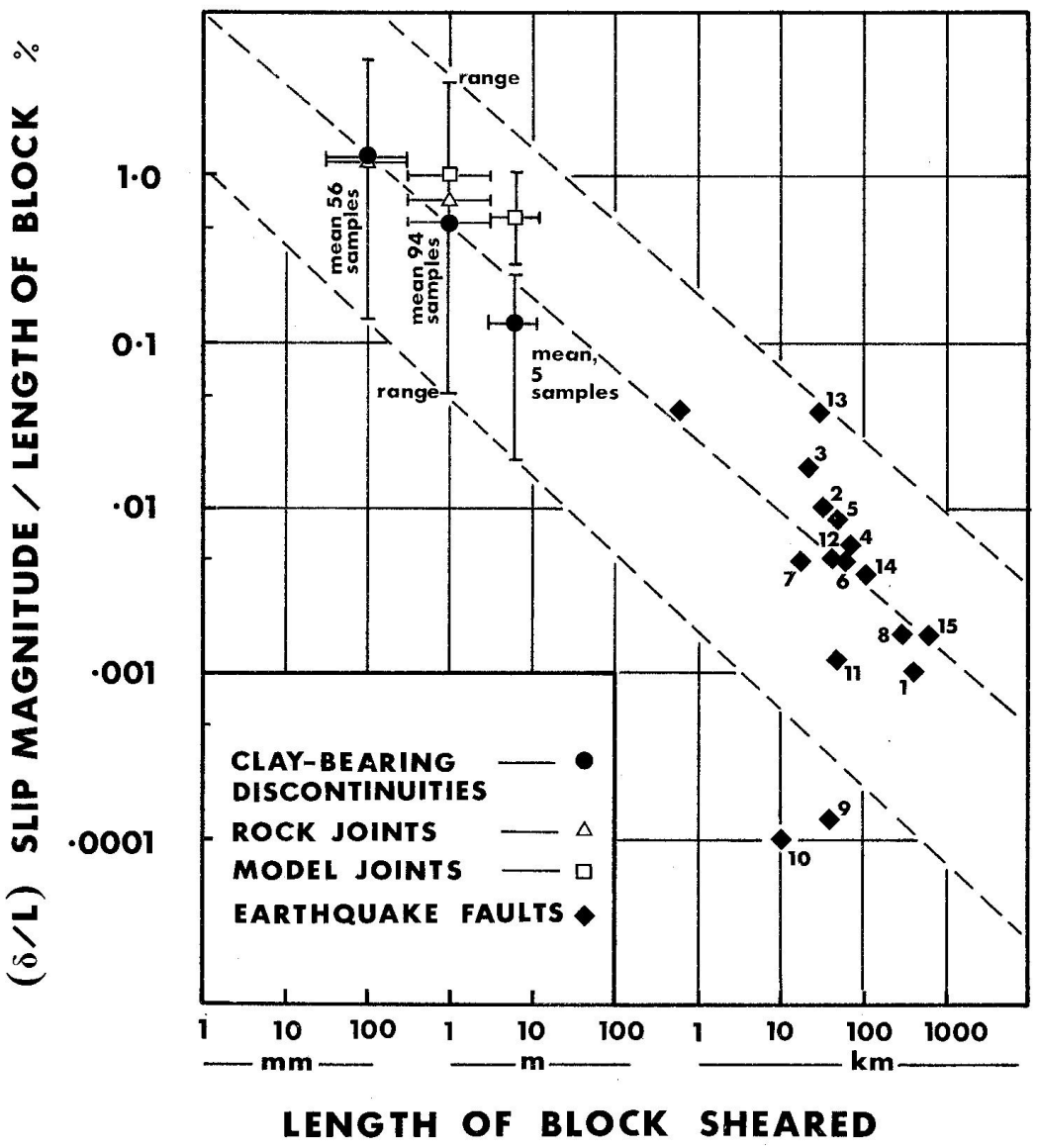
Shear behaviour from UK ignored in Stanford/ USA geomech-anics.

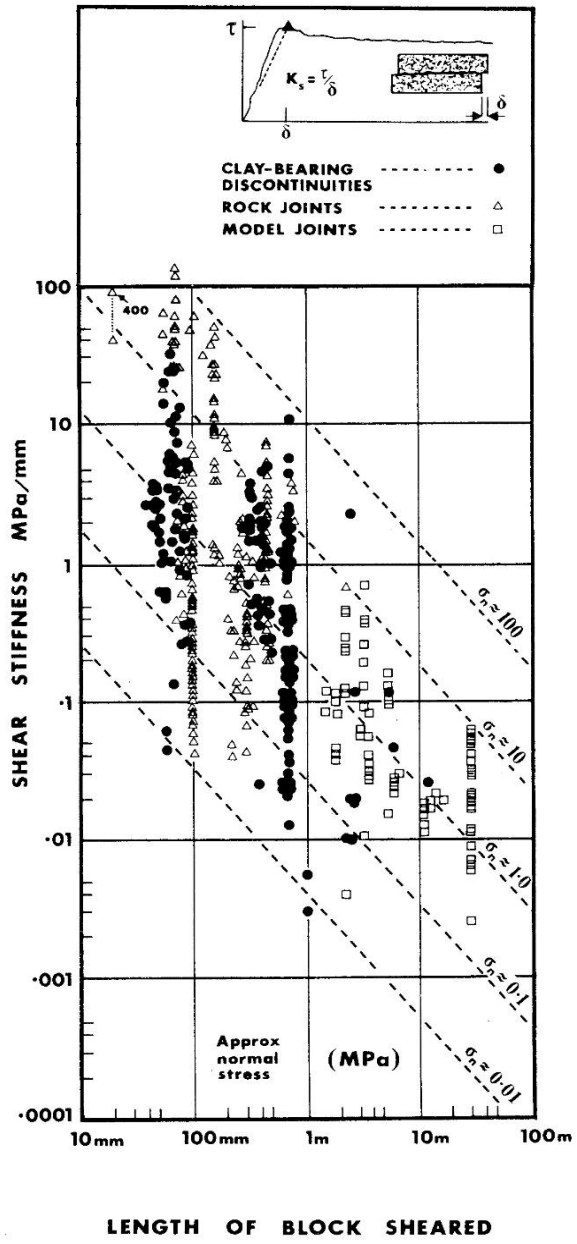
(Bandis, 1980, Bandis et al. 1983)

