EAGE: UNCONVENTIONAL GEOMECHANICS

Dubai, May 2014

Is Non-Linear Rock Mechanics used in the Petroleum Industry?

(of course it is, but not sufficiently!)

Nick Barton (NB&A), Oslo, Norway

STATUS OF ROCK MECHANICS IN GEOMECHANICS ?

THE NON-LINEAR PART OF ROCK MECHANICS SEEMS TO BE LARGELY IGNORED IN THE SERVICE AND OIL COMPANIES. SINCE BYERLEE/ZOBACK/BARTON (no relation/TOWNEND /MOOS IN STANFORD, *'EVERYONE'* THINKS THAT LINEAR MOHR COULOMB FOR THE MATRIX AND FOR THE FRACTURES IS REAL 'CROSS-DISCIPLINE' GEOMECHANICS. IN FACT IT IS LONG OUT-OF-DATE AND MISLEADS IN THE PRODUCTION FROM RESERVOIRS, ESPECIALLY THOSE THAT ARE FRACTURED AND WITH WEAKER BEHAVIOUR.

SEVERAL TOPICS TO BE MENTIONED

SHEAR STRENGTH OF INTACT ROCK – *IS NON-LINEAR*

SHEAR STRENGTH OF FRACTURES – *IS NON-LINEAR*

STRESS-CLOSURE-PERMEABILITY *IS NON-LINEAR*

SHEAR-DILATION-PERMEABILITY *IS NON LINEAR*

GAS-SHALES DECLINE FAST *DUE TO NON-LINEARITY*

BOREHOLE FAILURE/BREAK-OUT *IS NON-ELASTIC*

QUESTION? WHEN DOES LOG-SPIRAL SHEAR FAILURE BECOME BREAK-OUT?

THIS IS DISCONTINUOUS SHEAR-BEHAVIOUR, FOLLOWING INITIAL

$\sigma_\theta = 3\,\sigma 1 - \sigma 3$. SO THE ASSUMED STRESS CHANGES RADICALLY

APPRPOS

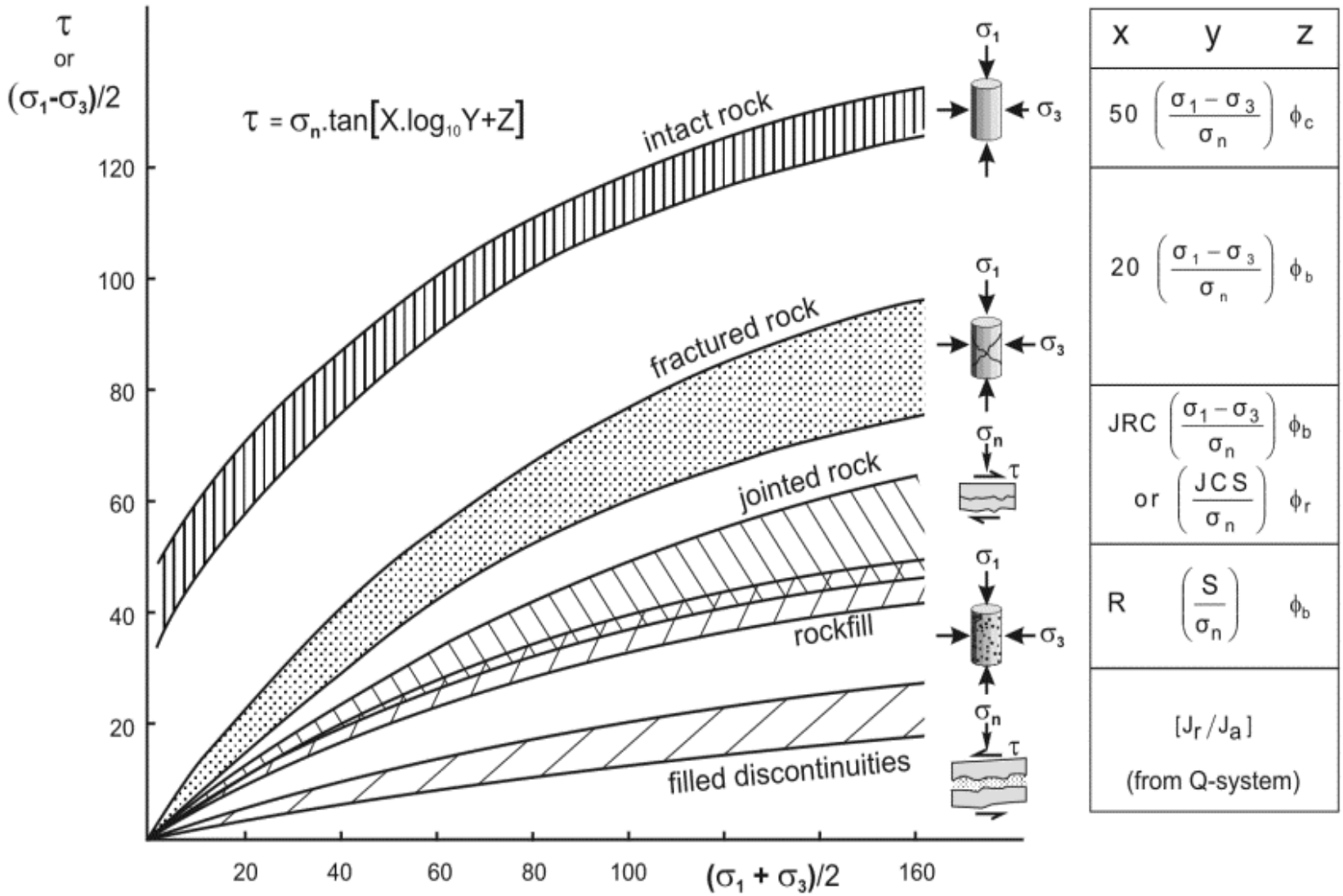
- A SELECTION OF FIGURES WITH TOPICS/ METHODS USED FOR MANY YEARS IN ROCK MECHANICS/ MINING, WHICH HAVE NOT FOUND THEIR WAY INTO THE PETROLEUM GEO-AREA – APPARENTLY.

- ONE OF THESE POSSIBLE CONTRIBUTIONS WILL BE ‘THE Q-SYSTEM’ (and its useful ‘add-ons’).

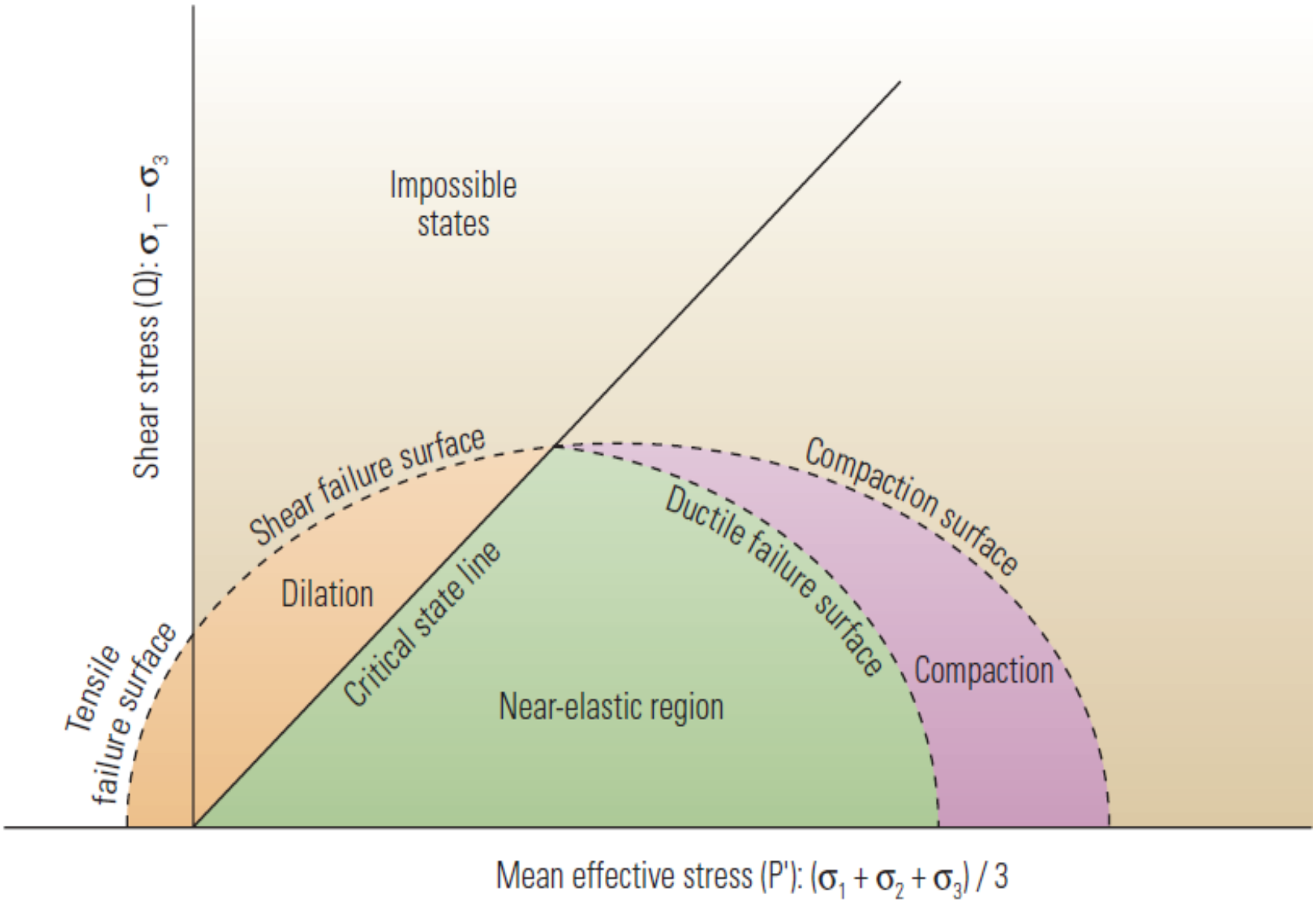
Bakhtiary dam site, Zagros Mountains, Iran

Anisotropy – of course. Non-linearity – of course.

Symbolic of the reality – a non-linear geo-world



Promising signs: Oilfield Review, 2007.
"Rocks Matter – Ground Truth in Geomechanics''

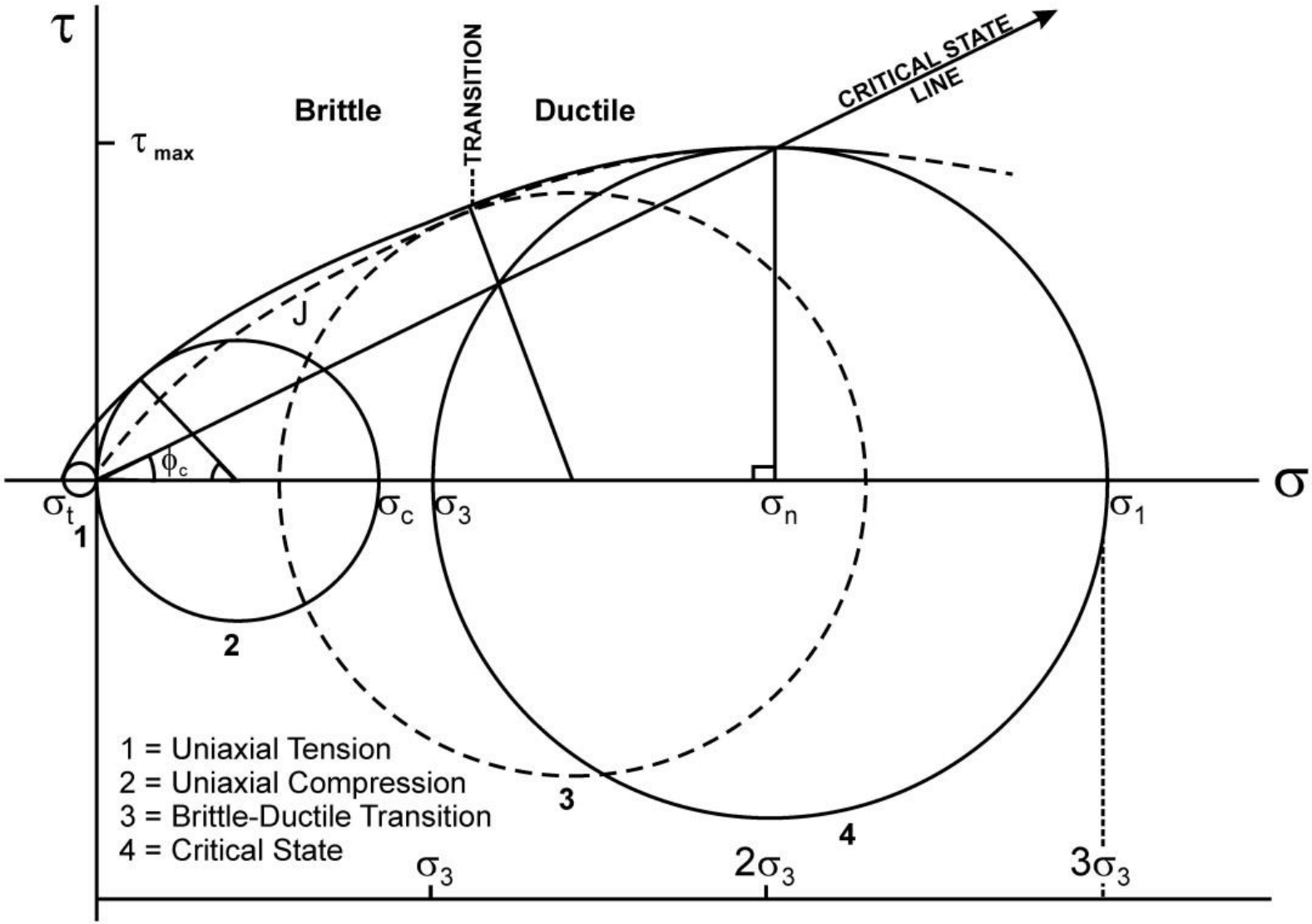


BUT LINEAR MOHR-COULOMB IS USED IN (MOST?) APPLICATIONS

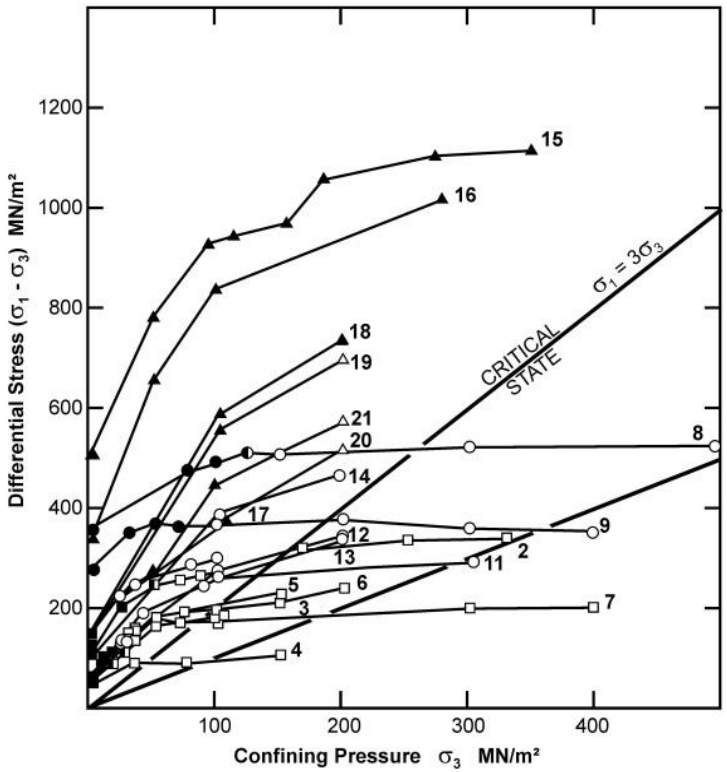
……also by SCHLUMBERGER judging by workshop presentations. *They refer to non-linear behaviour, but do not seem to apply it….regarding M-C for fractures and intact rock.*

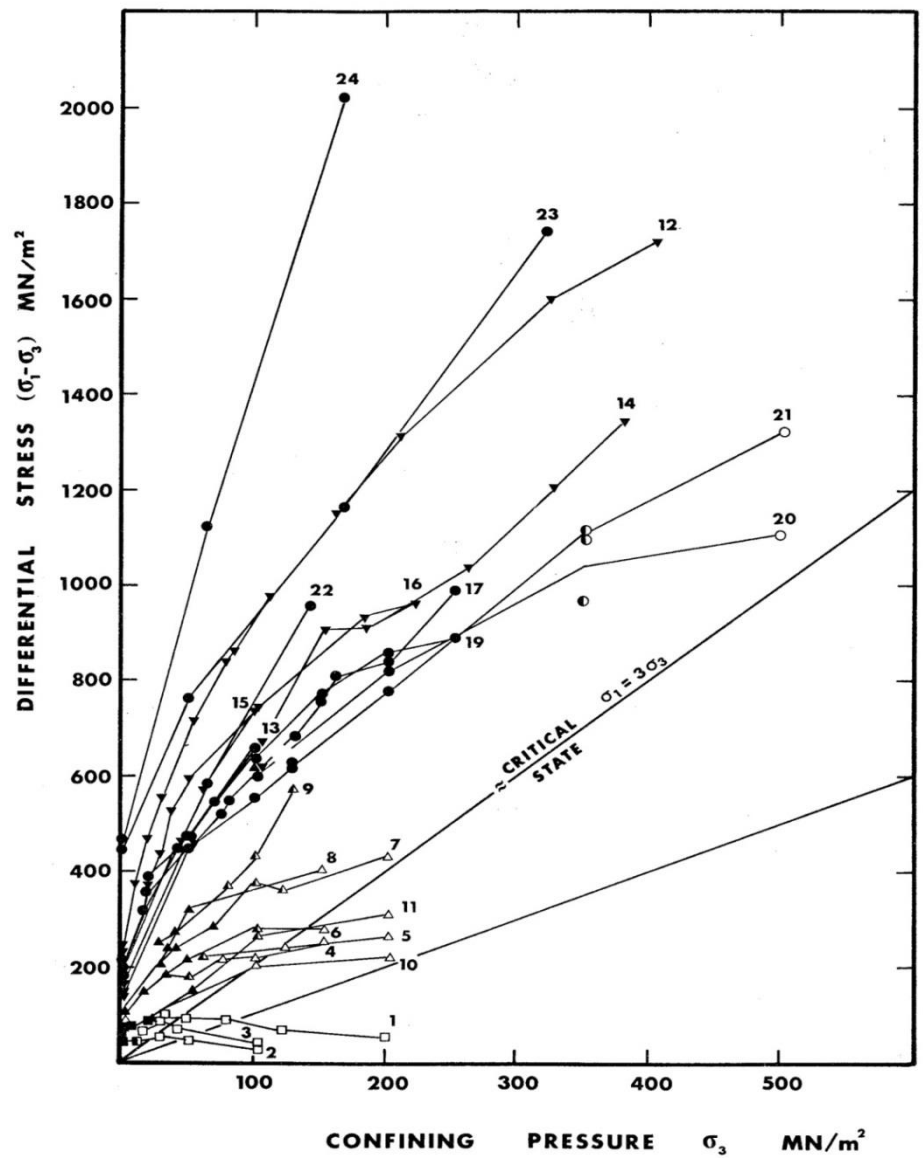
Critical state suggestion for rock:

σ_1(max strength) = ***3 x*** σ_3(critical) (Barton, 1976, Singh et al. 2011)



SOME OF THE EARLY EVIDENCE – BOTH AT HIGH AND LOW STRESS LEVELS





- Dry carbonate rocks: Mogi 1964

Dry silicate rocks: Mogi 1964

WHY IS NON-LINEARITY LIKELY?

Reservoir rocks have some porosity.

