NON-LINEAR SHEAR STRENGTH DESCRIPTIONS ARE STILL NEEDED IN *PETROLEUM GEOMECHANICS*, DESPITE 50 YEARS OF LINEARITY

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(ARMA16-***252***)

CONTENT OF LECTURE

- NON-LINEAR STRENGTH FOR THE MATRIX – VERY BRIEFLY
- NON-LINEAR STRENGTH FOR THE FRACTURES (JOINTS) – NOT SO BRIEFLY
- IMPORTANCE OF SHEARING (ALSO PRE-PEAK SHEARING)
- FRACTURE DEFORMATION – DILATION – CONDUCTIVITY COUPLING
- THE COMPONENTS OF SHEAR STRENGTH: A PROGRESSIVE CASCADE
- STRESS TRANSFORMATION ERROR IN EARTH SCIENCES?

- STRESS-SENSITIVE RESERVOIRS (CLOSURE INSTEAD OF SHEAR)

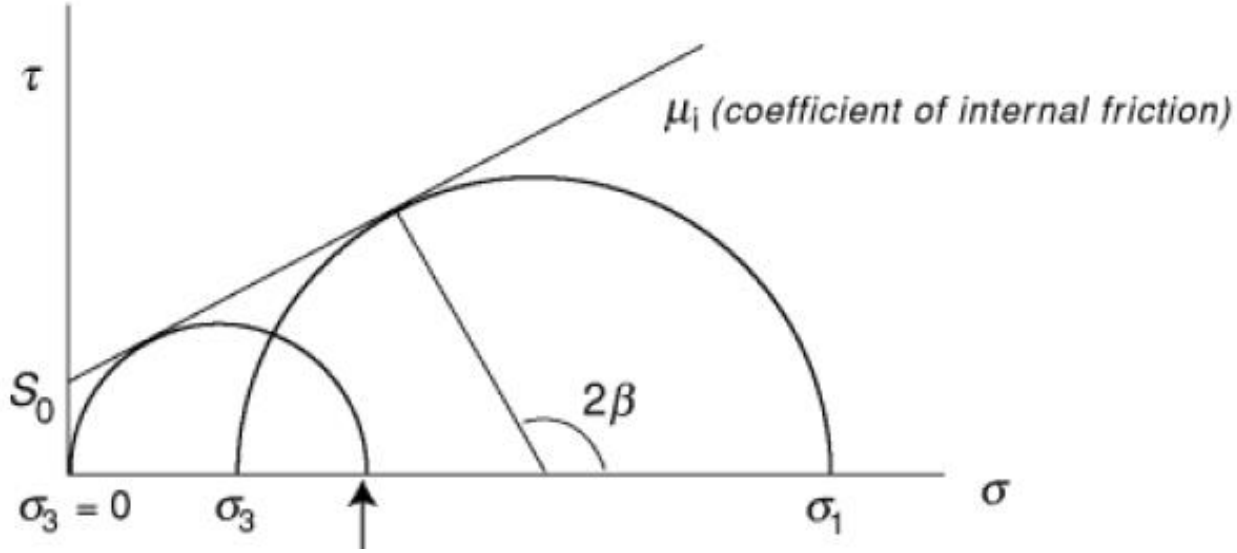
INTRODUCTION

RESERVOIR GEOMECHANICS WORKSHOPS (in the last 10 years) ON BOTH SIDES OF THE ATLANTIC AND IN THE MIDDLE-EAST, GIVE EVIDENCE OF THE *GEOMECHANICS BELIEF* IN LINEAR SHEAR STRENGTH ENVELOPES FOR THE MATRIX AND FOR THE FRACTURES OF NFR AND OIL-SHALES/GAS-SHALES.

UNIVERSITY COURSES (IN GEOMECHANICS), AND 'LEARNED' BOOKS, FOLLOW THIS PATTERN TOO.

BUT ROCK MASSES CANNOT OBEY THESE TWO COMMON 'ALL-IS-LINEAR' ERRORS – WHEN EFFECTIVE STRESS VARIES OVER A BIG RANGE (and when fractures are non-planar).

Why is linearity believed - especially in a producing reservoir?



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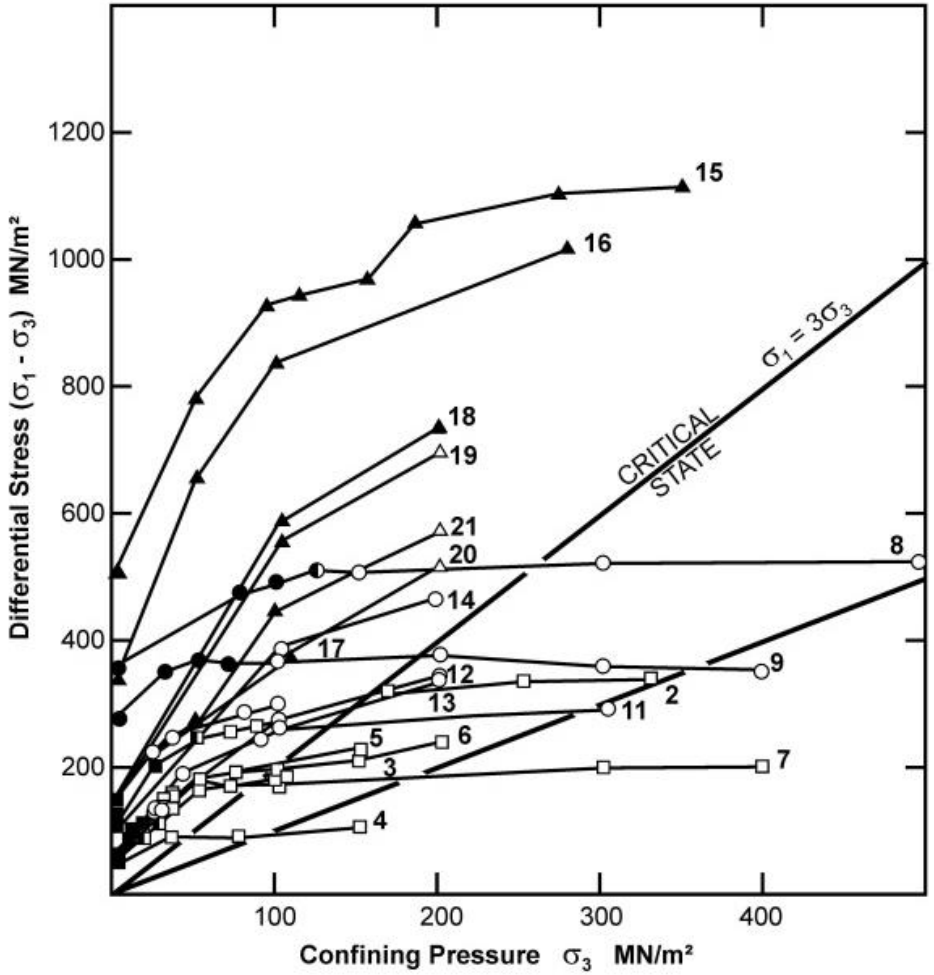


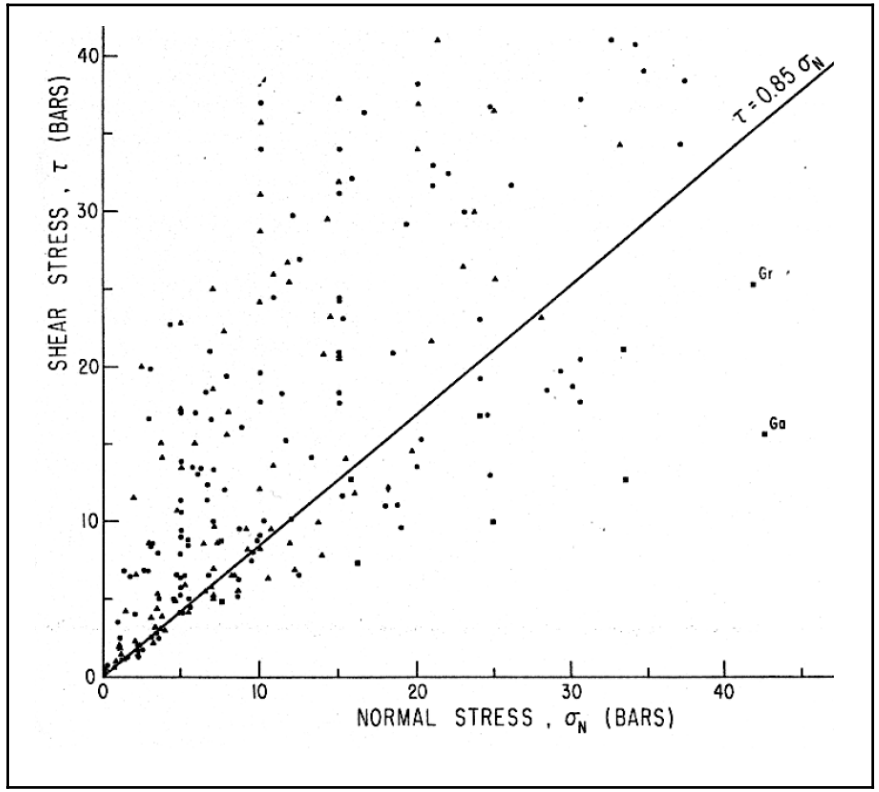
ARE *MULTI-DISCIPLINE TEAMS* IN PETROLEUM (AND SERVICE) COMPANIES USING ROCK MECHANICS IN THEIR GEOMECHANICS DELIBERATIONS?

THE USE OF FRICTION COEFFICIENTS FOR FRACTURES (BYERLEE 1978, C. BARTON et al. 1995, ZOBACK 2007 and many others) AND LINEAR MOHR-COULOMB STRENGTH FOR THE MATRIX IS FAR FROM 'CUTTING EDGE' TECHNOLOGY – WHERE SO MUCH ELSE IN THE SAME PETROLEUM (AND SERVICE) COMPANIES *IS NO DOUBT AT THE HIGHEST POSSIBLE TECHNICAL LEVELS*.

Pageoph, Vol. 116 (1978), Birkhauser Verlag,

Friction of Rocks

By J. BYERLEE



A TROUBLING PUBLICATION: BYERLEE, 1978
(DOES THIS LOOK LIKE A 'LAW of BEHAVIOUR'?)
AND WHO ARE 'H. BARTON' and 'M. BARTON'?

REFERENCES

BARTON, H. (1976), *The shear strength of rock and rock joints,* Int. J. Rock Mech. Min. Sci. *13*, 255-279.

BARTON, M. (1973), *Review of a new shear strength criterion for rock joints,* Eng. Geol. *7*, 287-332.