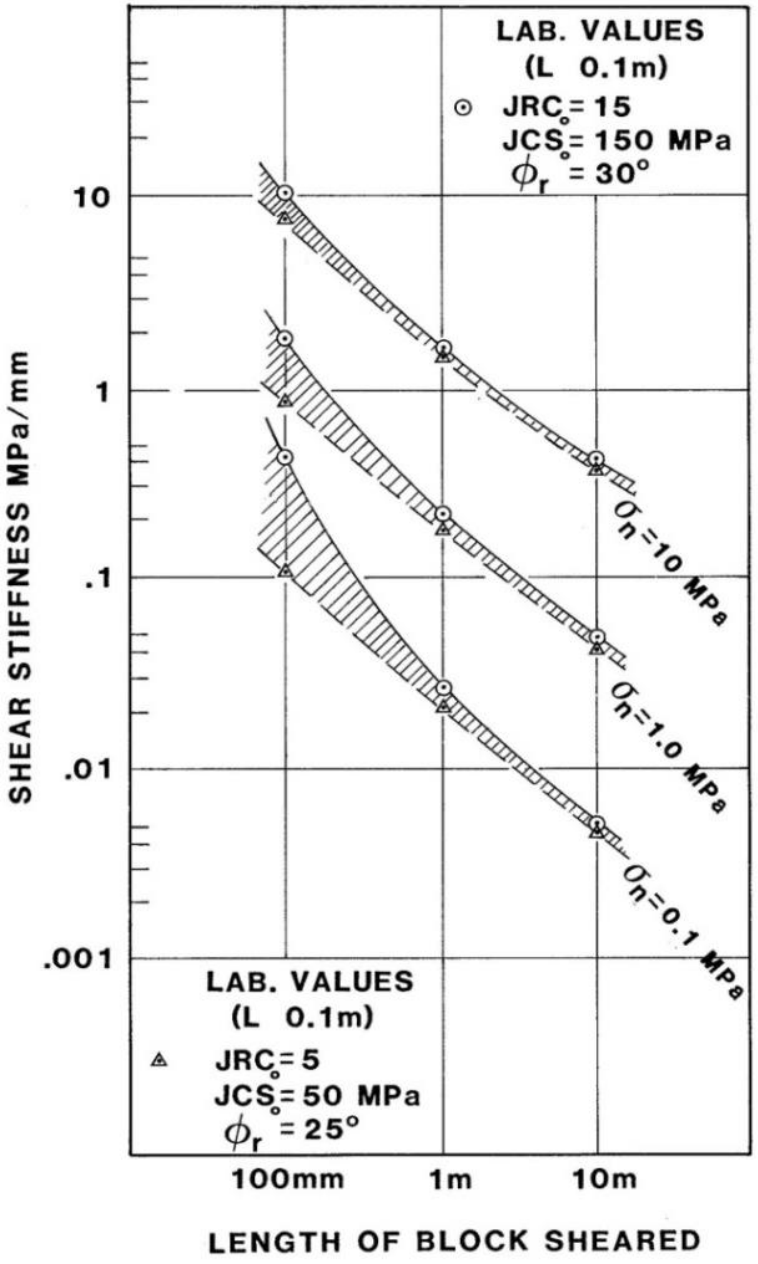
Brittle cast replicas of natural rock joints/fractures, show scale effects when tested at different scale. (Provides more than μ, more than 1 cm artificially sheared samples!)

Scale effects on shear stiffness

(Barton, 1982)







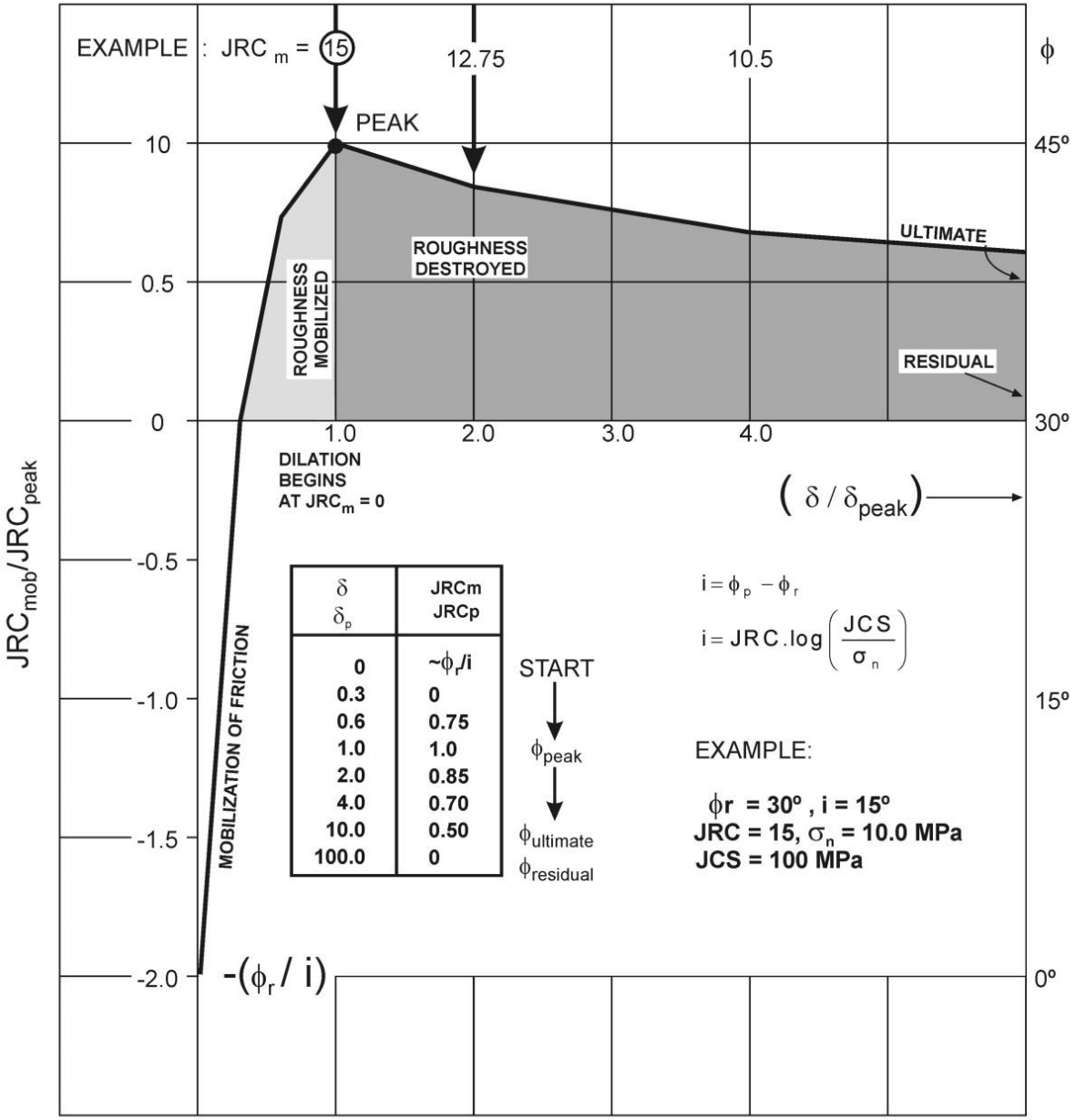
Examples of sensitivity to input data:

Top = rough-undulating, strong rock
Bottom = smooth-planar, weak rock
(*similar to competent shale*). (Barton, 1982)

Note: In the early life of the shale-gas (e.g. Year 1), the 'ease-of-shear' (= shear stiffness) maybe from 1 to 10 MPa/mm. As gas-pressure drops, shearing *(and maintenance of permeability)* will be more difficult.