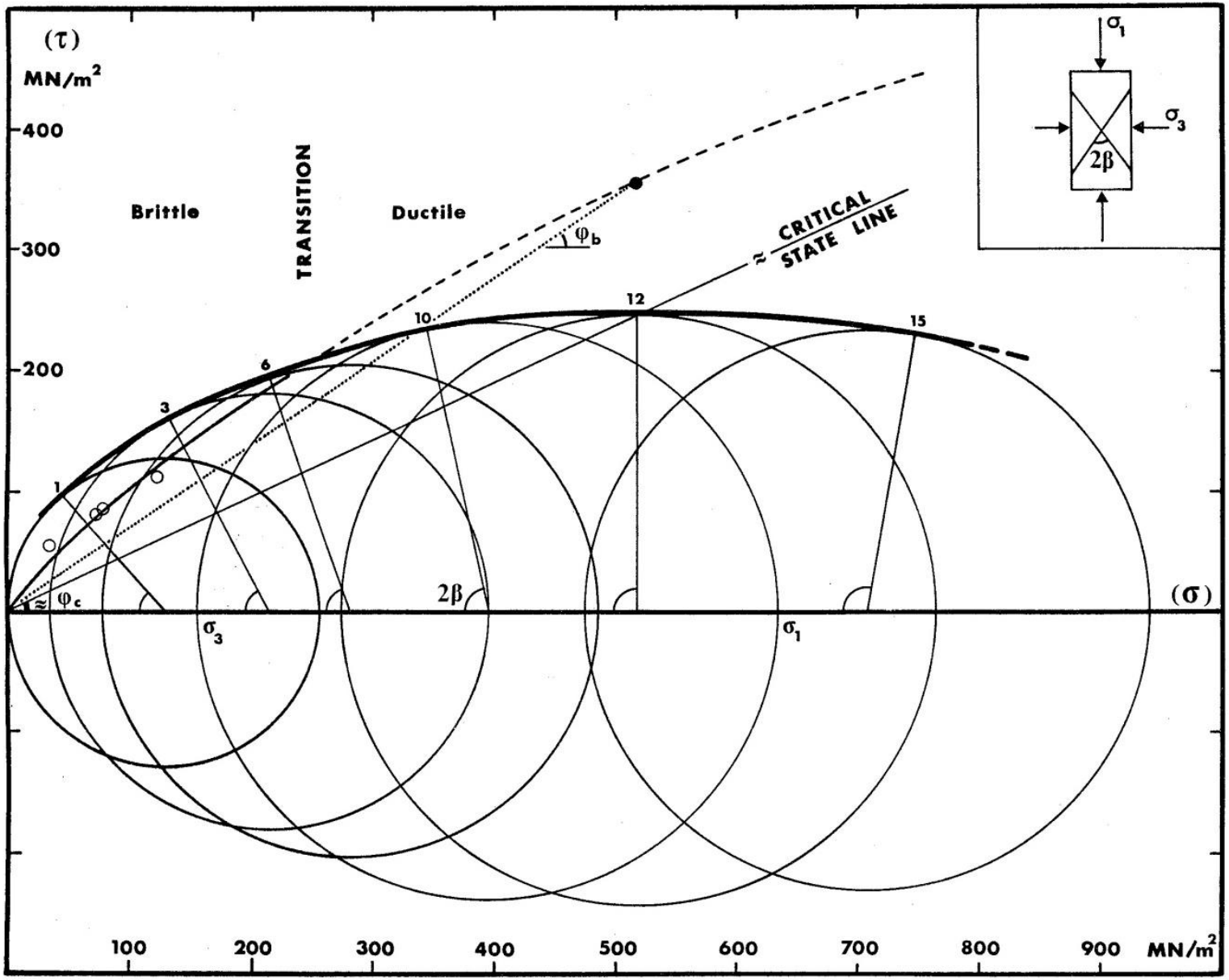
Thinking simplistically – they therefore have somewhat lowered strength.

During production of petroleum, effective stress levels may increase by 10's of MPa.

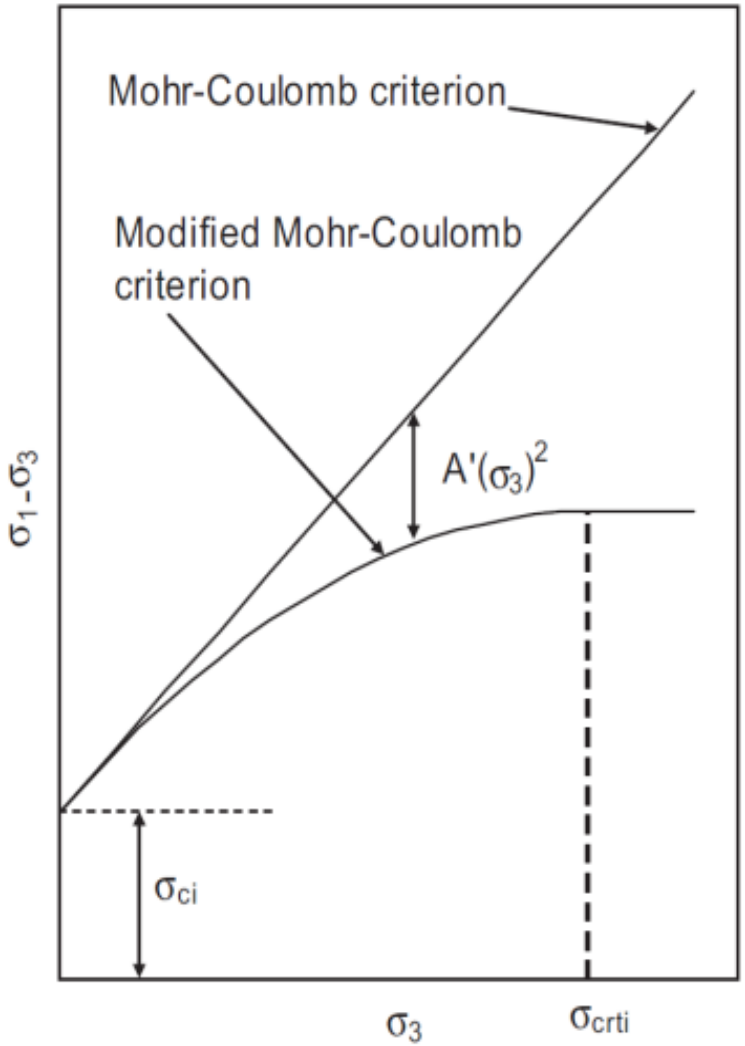
Unless very strong (no porosity), *non-linear shear strength is unavoidable.*

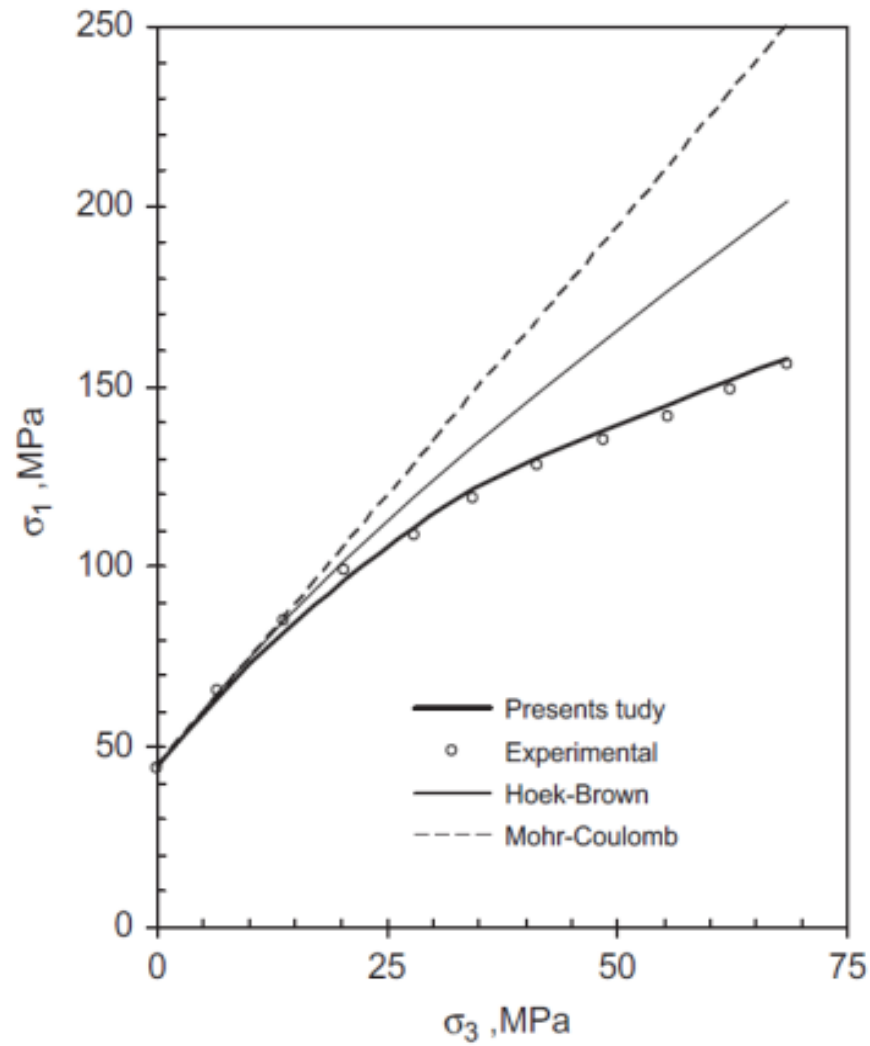
Nevertheless non-linearity is 'avoided' (ignored).

Consider angle ***2β*** – and the consequences for fractured pavement ***extrapolation*** to reservoir depth (Limestone data, based on Byerlee, 1968)



The critical state concept recently used by Singh et al. 2011





KEY FEATURES.

- **Tests at low confining pressure suffice to define the complete shear strength envelope, which is obviously not the case when applying linear Mohr-Coulomb, nor even when applying non-linear Hoek-Brown.**

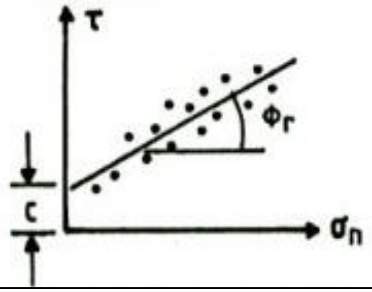
- **The value of σ (critical) is often ≈ UCS**

- **The Singh-Singh criterion is also given in polyaxial form. It is the best available in rock mechanics, in both cases, as verified by a recent 'competitor'.**

NATURAL FRACTURES

(1) $\tau = \sigma_n \tan \Phi_r + c$

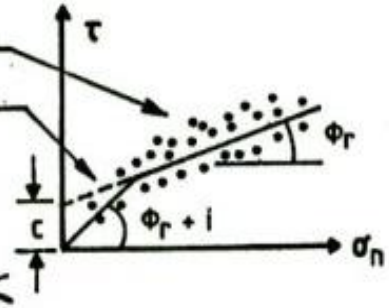
Mohr - Coulomb



(2) $\tau = \sigma_n \tan \Phi_r + c$

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

Patton

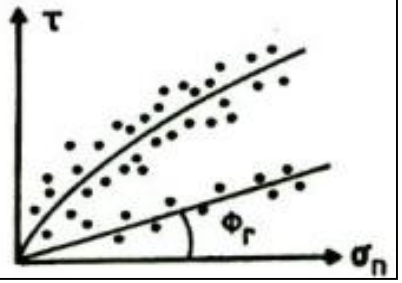


(3) $$\tau = \sigma_n \tan \left[JRC \log \left(\frac{JCS}{\sigma_n} \right) + \Phi_r \right]$$

JRC = joint roughness coefficient

JCS = joint wall compression strength

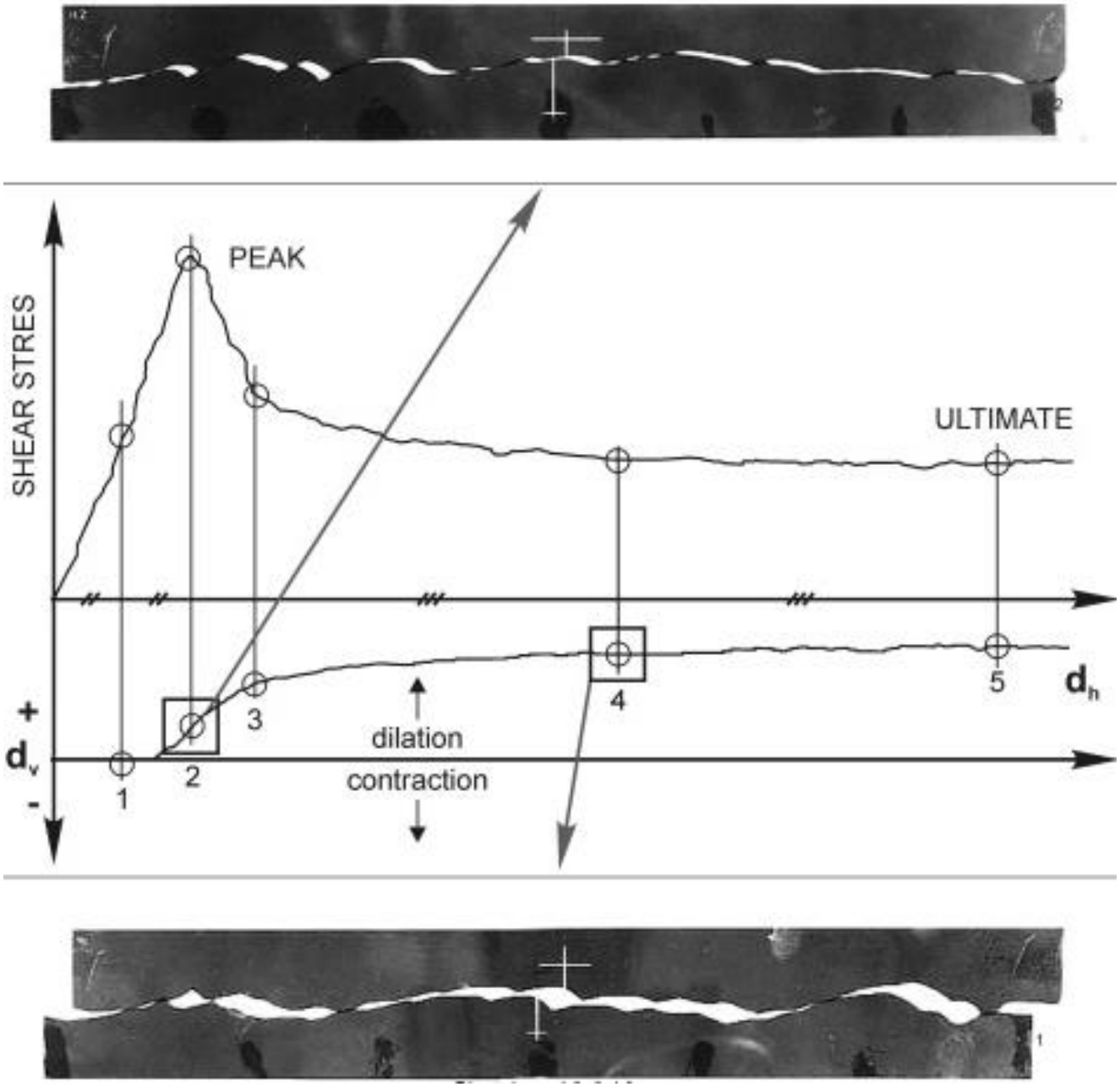
Φ_r = residual friction angle



STRESS-CLOSURE-PERMEABILITY BEHAVIOUR IS NON-LINEAR

and

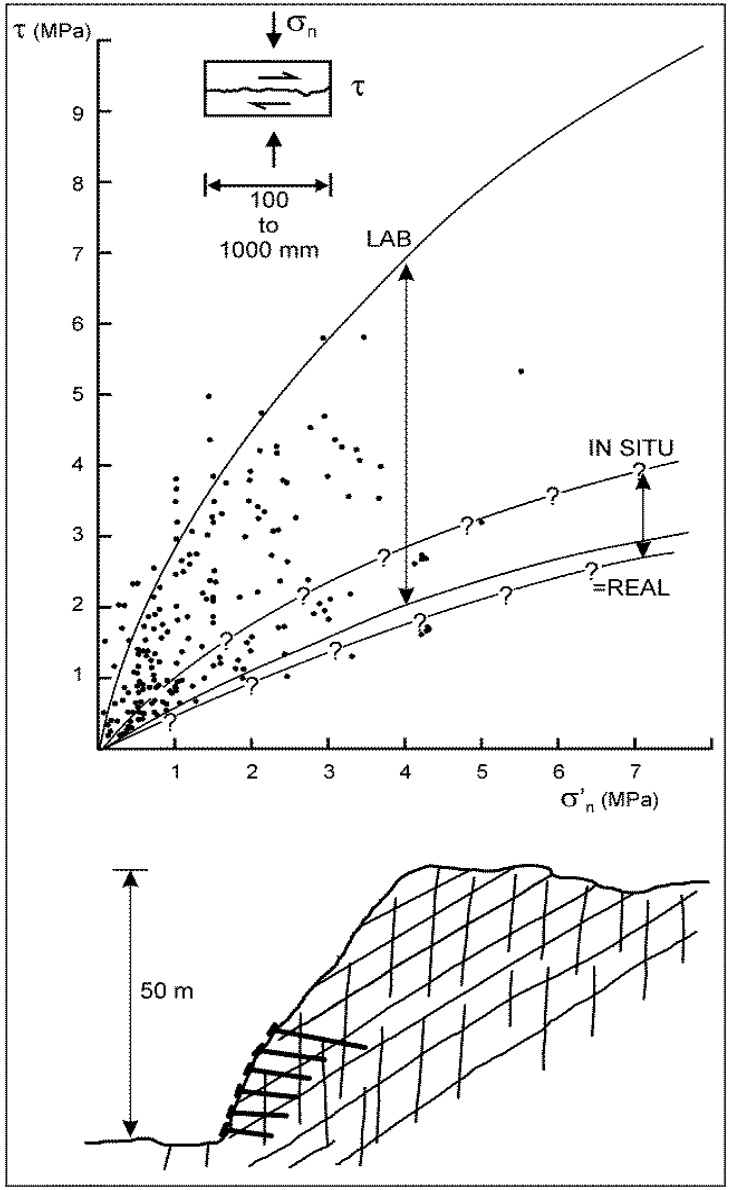
SHEAR-DILATION-PERMEABILITY COUPLING IS ALSO NON-LINEAR

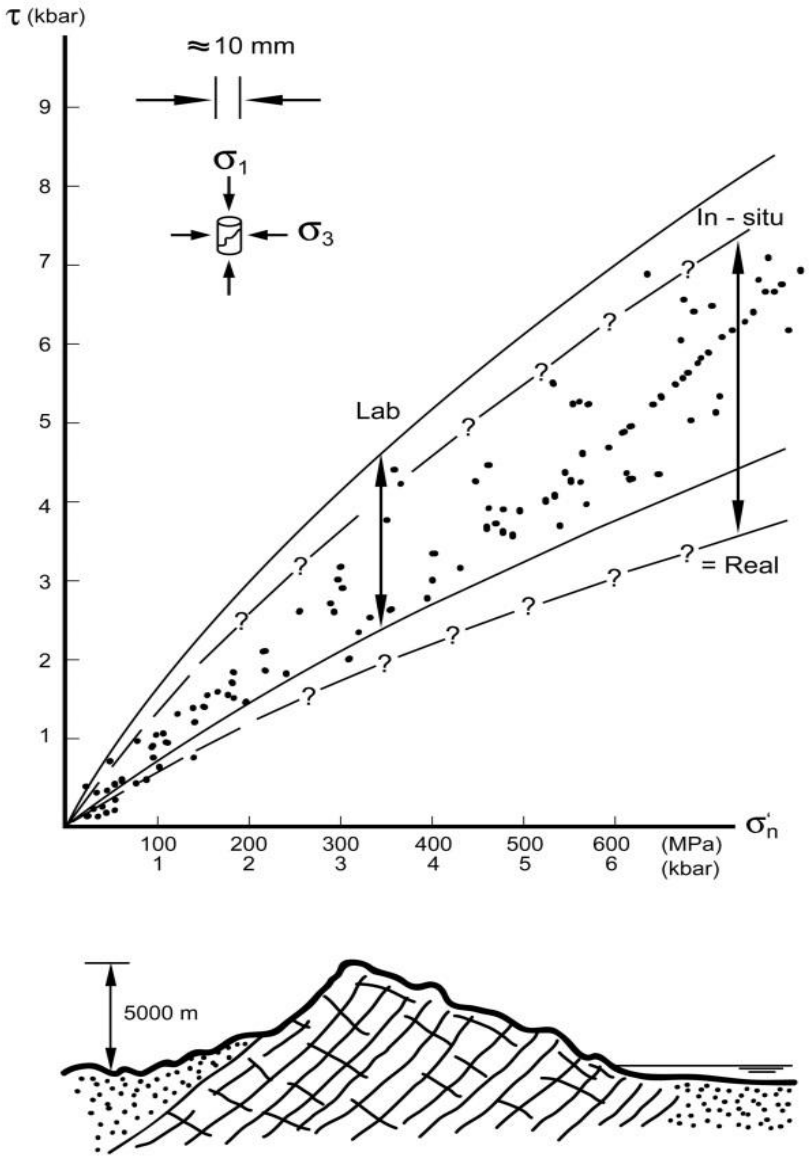


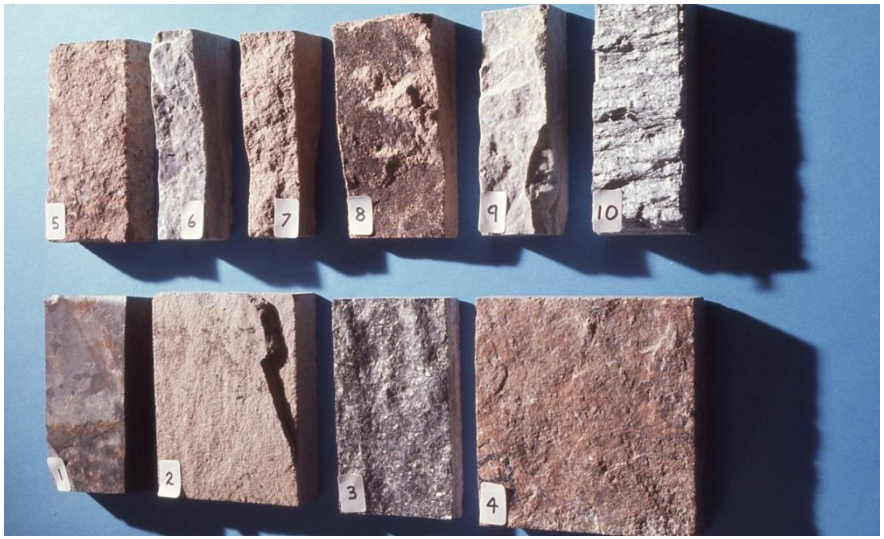
AN EXAGGERATED EXAMPLE of WHY THERE IS NON-LINEARITY

(Barton, 1973)

Shear strength of rock joints (natural fractures) and of artificial fractures. Why is Byerelee's 'law' μ = 0.85? *There is variation!*