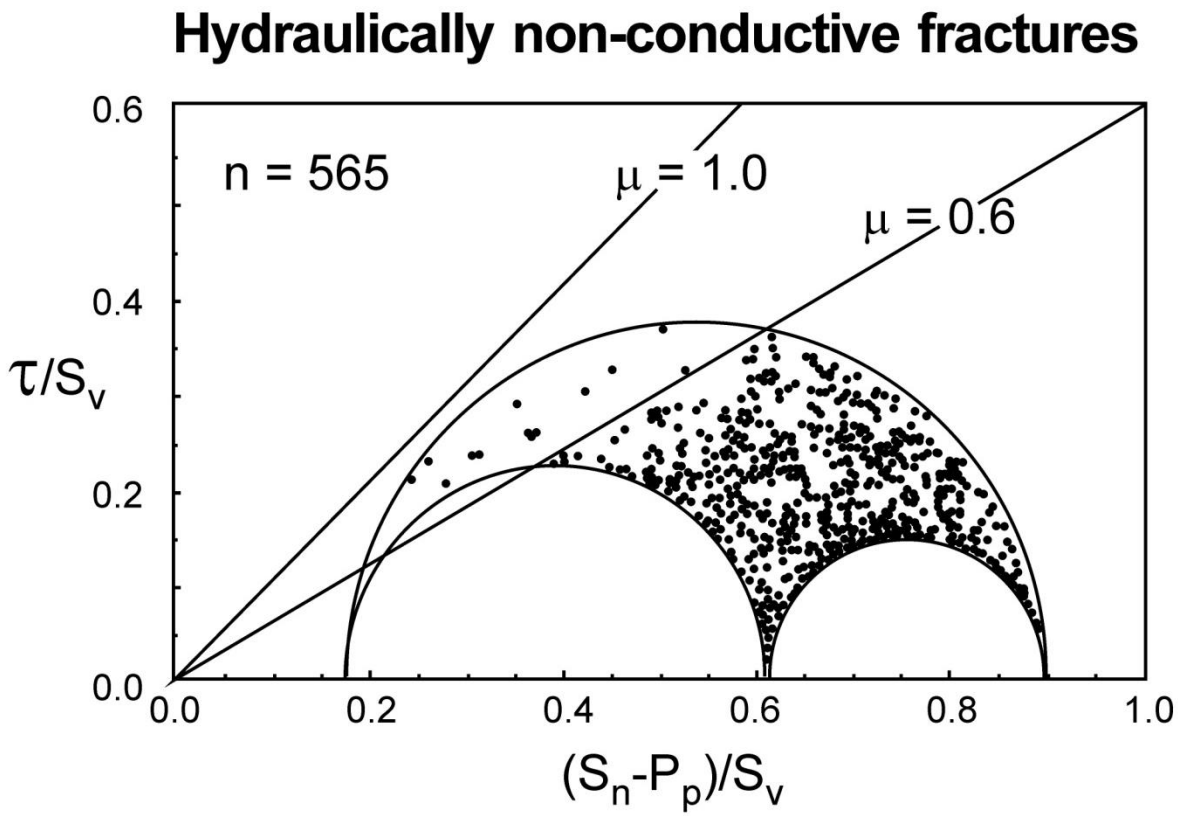
CAN THE '*LINEARITY-IN-GEOMECHANICS*' PROBLEM BE 'BACK-TRACKED' TO BYERLEE OPINIONS ABOUT THE (BY NOW WIDELY USED) NON-LINEAR SHEAR STRENGTH JOINT/FRACTURE DESCRIPTION and MODELLING METHODS (i.e. the Barton-Bandis CRITERION) ?

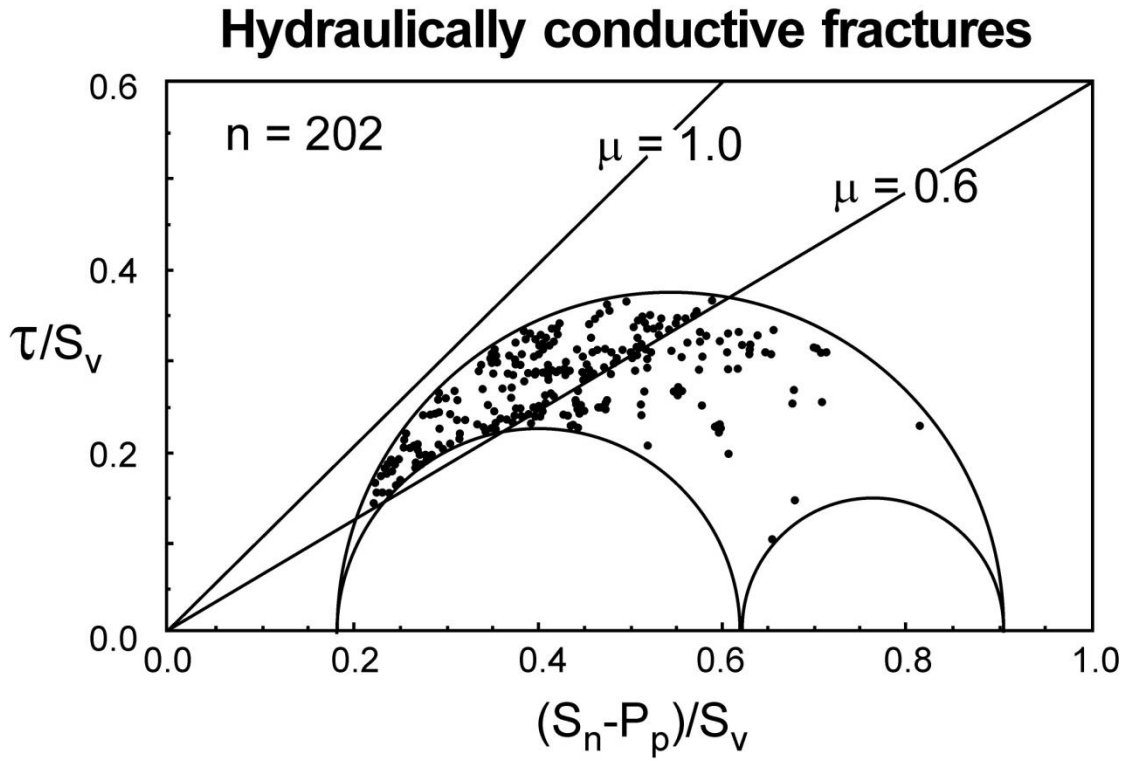
Quoting from Byerlee, 1978 concerning the 'new' JRC and JCS method:

'There are so many variable (sic), whose precise value is uncertain, in the equation, (sic) that its validity cannot be tested'.

Byerlee, 1978 referred to the Barton, 1973 and Barton, 1976 *JRC-JCS-φ_b* equation. Since he managed to give this author (NB) the initials 'M' and 'H' in reference to these two papers, their future use – *in petroleum geomechanics* - was perhaps compromised by his lack of care. Later a 'third' Barton (Colleen) appeared (in Stanford) – so no need for an 'N'?

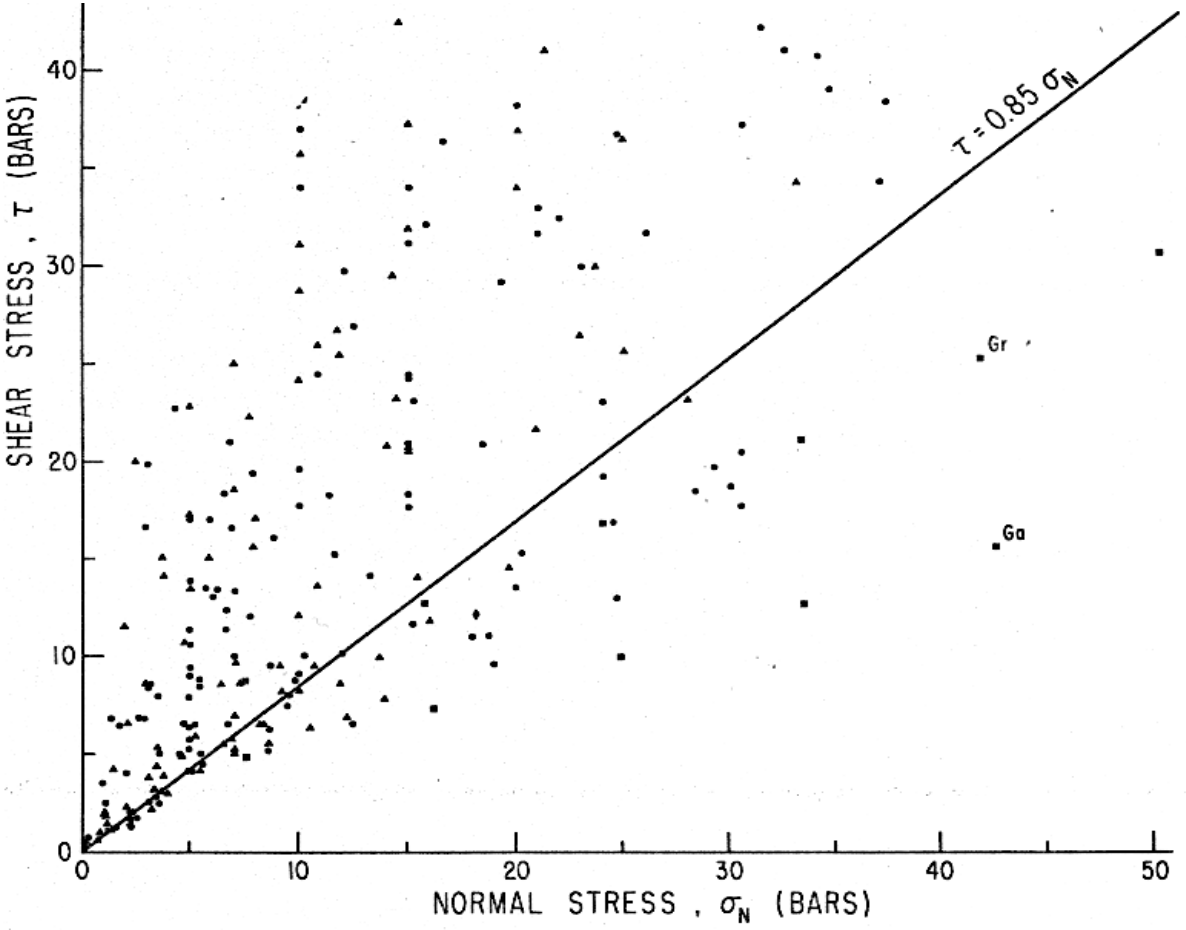
The friction coefficient approach of Colleen B, as widely used in petroleum geomechanics.





Transformed shear stress (and effective normal stress) each normalized by *σ_v, helps* distinguish between non-conductive and conductive fractures in deep wells.

Colleen Barton, Zoback and Moos, 1995.