Due to the scale effects on *Ks*, and the much higher (x 100) *Kn*, *anisotropic behaviour* is automatic if considering jointed-rock-mass behaviour

9. THE MOBILIZED ROUGHNESS CONCEPT

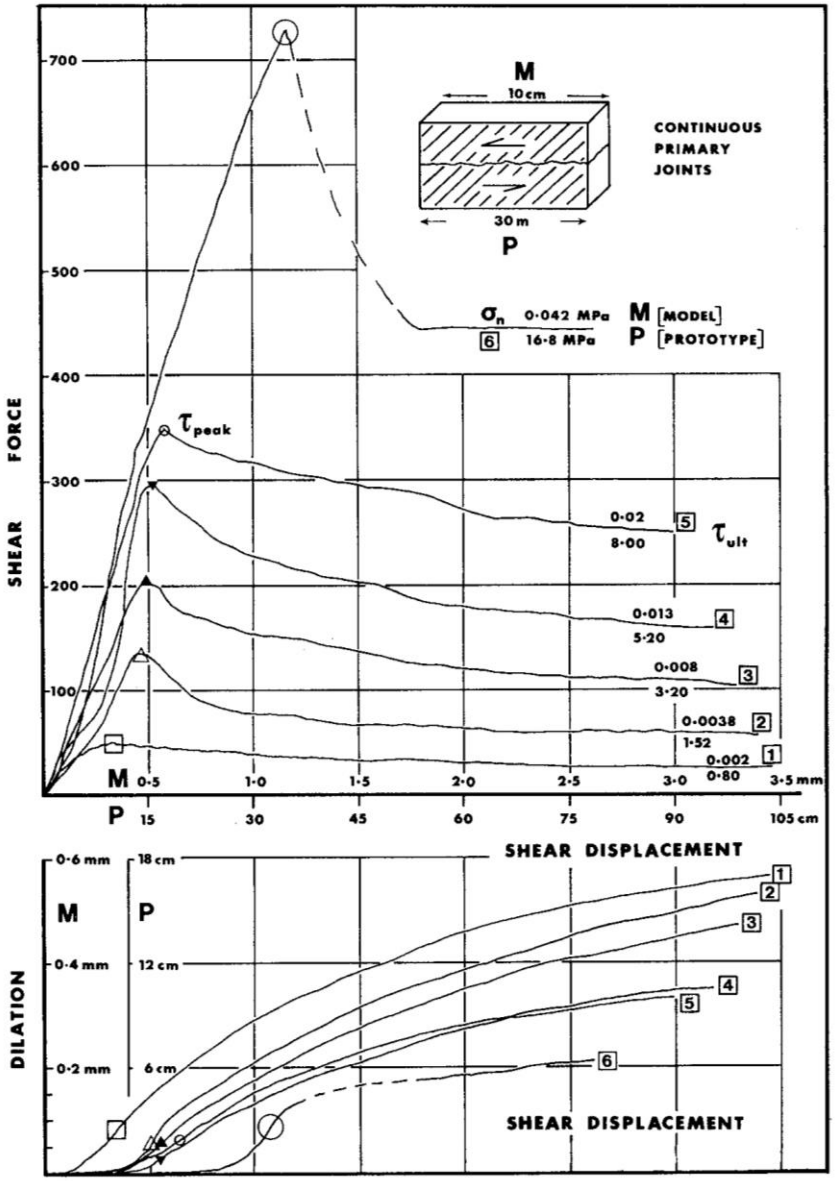


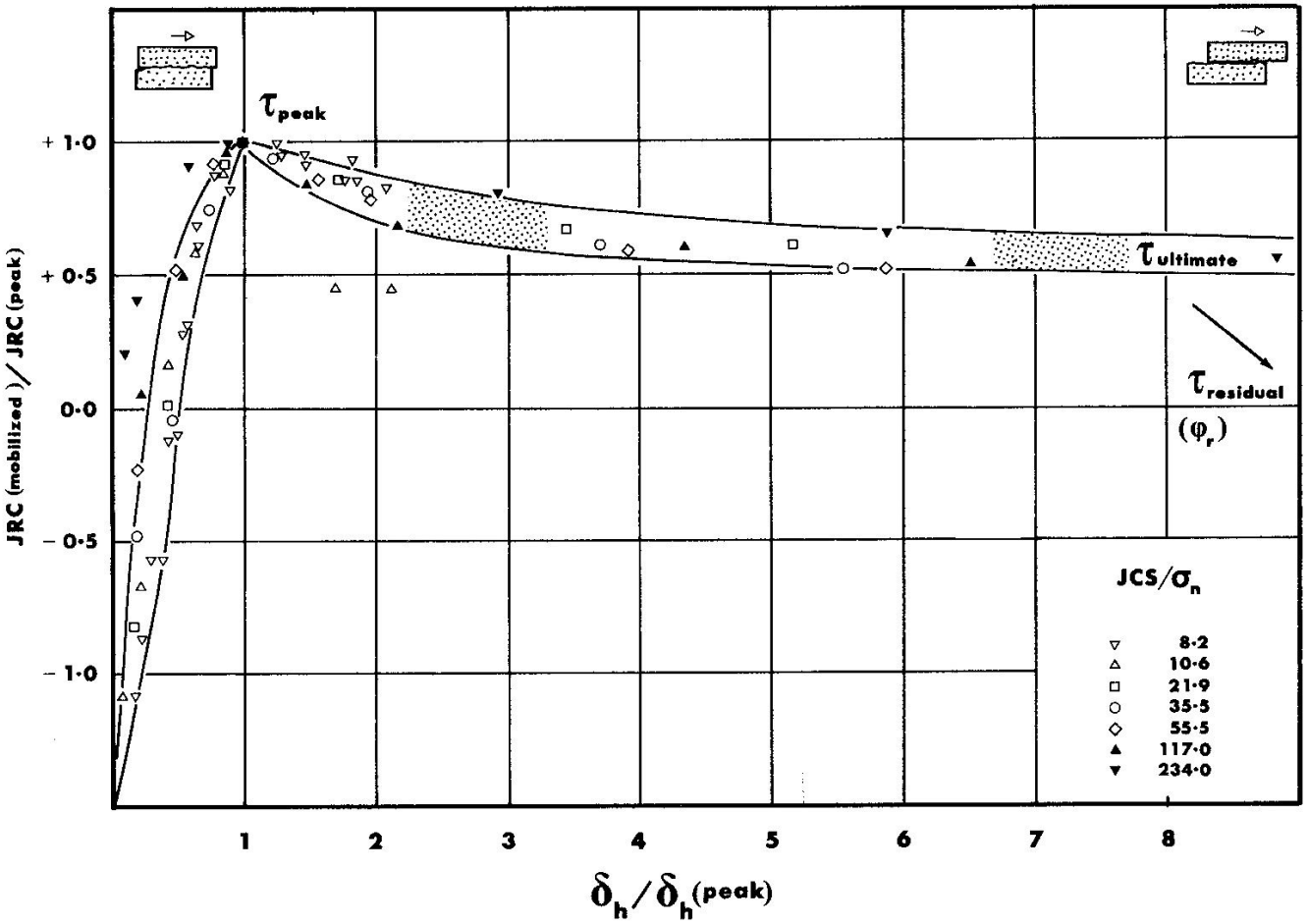
The JRC mobilized method matches the details of fracture behaviour (see next screens) (Barton, 1982)

Note different level of information compared to one ‘peak’ friction coefficient μ (top point of figure only).

A dimensionless method for ‘compressing’ shear test data.