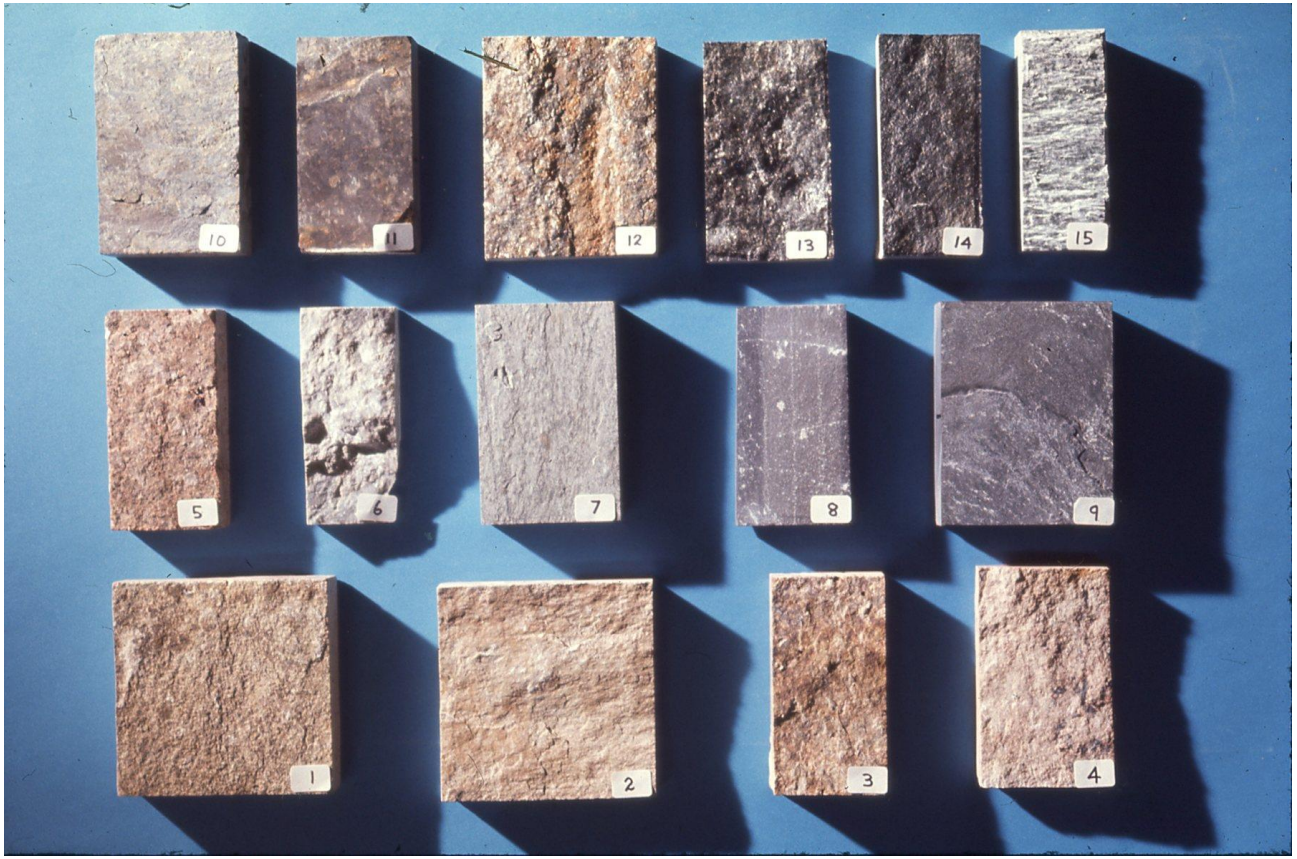


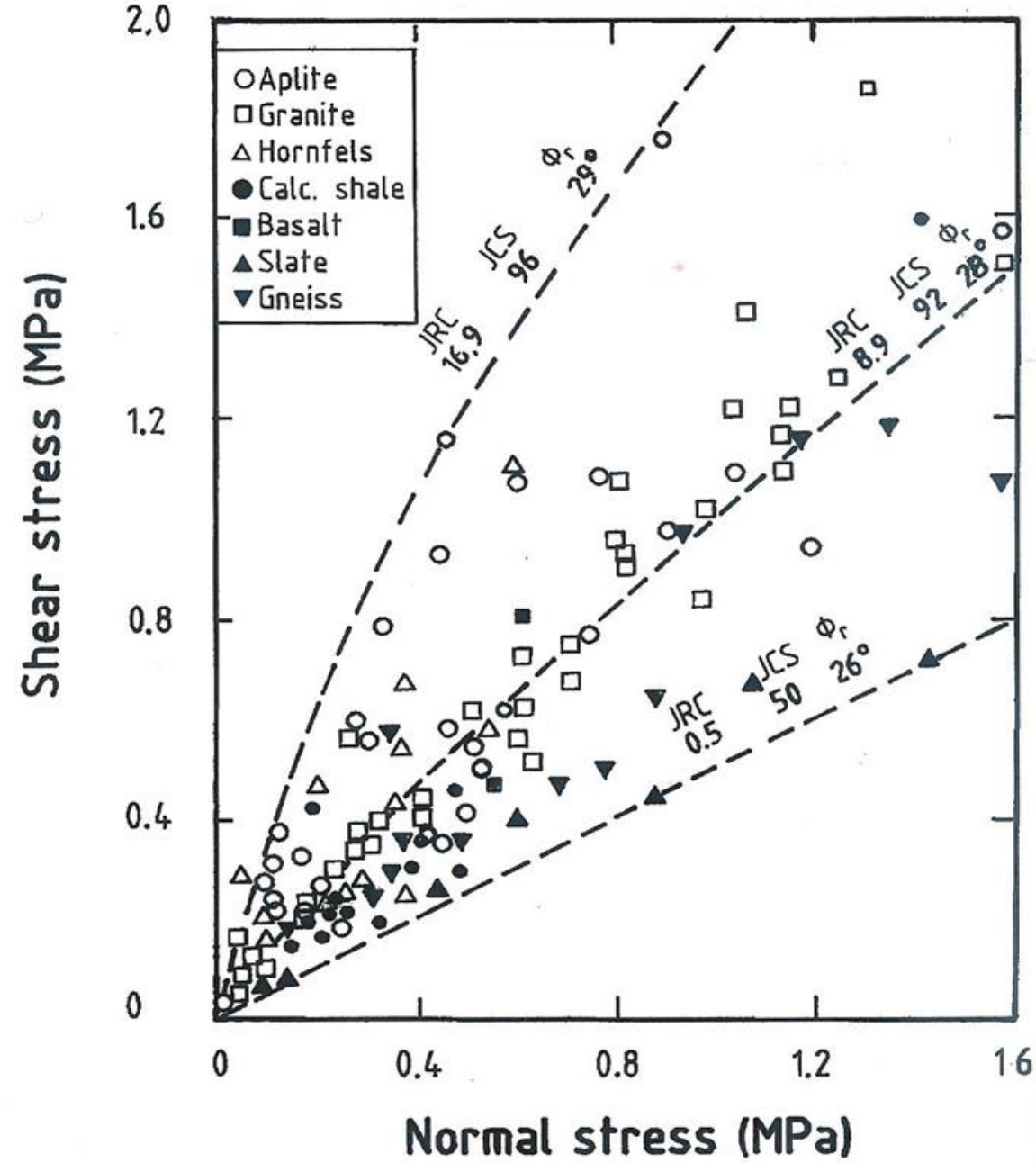




SOME OF THE 130 NATURAL JOINT SAMPLES SAWN FROM BLOCKS

Barton and Choubey, 1977.





130 rock-joint samples

(Barton and Choubey 1977)

Three curved **peak shear strength** envelopes shown:

1. Maximum strength with JRC = 16.9

2. Mean parameters
JRC=8.9,
JCS=92MPa
ϕr=28º

3. Minimum strength with $\varphi_r = 26^o$

The alternative to M-C

1. $\tau = \sigma_n' \tan [JRC \log_{10}(JCS/ \sigma_n') + \varphi_b]$

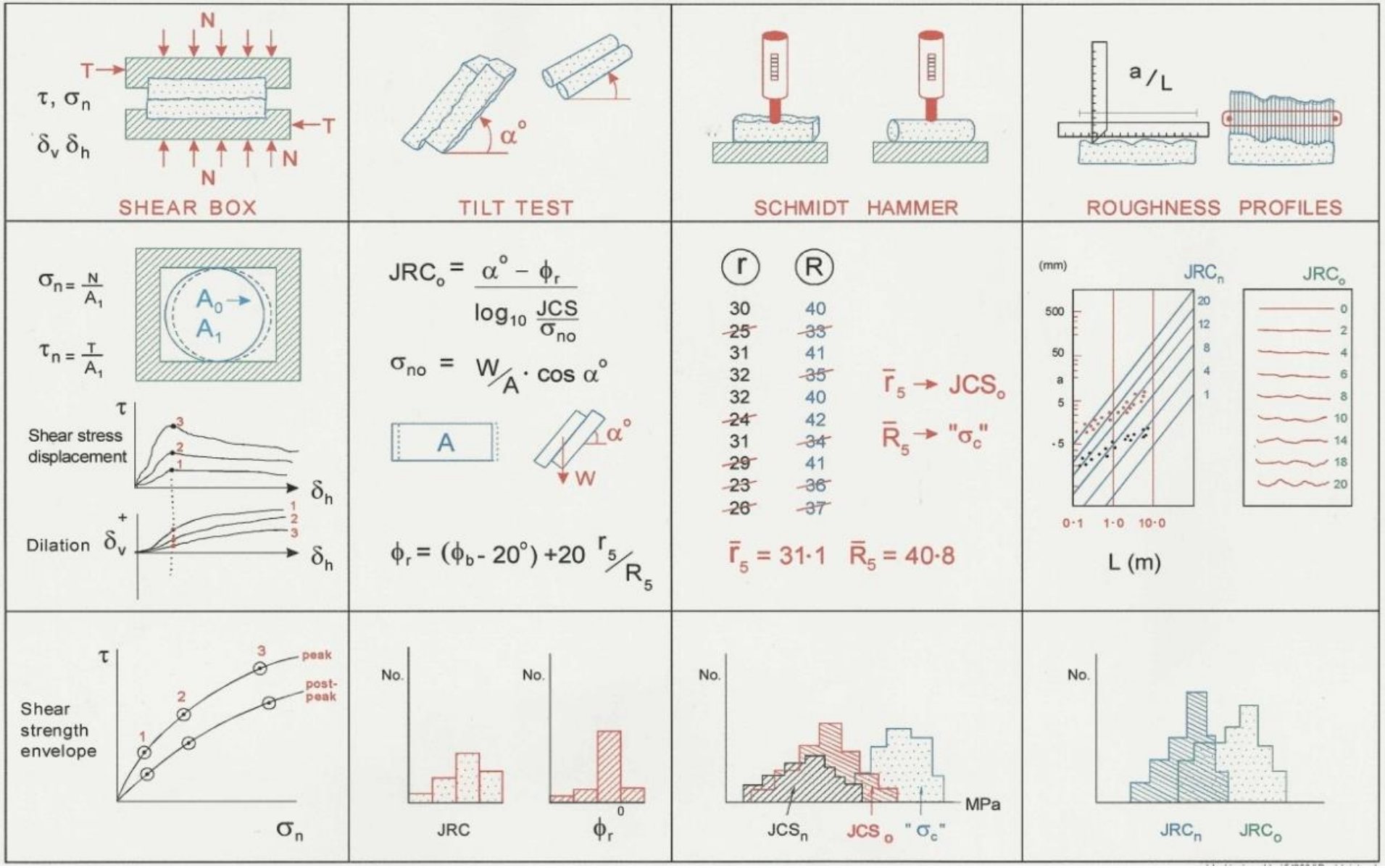
(Barton, 1973)

2. $\tau = \sigma_n' \tan [JRC_0 \log_{10}(JCS_0 / \sigma_n') + \varphi_r]$

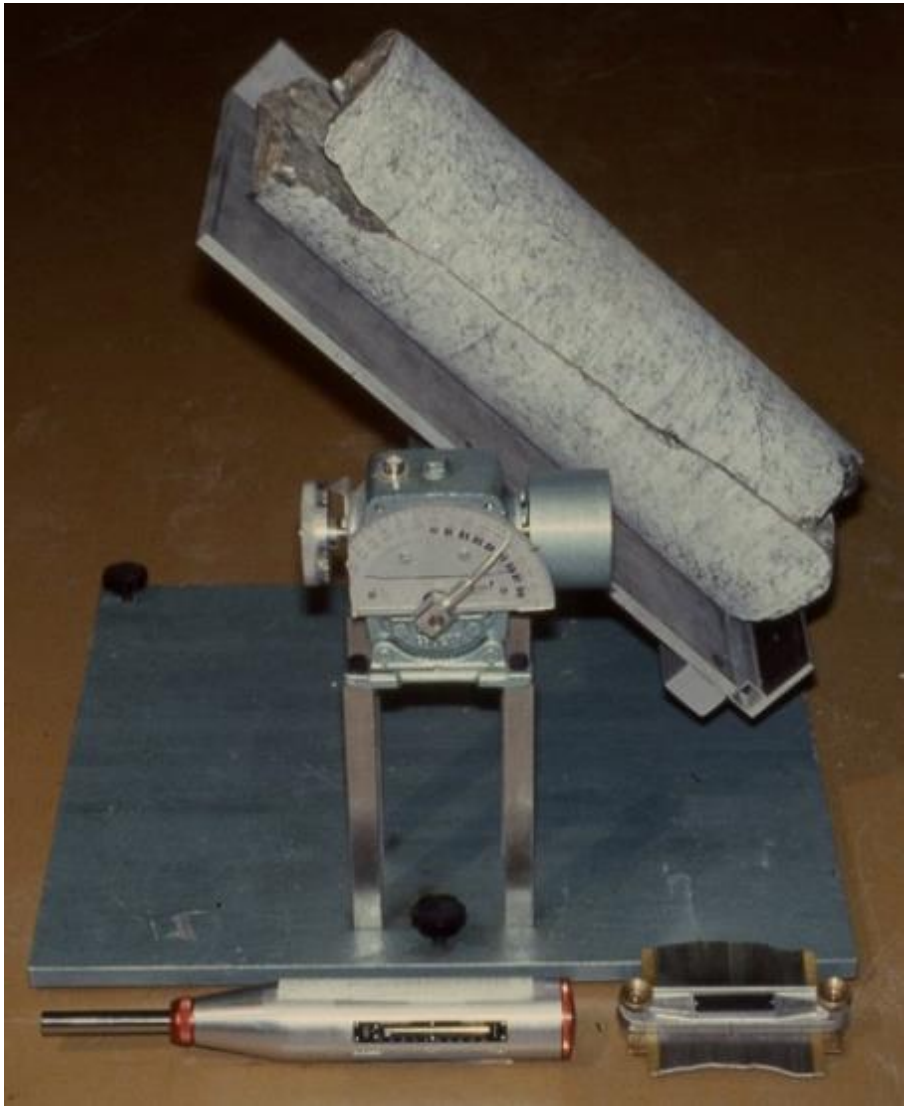
(Barton and Choubey, 1977) – laboratory scale

3. $\tau = \sigma_n' \tan [JRC_n \log_{10}(JCS_n / \sigma_n') + \varphi_r]$

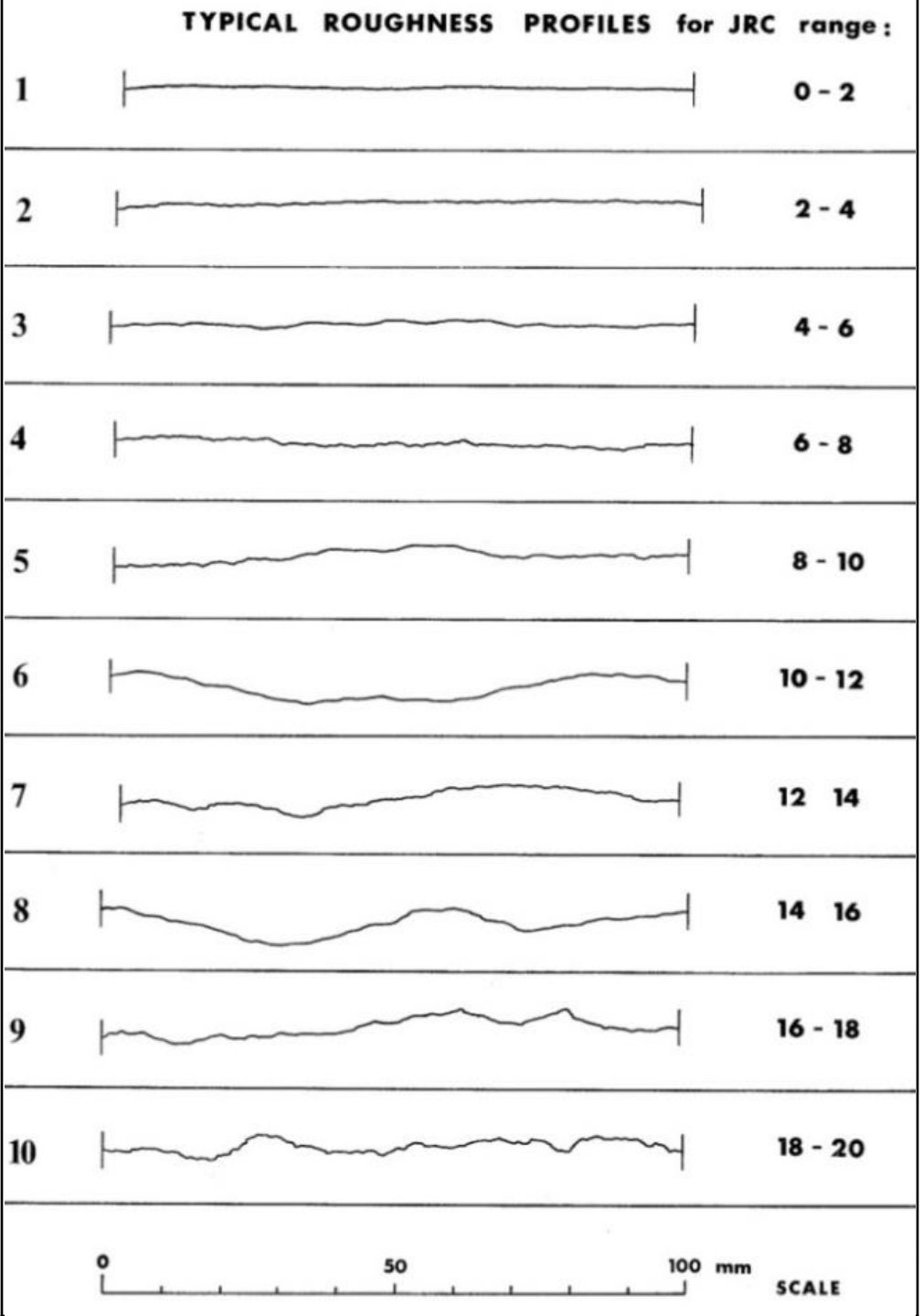
(Barton and Bandis, 1982) – field scale (natural block size L_n)

