RECENT ROCK MECHANICS EXPLANATIONS FOR CLIFF, MOUNTAIN WALL AND MOUNTAIN HEIGHT LIMITS - WITH APPLICATION IN COASTAL EROSION AND GEOMORPHOLOGY

Nick Barton, PhD, NB&A, Høvik, Norway

Baotang Shen, CSIRO-Australia
(FRACOD, σt / ν, non-linearity)

Mahendra Singh, U. of Roorkee
India. (σ3 critical ≈ UCS)

Eystein Grimstad, Consultant
(Q-system case records)

THREE INTERNATIONAL COLLEAGUES WHO HAVE MADE THE FOLLOWING ADVANCES POSSIBLE

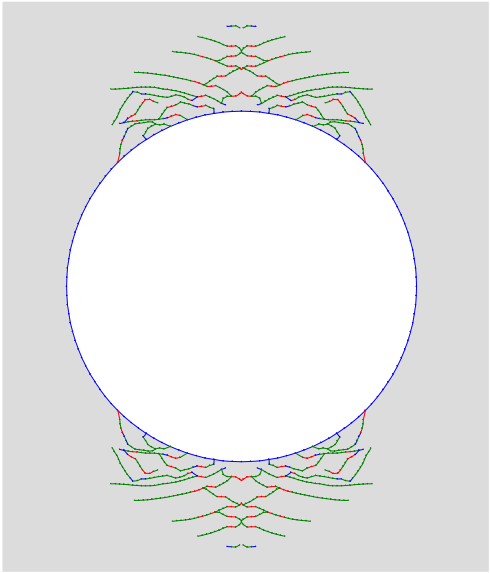
SUBJECTS DISCUSSED:

- DEEP TUNNELS (1 TO 3 km?) – what ‘SRF’ to use?
- VERTICAL CUTS in SOIL, CLIFFS in ROCK (10m to 100m?)
- MOUNTAIN WALLS (750 to 1,350m)
- JOINTED SLOPES – PROGRESSIVE FAILURE – CcSs criterion
- PREKESTOLEN in NORWAY – safe for a picnic, or not?
- MOUNTAINS (EVEREST – WHY ‘ONLY’ 8.9KM HIGH?)

- KEY TECHNICAL ISSUES
- Extension-strain fracturing – is easiest
- Mohr-Coulomb problems with rock: **cohesion c** is too high
- Critical State shear strength limit: looks like UCS, but cannot be

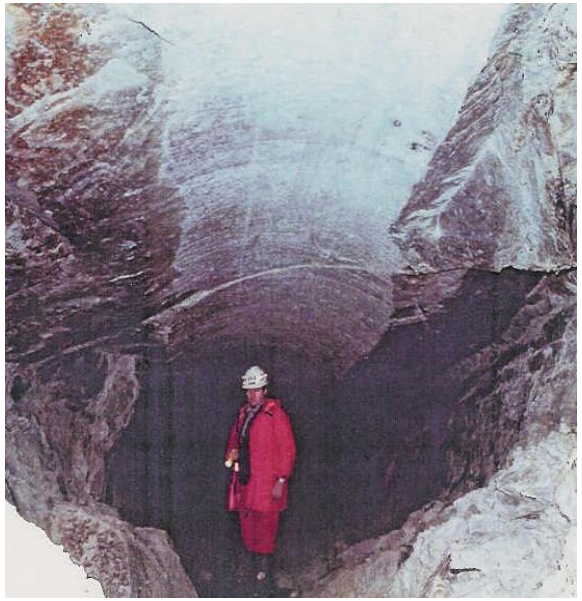
ARCHING – ALSO ABOVE TUNNELS

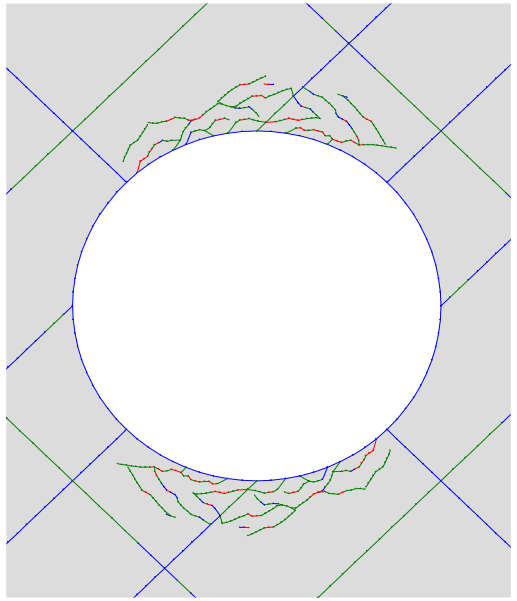
(Tangential stress and radial stress – make the bridge/tunnel stable)



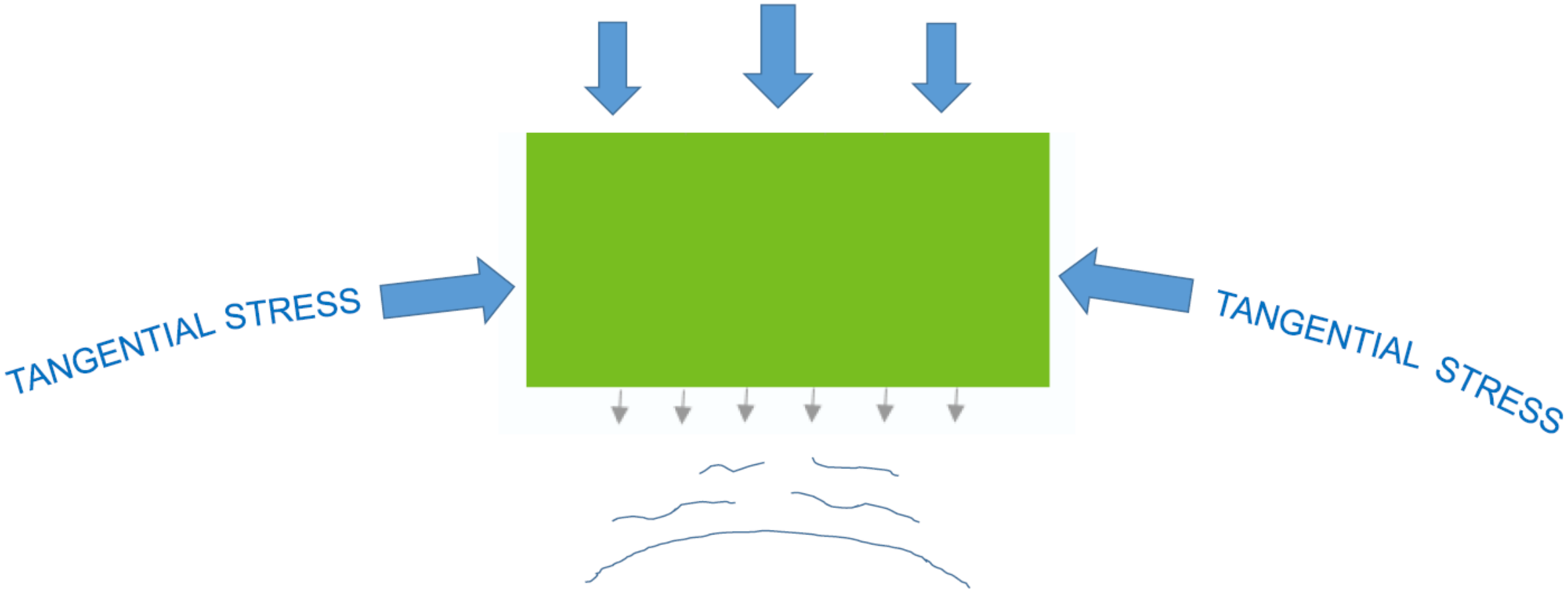
A selection of tunnel failure modes when higher stress:

- **Physical models**
- **TBM tunnel tragedy**
- **Numerical models**





AROUND A TUNNEL: Poisson's ratio causes lateral strain



NEXT TO THE TUNNEL MAY GET (TENSILE) CRACKING

– EVEN WHEN ALL STRESSES ARE STILL COMPRESSIVE

All river diversion tunnels (14x16m) fractured like this – arch and invert. UHE Ita, Brazil

‘BRITTLE ROCK CAN FAIL (in tension) DUE TO EXTENSION STRAIN OVER-COMING THE TENSILE LIMIT, *EVEN WHEN ALL THREE PRINCIPAL STRESSES ARE COMPRESSIVE*’

thanks to Poisson’s ratio, acting together with sufficiently anisotropic stresses, as near a tunnel *(or behind a rock face)*

THE ‘Q-system’ ?

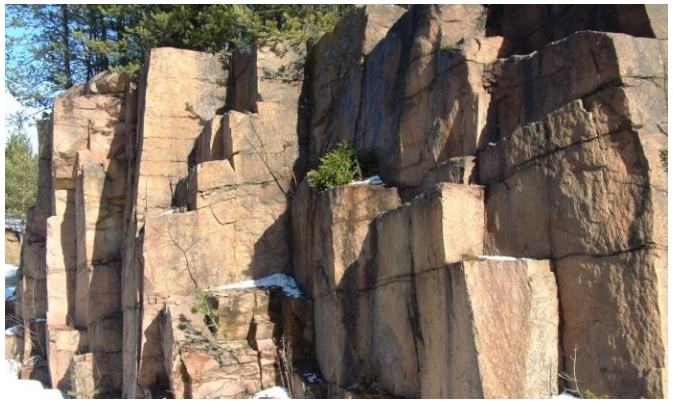
Q used here!