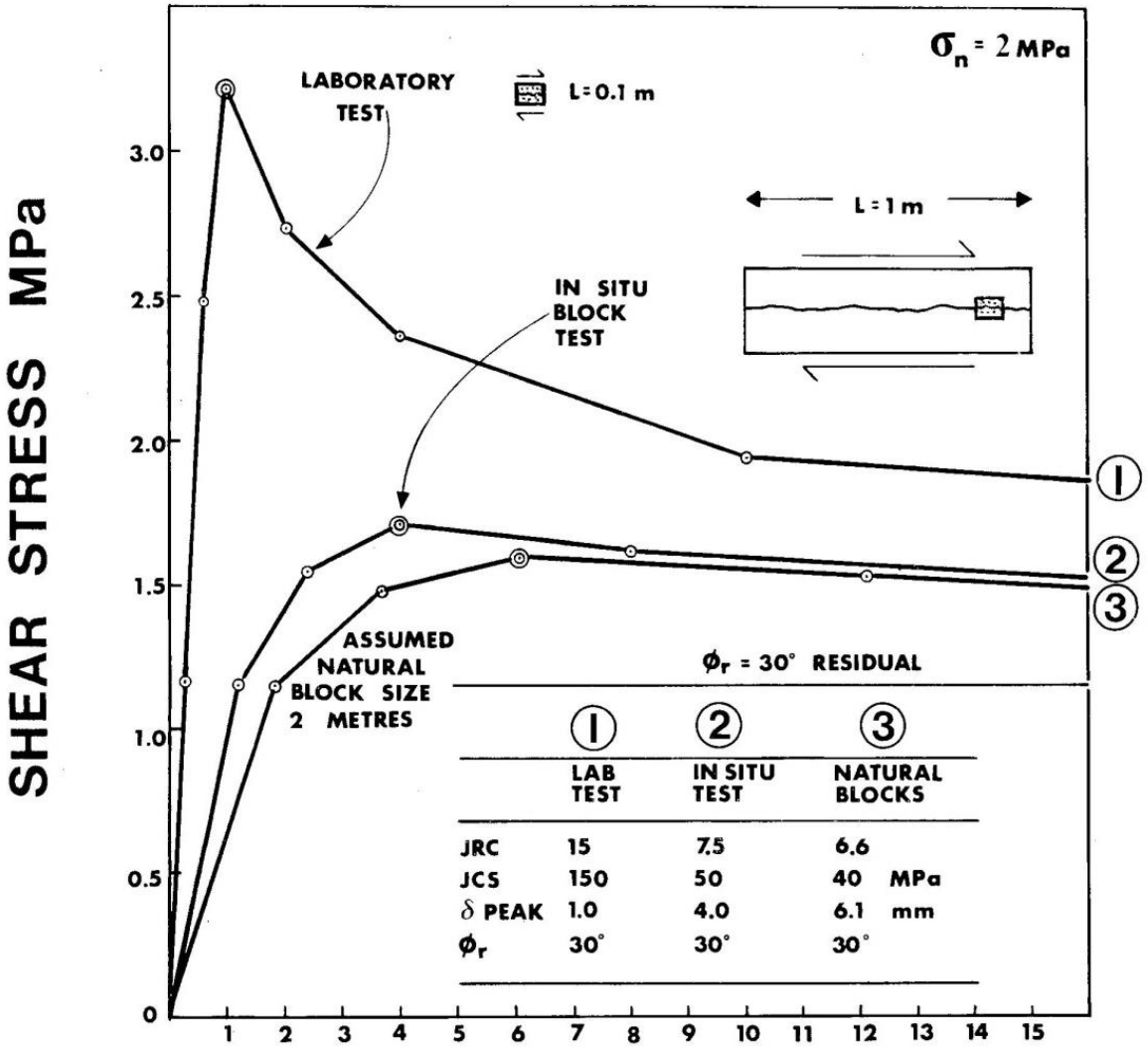
Note use of JRC mobilized /JRC peak. (Barton, 1980)