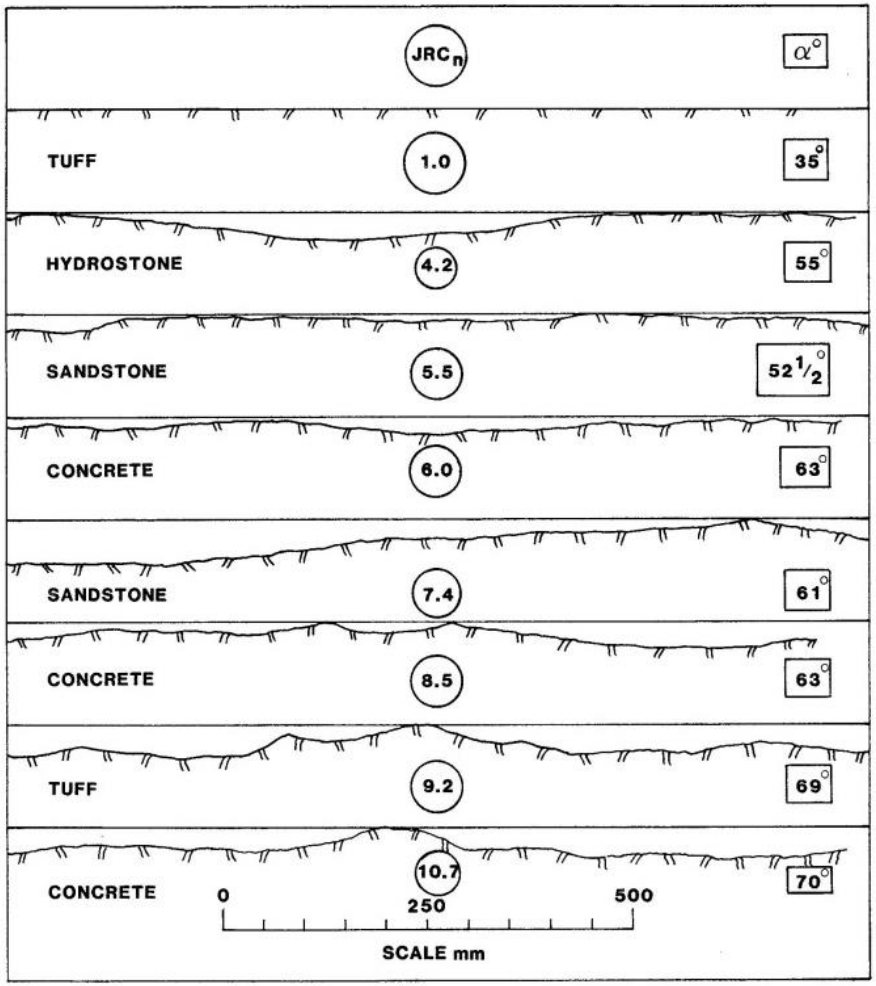


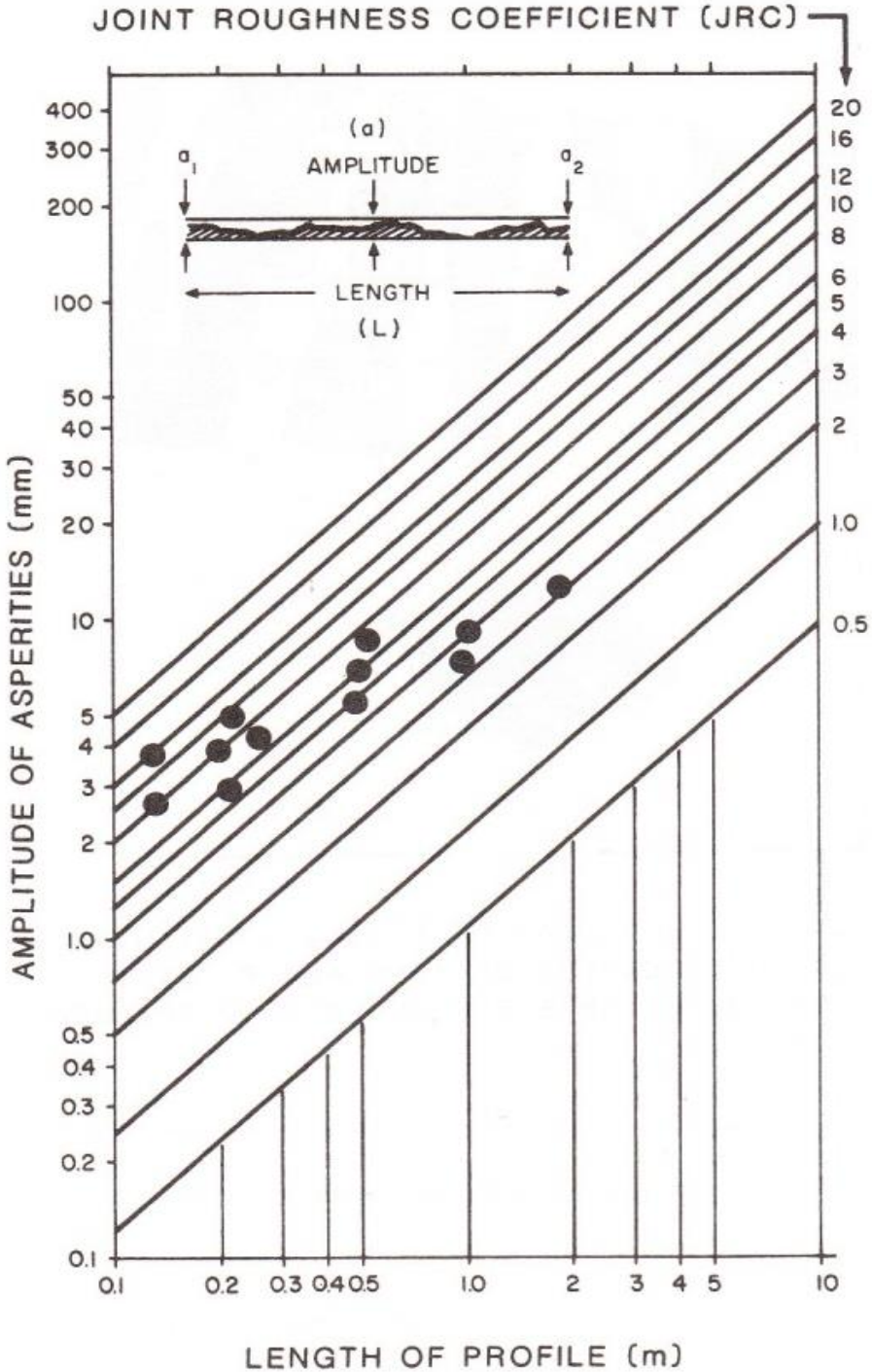
Shear tests on natural fractures, index tests, JRC/JCS/ϕ_r model. ***Missing from petroleum geomechanics practice?***



TILT TESTS FOR JRC, **TILT TESTS FOR ϕ_b**

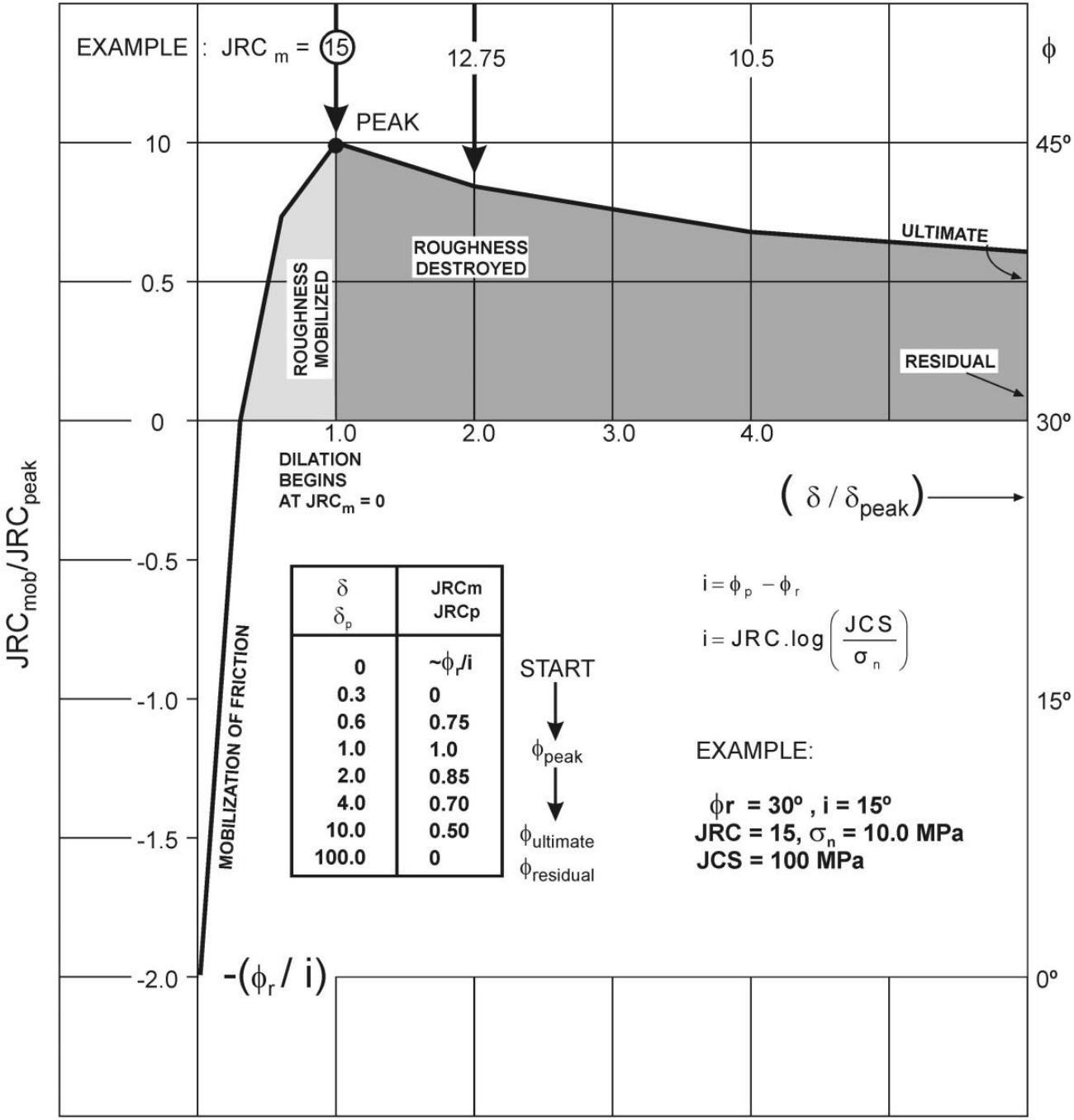

TYPICAL ROUGHNESS PROFILES for JRC range:
1
0 - 2
2
2 - 4
3
4 - 6
4
6 - 8
5
8 - 10
6
10 - 12
7
12 14
8
14 16
9
16 - 18
10
18 - 20
0
50
100 mm
SCALE


JRCn
α°
TUFF
1.0
35°
HYDROSTONE
4.2
55°
SANDSTONE
5.5
52 1/2°
CONCRETE
6.0
63°
SANDSTONE
7.4
61°
CONCRETE
8.5
63°
TUFF
9.2
69°
CONCRETE
10.7
70°
0
250
500
SCALE mm



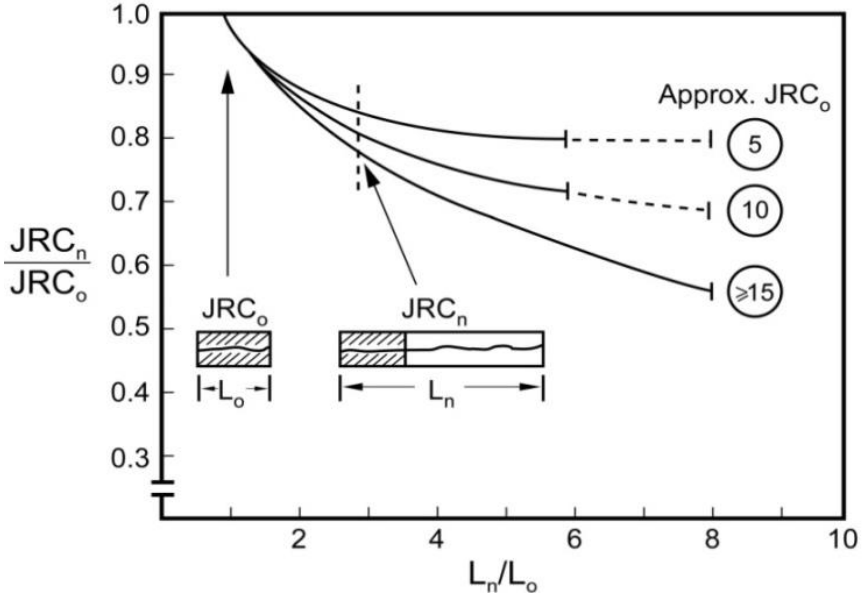
Can get more out of pavement studies / drone photos than at present?

(Differentiate the different fracture sets in terms of roughness JRC)

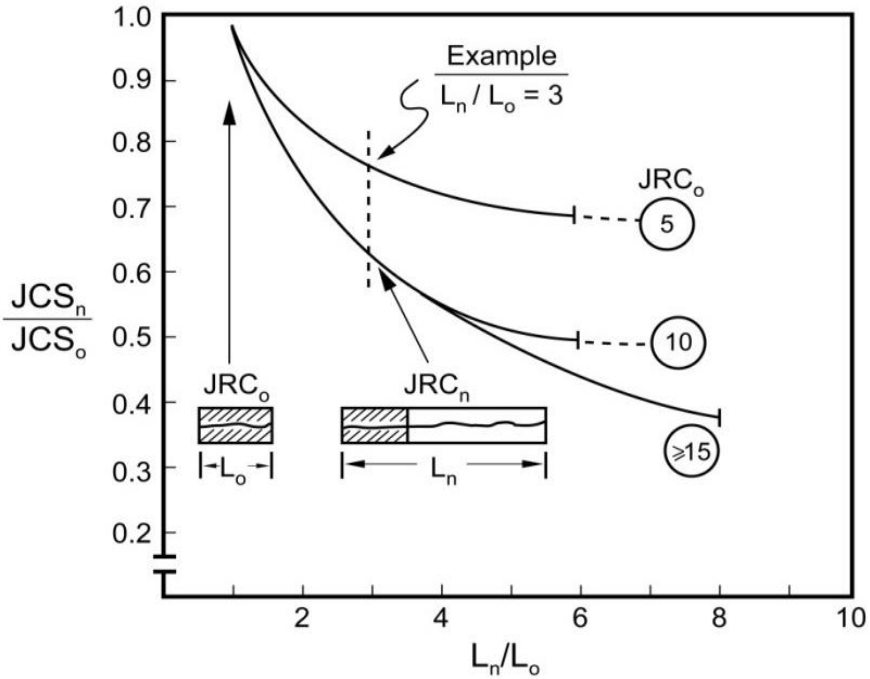


A DIMENSIONLESS WAY TO REPRESENT SHEAR-STRESS-DISPLACEMENT BEHAVIOUR

(Barton, 1982).

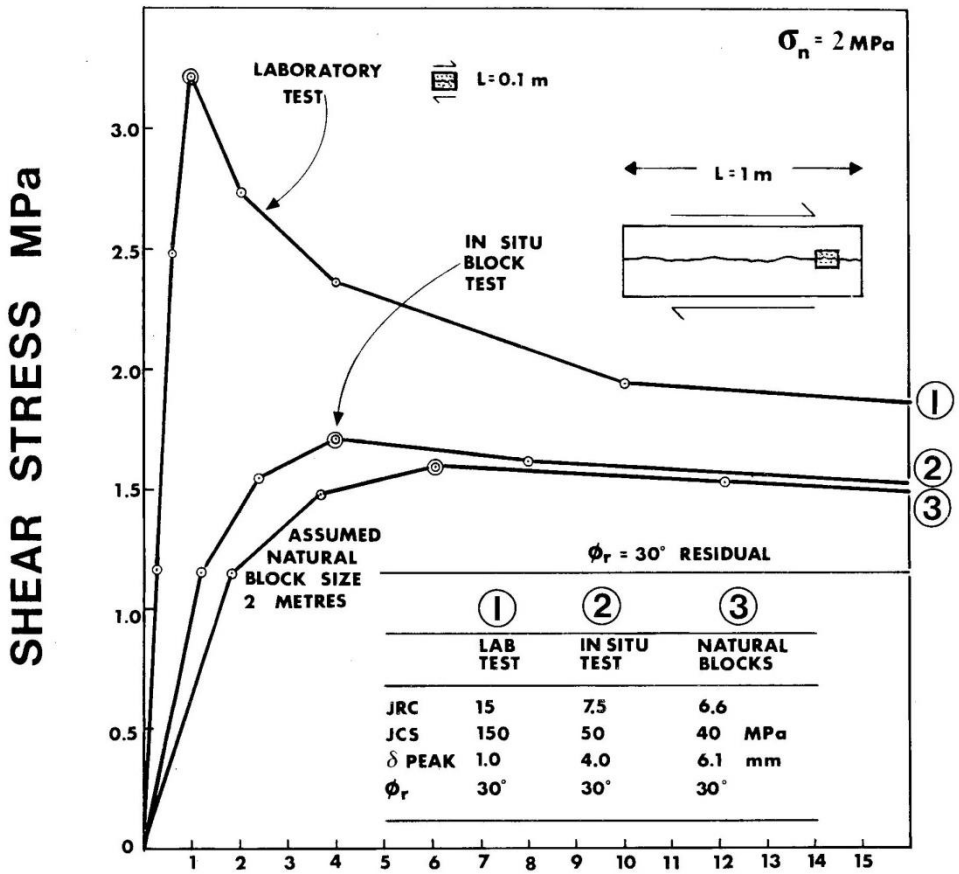


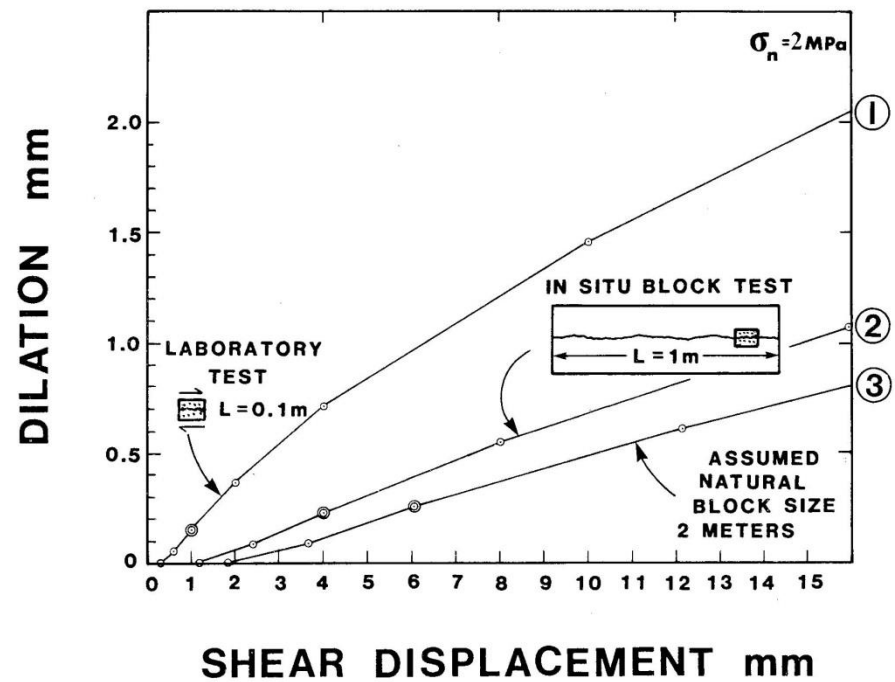
$$JRC_n \approx JRC_o \, [\, L_n/L_o \,]^{-0.02\, JRC_o}$$

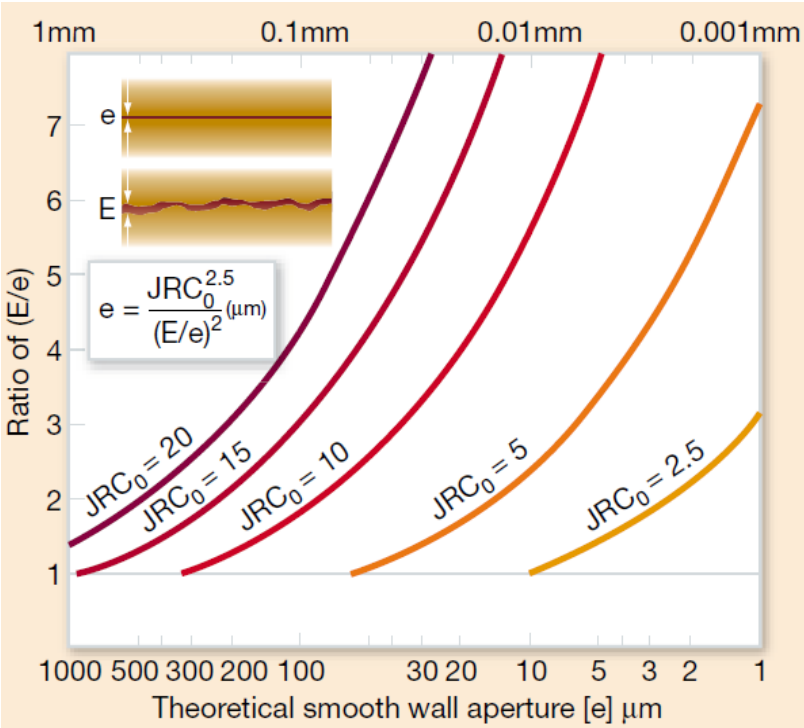


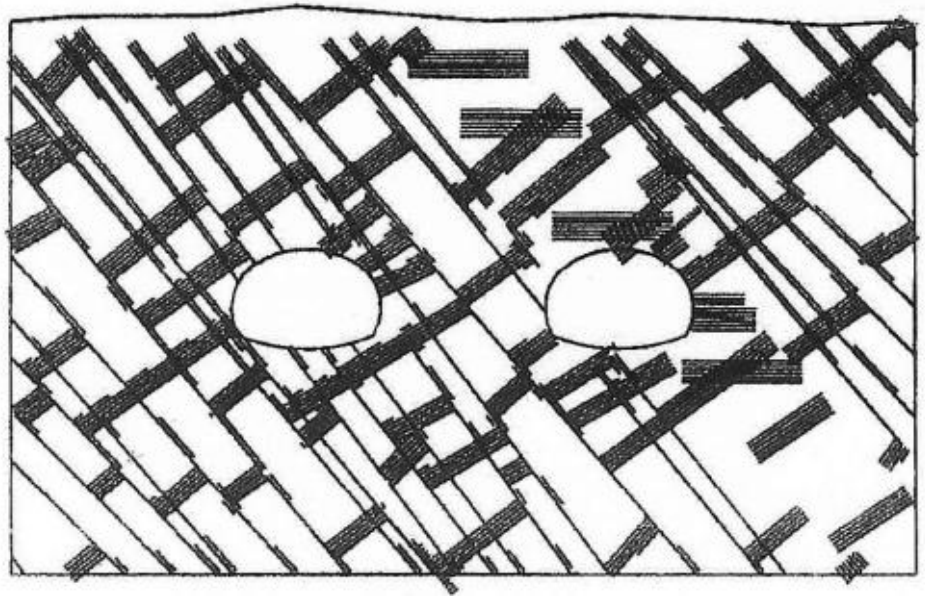
$$JCS_n \approx JCS_o \, [\, L_n/L_o \,]^{-0.03\, JRC_o}$$

Examples of ‘up-scaling’ to lower strength (as in shearing reservoir fractures)