As a briefest introduction:

Q means *<u>rock</u> mass quality*.

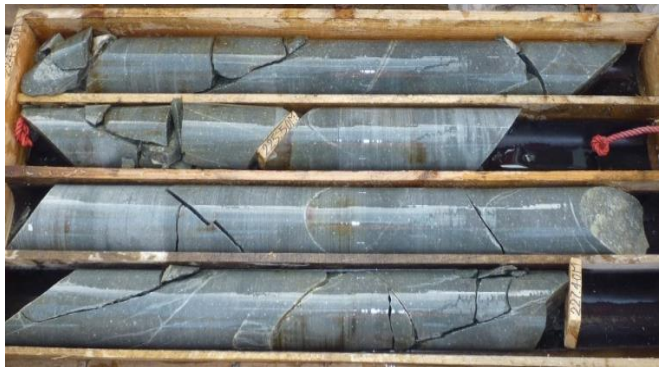
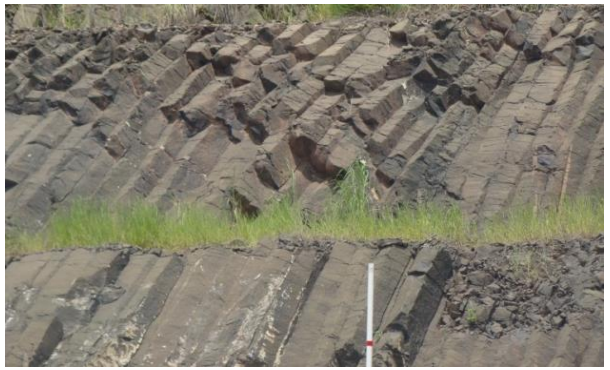
Q consists of *ratings for six parameters*.

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF}$$ = **(Block size) x (friction) x (‘active stress’)**



NORWAY
CHINA
BRAZIL

KASHMIR
IRAN
BRAZIL

HONG
KONG
PANAMA
BRAZIL

CANNOT TEST A ROCKMASS 'SAMPLE', AS WITH STEEL OR CONCRETE (or soil?).

'Q' saves us from having to perform impossible sizes of *in situ* rock mass testing.

Q = 1000 (or better)
(Q ≈ 100/0.5 x 4/0.75 x 1/*1*)

Q = 0.001 (or worse)
(Q ≈ 10/20 x 1/8 x 0.5/*20*)

BESIDES LARGE SCALE, *WIDE NUMERICAL RANGE OF Q REALISTICALLY* REFLECTS HUGE POTENTIAL DIFFERENCES IN *ROCKMASS* PROPERTIES

INDEPENDENT DATA (from Canada, South Africa) shows 'stress-induced' failure when: $\sigma_{\theta\,max}/\sigma_c > 0.4 +/- 0.1$ …**WE GET SAME TREND with Q-system SRF**

- **Maximum tangential stress estimate: $\sigma_{\theta\,max} \approx 3\sigma_1 - \sigma_3$**

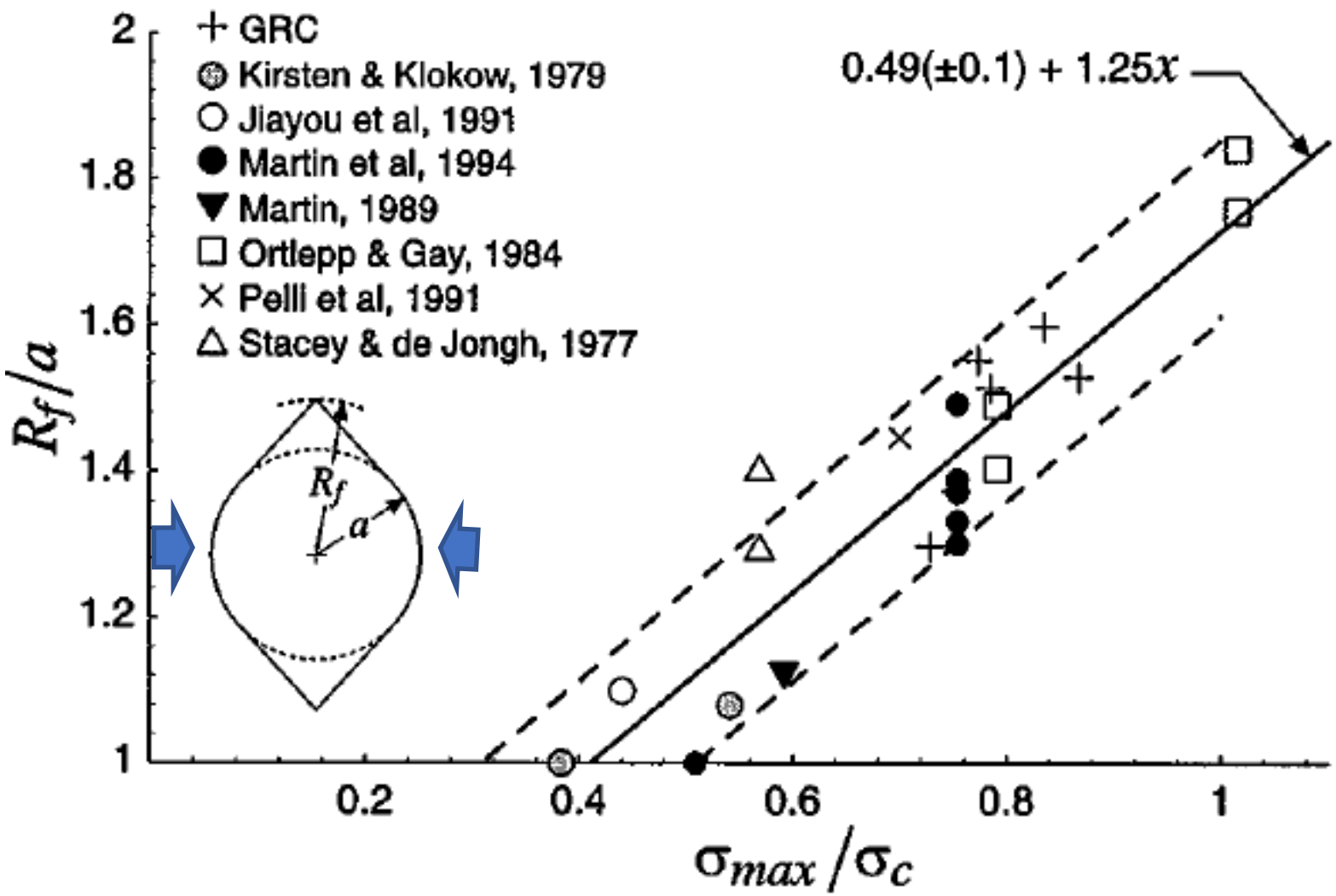


Figure from:
Martin et al. 1998)

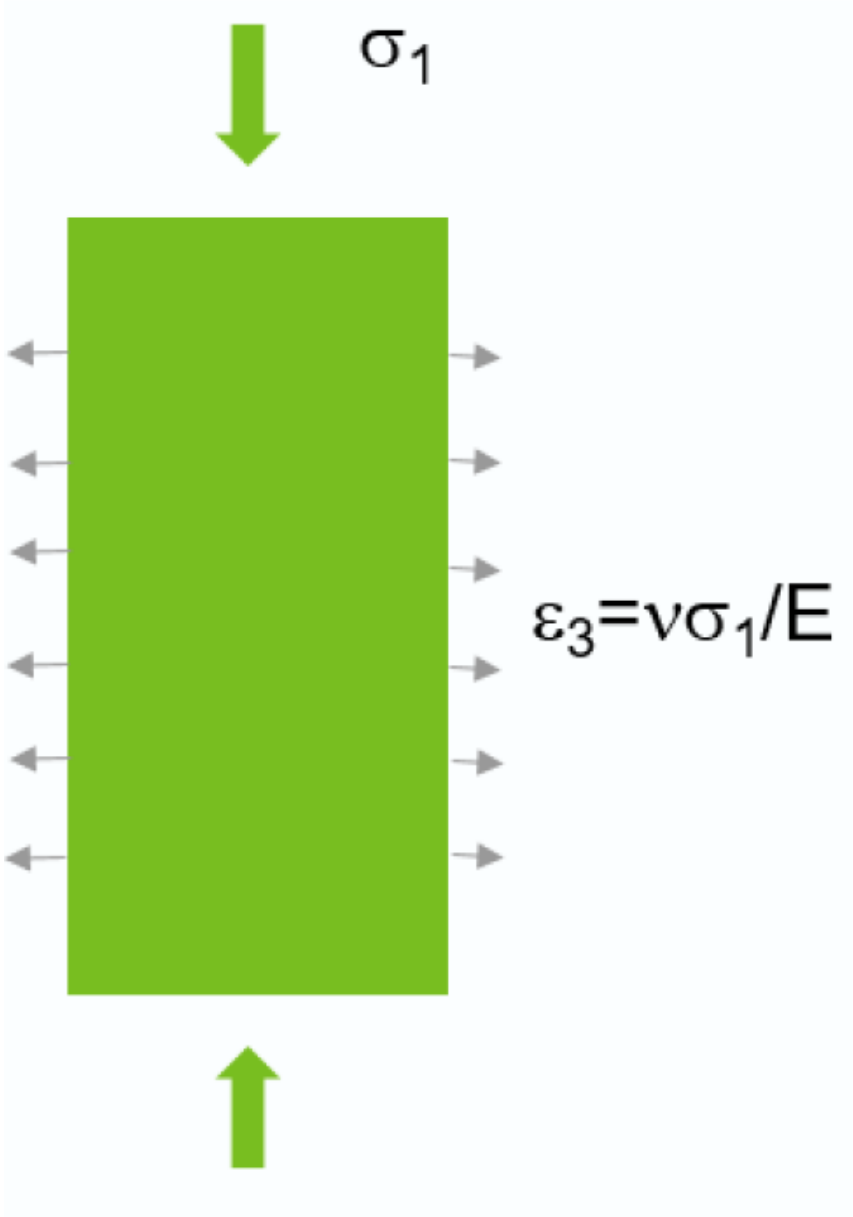
Q-SYSTEM, independent case records: If $\sigma_{\theta\,max}/\sigma_c > 0.4$, need: ***higher SRF*** – gives lower Q-value – and more tunnel support.