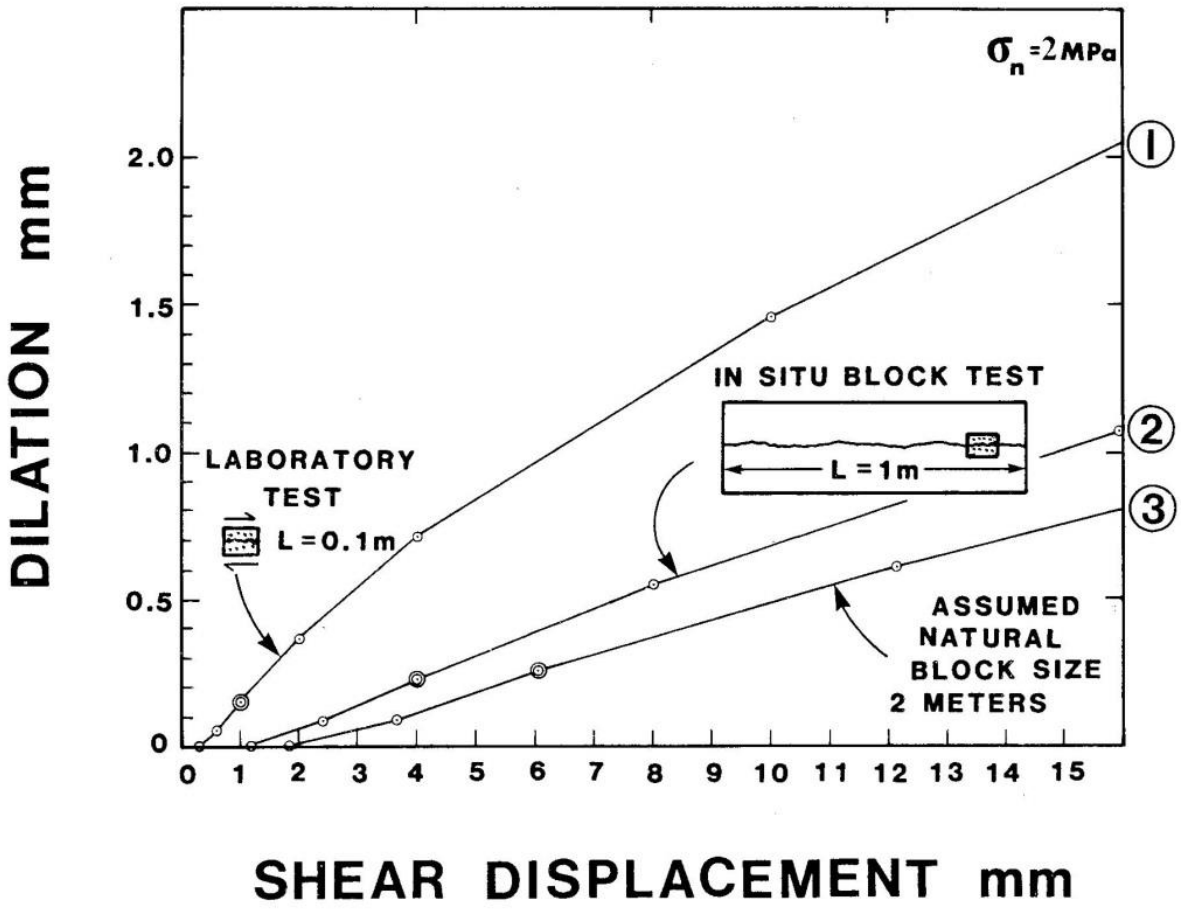


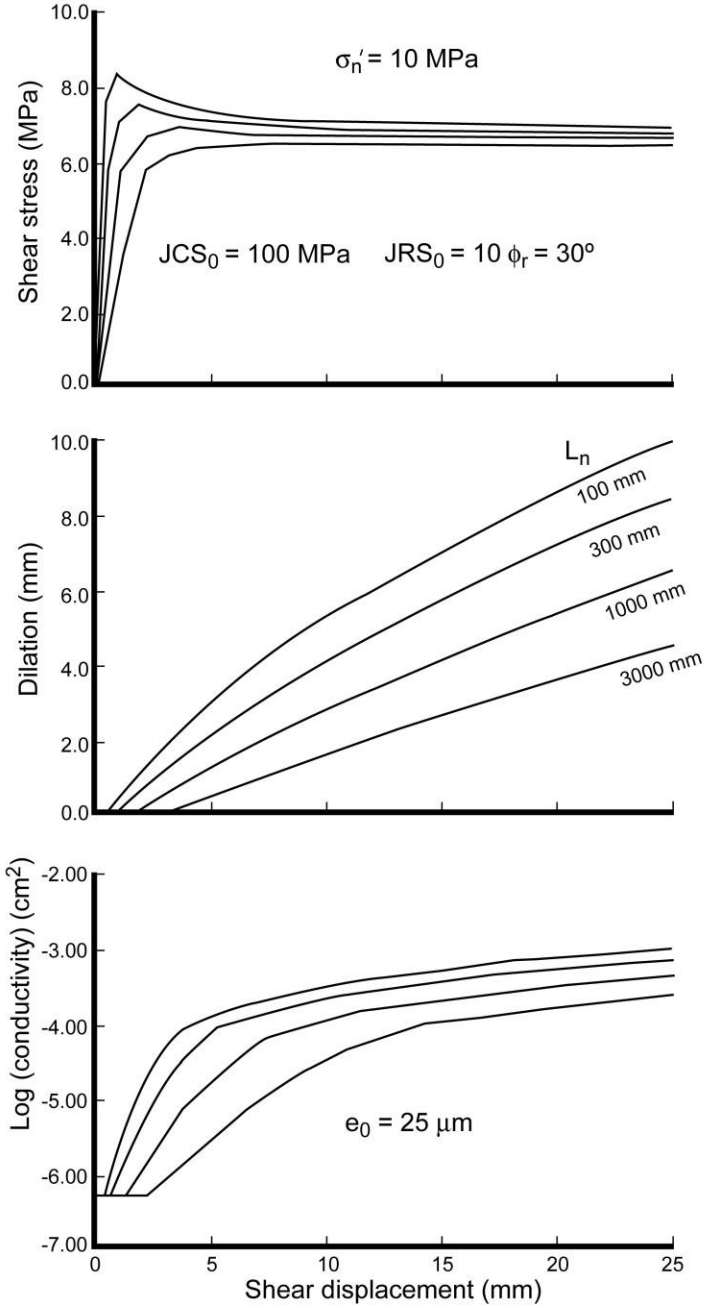


Examples of ‘up-scaling’ to the lower strength of *in situ* block sizes.

(One friction coefficient μ is not sufficient description!) (Barton, 1982)





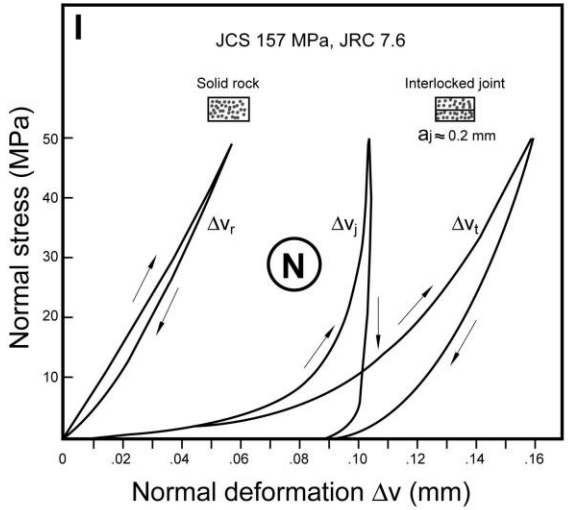


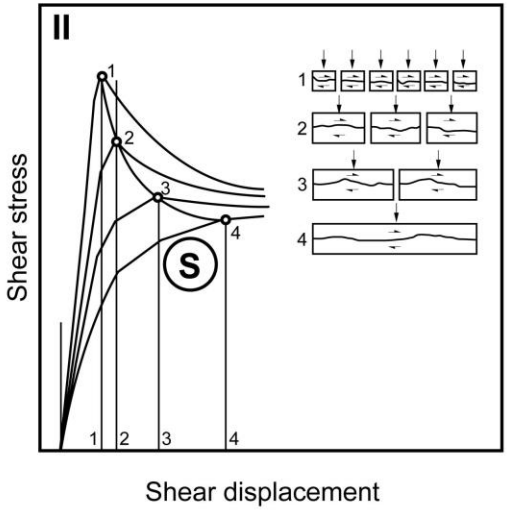
Coupled shear-dilation-permeability modelling

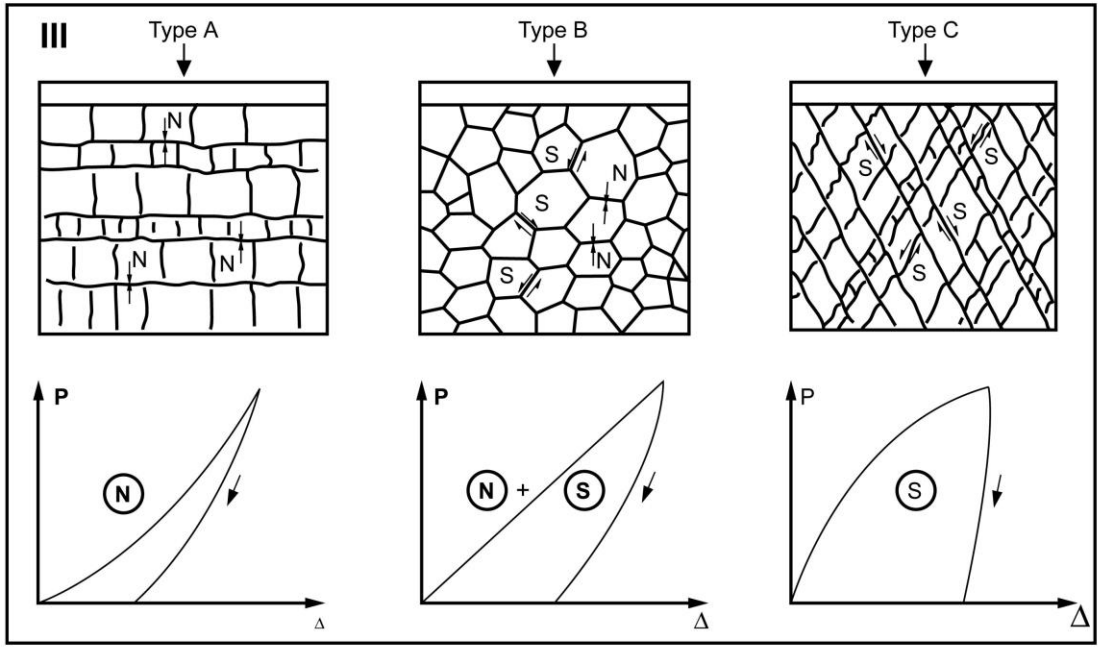
(Barton and Bakhtar, 1983)