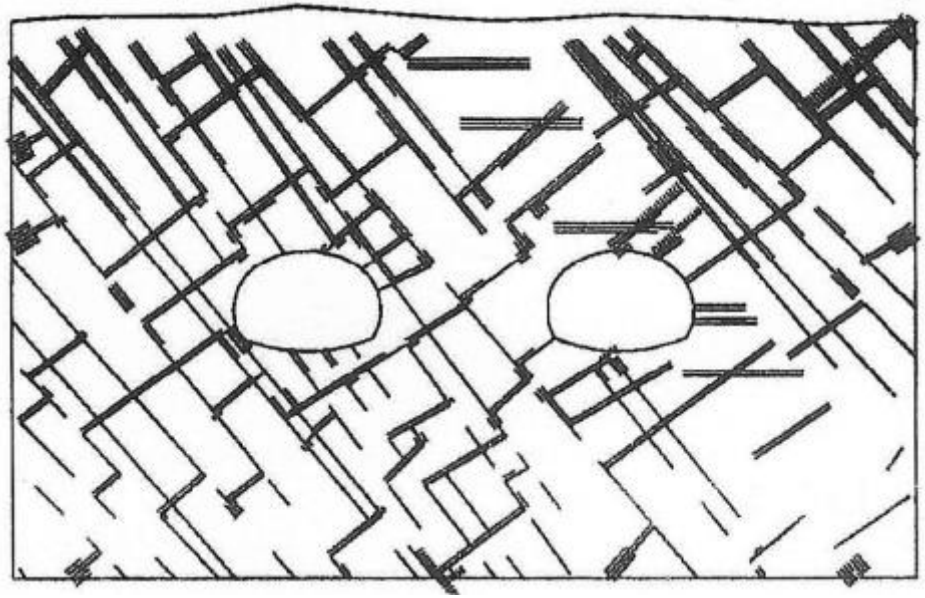




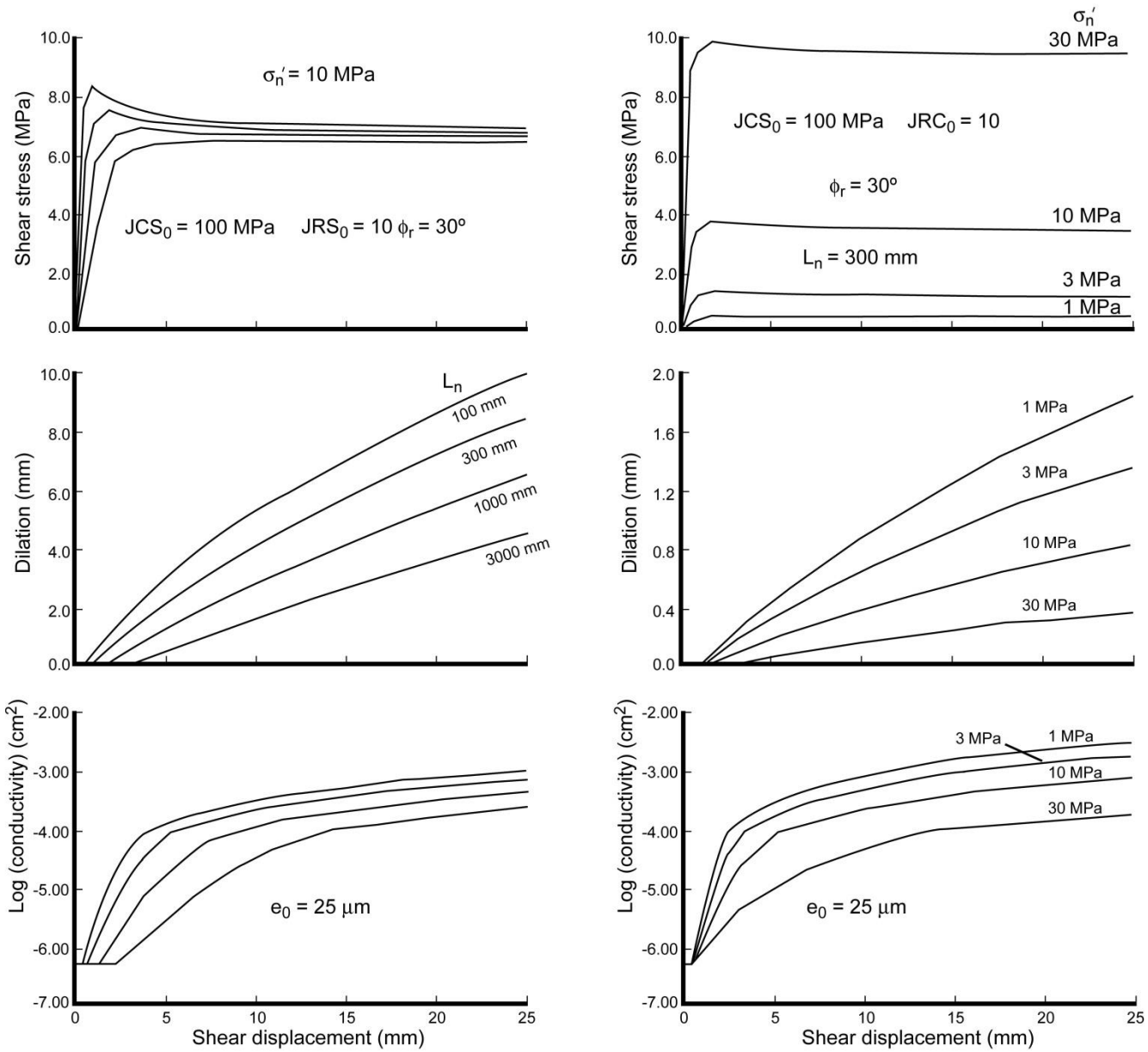




Unequal physical and hydraulic apertures

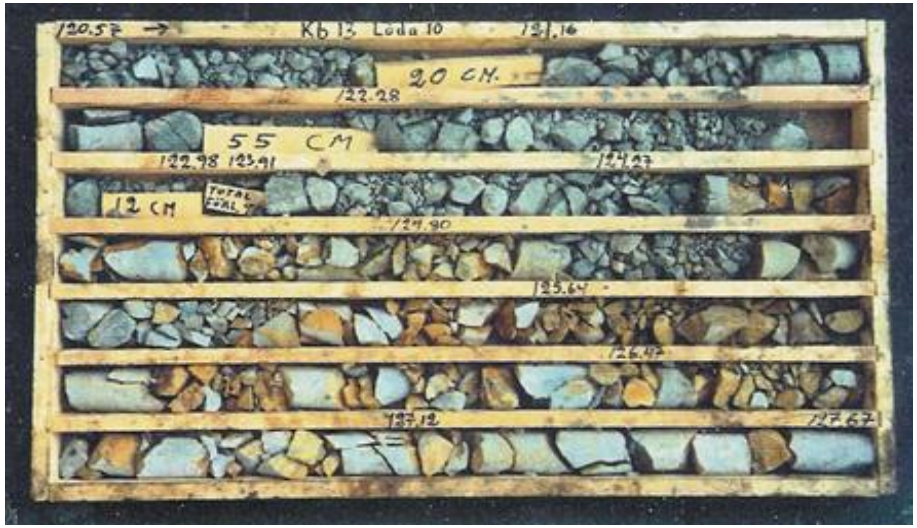


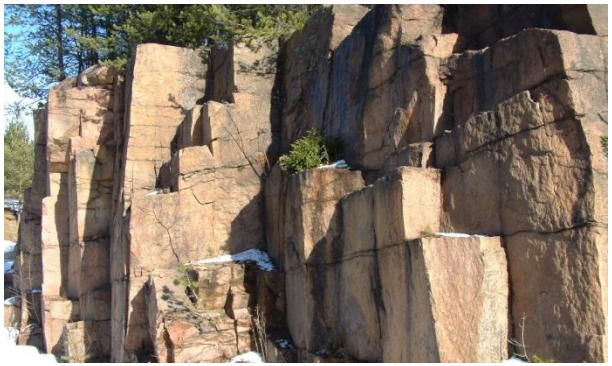
Coupled shear-dilation-permeability modelling. Barton et al., 1985

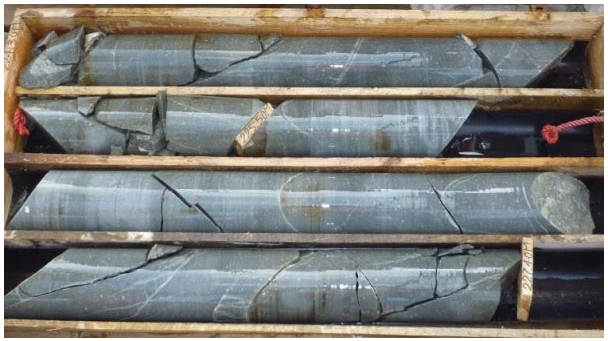
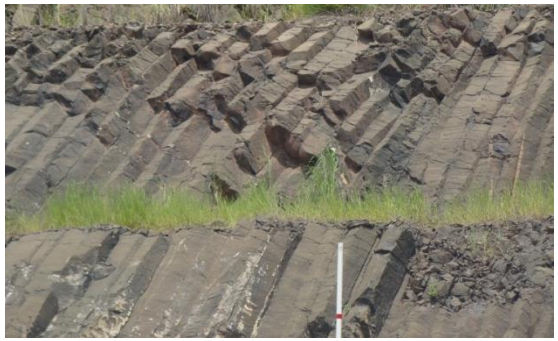


APPROPOS SPARSE DATA, NEED FOR ESTIMATION

Examples of Q ≈ 1,000 and Q ≈ 0.001





VARIABLE WORLD NEEDS *BROAD-REACH CLASSIFICATION* METHOD

WHAT IS ‘Q’ ?

- A PARAMETER DESCRIBING ROCK QUALITY (OR LACK OF QUALITY) USED ON TENS/HUNDREDS OF THOUSANDS OF PROJECTS WORLD-WIDE.

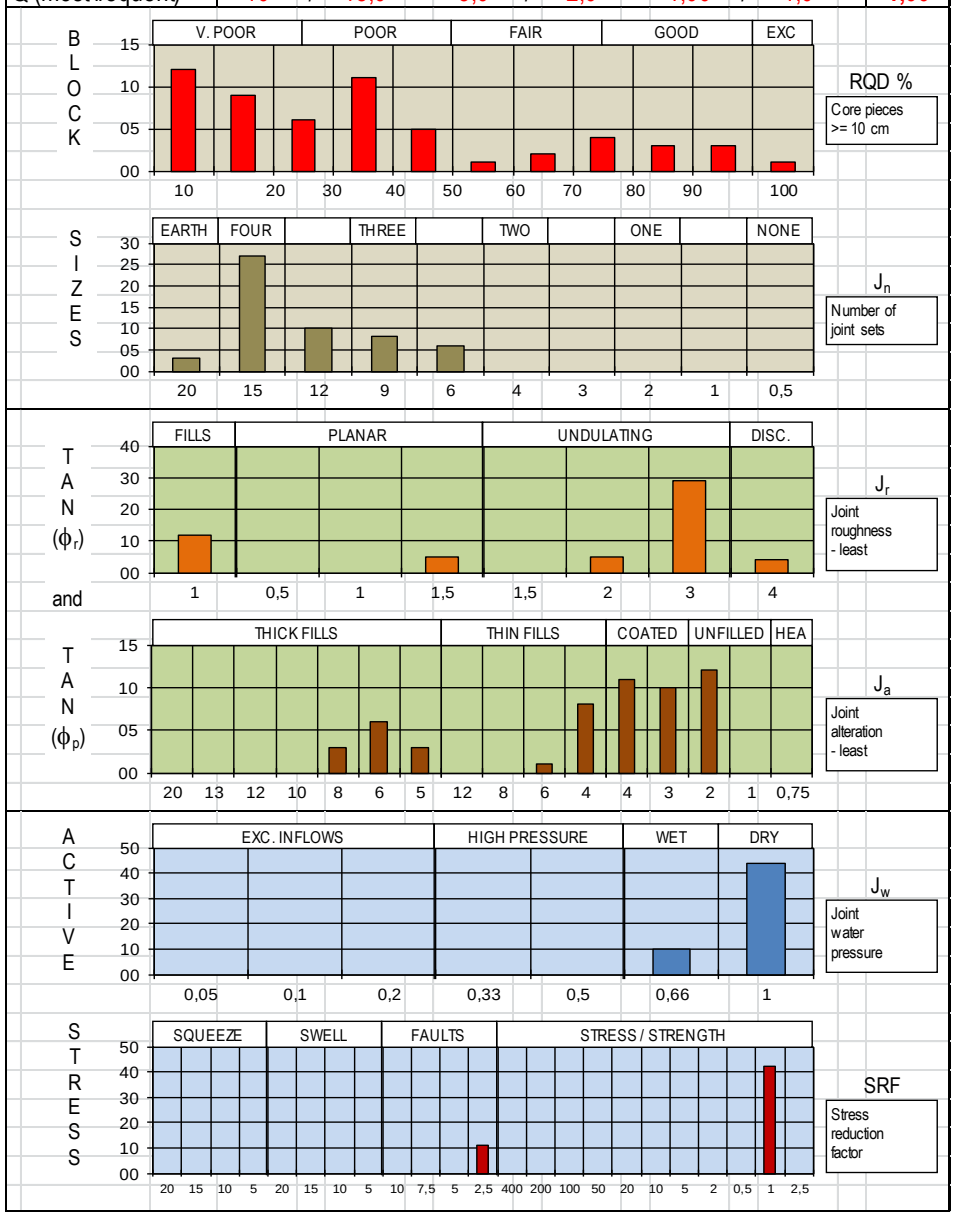
  (TUNNELLING/MINING/CAVERNS).

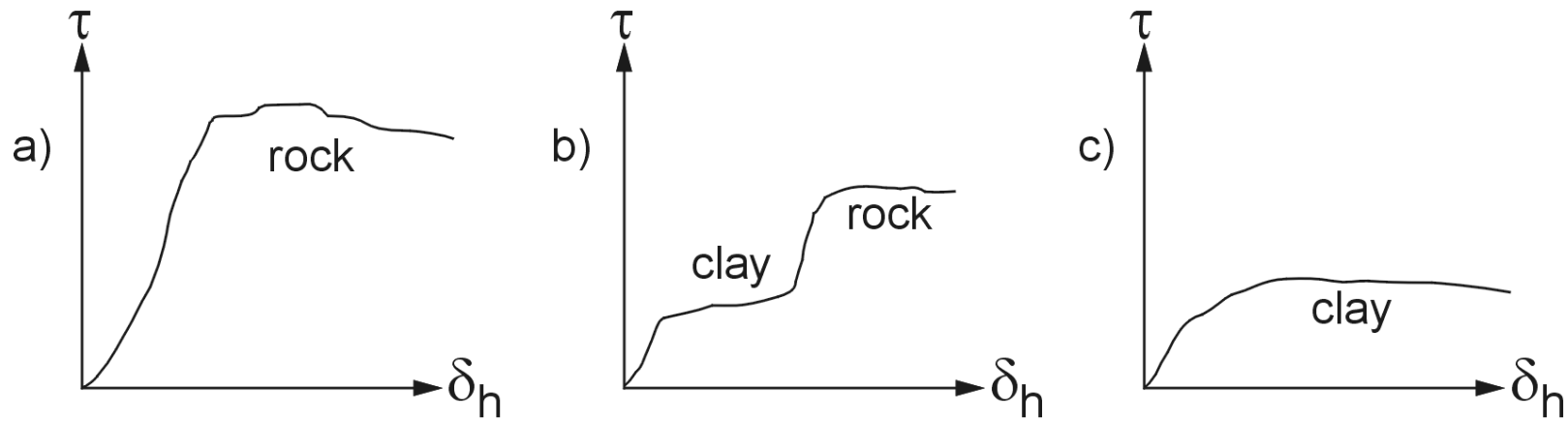
- **A PARAMETER UNKNOWN IN PETROLEUM ENGINEERING / GEOMECHANICS.**

- DEVELOPED IN 1974 (Barton Lien Lunde, 1974)

Q-parameter statistics from core logging

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	10	/	15,0	*	1,0	/	6,0	*	0,66	/	2,5	=	**0,029**
Q (typical max)=	75	/	6,0	*	4,0	/	2,0	*	1,00	/	1,0	=	**25,0**
Q (mean value)=	38	/	12,8	*	2,4	/	3,9	*	0,94	/	1,3	=	**1,29**
Q (most frequent)=	10	/	15,0	*	3,0	/	2,0	*	1,00	/	1,0	=	**1,00**



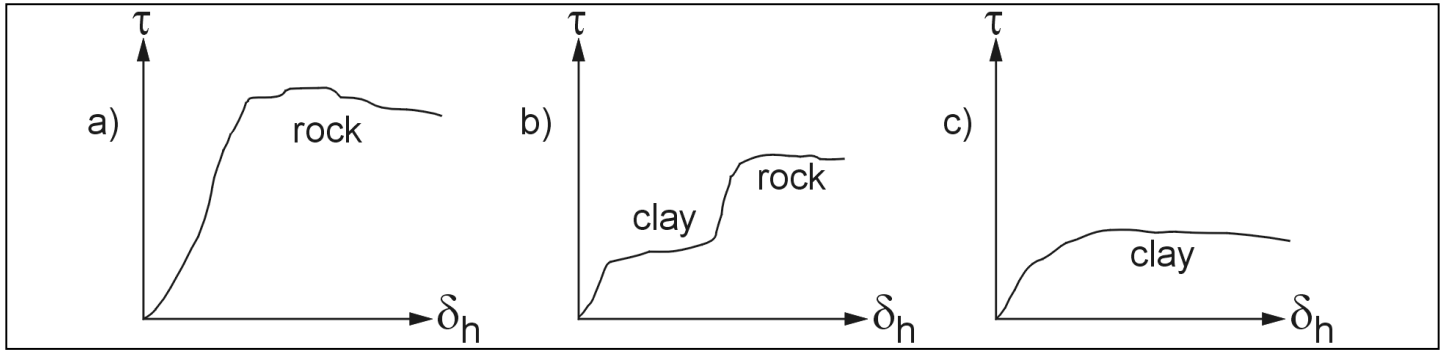


(a) Rock wall contact

(thin coatings)

	Ja/Jr =	0.75	1.0	2	3	4
		$\tan^{-1}(Jr/Ja)$°				
A. Discontinuous joints	4	79°	76°	63°	53°	45°
B. Rough, undulating	3	76°	72°	56°	45°	37°
C. Smooth, undulating	2	69°	63°	45°	34°	27°
D. Slickensided, undulating	1.5	63°	56°	37°	27°	21°
E. Rough, planar	1.5	63°	56°	37°	27°	21°
F. Smooth, planar	1.0	53°	45°	27°	18°	14°
G. Slickensided, planar	0.5	34°	27°	14°	9.5°	7.1°

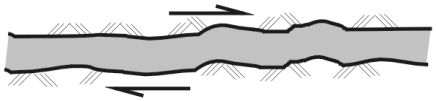
Jr/Ja (3rd and 4th Q-parameters) **MOSTLY φ + i (*dilating-during-shear* joints)**



(b) Rock wall contact when sheared

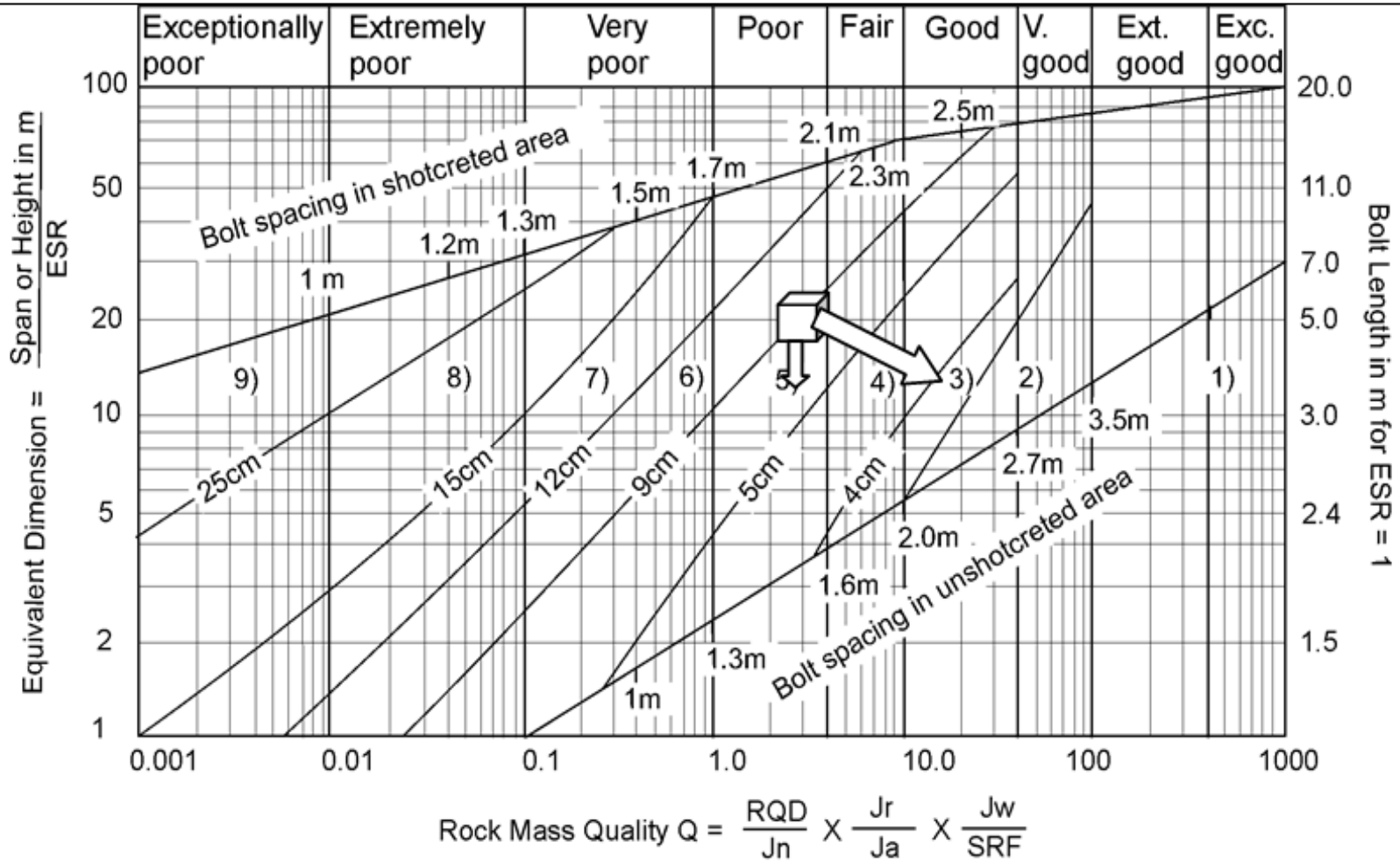
	(thin fillings)				
Ja/Jr =	4	6	8	12	
	$\tan^{-1}(Jr/Ja)$°				
A. Discontinuous joints	4	45°	34°	27°	18°
B. Rough, undulating	3	37°	27°	21°	14°
C. Smooth, undulating	2	27°	18°	14°	9.5°
D. Slickensided, undulating	1.5	21°	14°	11°	7.1°
E. Rough, planar	1.5	21°	14°	11°	7.1°
F. Smooth, planar	1.0	14°	9.5°	7.1°	4.7°
G. Slickensided, planar	0.5	7°	4.7°	3.6°	2.4°