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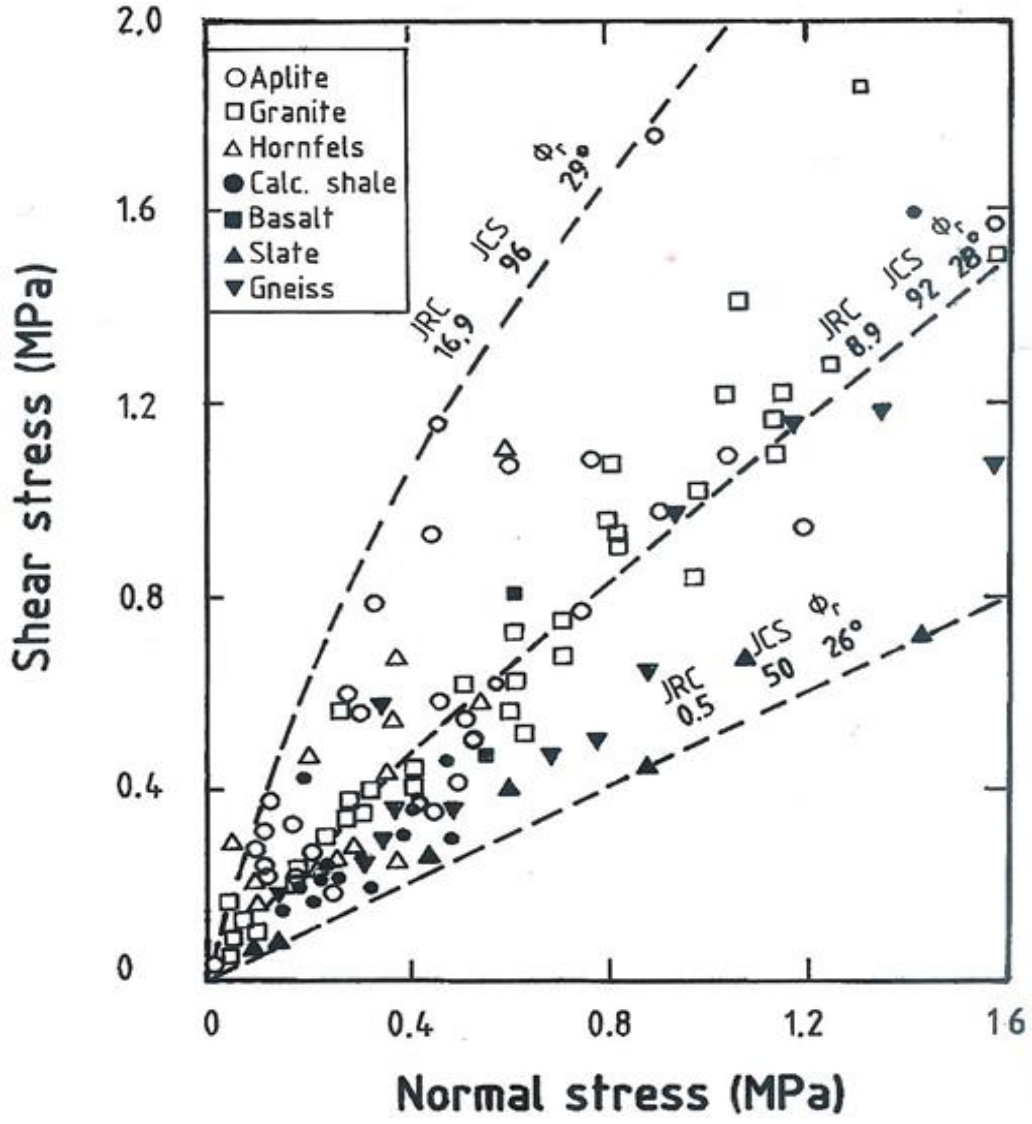


THE VALIDITY (of JRC and JCS) WAS PROVED BEFORE BYERLEE, 1978 (IN 1973, 1977) BUT HIGHER STRESSES ARE NEEDED FOR MODELLING PETROLEUM RESERVOIRS. CONTRARY TO BYERLEE, ROCK TYPE IS IMPORTANT.

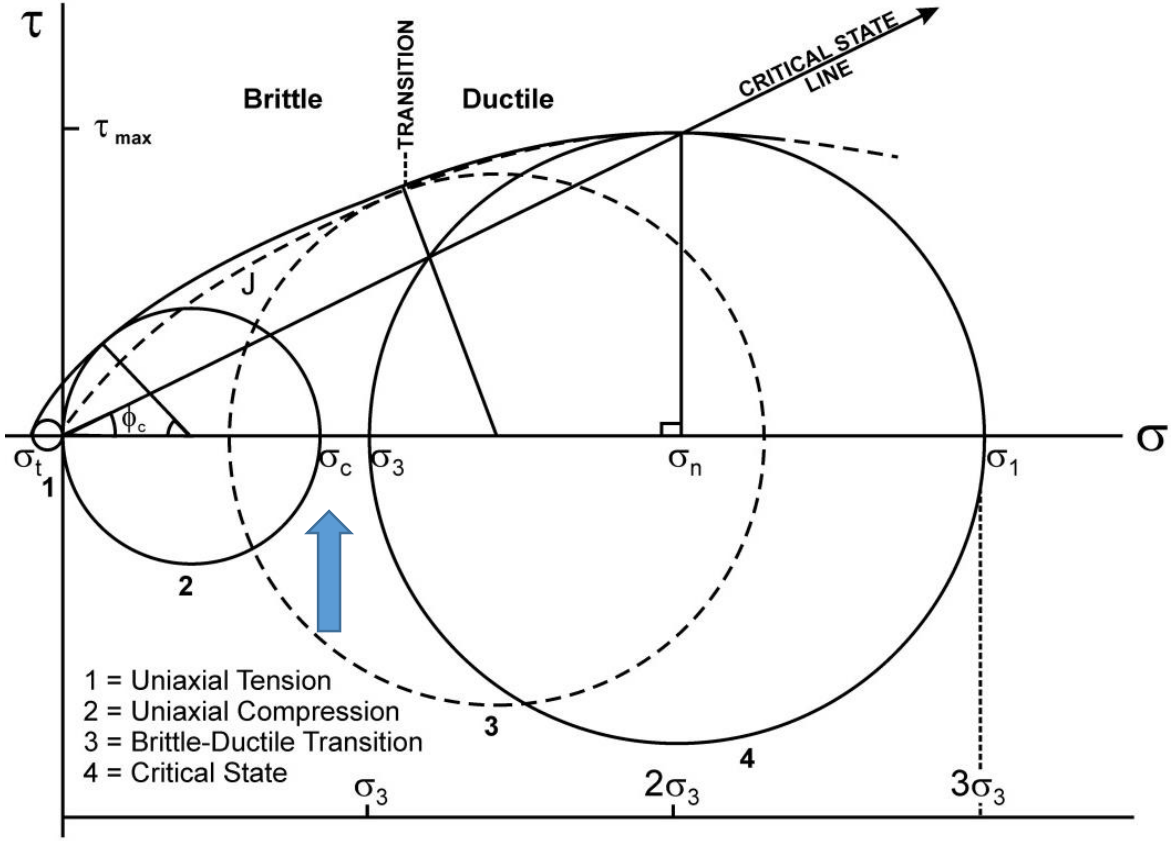
(LEFT: Byerlee 1978, RIGHT: Barton and Choubey 1977, Barton and Bandis, 1990)

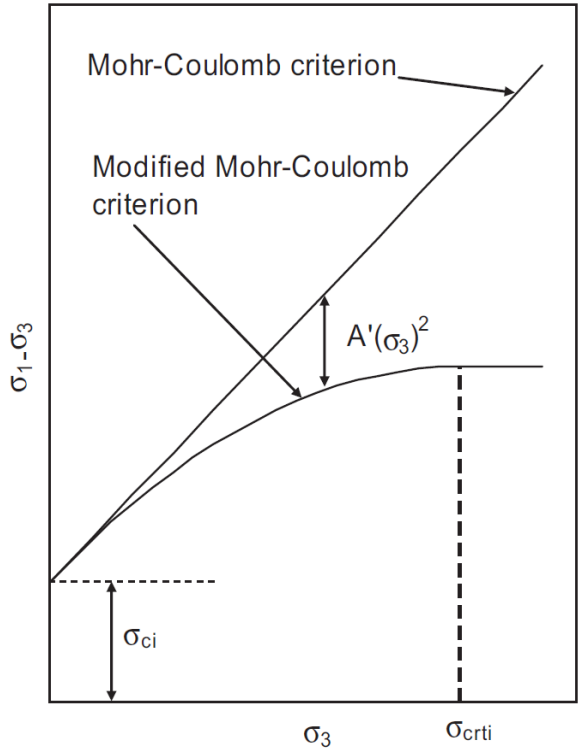
Seriously negative opinion from an influential professor (?) at Stanford, and preference for friction coefficients (Byerlee 'law') perhaps set the scene for *linear geomechanics*, and for the next generations at Stanford to take no interest (not see?) the non-linear work occurring across the Atlantic? See Zoback, 2007.

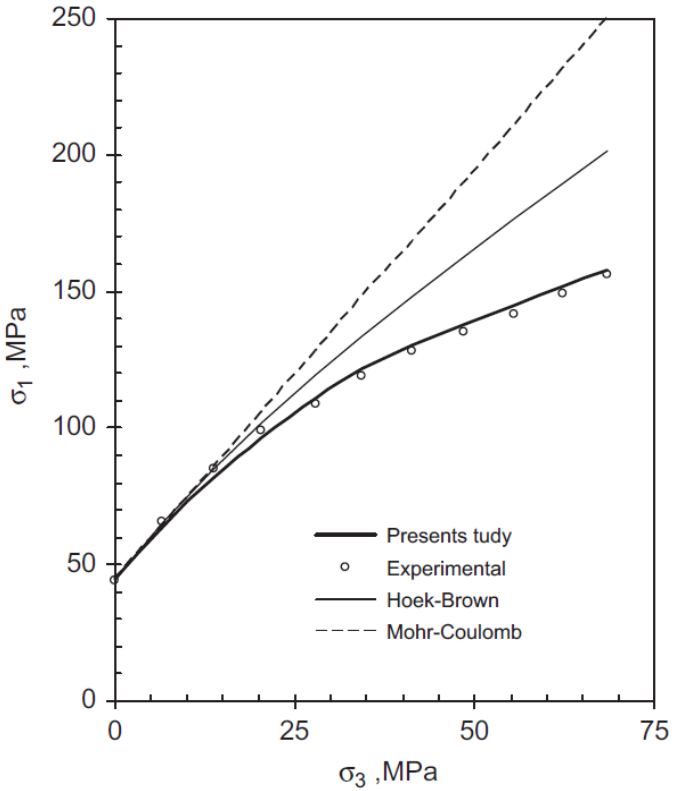
(Despite the U. of Stanford linear-influence, we should remember that Patton, U. of Illinois, more or less started the trend of non-linearity with his Patton, 1966 'ϕ+i' 'saw-teeth' model – which NB was trying to improve: i.e. quantifying the Patton 'i'-value.)