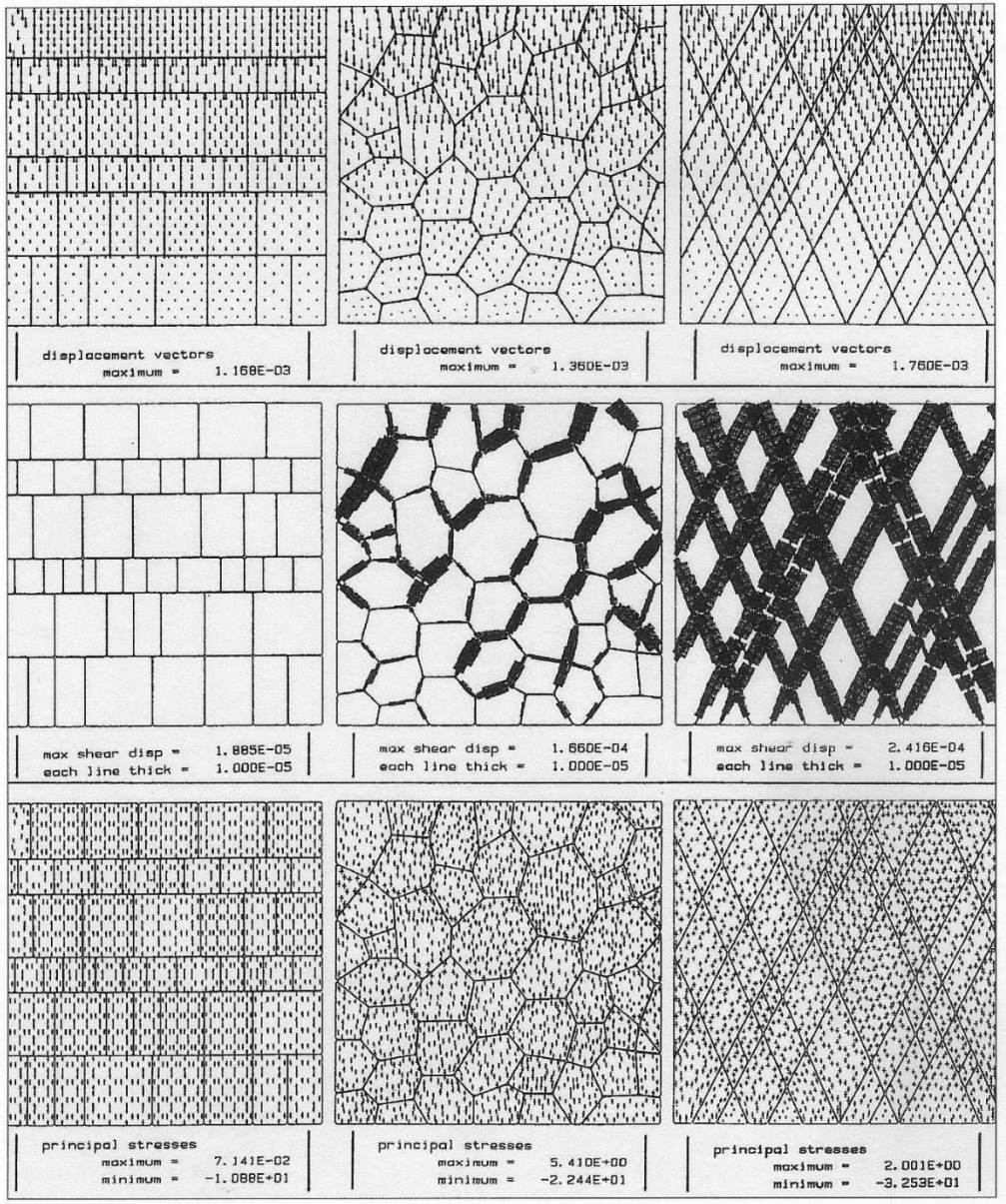
Permeability is enhanced by shearing, due to potential for slight dilation.

Note the predicted delay in dilation (and therefore Δk) with larger block-sizes.

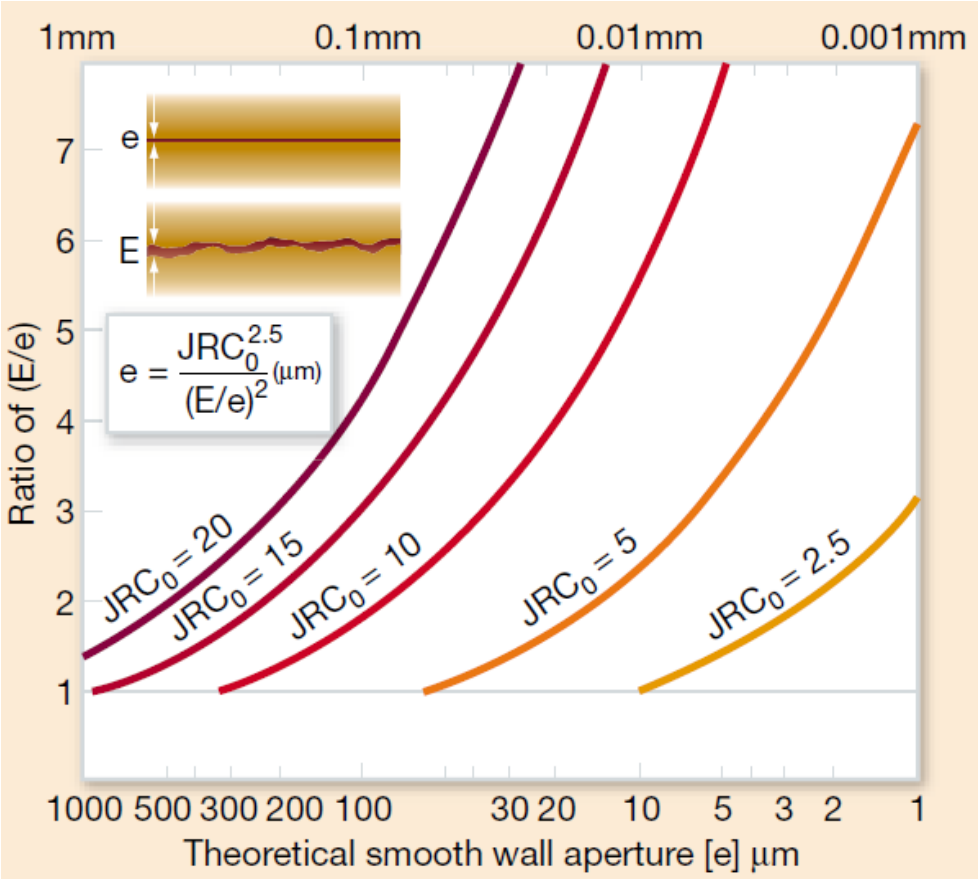

I
JCS 157 MPa, JRC 7.6
Solid rock
Interlocked joint
aj ≈ 0.2 mm
Δvr
Δvj
Δvt
N
Normal stress (MPa)
Normal deformation Δv (mm)