(c) No rock wall contact when sheared



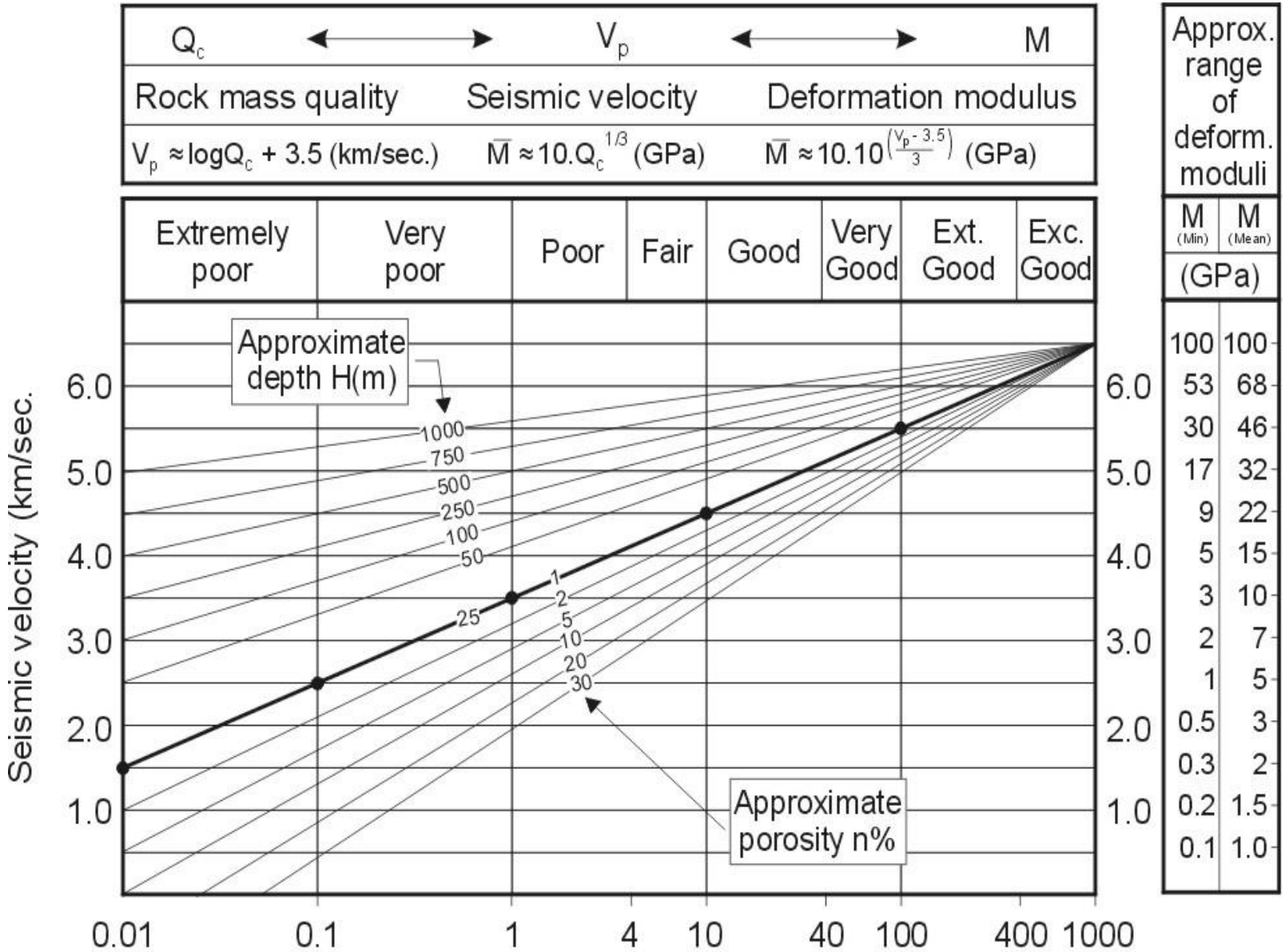
	(thick fillings)						
Ja/Jr =	5	6	8	12	13	16	20
	$\tan^{-1}(Jr/Ja)$°						
Nominal roughness of discontinuity rock walls	1.0	11.3°	9.5°	7.1°	4.8°	4.4°	3.6°	2.9°

MOSTLY φ-i (*contracting-during-shear* filled discontinuities

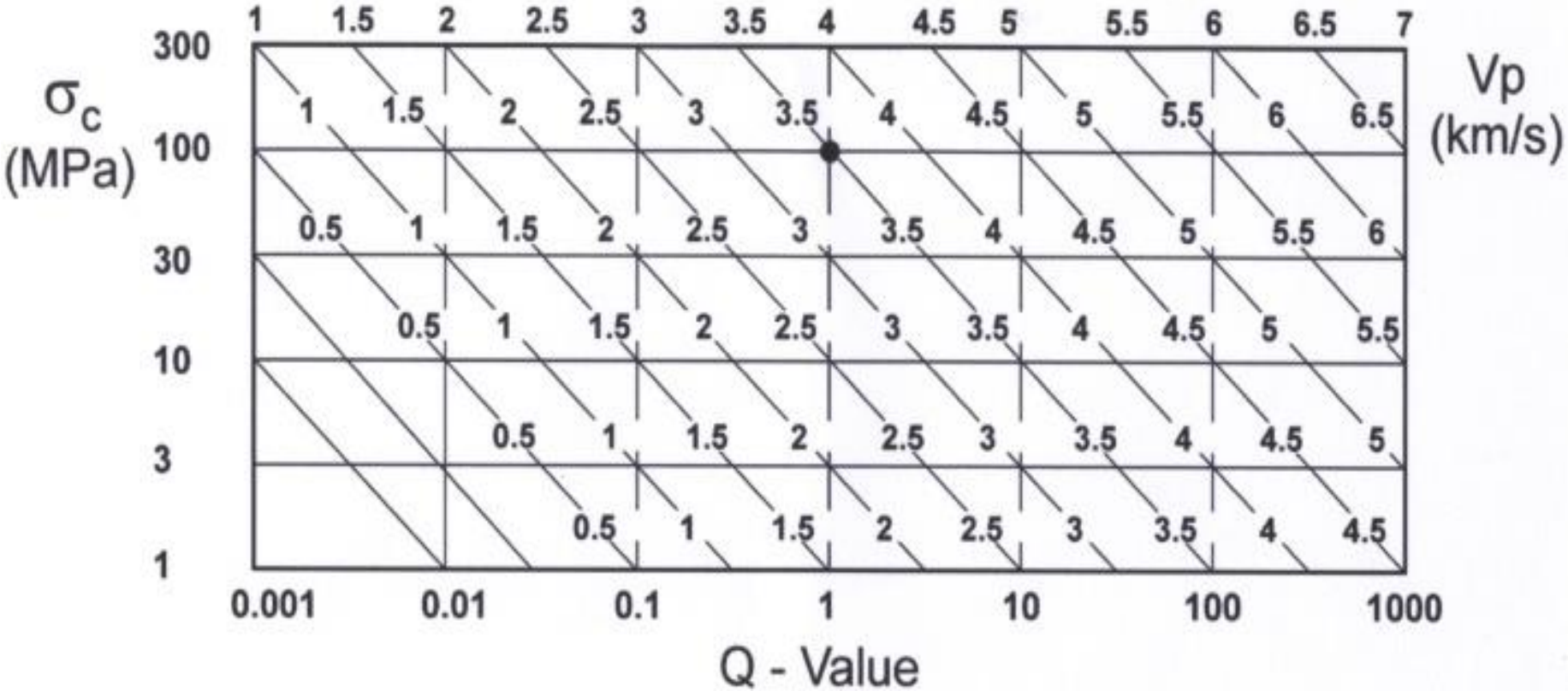


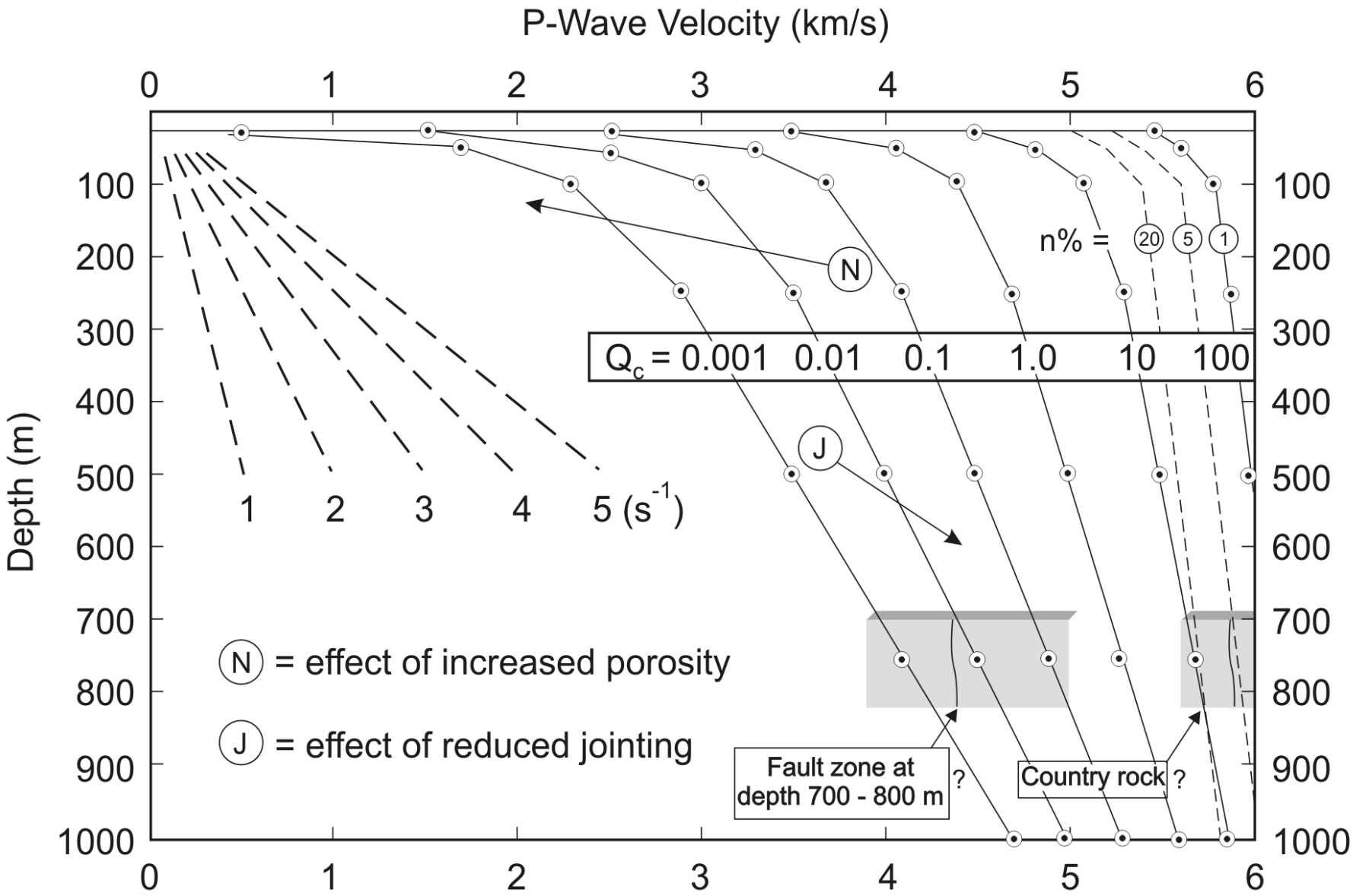
REINFORCEMENT CATEGORIES

1) Unsupported
2) Spot bolting, sb
3) Systematic bolting, B
4) Systematic bolting (and unreinforced shotcrete, 4-10cm, B(+S)
5) Fiber reinforced shotcrete and bolting, 5-9cm, Sfr+B
6) Fiber reinforced shotcrete and bolting, 9 - 12cm, Sfr+B
7) Fiber reinforced shotcrete and bolting, 12 - 15cm, Sfr+B
8) Fiber reinforced shotcrete > 15cm, reinforced ribs of shotcrete and bolting, Sfr, RRS+B
9) Cast concrete lining,CCA



$$Q_c = \left[\frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \right] \frac{\sigma_c}{100}$$


σc
(MPa)
300
100
30
10
3
1
Vp
(km/s)
1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7
1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5
0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6
0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5
0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
0.5 1 1.5 2 2.5 3 3.5 4 4.5
0.001 0.01 0.1 1 10 100 1000
Q - Value

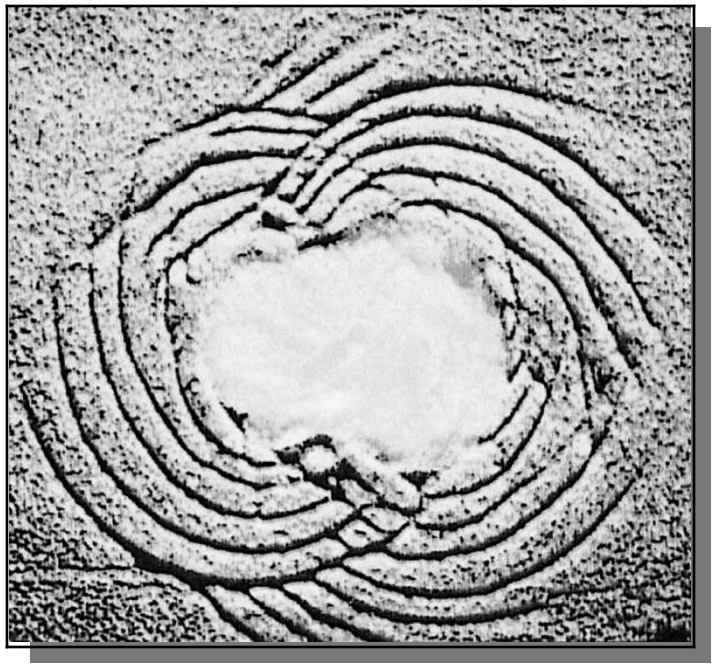

P-Wave Velocity (km/s)
0
1
2
3
4
5
6
Depth (m)
100
200
300
400
500
600
700
800
900
1000
n% =
20
5
1
N
Q$_c$ = 0.001 0.01 0.1 1.0 10 100
J
1 2 3 4 5 (s^{-1})
N = effect of increased porosity
J = effect of reduced jointing
Fault zone at depth 700 - 800 m
?
Country rock
?

$$CC = \frac{RQD}{J_n} \times \frac{1}{SRF} \times \frac{\sigma_c}{100}$$

$$FC = \tan^{-1}\left(\frac{Jr}{Ja} \times Jw\right)$$

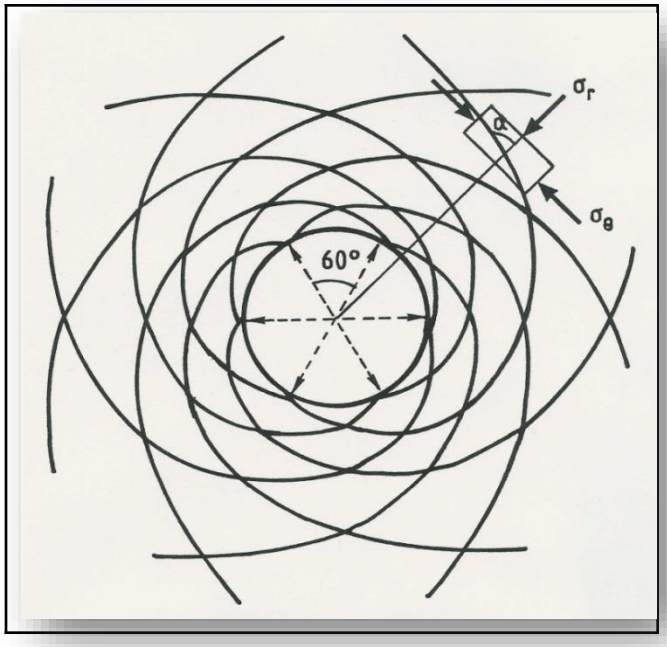
RQD	J_n	J_r	J_a	J_w	SRF	Q	σ_c	Q_c	FC°	CC MPa	V_p km/s	E_{mass} GPa
100	2	2	1	1	1	100	100	100	63°	50	5.5	46
90	9	1	1	1	1	10	100	10	45°	10	4.5	22
60	12	1.5	2	0.66	1	2.5	50	1.2	26°	2.5	3.6	10.7
30	15	1	4	0.66	2.5	0.13	33	0.04	9°	0.26	2.1	3.5
10	20	1	6	0.5	5	0.008	10	0.0008	5°	0.01	0.4	0.9

APPROPOS BREAK-OUT MODELLING



Borehole stability studies at NGI.

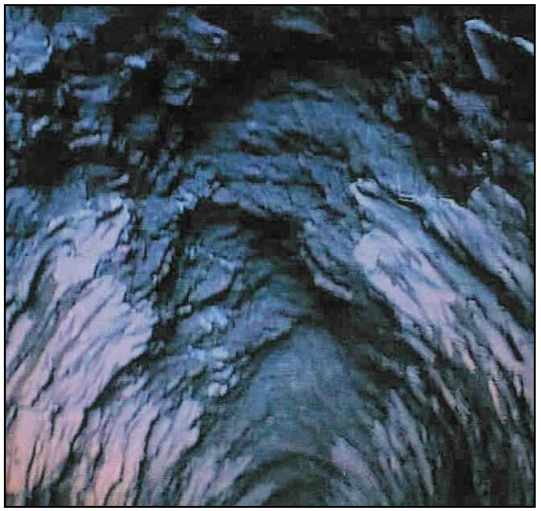
(Joint Industry Project). Addis et al., SPE, 1990.