(Patton's 'i-value' is *stress-, strength-, and scale-dependent*. This is 'unfortunate', but true – AND PART OF ROCK MECHANICS)

SHEAR STRENGTH OF *MATRIX* ('MMC' Singh et al. criterion)

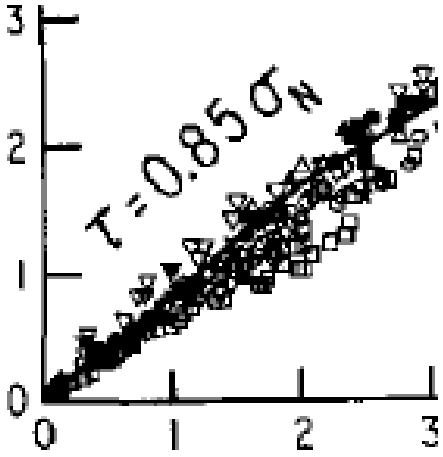


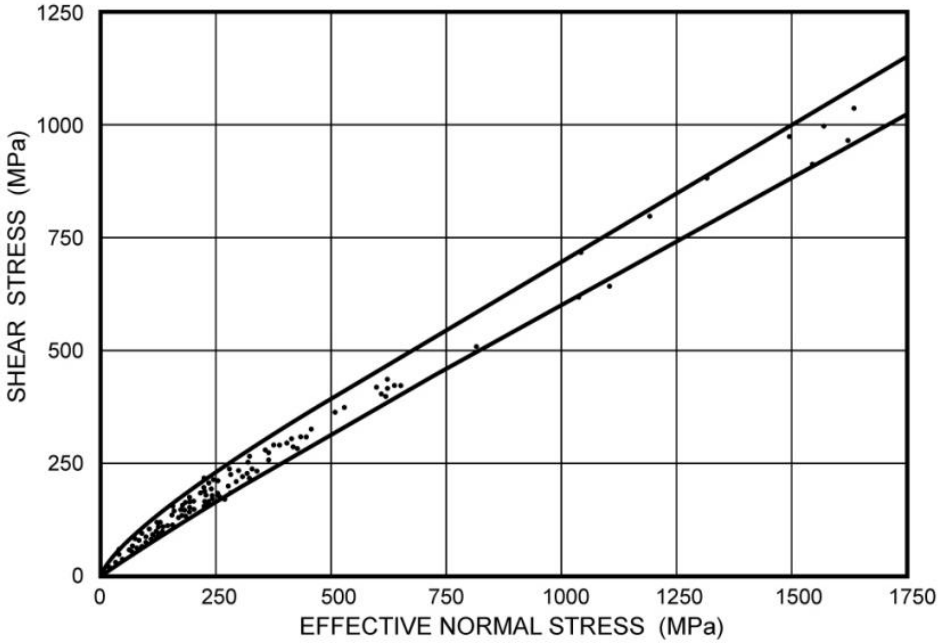




- **CRITICAL STATE SUGGESTION *(Barton, 1976)* USED BY *Singh et al. 2011, 2015:***
CRITERIA FOR ISOTROPIC AND ANISOTROPIC TRIAXIAL & POLYAXIAL STRENGTH

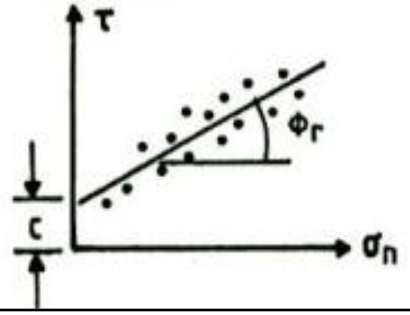
SHEAR STRENGTH OF *FRACTURES* (Byerlee 1978, M-C, P or B-C)





① $\tau = \sigma_n \tan \Phi_r + c$

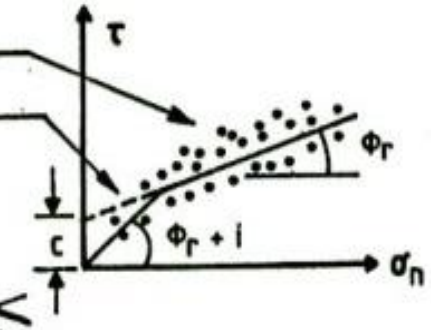
Mohr - Coulomb



② $\tau = \sigma_n \tan \Phi_r + c$

$\tau = \sigma_n \tan (\Phi_r + i)$

Patton

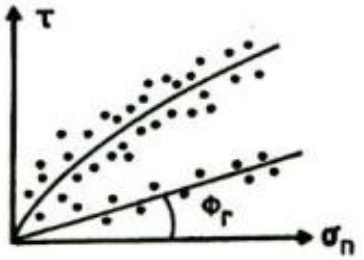


③ $\tau = \sigma_n \tan \left[JRC \log \left(\frac{JCS}{\sigma_n} \right) + \Phi_r \right]$