II
S
Shear stress
Shear displacement


III
Type A
Type B
Type C
N
S
P
Δ


displacement vectors
maximum = 1.168E-03
displacement vectors
maximum = 1.360E-03
displacement vectors
maximum = 1.760E-03
max shear disp = 1.885E-05
each line thick = 1.000E-05
max shear disp = 1.660E-04
each line thick = 1.000E-05
max shear disp = 2.416E-04
each line thick = 1.000E-05
principal stresses
maximum = 7.141E-02
minimum = -1.088E+01
principal stresses
maximum = 5.410E+00
minimum = -2.244E+01
principal stresses
maximum = 2.001E+00
minimum = -3.253E+01

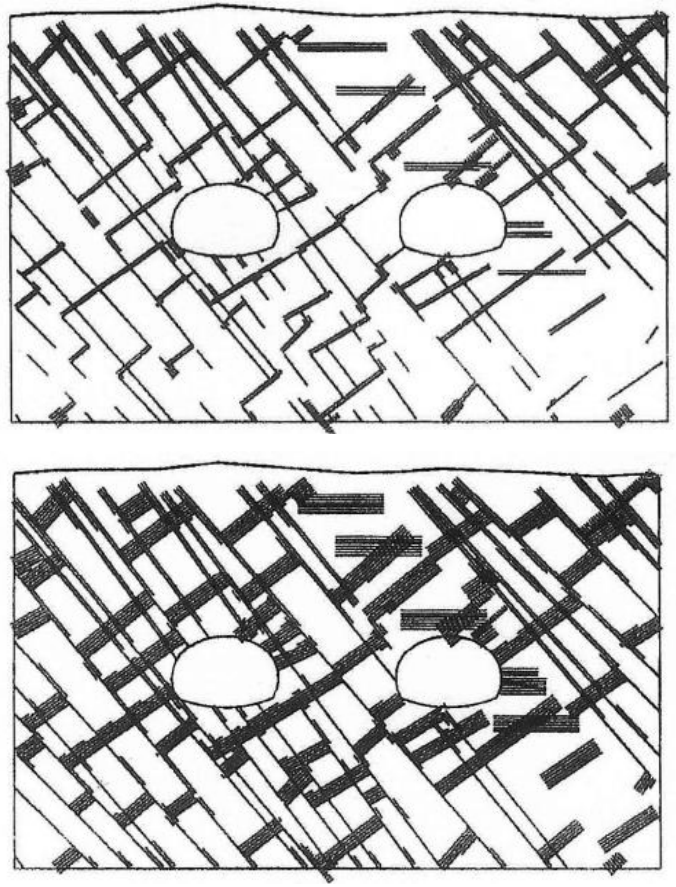
9. HYDRAULIC AND PHYSICAL APERTURES AND THEIR CONVERSION

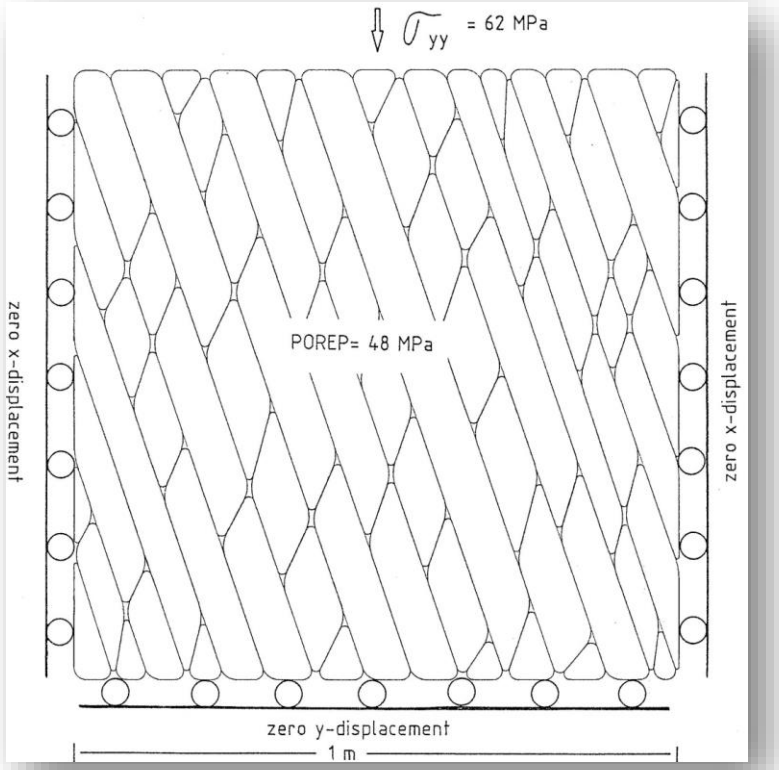


E ≥ e, and strong dependence on JRC (or a/L) is evident.

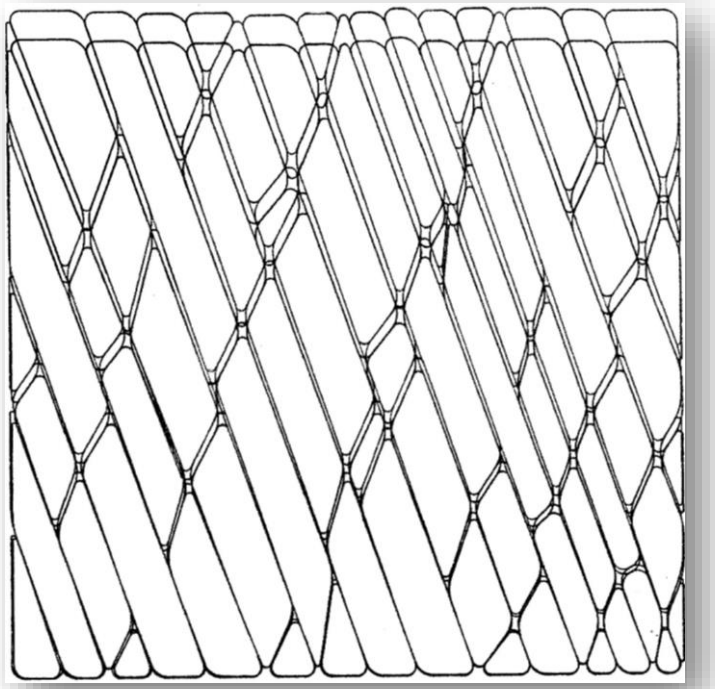
(Barton and Quadros, 1997)