CASE RECORDS

(**Table 6b** of Grimstad and Barton, 1993)

b) Competent rock, rock stress problems		σ_c/σ_1	σ_θ/σ_c	**SRF**
H	Low stress, near surface, open joints.	> 200	< 0.01	2.5
J	Medium stress, favourable stress condition.	200-10	0.01-0.3	1
K	High stress, very tight structure. Usually favourable to stability, may be unfavourable for wall stability.	10-5	0.3-0.4	0.5-2
L	Moderate slabbing after > 1 hour in **massive** rock.	5-3	0.5-0.65	5-50
M	Slabbing and rock burst after a few minutes in **massive** rock.	3-2	0.65-1	50-200
N	Heavy rock burst (strain-burst) and immediate dynamic deformations in **massive** rock.	< 2	> 1	200-400

NOW
AN INTERPRETATION
CLOSER TO THE REALITY



TENSILE STRAIN CRITERION

(Proposed by Stacey, 1981, but fully applied by Baotang Shen in 2015-2016)

$\varepsilon_1 = \sigma_1/E$ …… $\varepsilon_3 = \nu\sigma_1/E$

Critical tensile strain for tensile failure:

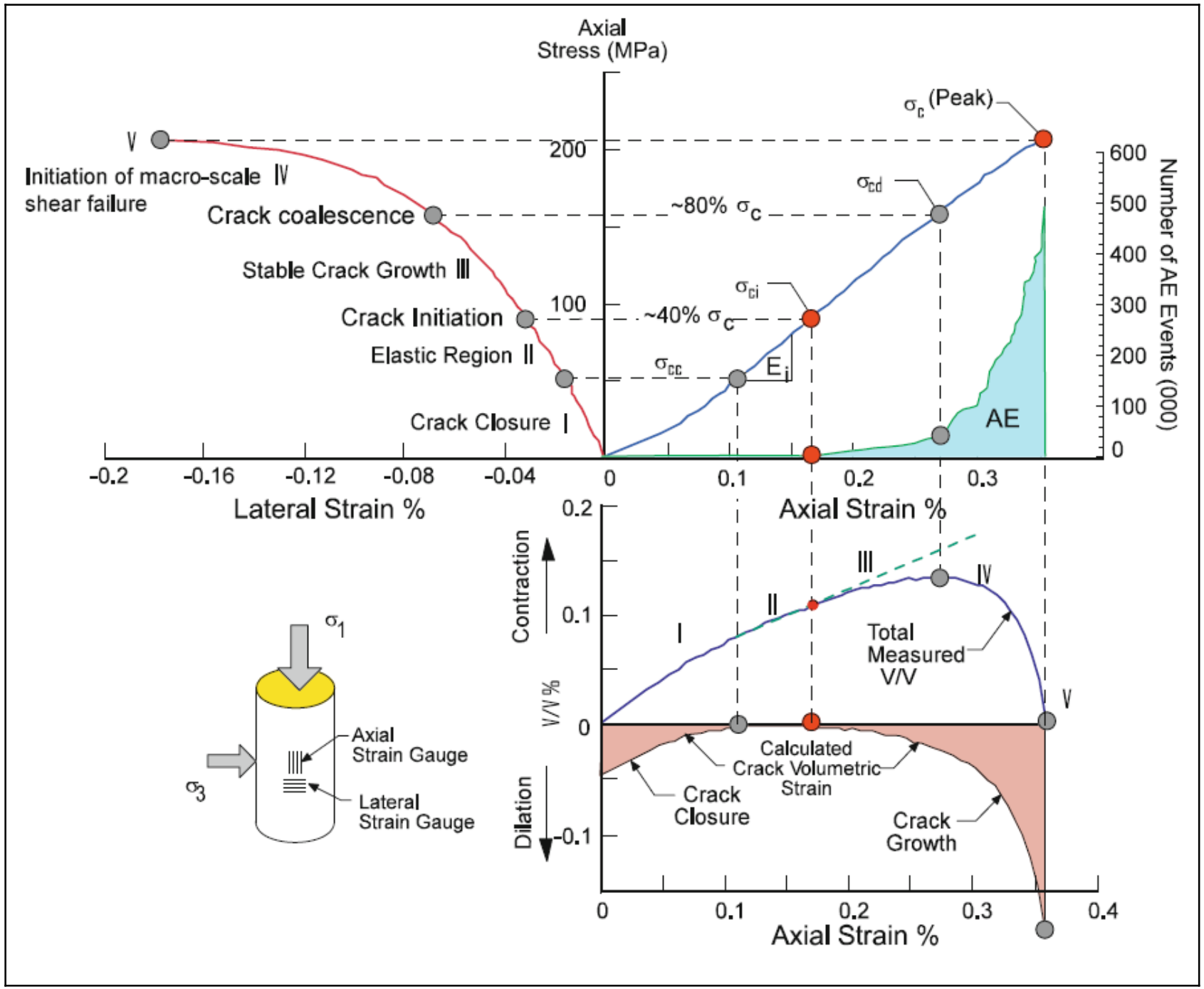
$\varepsilon_c = \sigma_t/E$ (a definition)

Equate strains, and eliminate E.

Therefore:

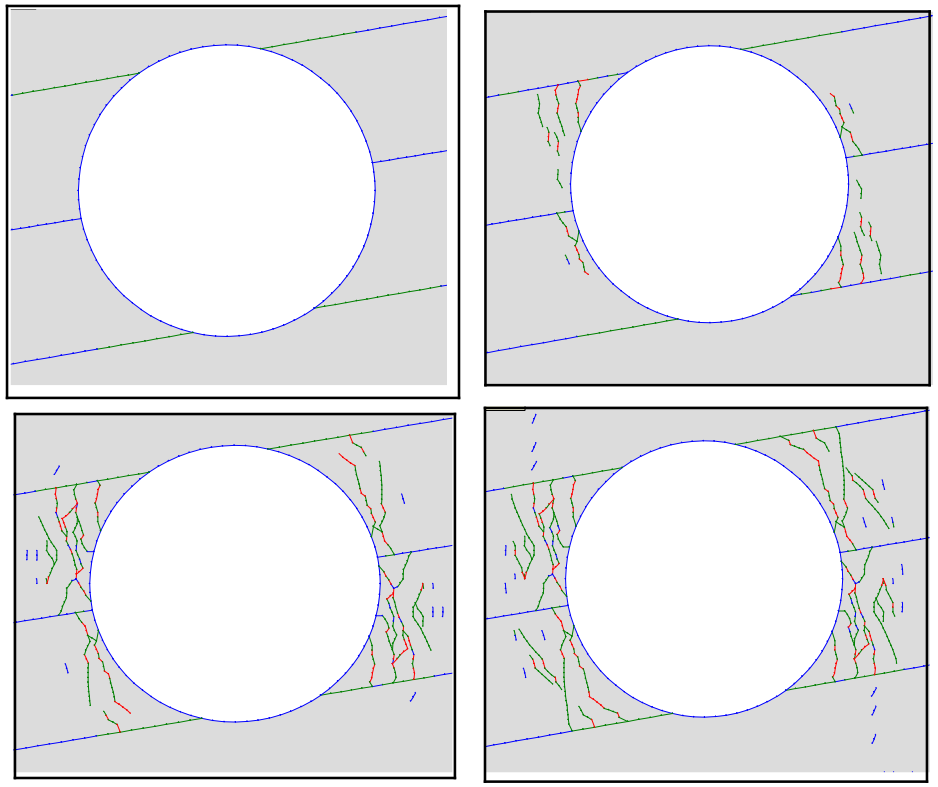
$\boldsymbol{\sigma_{1\,(critical)} = \sigma_t/\nu}$ **(≈ *0.4* x UCS)**

(We get '0.4' if UCS/σ_t ≈10, and ν ≈ 0.25)