JRC = joint roughness coefficient

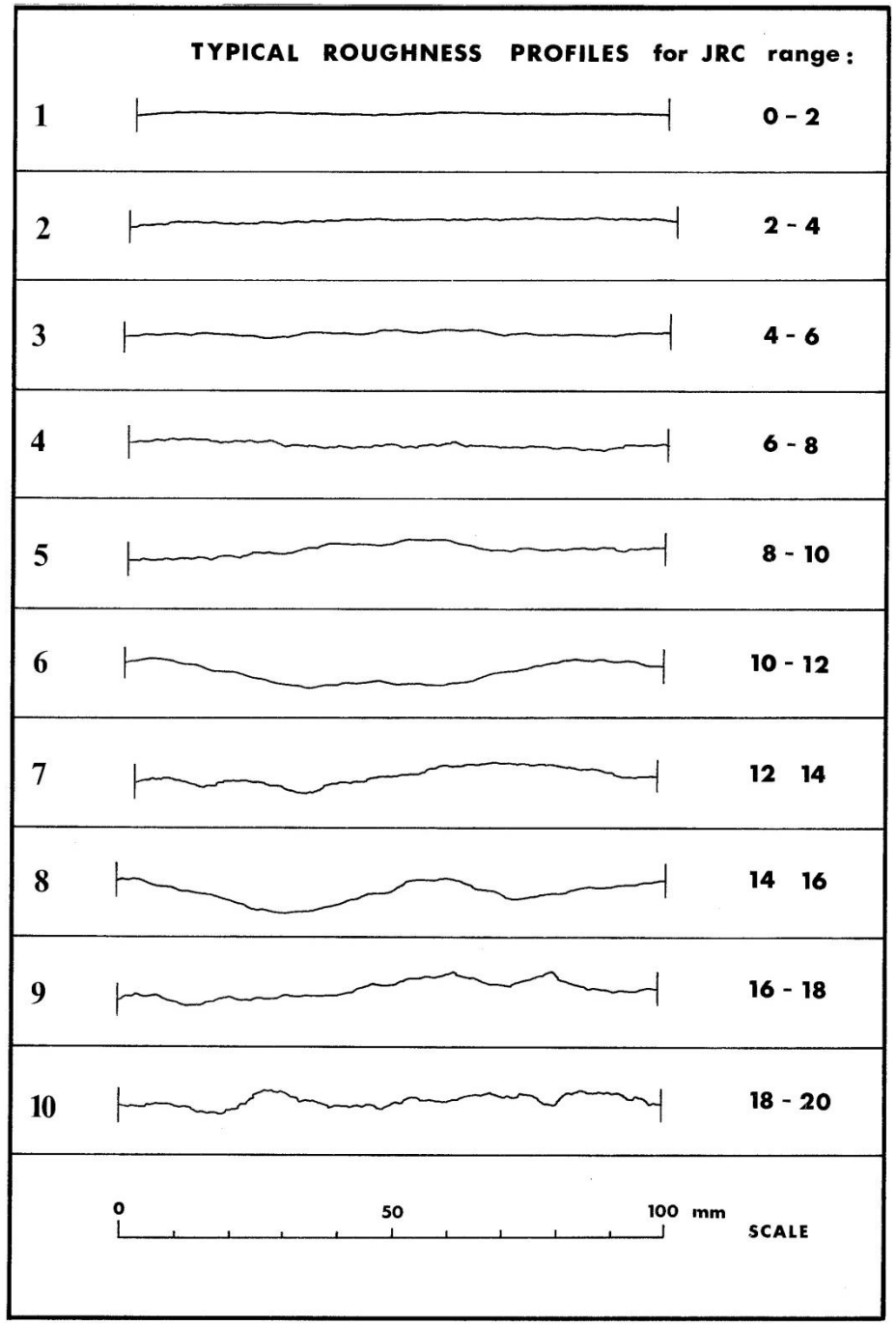
JCS = joint wall compression strength

Φ_r = residual friction angle



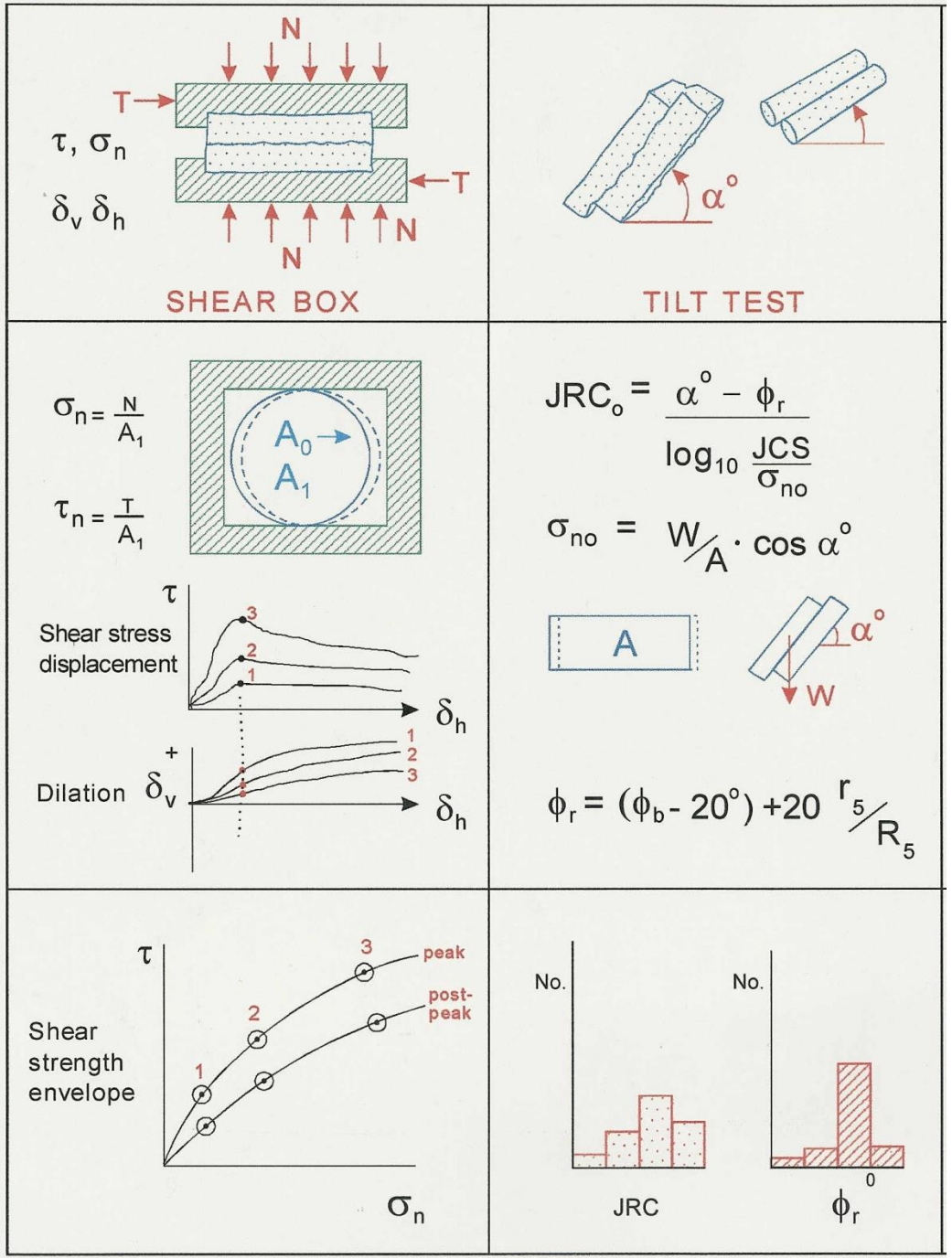
VARIATION AND NON-LINEARITY ALSO AT RESERVOIR EFFECTIVE STRESSES

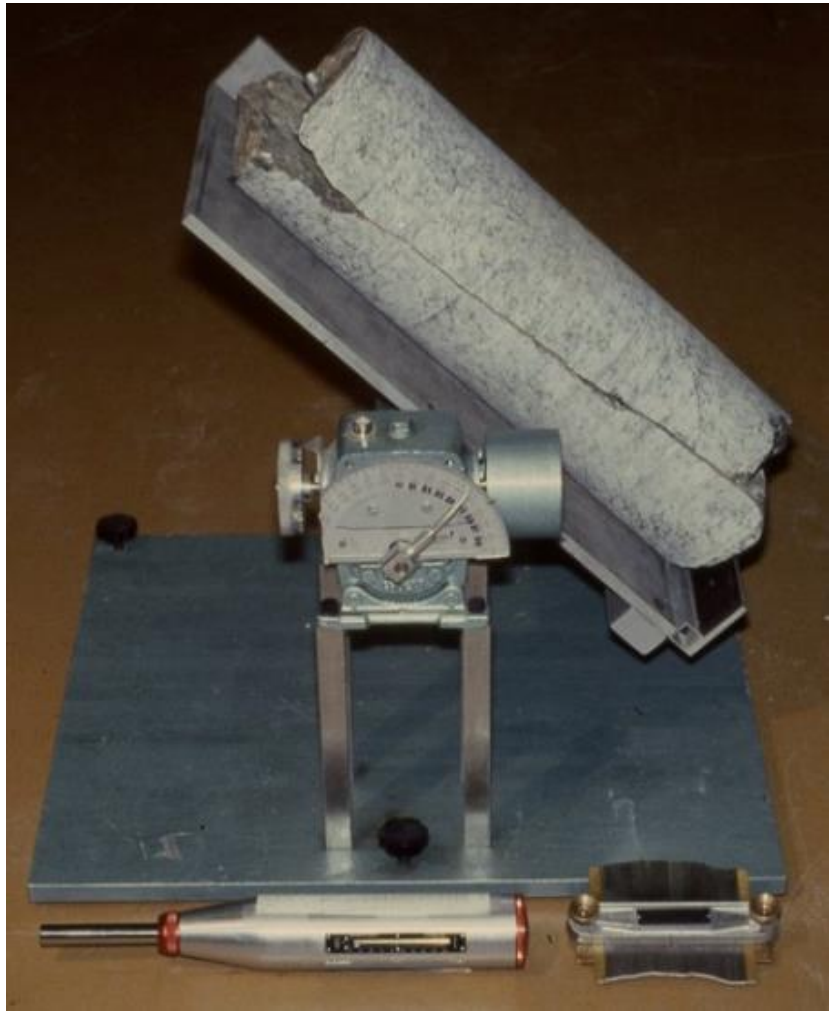
FRACTURE/or JOINT ROUGHNESS VARIES FROM SET-TO-SET, ALSO IN PETROLEUM RESERVOIRS (Ten of 130 joint samples tested by Barton and Choubey, 1977)



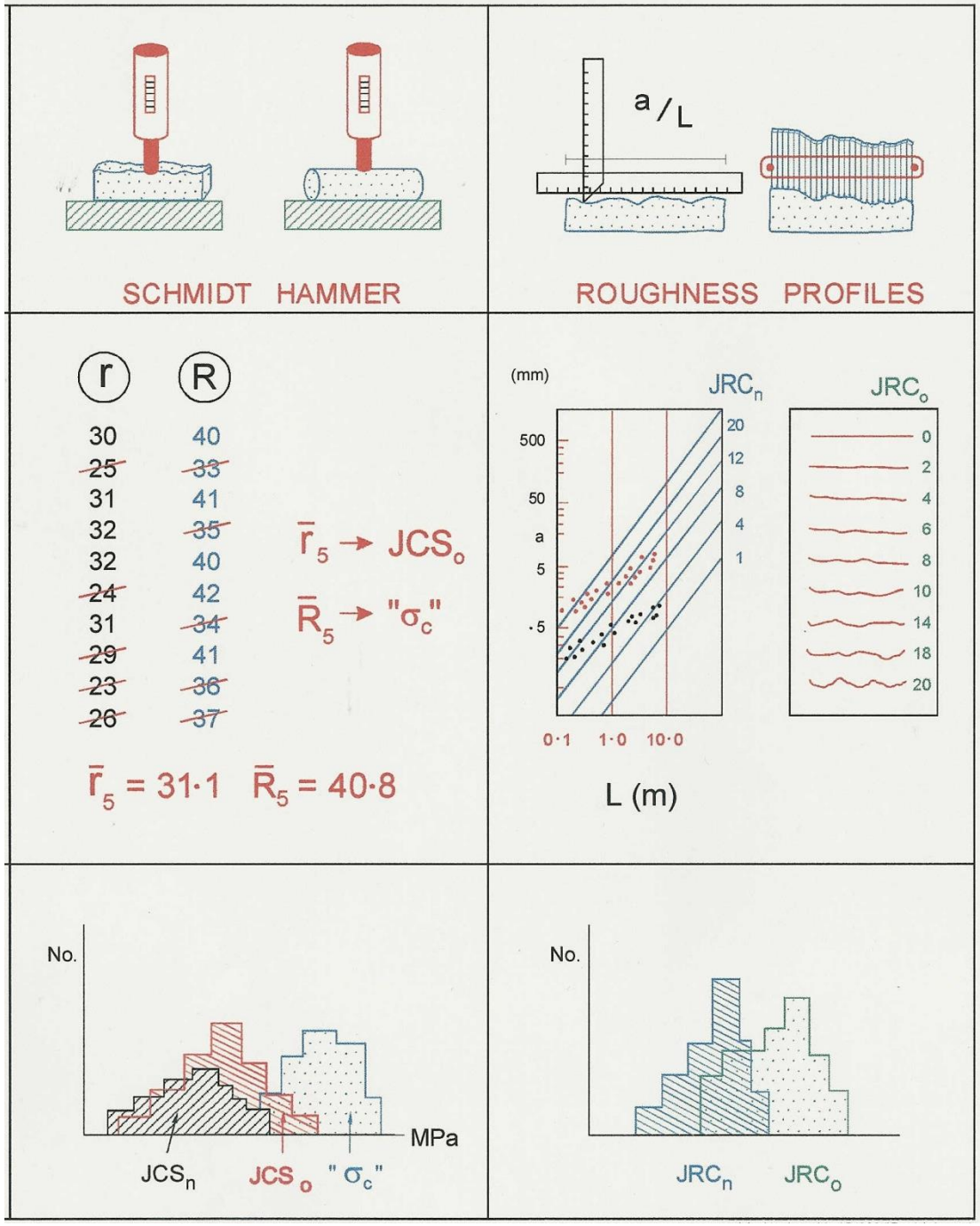
IS IT NOT USEFUL TO HAVE A 'SCALE OF ROUGHNESS' – EVEN IN GEOMECHANICS?

(Yucca Mt. Welded tuff)





INDEX TESTS ARE SIMPLE, AND ALSO APPLY TO *FRACTURED RESERVOIRS. TEST CORES PRIOR TO SLABBING!*



INDEX TESTS (continued)

ALLOW THE PARAMETERS:

JCS (wall strength)

JRC (wall roughness)

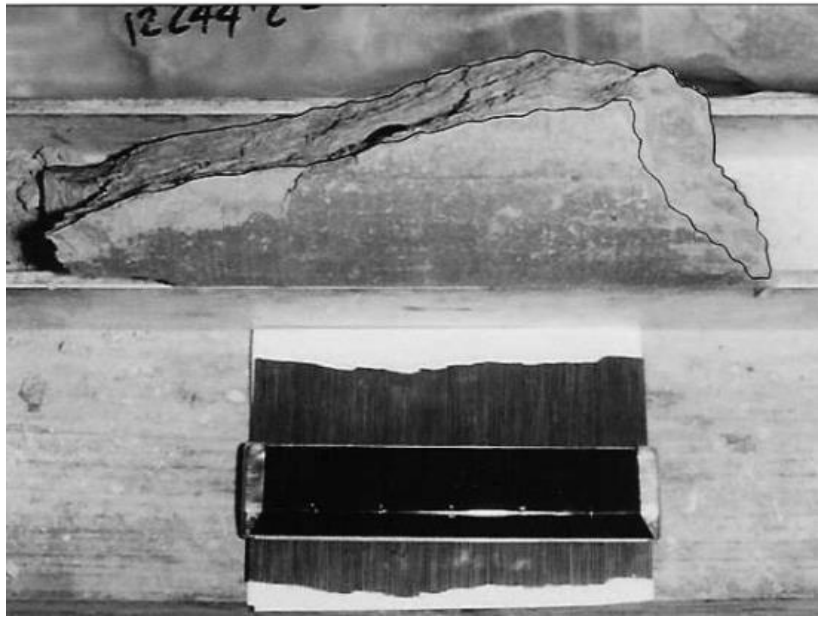
TO BE ESTIMATED

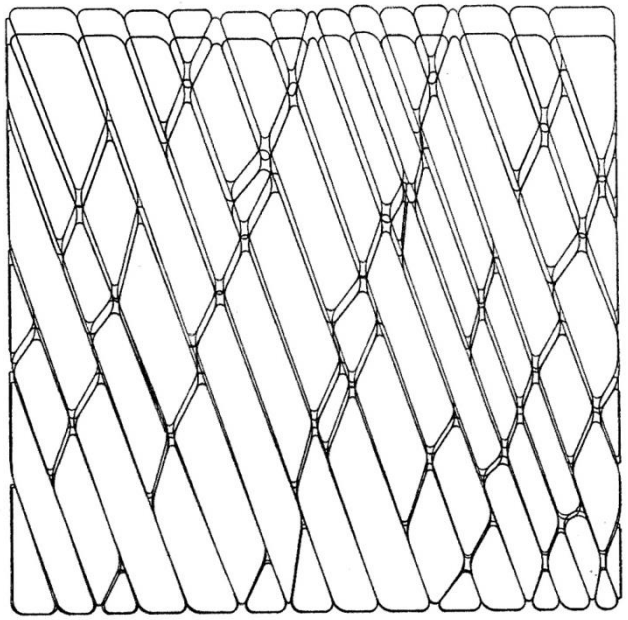
(for input to UDEC-BB)