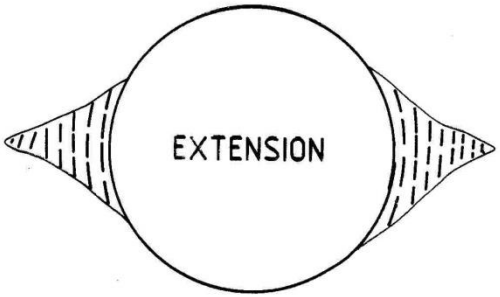


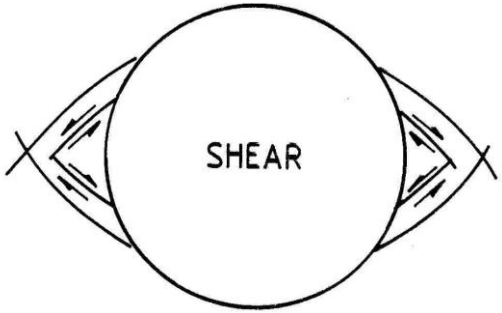
Drilling into $\sigma_1 > \sigma_2 > \sigma_3$ loaded cubes

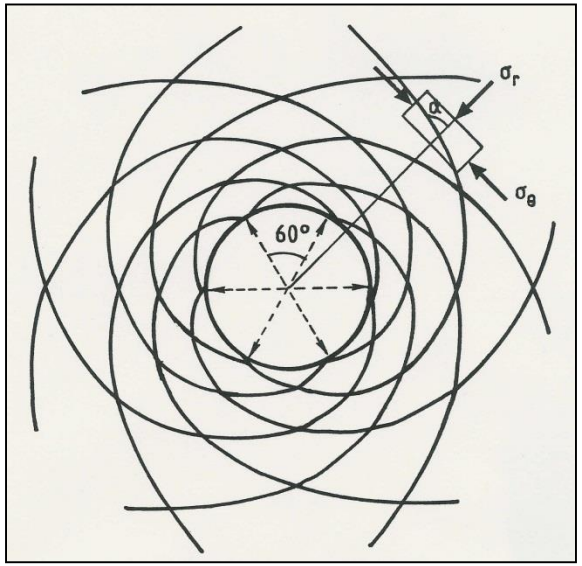
0.5 x 0.5 x 0.5 m

of model sandstone

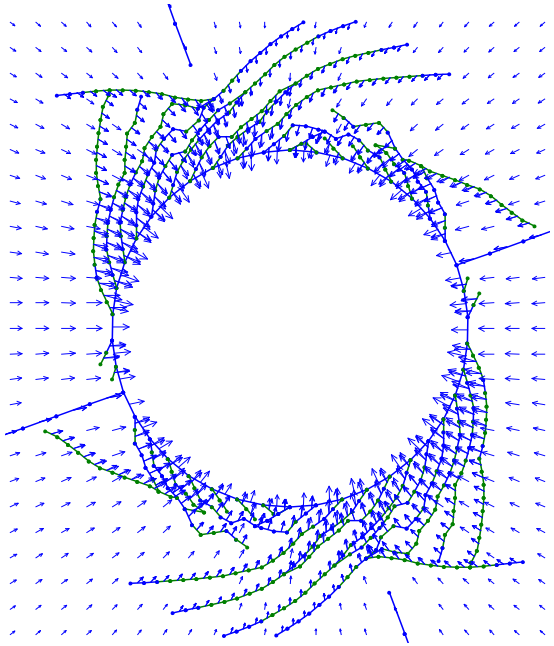


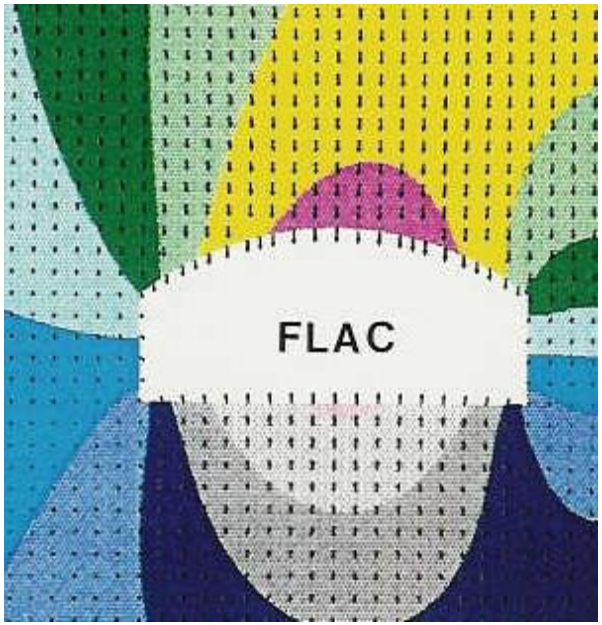


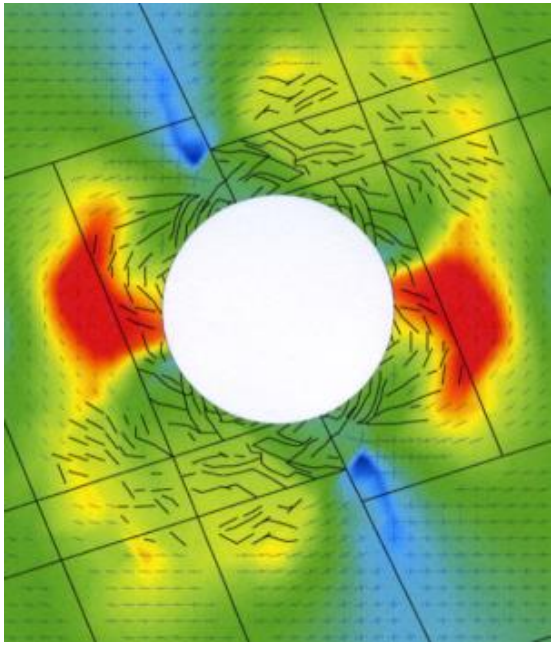


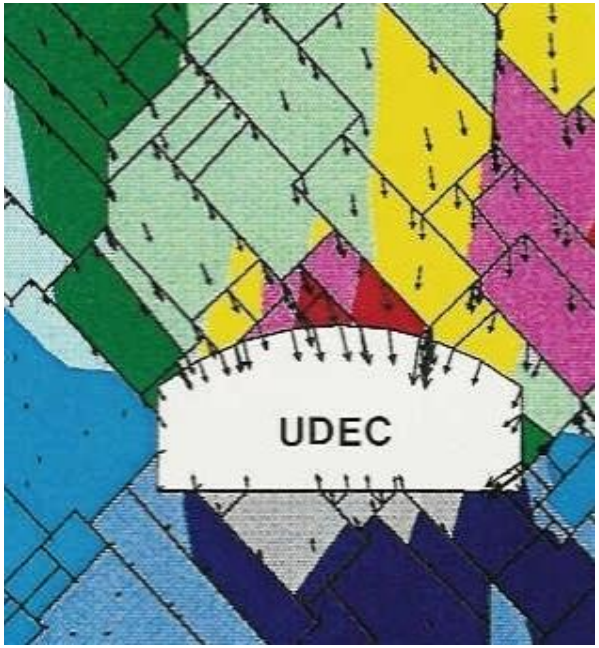


Stress-induced failures in tunnels, a model and theory

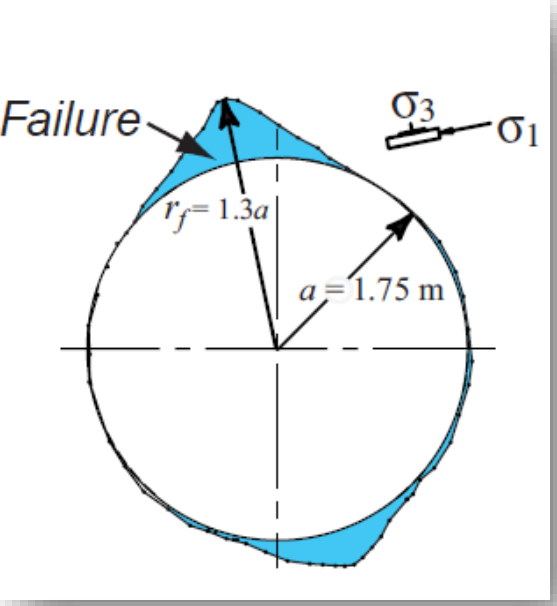



FLAC




UDEC

NEED for CHANGE

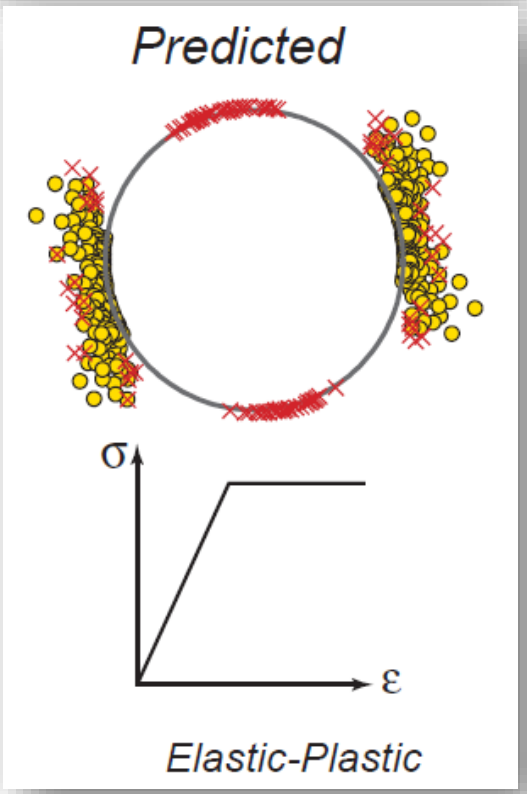


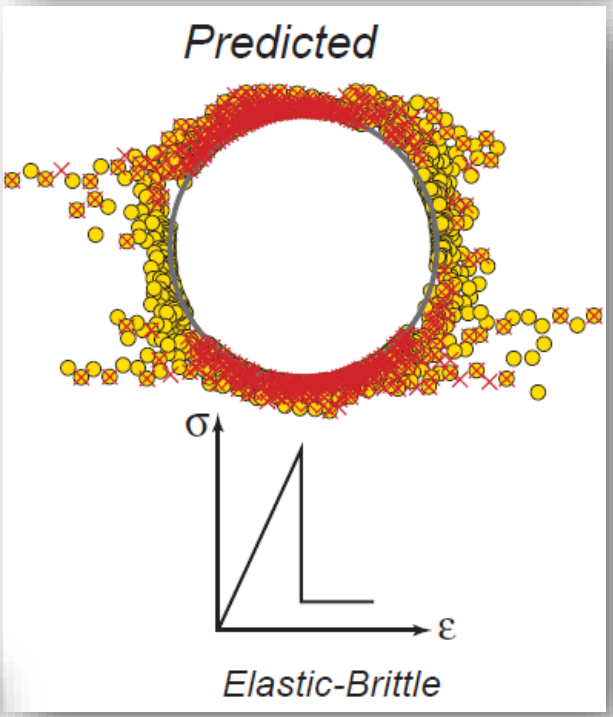
CONVENTIONAL continuum modelling methods.

Poor simulation with Mohr Coulomb or Hoek and Brown strength criteria.

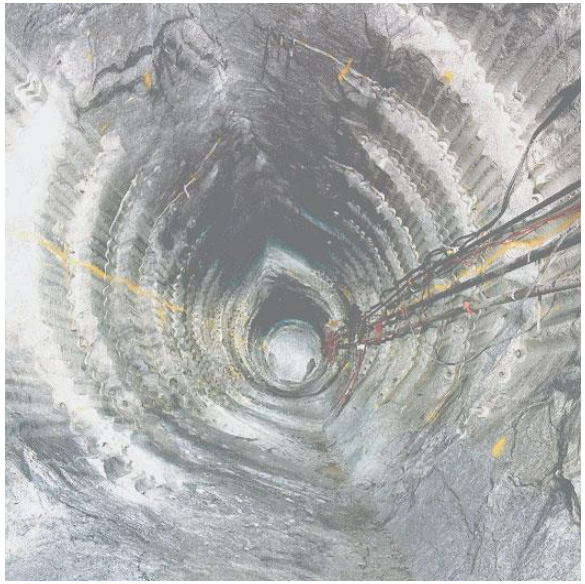
(Hajiabdolmajid, Martin and Kaiser, 2000 "Modelling brittle failure", NARMS.)

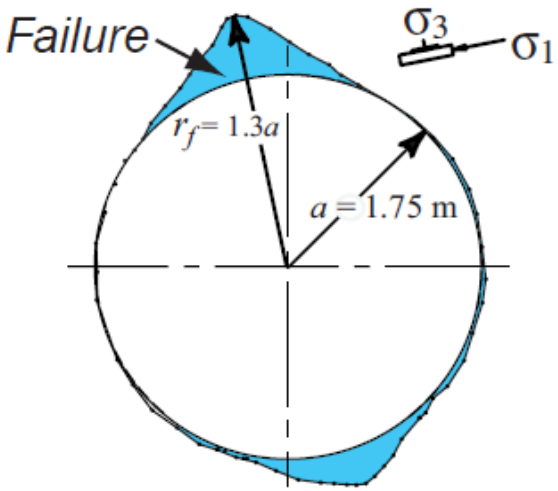
So why performed by so many consultants?