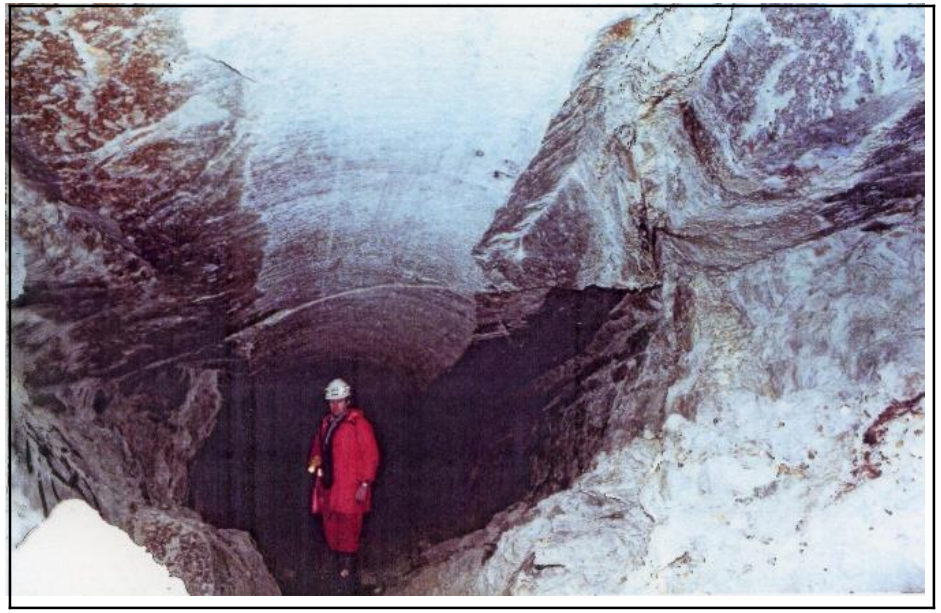
Note AE ***also*** starting at **40% of σc**

(Test data from Martin, 1997)



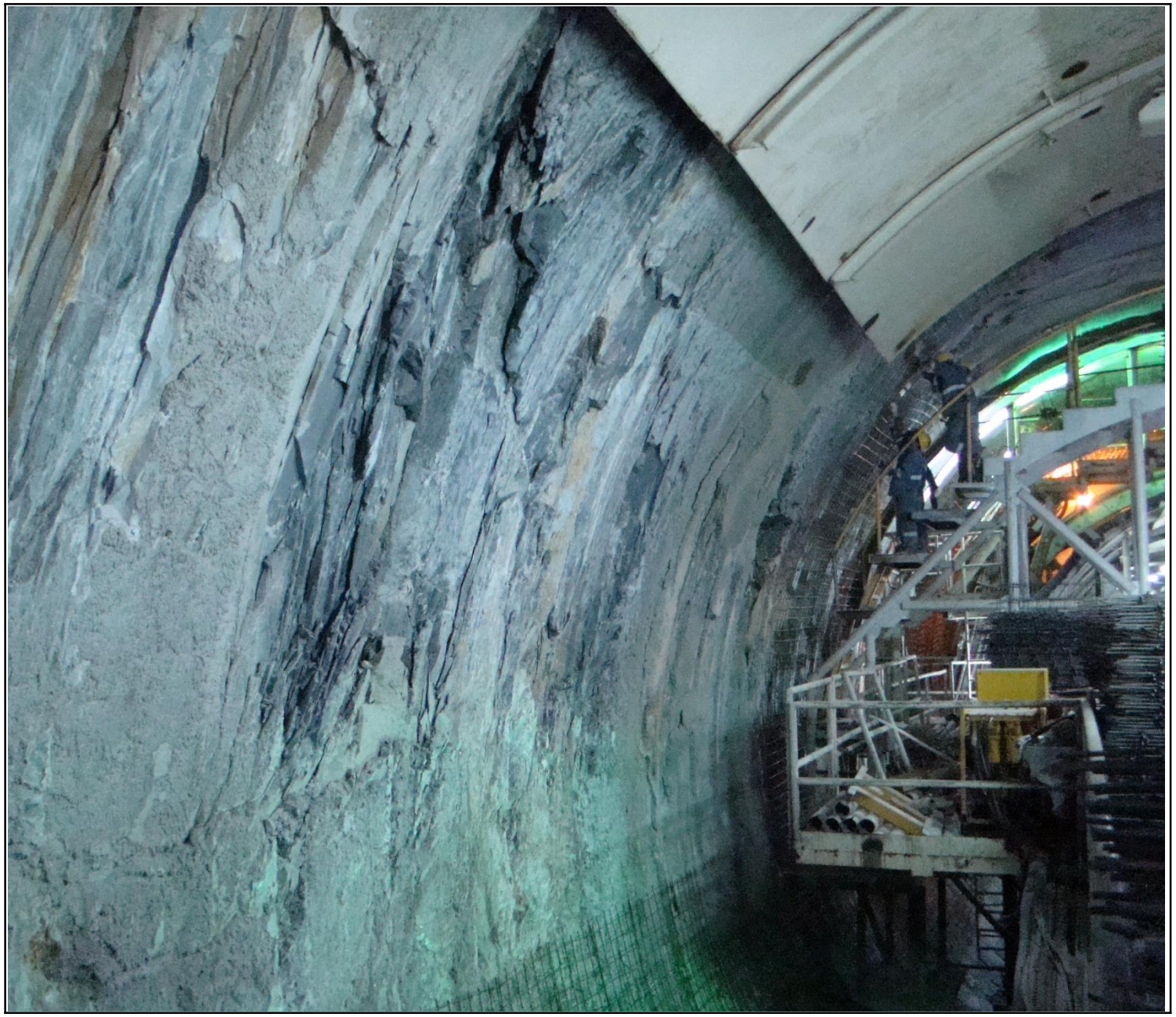
- ***CRITICAL EXTENSION STRAIN:***
- ***Marks start of spalling which is cracking in tension. May get propagation in shear)***
- (Baotang Shen, in Barton and Shen, 2017)

$$\sigma_{critical\ tangential\ stress} \approx (0.4 \times UCS) \approx \sigma_t / \nu$$



Example of FRACOD modelling of 1880 (Beamont/English) TBM in chalk marl). Here: assume

$\sigma_h = 1/3\ \sigma_v$ (due to nearby CLIFF FACE)



Tell-tale signs of *over-stress?*

PROBABLY *over-strain.*

(Jinping II, China)

During the August heat-wave in UK with 40° C

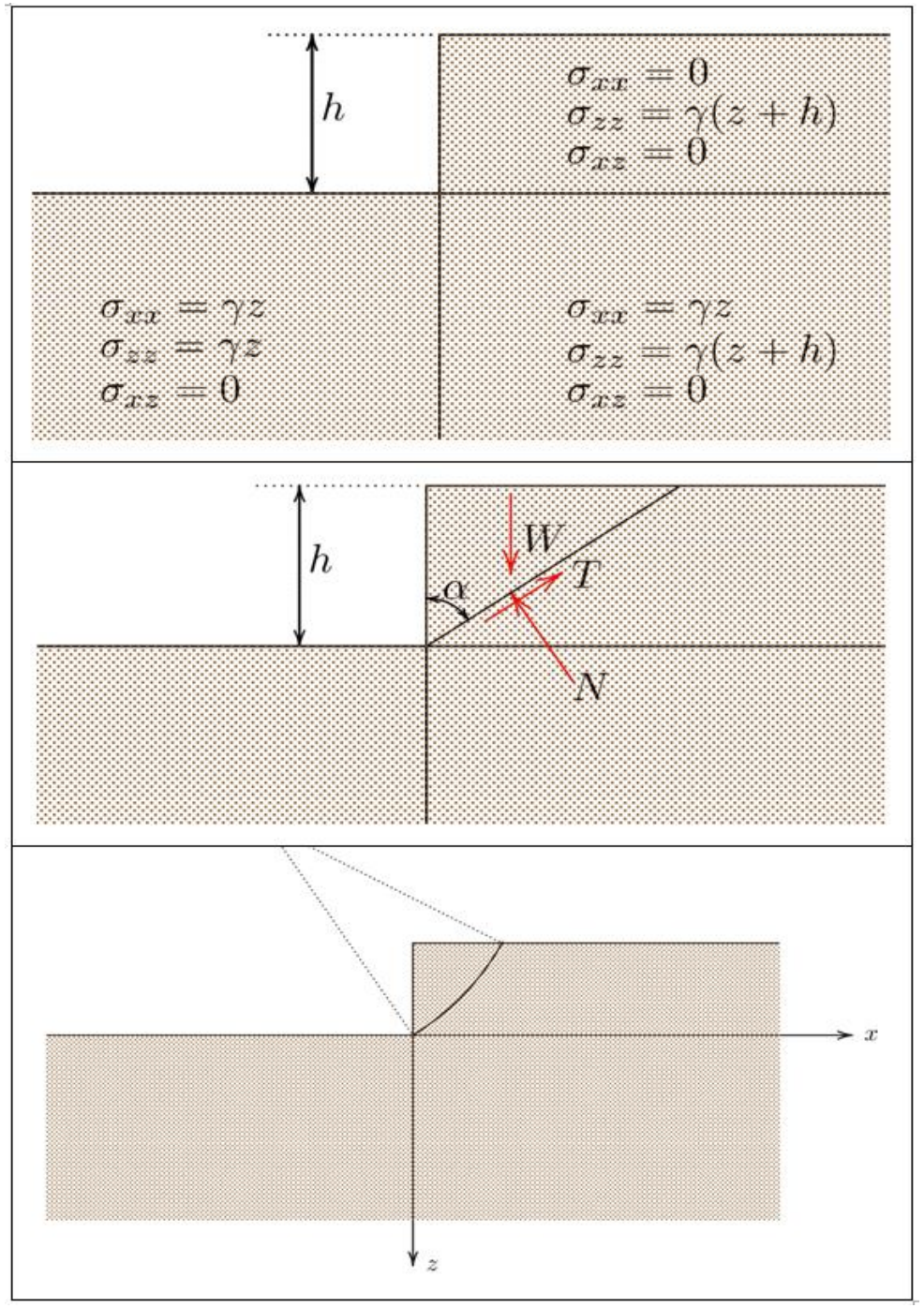
A major section of cliff collapsed at Sidmouth in Devon on Monday
A series of dramatic cliff falls wiped away parts of the Devon coastline and left huge clouds of dust hanging over a seaside resort.