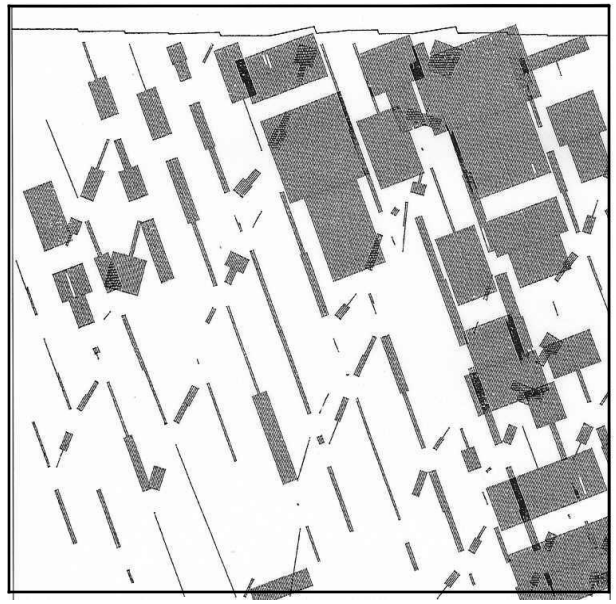
FOR INPUT TO RESERVOIR BEHAVIOUR CONCEPTS?

(Will then need upscaling into reservoir models)

INDEX TESTS ON FRACTURES IN CHALK, THEN UDEC-BB MODELLING OF THE EKOFISK RESERVOIR *COMPACTION/PRODUCTION*. Barton et al. 1986, 1988.



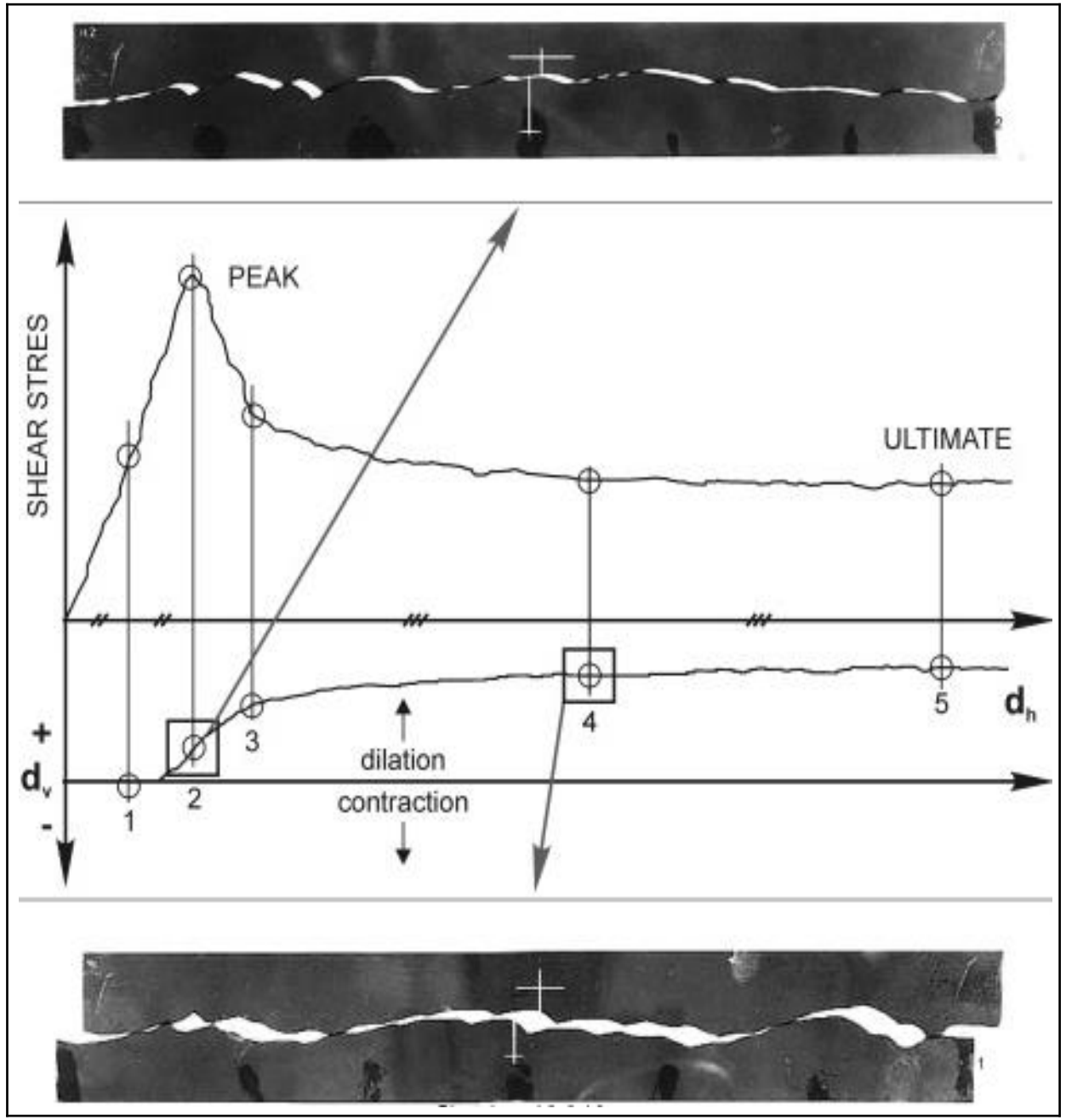




NUMERICAL MODELLING BY MARK CHRISTIANSON of ITASCA : UDEC-BB

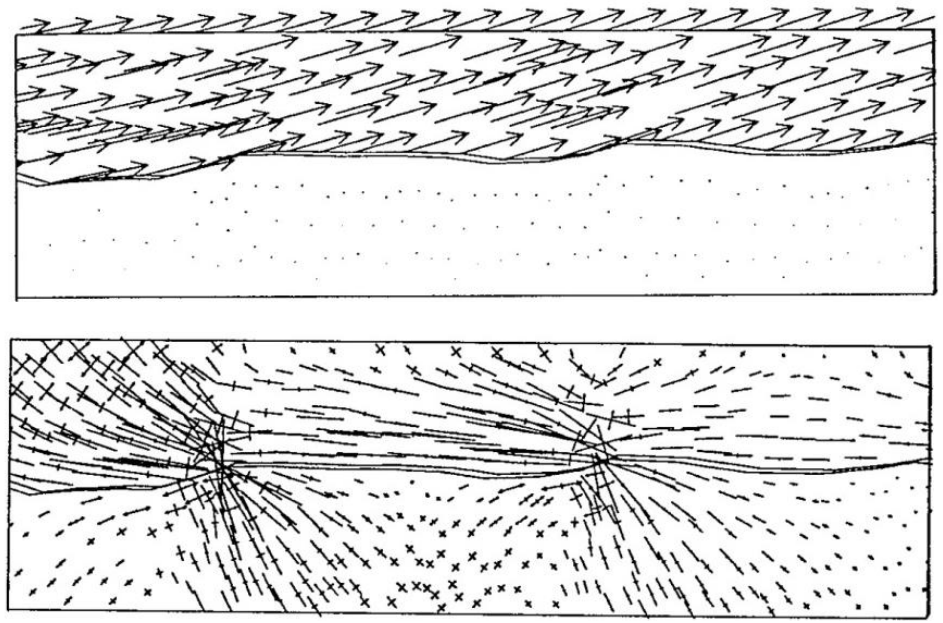
A 20 MPa REDUCTION (48 to 28MPa) IN FLUID PRESSURE CAUSES ENOUGH *MATRIX COMPACTION* TO ALLOW FRACTURE SHEARING, DESPITE 1D COMPACTION).

MAINTENACE OF PERMEABILITY – DUE TO non-linear SHEARING/and SLIGHT DILATION!



Understanding the potential behaviour of shearing or closing of fractures could also be useful in reservoir geomechanics?

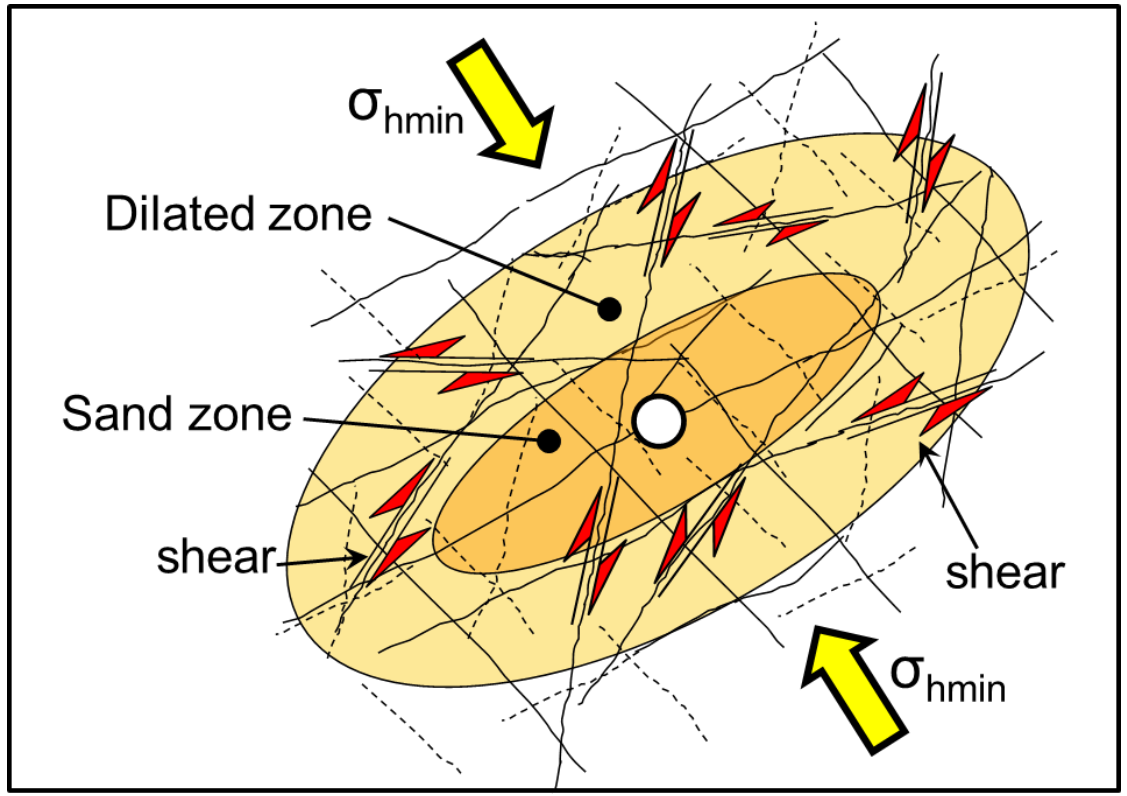
(This is so obvious but needs to be said)