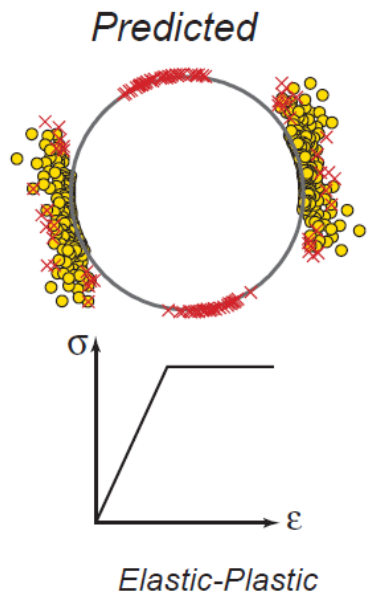




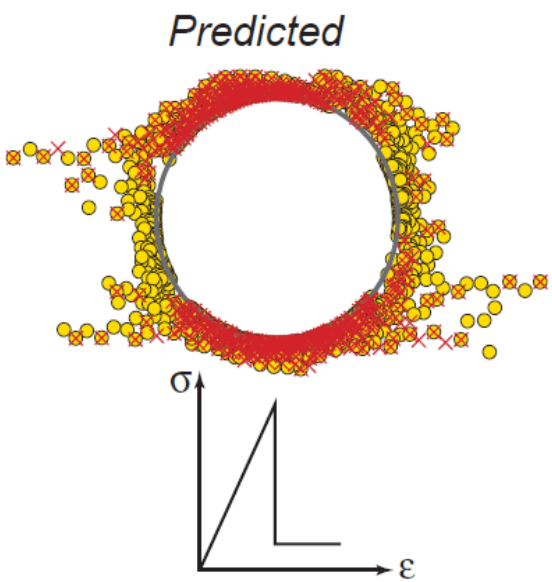
× Shear failure ○ Tensile failure



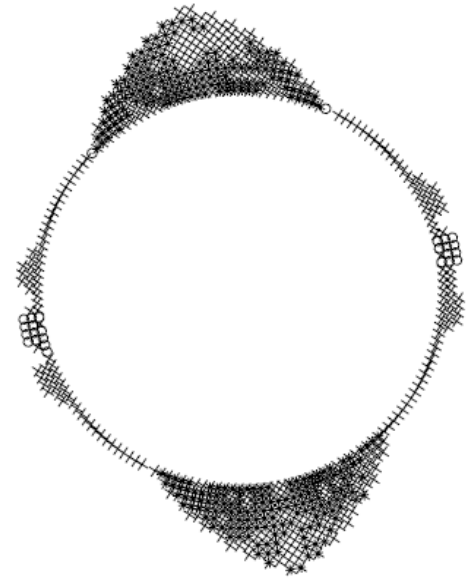


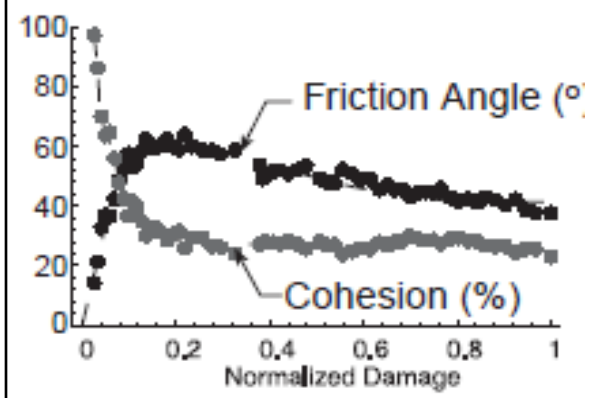


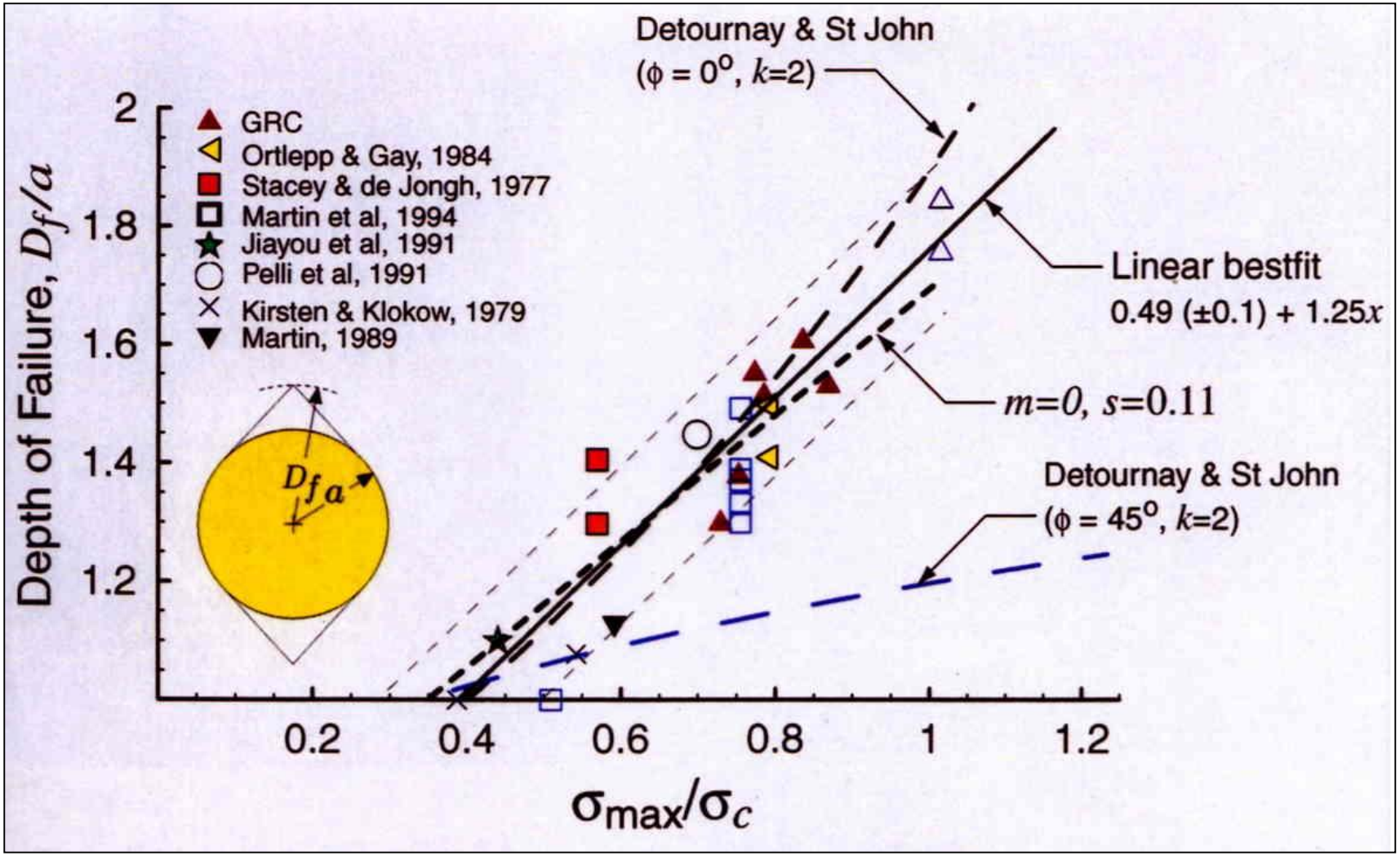
Elastic-Plastic



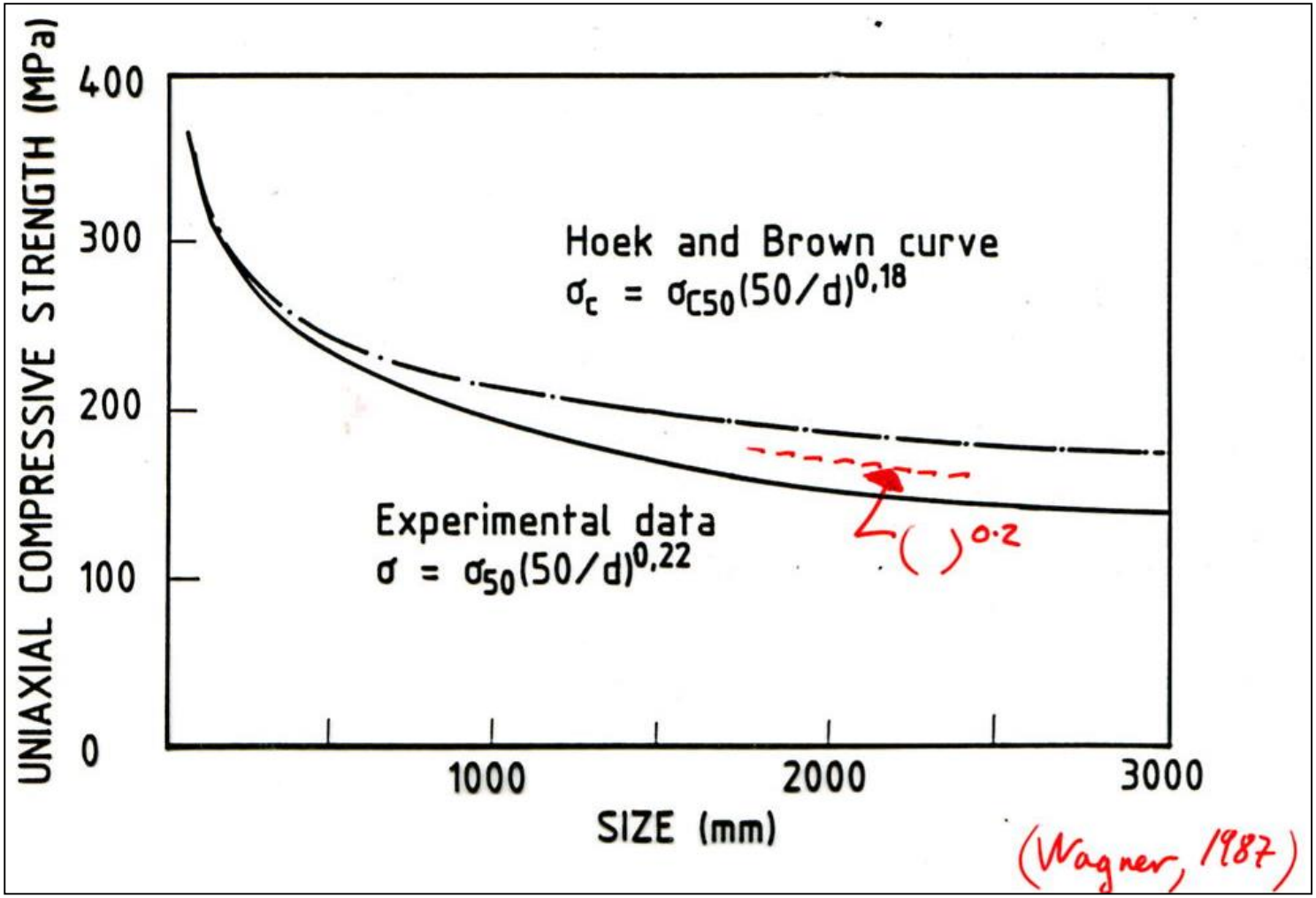
Elastic-Brittle



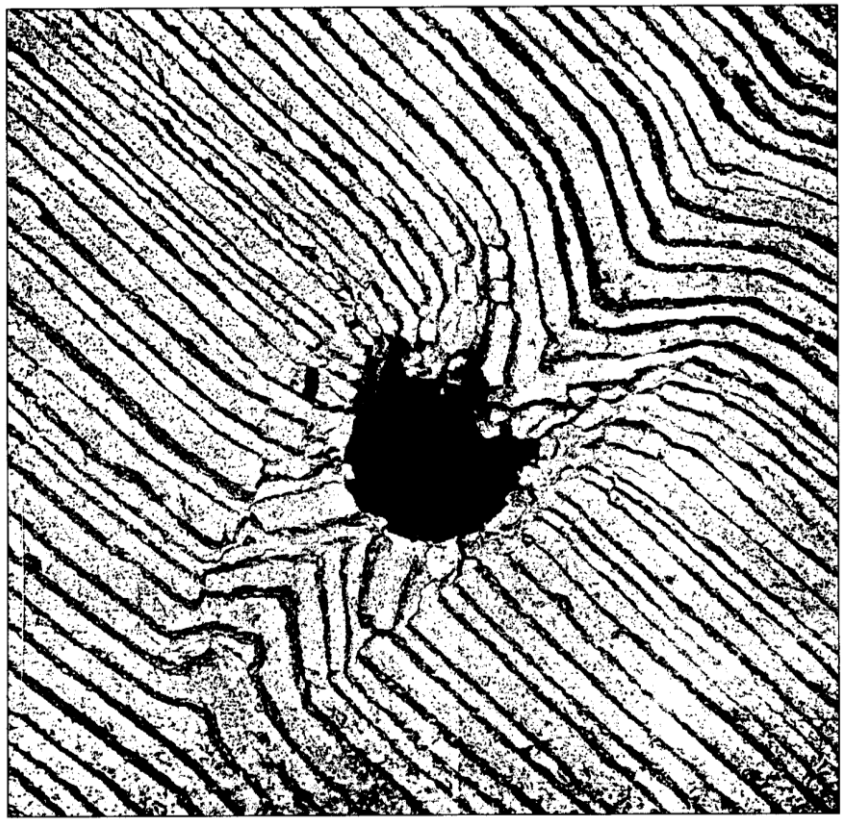


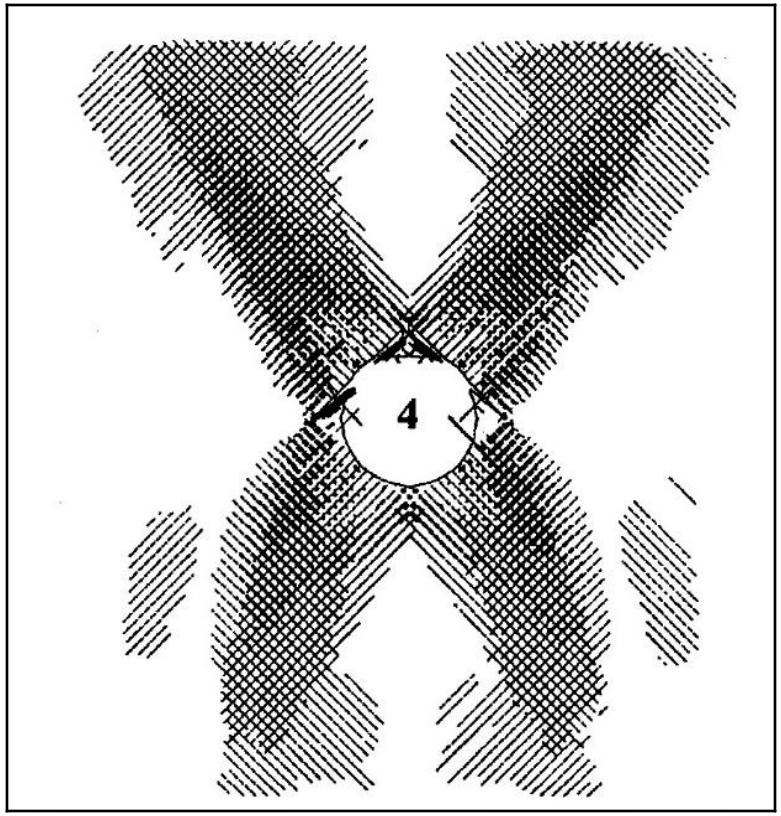


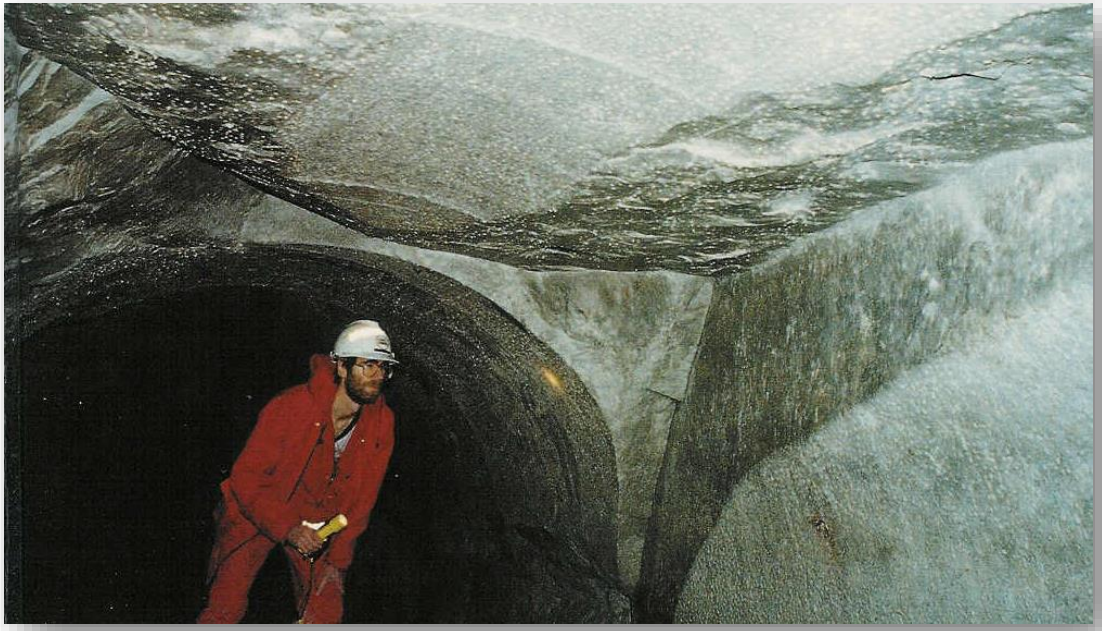
(After Martin et al. 1997)

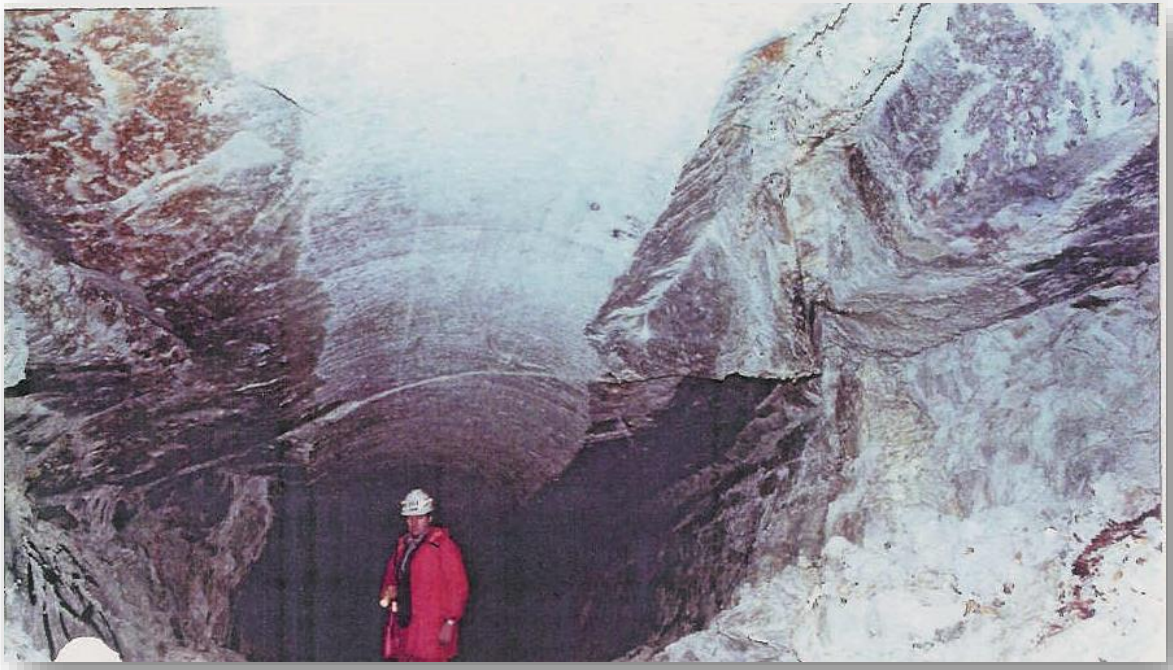


Hoek and Brown UCS scaling curve, Wagner mining data, NB 1987 '0.2' suggestion. (SINCE 2015 KNOW OF OTHER REASONS FOR CRITICAL VALUE FOR FRACTURING '0.4' X UCS…..NOT A SCALE EFFECT)

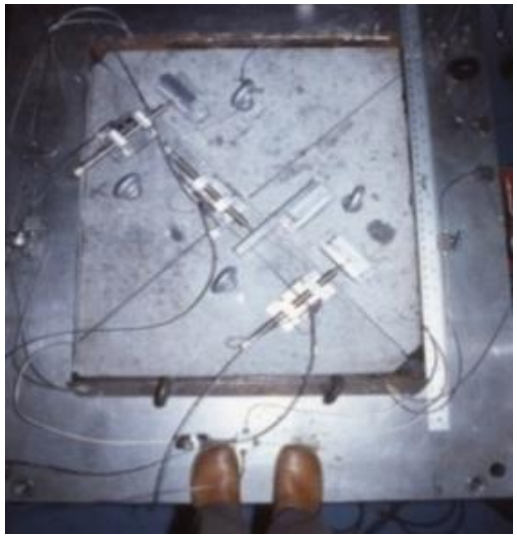


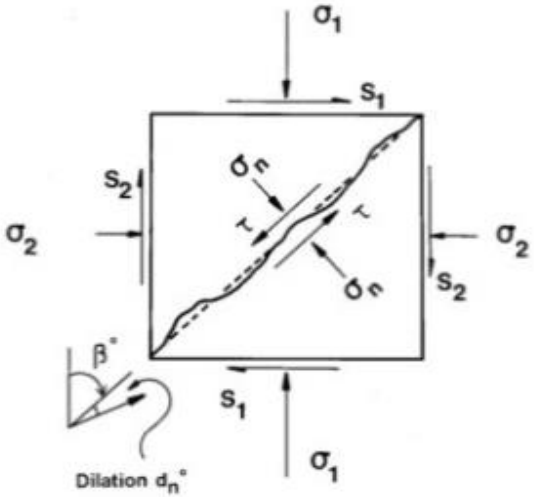

4

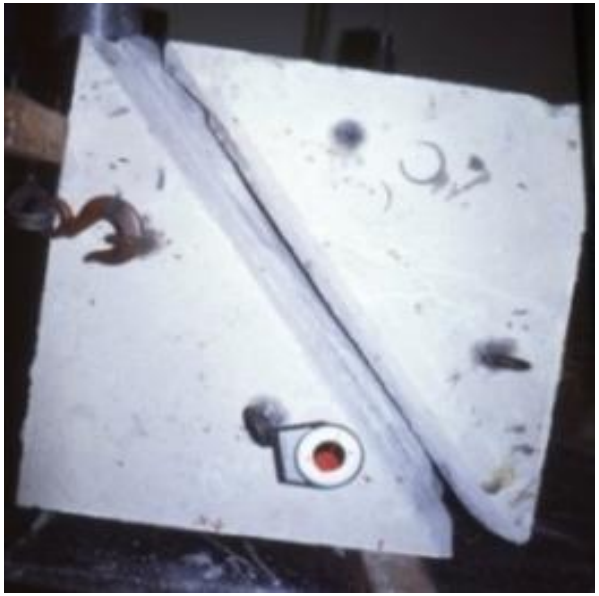


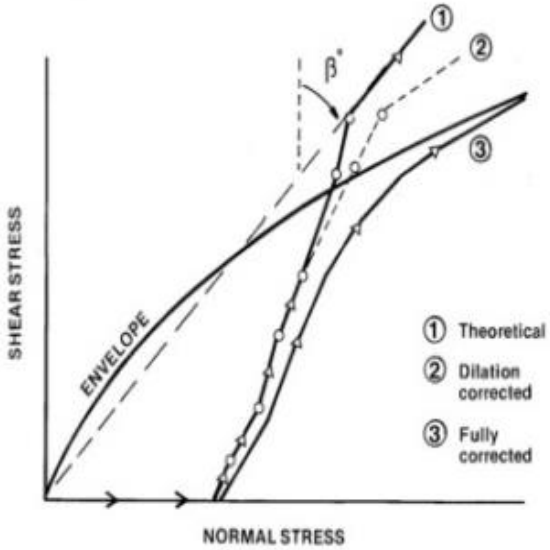


APPROPOS STRESS TRANSFORMATION ERROR




σ1
S1
S2
σ2
σ2
S2
δn
τ
τ
δn
β°
S1
σ1
Dilation dn°




β°
①
②
③
SHEAR STRESS
ENVELOPE
NORMAL STRESS
① Theoretical
② Dilation corrected
③ Fully corrected

$$\sigma_n = \frac{1}{2}(\sigma_1 + \sigma_2) - \frac{1}{2}(\sigma_1 - \sigma_2)\cos(2\beta)$$

$$\tau = \frac{1}{2}(\sigma_1 - \sigma_2)\sin(2\beta)$$

$$\sigma_n = \frac{1}{2}(\sigma_1 + \sigma_2) - \frac{1}{2}(\sigma_1 - \sigma_2)\cos[2(\beta + d_{n\,mob})]$$

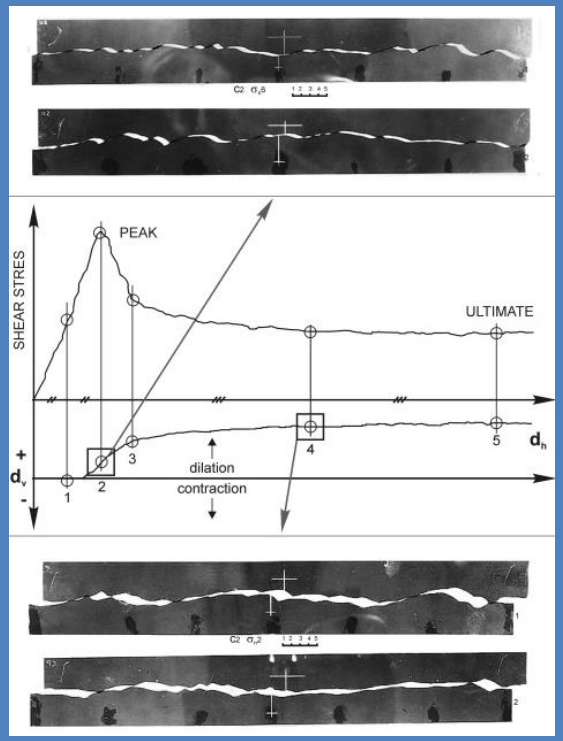
$$\tau = \frac{1}{2}(\sigma_1 - \sigma_2)\sin[2(\beta + d_{n\,mob})]$$

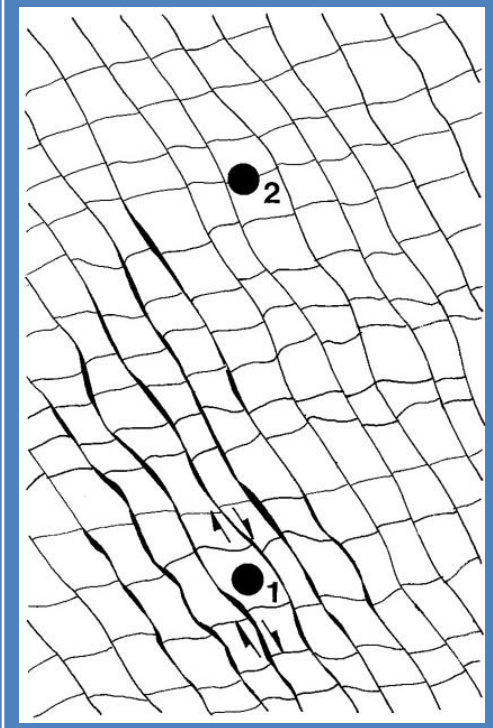
$$d^0_{n(peak)} = \frac{1}{2}JRC_{(peak)}\log_{10}\left(\frac{JCS}{\sigma'_n}\right)$$

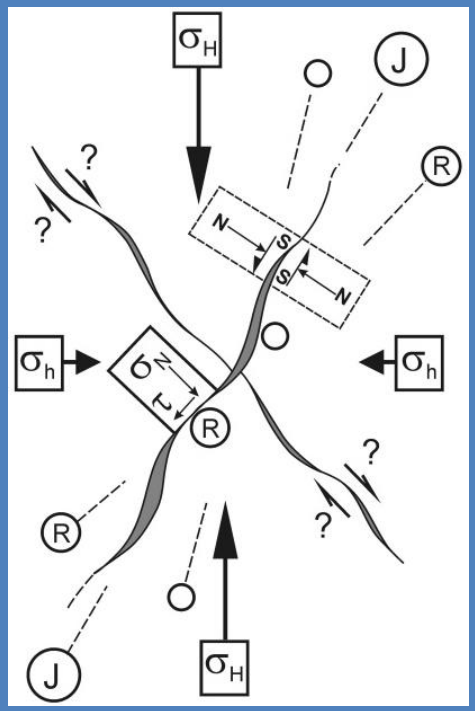
$$d^0_{n(mob)} = \frac{1}{2}JRC_{(mob)}\log_{10}\left(\frac{JCS}{\sigma'_n}\right)$$

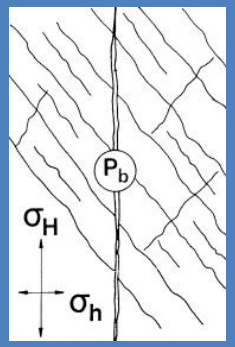
Stress-transformation: no presence, no shearing, no dilation. Actual: presence, shearing, dilating.

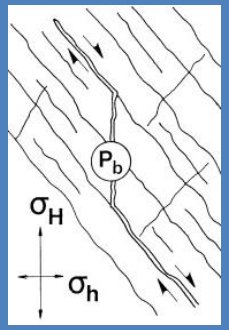
APPROPOS MICROSEISMIC AND SHEARING IN GEOTHERMAL AND GAS-SHALE RESERVOIRS

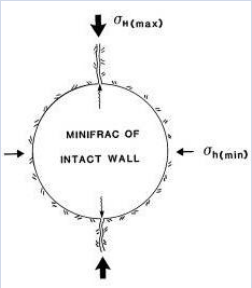

PEAK
ULTIMATE
SHEAR STRES
dilation
contraction
d_h
d_v
+
-
1
2
3
4
5

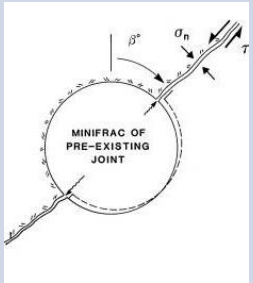

2
1

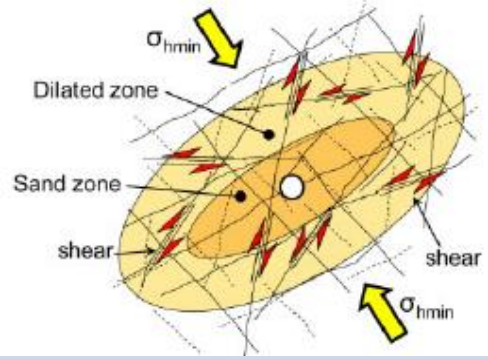

σ_H
J
R
?
N
S
σ_h
σ_h
R
R
J
σ_H


P_b
σ_H
σ_h


P_b
σ_H
σ_h


$\sigma_{H(max)}$
MINIFRAC OF
INTACT WALL
$\sigma_{h(min)}$


$\beta°$
σ_n
τ
MINIFRAC OF
PRE-EXISTING
JOINT


σ_{hmin}
Dilated zone
Sand zone
shear
shear
σ_{hmin}

CONCLUSIONS:

1. **The world is generally not what has been assumed in our models (mine too).**

2. Non-linearity, anisotropy, inhomogeneity dominate over elastic, isotropic, continuum.

3.How to solve this problem? Be open to change.

THE END
9 MAI 2009