Walkers watch as a large section of Sidmouth cliff, Devon, crashed onto the beach at 9.15am
The brittle cliffs of the Jurassic Coast have been cracking under the recent heatwave, weakening the brittle surface and triggering landslides.

WHAT REASONS? CHANGE IN ROCK STRENGTH? INCREASE IN POISSON'S RATIO?

EXTENSION-STRAIN FRACTURING *NOW APPLIED* TO FAILURE OF *VERTICAL CLIFFS and MOUNTAIN WALLS*

FIRST A LOOK AT CLASSIC SOIL MECHANICS SOLUTIONS TO THE ‘VERTICAL-CUT’ PROBLEM



(a) Assumed equilibrium of three zones (*of soil*) gives a *lower-bound* solution for <u>*h*</u> . (Verruijt, 2001)

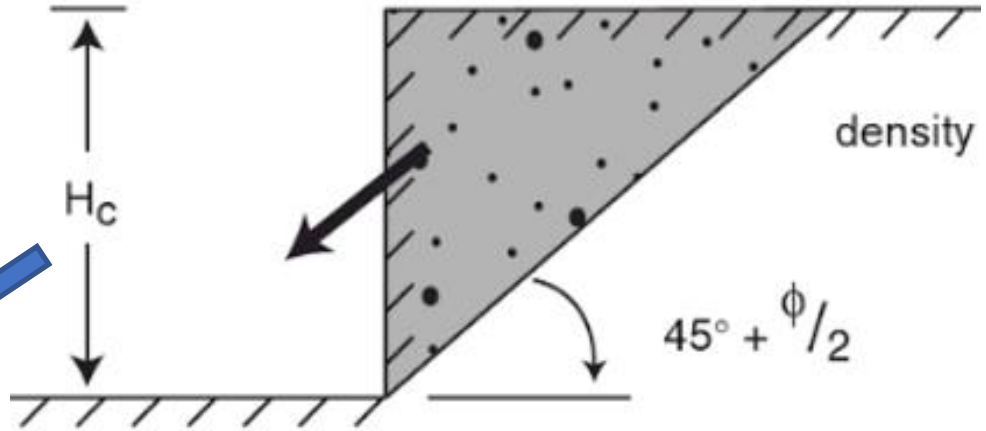
(b) *Upper-bound* solution for <u>*h*</u> involves a specific shear surface. (Verruijt, 2001).

(c) Circular failure surface. Fellenius, 1927 ('3.85' multiplier)

$h \geq 2c/\gamma \,.\, \tan(45^\circ + \phi/2)$ <u>*lower-bound*</u>

$h \leq 4c/\gamma \,.\, \tan(45^\circ + \phi/2)$ <u>*upper-bound*</u>

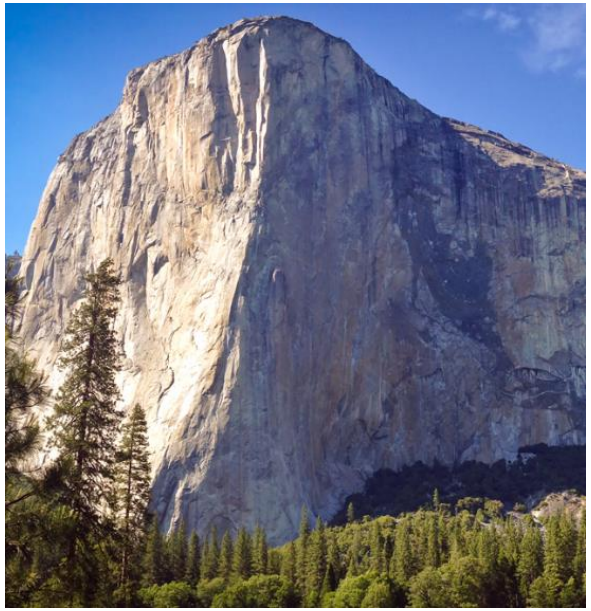
‘SOIL MECHANICS’ THEORIES:



- ***2c/γ* . tan(45°+ φ/2) ≤ *Hc* ≤ *4c/γ* . tan(45°+ φ/2)**
- (Mohr-Coulomb, lower- and upper-bound)

- UNFORTUNATELY these classic solutions for soil are 3X to 6X IN ERROR WHEN ***EXTENSION FAILURE – and NOT SHEAR*** FAILURE OF **INTACT** ROCK IS OCCURING.

VERTICAL HEIGHT LIMITS OF CLIFFS AND MOUNTAIN WALLS – WITH ***NEW APPROACH***:



El Capitain, Yosemite, California. granites, UCS = 100-150MPa.

Beachy Head, England. Chalks, UCS = 10 MPa (saturated ?)

West Temple, Zion, Utah. Sandstones, UCS = 50-75MPa.

Cappadocia, Turkey. Volcanic tuff, UCS = 1-2MPa.

$$H_{critical} \approx 100.\sigma_t/\gamma\nu \text{ (meters)}$$

(Have assumed $\sigma_v \approx \gamma H/100$ MPa)

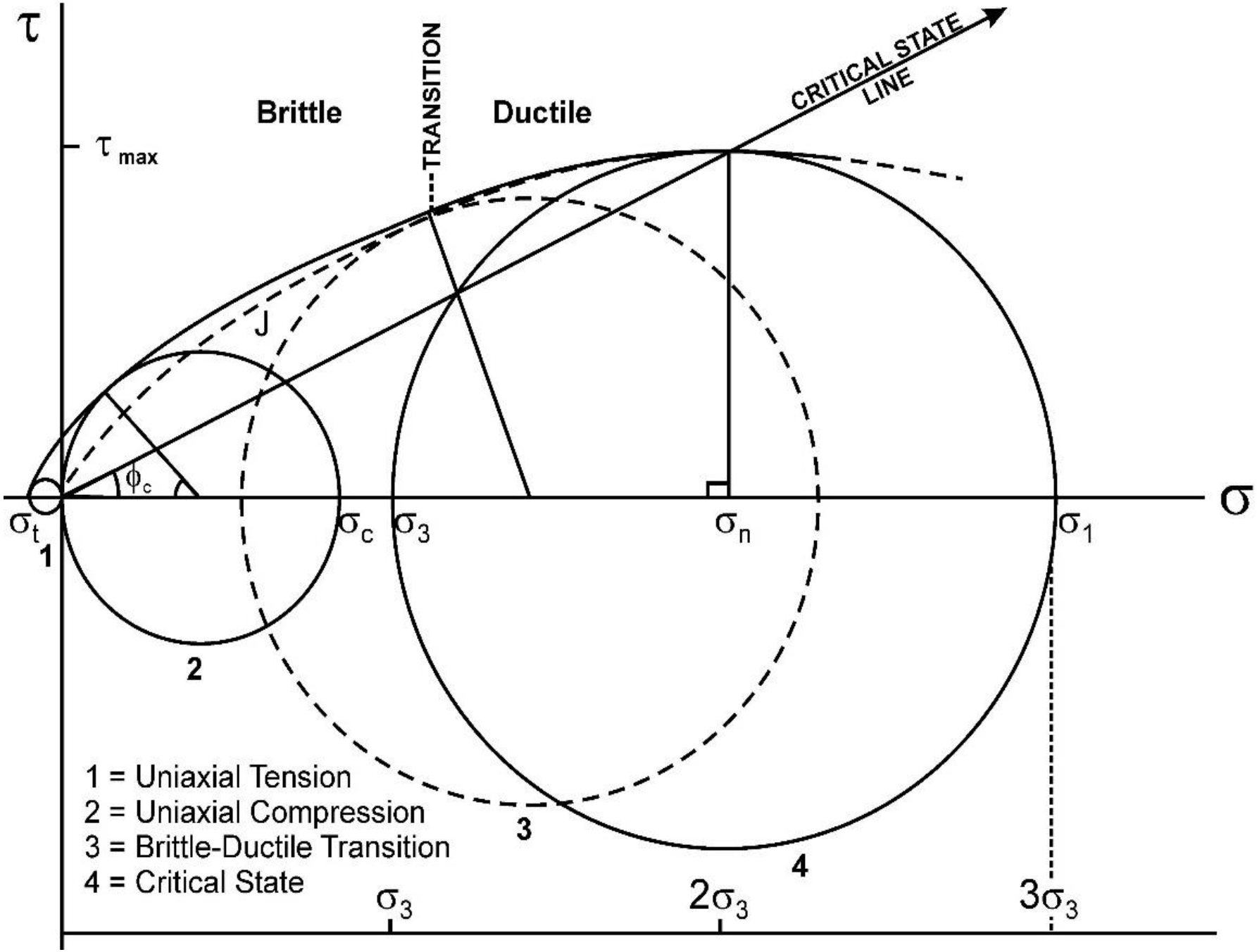
σ_t = tensile strength (MPa)

γ = density (when units are tons/m3)

ν = Poisson's ratio

Barton, 2016

FOR APPLYING Mohr-Coulomb WE NEED THE COHESIVE STRENGTH OF INTACT ROCK



$$C = \tfrac{1}{2}(\sigma_c \times \sigma_t)^{1/2}$$

(lower-bound estimate)

Assumes linear envelope between tensile and compression circles.

Actual cohesion is higher due to curvature.