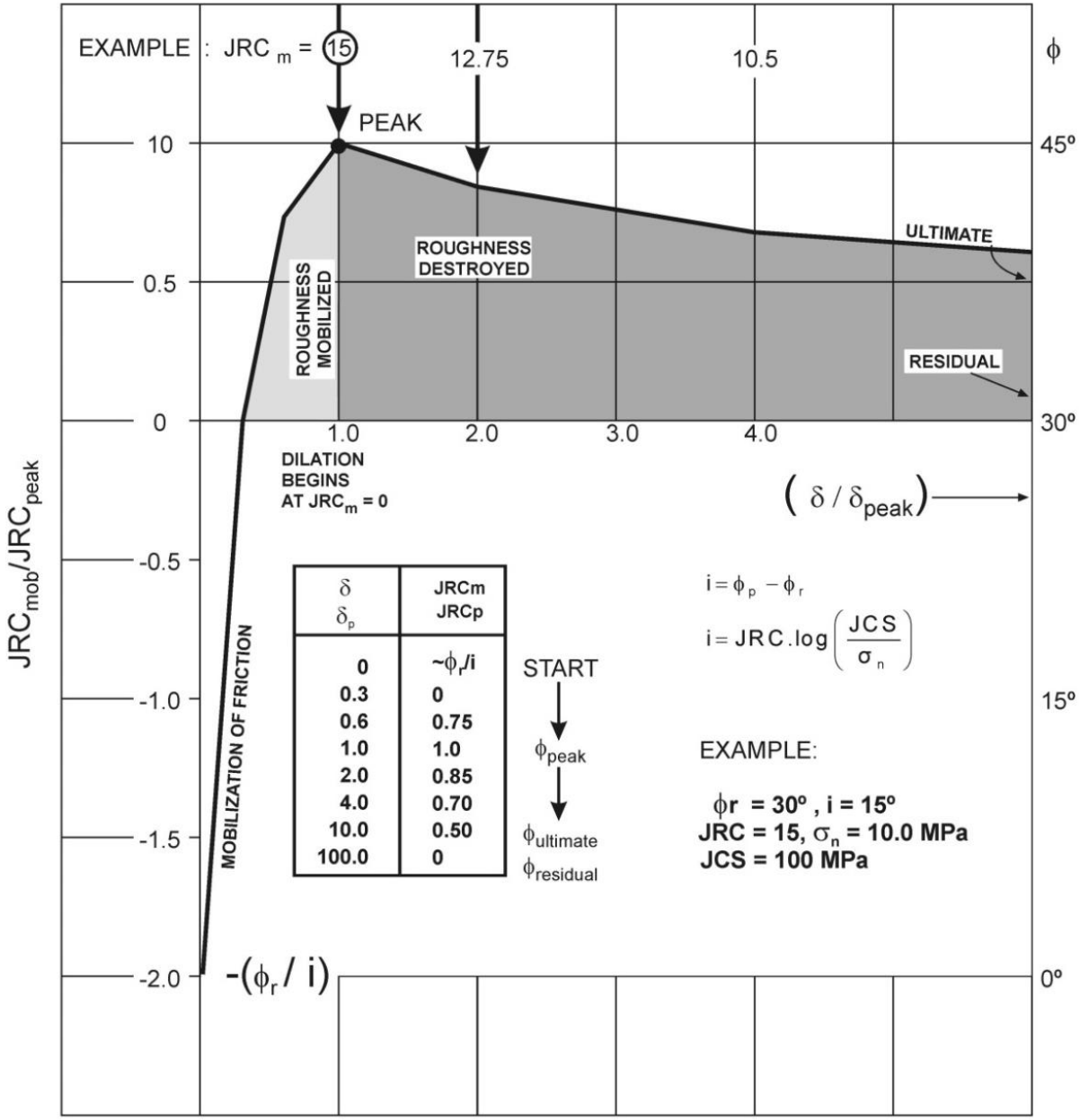


UDEC MODEL OF non-planar FRACTURE SHEAR (Gutierrez and Barton, 1994)

(Physical models from Barton, 1967, 1973)

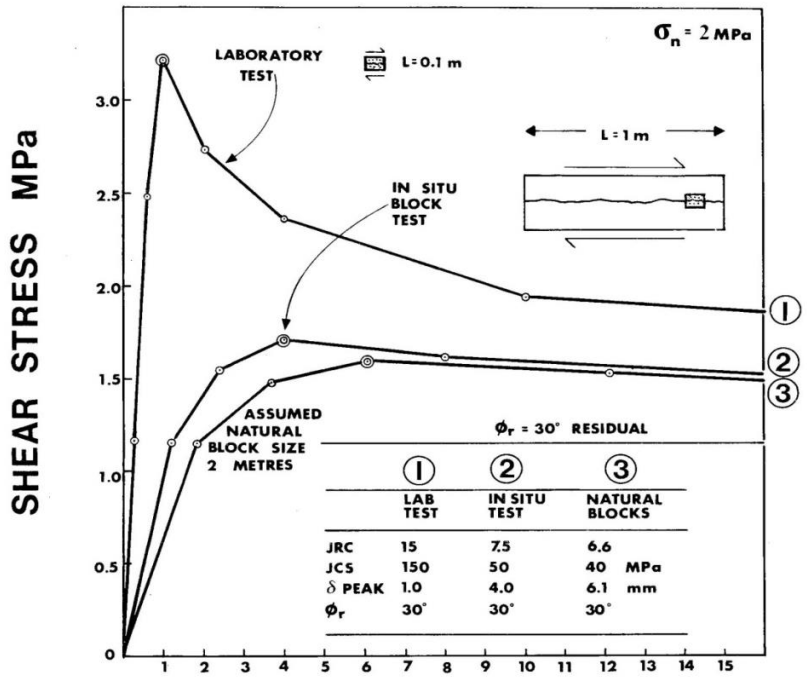
LEFT: CONCEPTUAL MODEL OF GAS-SHALE FRACTURE-SET SHEARING (Dusseault, 2013)

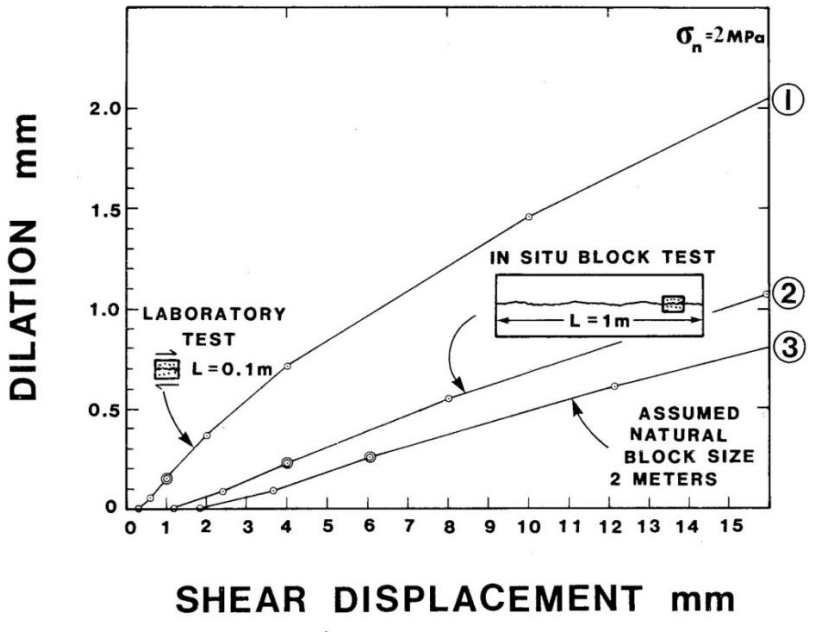


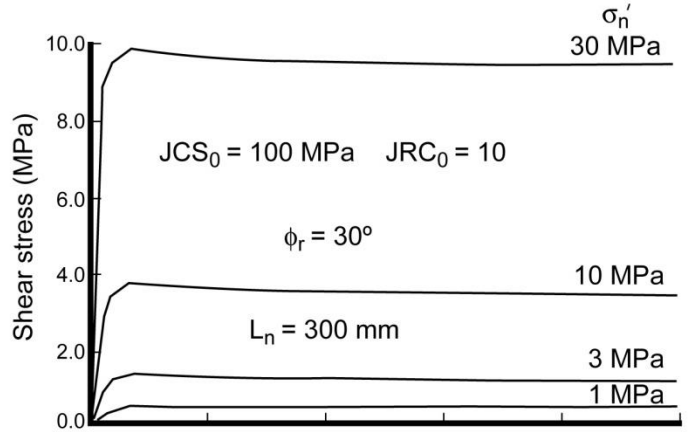


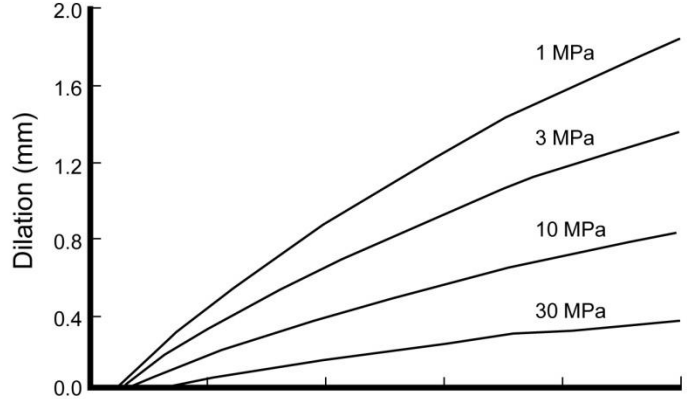
RIGHT: THE BB (Barton-Bandis) MODEL FOR *JRCMOBILIZED* PROBABLY <u>HAS A ROLE TO PLAY IN GAS-SHALE STIMULATION</u>, BECAUSE *PRE-PEAK, PEAK AND* POST-PEAK *BEHAVIOUR* ARE EACH NEEDED.

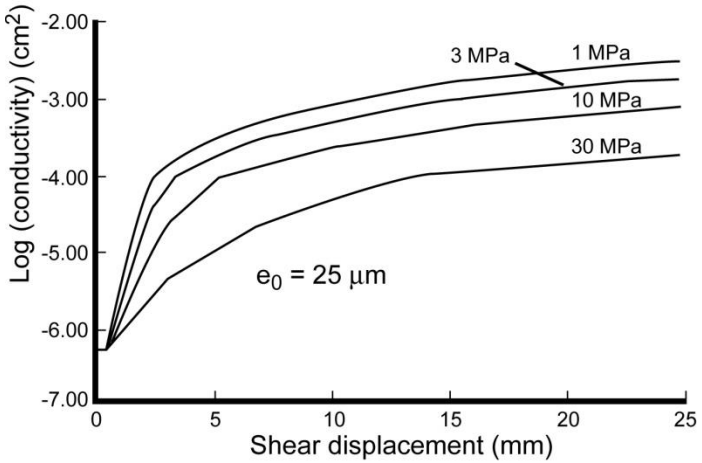
(Barton, 1982).