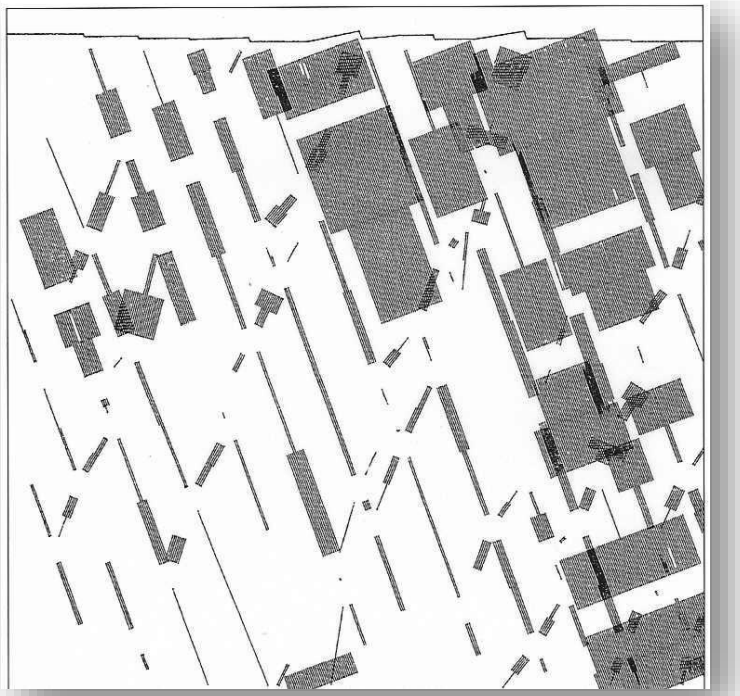
Hydraulic and physical apertures are usually of different magnitude (Barton, 1972, 1982, Makurat and Barton, 1988)





A DOMINANT JOINT SET LEADS TO ANISOTROPIC BEHAVIOUR: VERTICAL COMPACTION BUT MAINTAINED PRODUCTION DUE TO SHEAR.

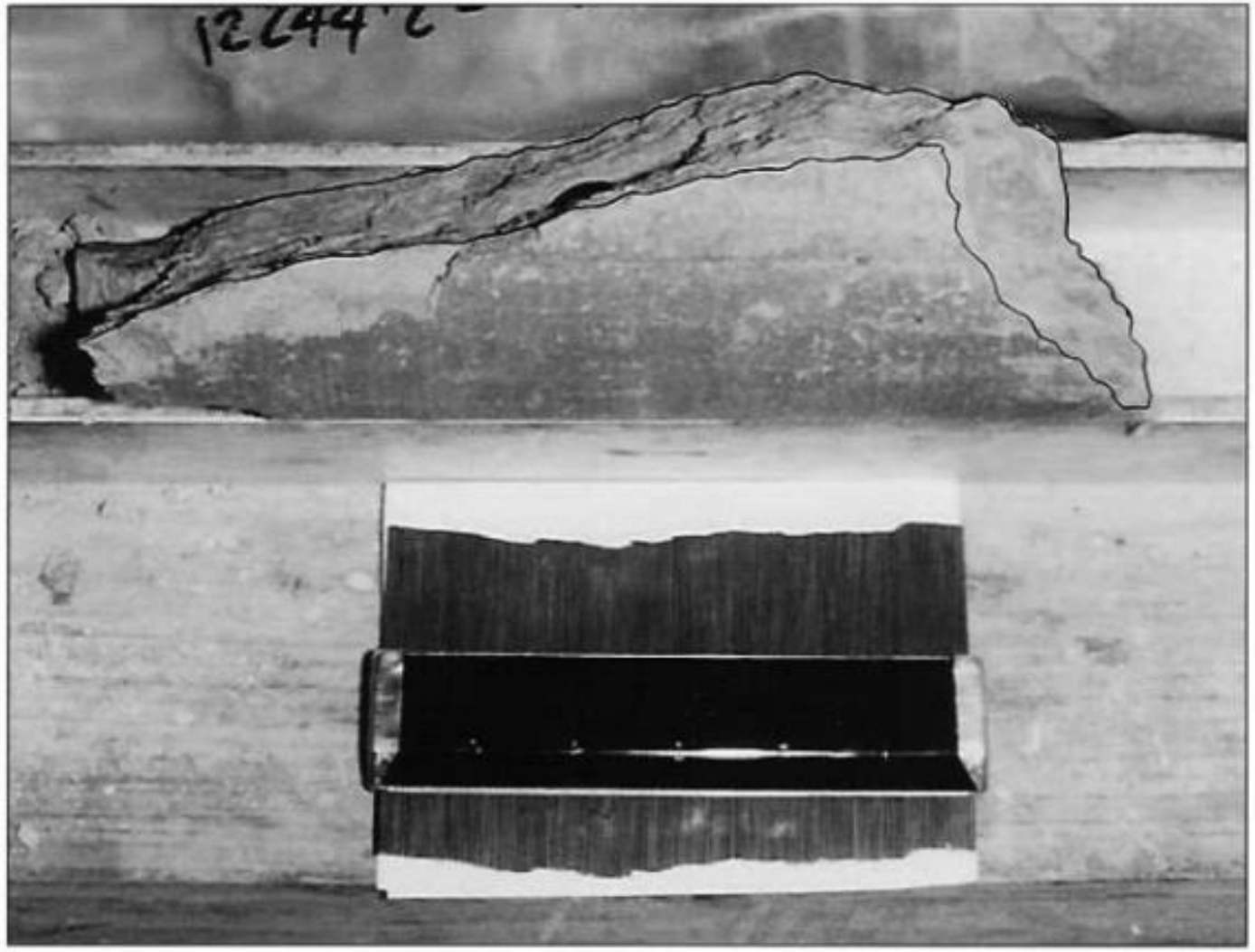




EKOFISK (1D) RESERVOIR COMPACTION MECHANISM.

(20 MPa reduction in pore pressure). UDEC-BB code.

(Barton et al., 1986)



One of numerous Ekofisk chalk (natural) fractures from 3 km depth, tested at NGI

(Barton et al. 1986)

10. CONCLUSIONS

1. PETROLEUM GEOMECHANICS IS PRESENTLY VERY 'USA-BASED'. SHEAR STRENGTH IS ACTUALLY FAR MORE THAN BYERLEE'S 'μ = 0.6 or 0.85' AS SEEN SO OFTEN WHEN *STANFORD / ZOBACK et al.* METHODS ARE FOLLOWED, OR THEIR ON-LINE COURSES ARE ATTENDED.

2. THE LIKELY REALITY WITH SHALES OF MODERATE STRENGTH, *DUE TO LARGE CHANGES OF EFFECTIVE STRESS*, IS THAT ASPERITY STRENGTH AND STIFFNESS (AND OVERALL MODULUS) MAY ACTUALLY DEPEND ON AN UNDERSTANDING OF NON-LINEAR SHEAR STRENGTH, BECAUSE THE *SHEARED ASPERITIES ON WHICH WE DEPEND FOR LARGE-VOLUME-MAINTAINED-DRAINAGE* ARE MUCH MORE HIGHLY STRESSED.

3. WILL THE NATURALLY- FRACTURED SHALE OUTSIDE THE CENTRAL PROPPED REGION BE STRONG AND STIFF ENOUGH TO MAINTAIN ITS 'PERMEABLE' SHEARED STATE FOR LONG ENOUGH? MAYBE NOT.

4. MORE COMPONENTS OF SHEAR BEHAVIOUR THAN (μ) NEED TO BE UNDERSTOOD, TOGETHER WITH BELIEF IN THE IMPORTANCE OF (ACTUAL) NON-LINEAR SHEAR STRENGTH AND DEFORMABILITY.