(Barton, 1976)

COMPARING 'SOIL MECHANICS' *SHEAR-STRENGTH*-BASED ESTIMATES of H_c WITH *EXTENSION-STRAIN* ESTIMATES

1. Sandstone

σ_c = 75MPa,

σ_t = 5MPa

$c = ½(75x5)^{1/2}$ = 9.7MPa

$$c = ½(\sigma_c \times \sigma_t)^{1/2}$$

2. Granite

σ_c = 150MPa,

σ_t = 10MPa

$c = ½(150x10)^{1/2}$ = 19.4MPa

1. Sandstone 'mountain wall' **($H_c = 2c/\gamma \times \tan(45°+\phi/2)$):**

H_c= 3,001m !

(This is a 'lower-bound' estimate!)

2. Granite 'mountain-wall' **($H_c = 2c/\gamma \times \tan(45°+\phi/2)$):**

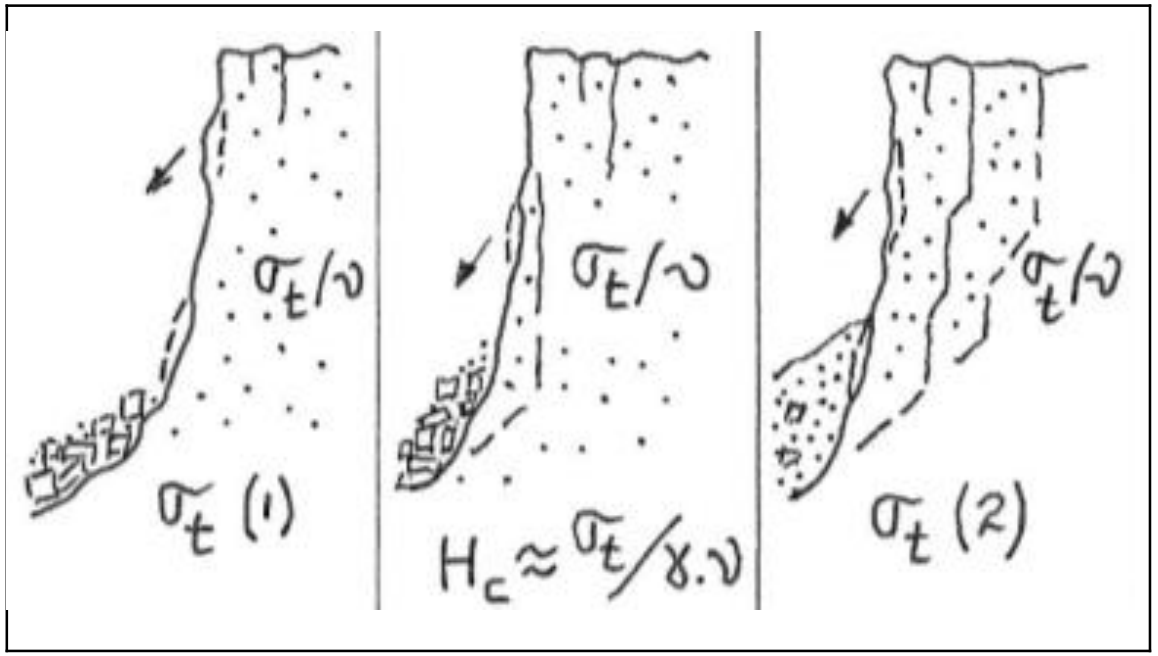
H_c= 5,456m !

(This is a 'lower-bound' estimate!)

BY COMPARISON *EXTENSION STRAIN THEORY*:

Sandstone: $100.\sigma_t/\gamma\nu$ = 100.5/2.5 x 0.25 = *800m*

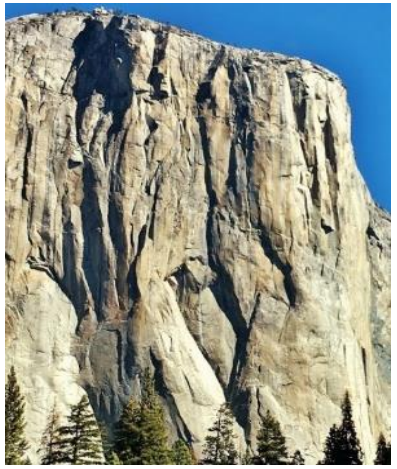
Granite: $100.\sigma_t/\gamma\nu$ = 100.10/2.75 x 0.25 = *1,456m*



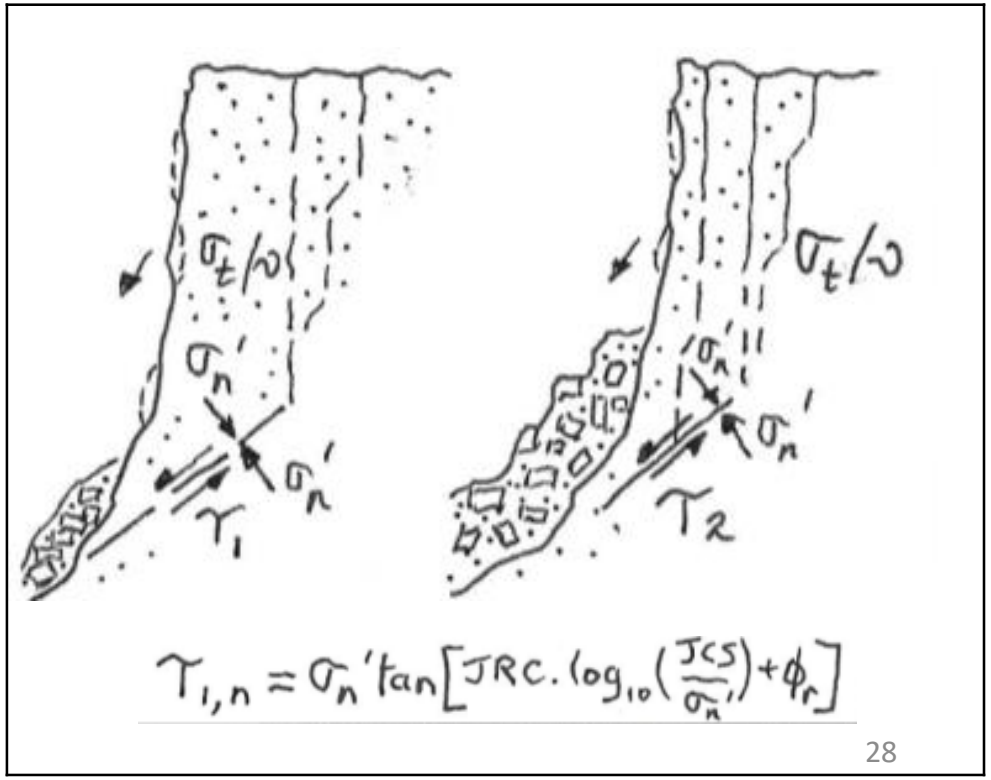
EXTENSION FAILURES CAUSE SHEETING FRACTURES, AND LIMIT ULTIMATE WALL HEIGHTS

(NOTE! σt REDUCES, OVER GEO-MORPHOLOGICAL TIME-SCALES)

SHEAR FAILURE (AND TENSION CRACKS) THREATENING FUTURE MOUNTAIN ROCK AVALANCHE?



El Capitan, CA. and Holtanna, Antarctic.



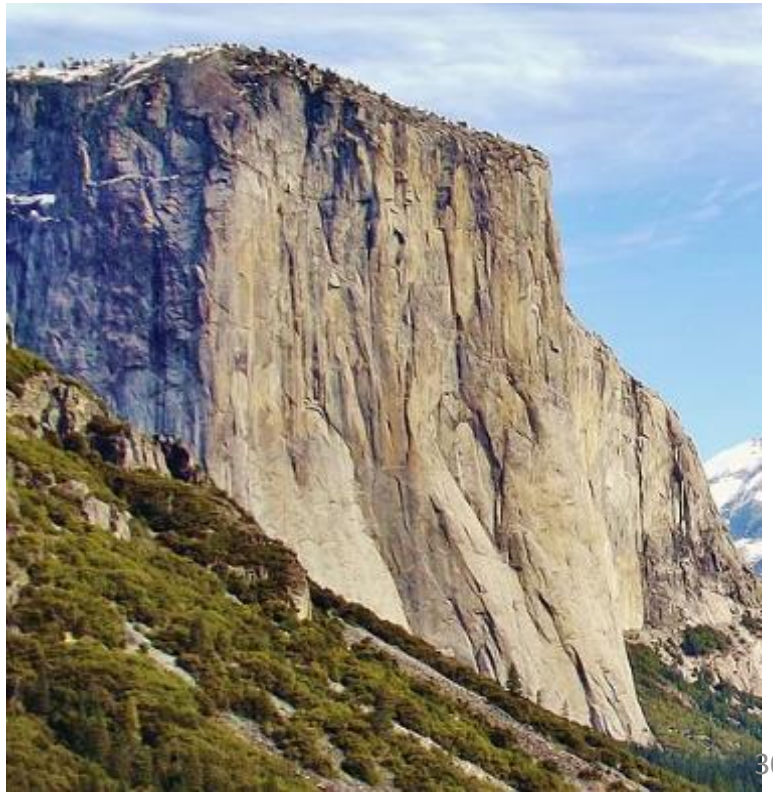
Lower-bound estimate M-C: $h = 2c/\gamma \tan(45° + \varphi/2)$		
σ_t = 0.2 MPa, σ_c = 2 MPa	γ = 2.0 t/m^3	h = 103m
σ_t = 0.5 MPa, σ_c = 5 MPa	γ = 2.0 t/m^3	h = 258m
σ_t = 5 MPa, σ_c = 50 MPa	γ = 2.5 t/m^3	h = 2,067m
σ_t = 10 MPa, σ_c = 100 MPa	γ = 2.8 t/m^3	h = 3,690m