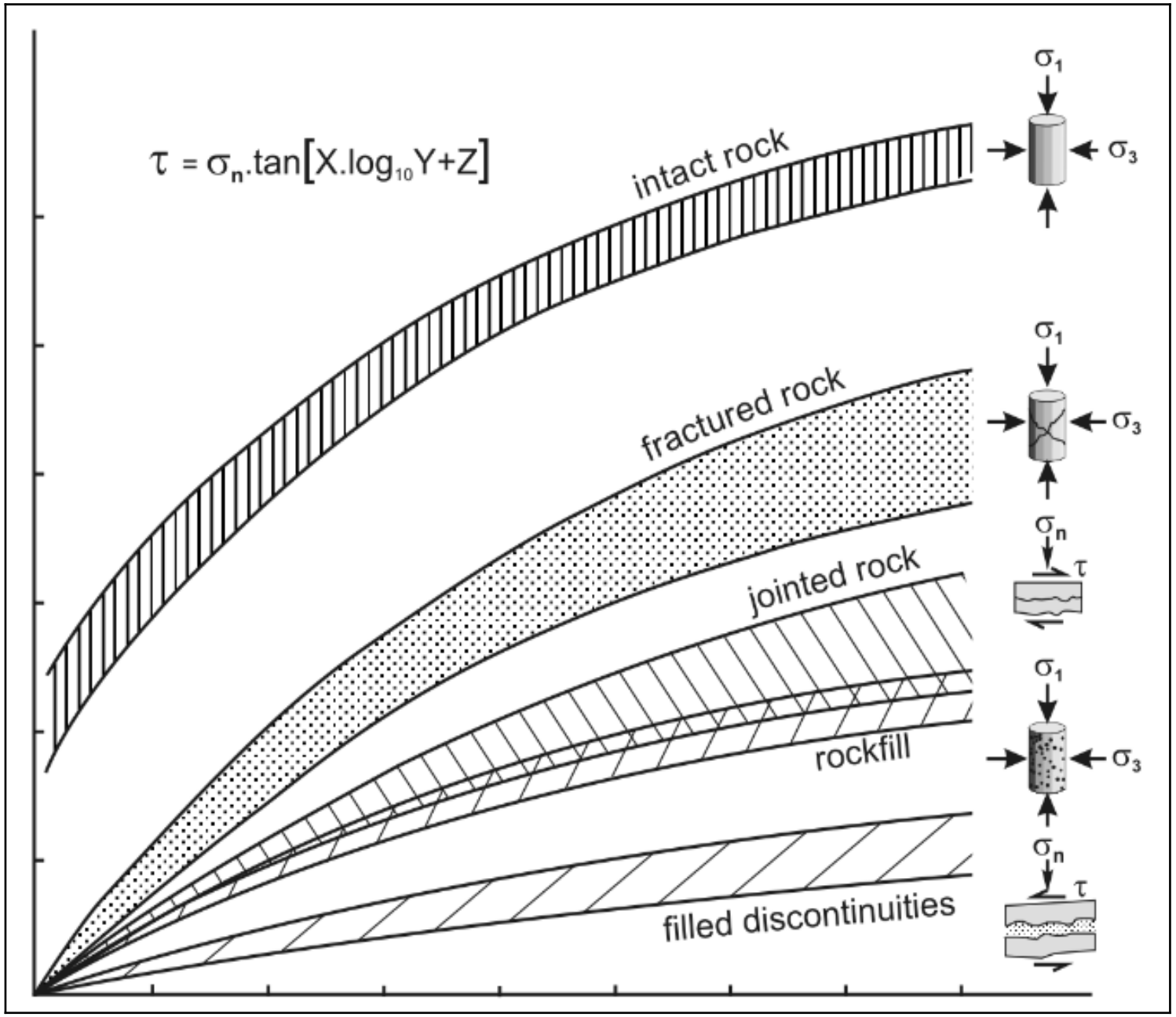




SHEAR STRESS-
DILATION-
CONDUCTIVITY-
COUPLING

BB-modelling
(using JRC MOBILIZED)

USEFUL INFORMATION COMPARED TO SOME PEAK FRICTION COEFFICIENTS?



THE SHEAR STRENGTH OF ROCK MASSES:

= c + σn′ tan ϕ ? .... NO!

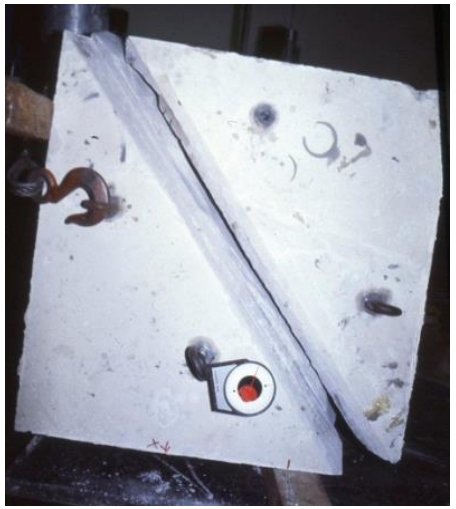
SHEAR RESISTANCE IS A CASCADE OF *THREE OR FOUR COMPONENTS*:

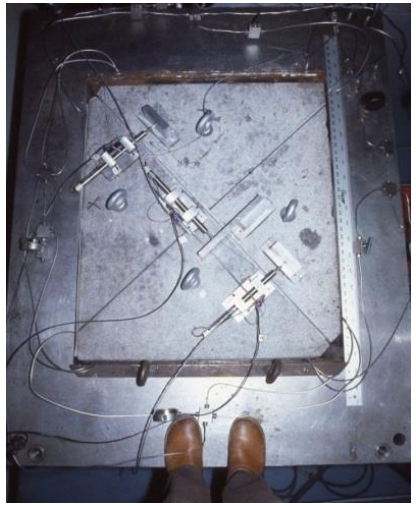
MOST ARE NON-LINEAR, AND ARE MOBILIZED AT SUCCESSIVELY LARGER SHEAR STRAINS. *THERE ARE ALSO SCALE-EFFECTS*.

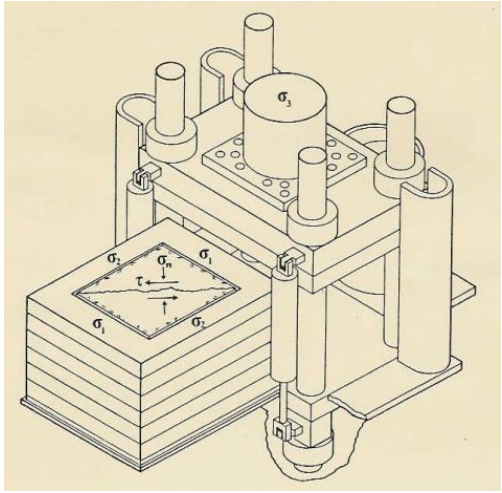
(Barton, 2006 and Barton and Bandis, 2017.....two books)

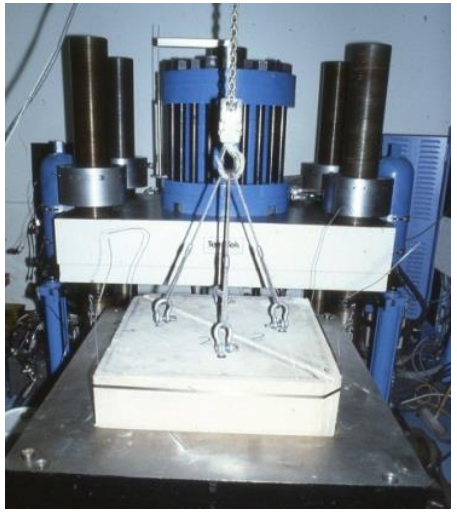
THEREFORE PROGRESSIVE FAILURE (AND MID-SUMMER FAILURES)

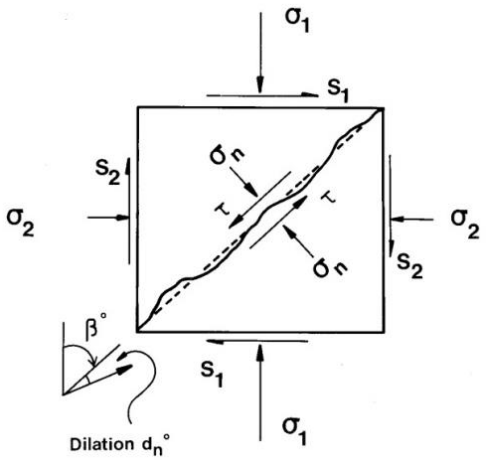
.....AND *CRACKED* TEETH FALLING OUT WHEN DRINKING MISO SOUP











DO WE TRANSFORM PRINCIPAL STRESSES TO SHEAR(ING) PLANES CORRECTLY?

ACTUALLY NO.....
BECAUSE THE PLANES SHOULD BE IMAGINARY AND SHOULD NOT SHEAR OR DILATE.
(B+B, TerraTek, 1983)

WE MUST NOT NEGLECT MOBILIZED DILATION ANGLE IN STRESS TRANSFORMATION.

A 'UNIVERSAL' (?) ERROR. SEE EQUATIONS ON NEXT SCREEN. (Bakhtar and Barton, 1984)

$$\left.\begin{aligned}\sigma_{\mathrm{n}} &= \frac{1}{2}(\sigma_1+\sigma_2)-\frac{1}{2}(\sigma_1-\sigma_2)\cos(2\beta)\\ \tau &= \frac{1}{2}(\sigma_1-\sigma_2)\sin(2\beta)\end{aligned}\right\}$$

CONVENTIONAL STRESS TRANSFORM

$$d_{\mathrm{n}}^{0}(\mathrm{mob}) = \frac{1}{2}JRC(\mathrm{mob})\log(JCS/\sigma'_{\mathrm{n}})$$

$$\left.\begin{aligned}\sigma_{\mathrm{n}} &= \frac{1}{2}(\sigma_1+\sigma_2)-\frac{1}{2}(\sigma_1-\sigma_2)\cos[2(\beta+d_{\mathrm{n\,mob}})]\\ \tau &= \frac{1}{2}(\sigma_1-\sigma_2)\sin[2(\beta+d_{\mathrm{n\,mob}})]\end{aligned}\right\}$$

CORRECTED STRESS TRANSFORM

CONCLUSIONS

1. FORGET FRICTION COEFFICIENTS – TRY JRC, JCS !
2. TEST NON-LINEAR BB – MODIFY YOUR PRODUCTION?
3. UTILIZE SIMPLE INDEX TESTS ON YOUR FRACTURES

- (Peter Cundall and NB joined a group at Imperial College with a large-scale direct shear machine – in 1966).

- (60% of petroleum reserves are in fractured reservoirs.....?)

4. HAVE AN INTERESTING (ROCK MECHANICS) DAY

5. THANK YOU FOR LISTENING!