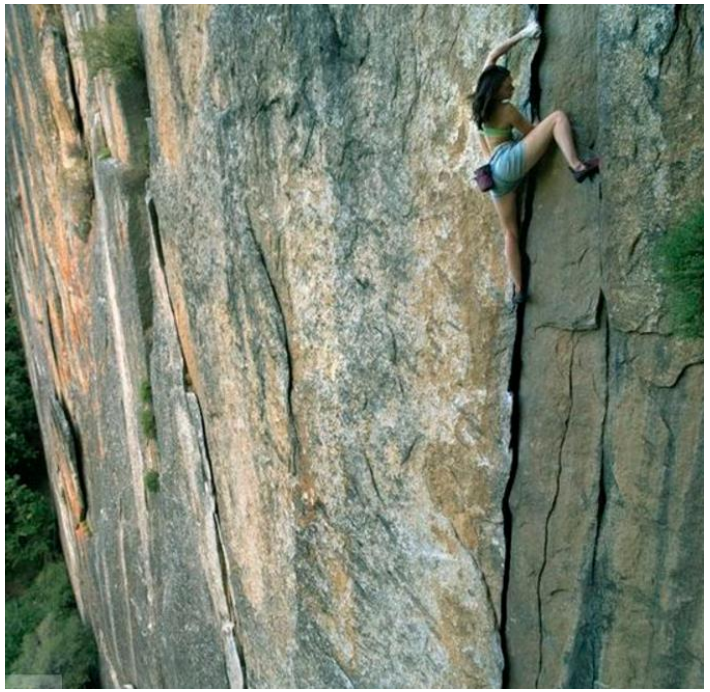
Extension strain based: $H_c = \sigma_t/\gamma\nu$		
σ_t = 0.2 MPa, σ_c = 2 MPa	ν = 0.2	H_c = 50m
σ_t = 0.5 MPa, σ_c = 5 MPa	ν = 0.2	H_c = 125m
σ_t = 5 MPa, σ_c = 50 MPa	ν = 0.25	H_c = 800m
σ_t = 10 MPa, σ_c = 100MPa	ν = 0.25	H_c = 1,430m

For rock cliffs and mountain walls the choice is clear: do not use M-C.

USGS artist C.A.Weckerly

Seems to have envisaged a future (or past?) ‘failure mechanism’.





SHEETING JOINTS (AND ASSOCIATED CRACKS)

(WITH $H_c = 100\sigma_t/\gamma\nu$ (EXTENSION-STRAIN-FRACTURING) **DO NOT NEED CURVATURE TO EXPLAIN SHEETING JOINTS)**

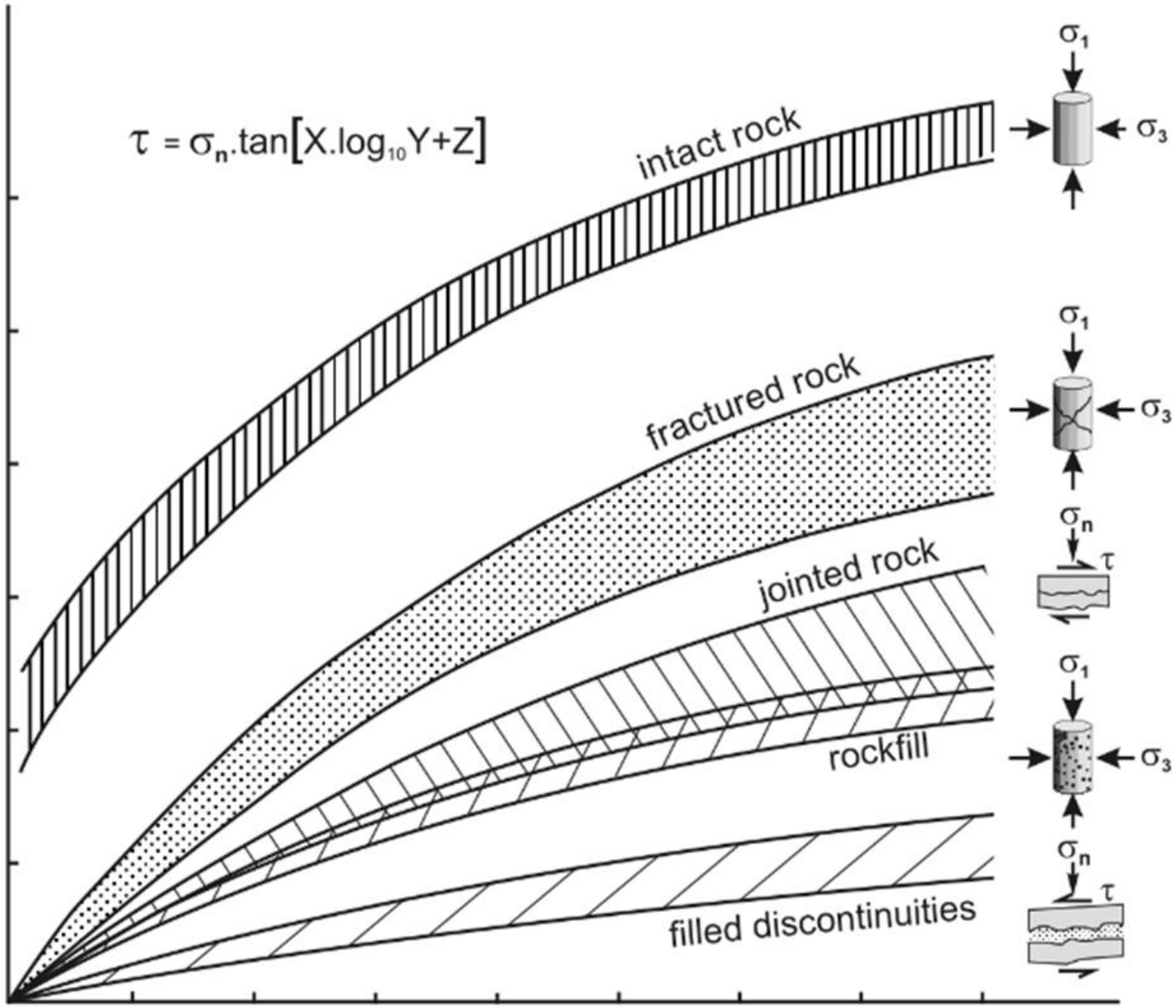
- Free-solo rock-climbing aces:
- *Steph Davis (see her book)*
- *Alex Honnold (see his book)*

World’s most frequently climbed rock wall

Honnold and Caldwell,
June 6th 2018: ‘The Nose’

1 hour 58 mins 7 secs
(3,000 feet, 914m)

COMPLICATIONS FROM *MULTI-COMPONENT* FAILURE-MODES (slopes + tunnels)

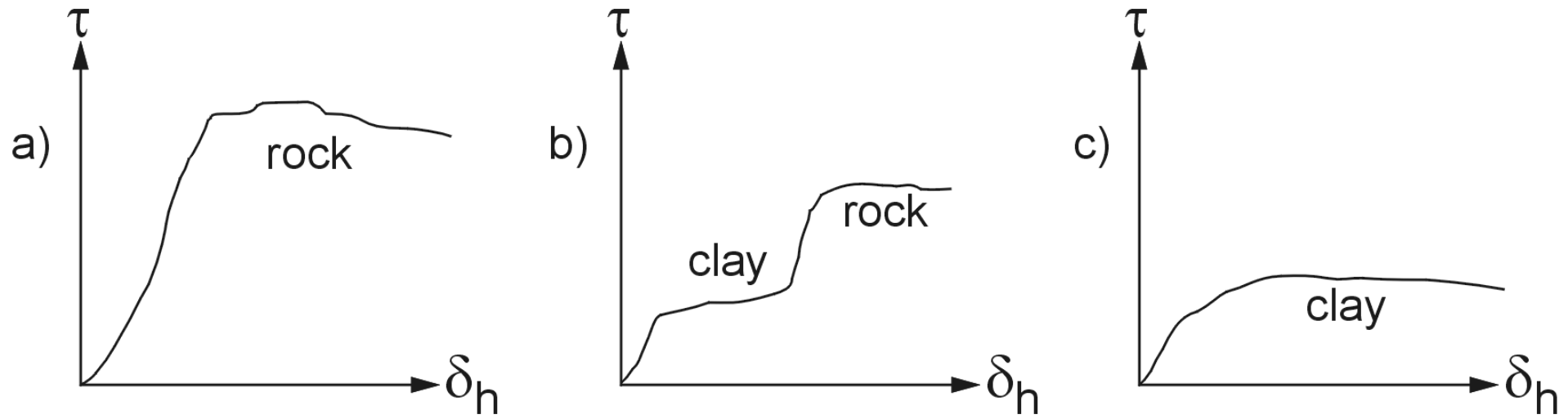


FOUR COMPONENTS:

process-dependent shear failure of e.g. high open-pit mine slopes.

***1.* FAILURE OF INTACT**	**'BRIDGES'**
***2.* SHEARING (OR NOT) ON THE NEW, FRESH, ROUGH SURFACES**	
***3.* MOBILIZATION (OR NOT) ALONG ROCK JOINTS**	
***4.* SHEARING ALONG CLAY-FILLED DISCONTINUITIES OR FAULTS, WITH LOW SHEAR STRENGTH**	

(Barton, 1999, 2013).



(a) Rock wall contact

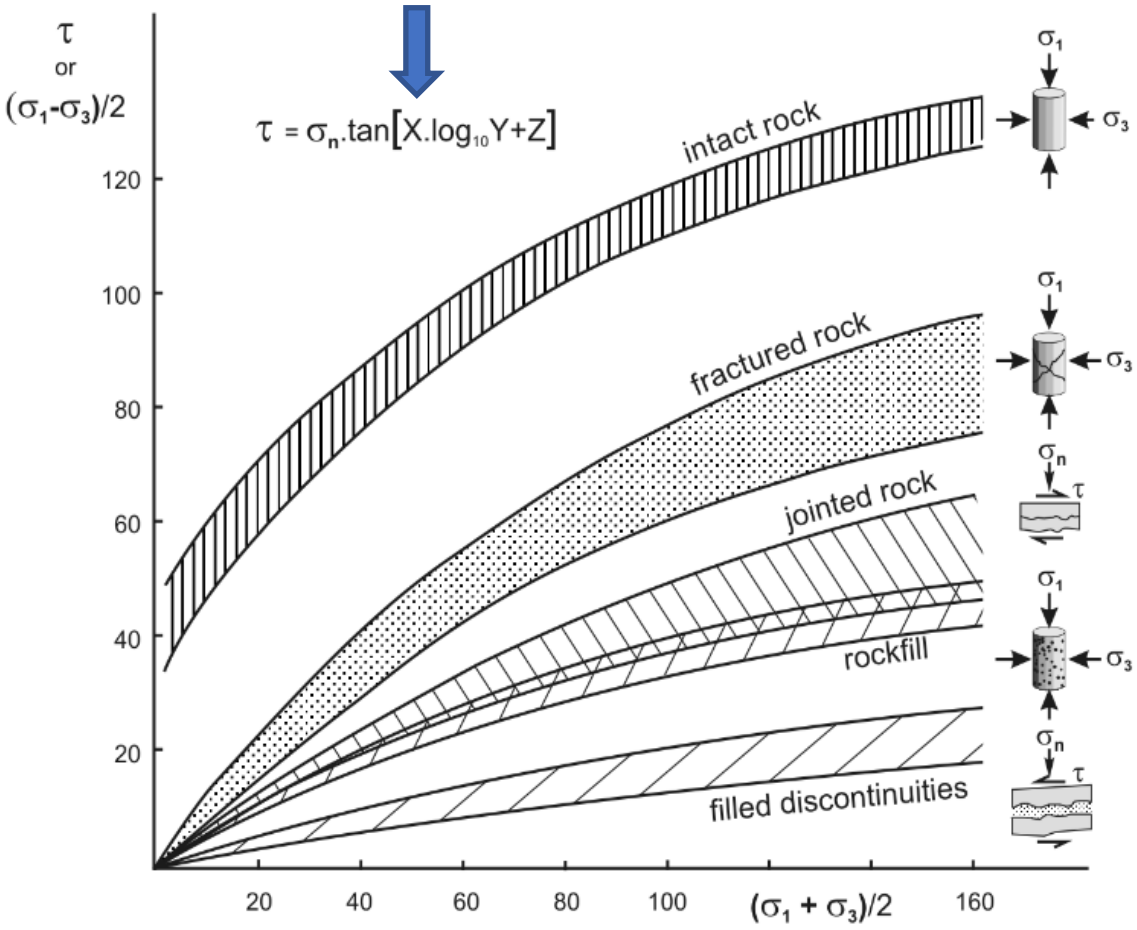
		(thin coatings)				
	$Ja/Jr =$	0.75	1.0	2	3	4
		$\tan^{-1}(Jr/Ja)^{o}$				
A. Discontinuous joints	4	79º	76º	63º	53º	45º
B. Rough, undulating	3	76º	72º	56º	45º	37º
C. Smooth, undulating	2	69º	63º	45º	34º	27º
D. Slickensided, undulating	1.5	63º	56º	37º	27º	21º
E. Rough, planar	1.5	63º	56º	37º	27º	21º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

From the Q-system Jr/Ja.

Clay-filled joints.

WHAT IS HELPING TO PREVENT SUDDEN COLLAPSES ?

(‘X’ ≈ *50, then 20, then JRC, then Jr/Ja*) Barton, 1999 **CcSs crack, crunch, scape, swoosh**



- **Bingham Pit: No casualties. Monitored. Progressive failure**....i.e. ‘τ = c *then* σ_n tan ϕ’

THIS IS NOT A CIRCUAR M-C FAILURE!

NOTE:
FAULT SURFACE

CcSs?

Which place to picnic at Norway’s Prekestolen?

Back-wall shear(?)

.....

tensile opening (?)

.....

triggering by $\sigma_t/\gamma\nu$?

(Photos from Katrina Mo, NTNU, M.Sc.)

How many geologists, engineering geologists, rock mechanics people in these crowds?

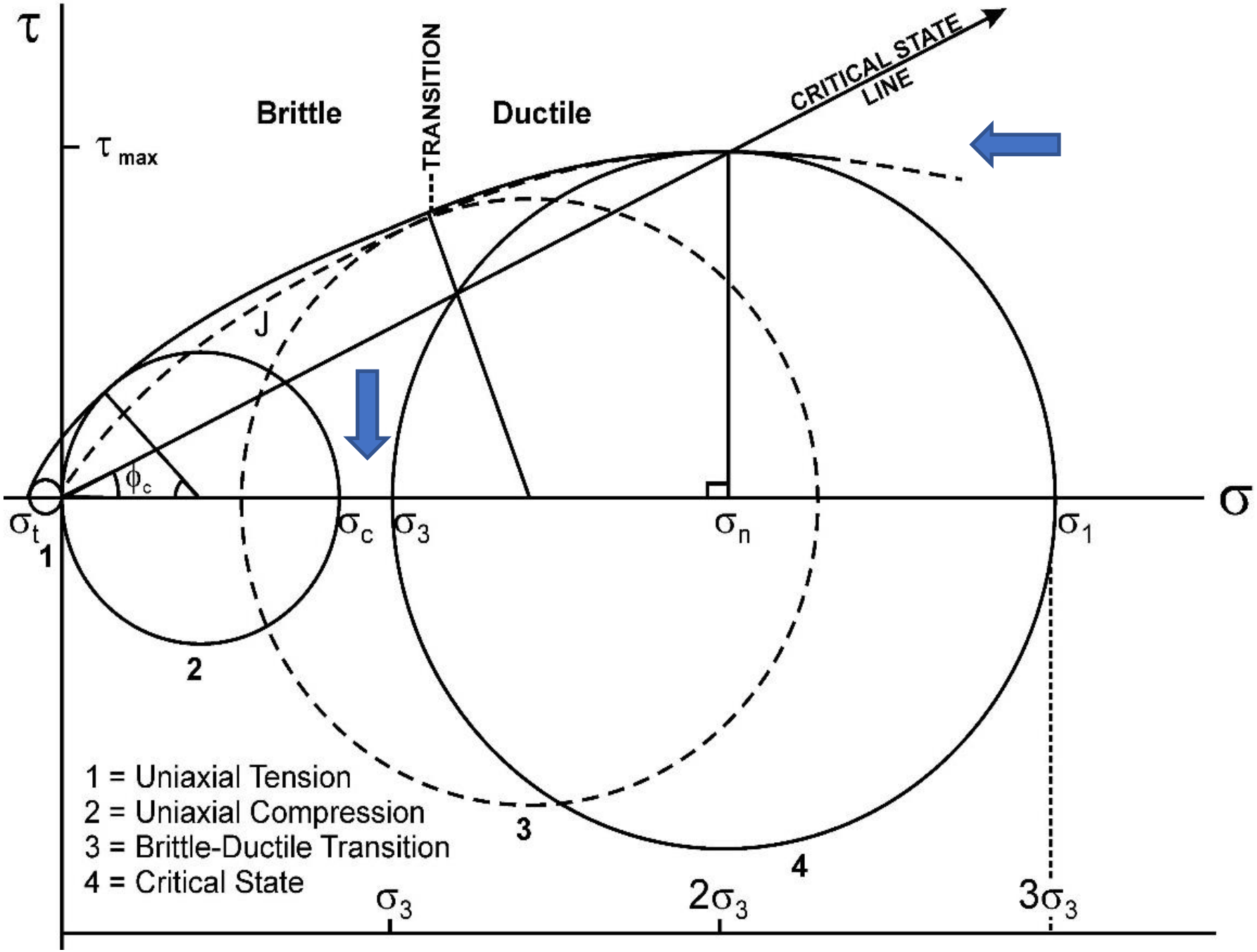
FINALLY:

WHY ARE THE HIGHEST (15) MOUNTAINS IN THE WORLD ‘LIMITED’ TO 8 - 9km?

Mount Everest 8,864m

(from Wikipedia photo)

- MISUSE OF 'TERZAGHI' FORMULA: GIVES
- $Hc = 100\ \sigma_c / \gamma$
- e.g. 100 x 250/2.8 = 8.9km?
- ***NO! HAS TO BE CONFINED*** *STRENGTH AT 9 KM* DEPTH AND THIS IS MUCH (2x) TOO HIGH!
- **CORRECT LOGIC SUGGESTS A LOWER *(CRITICAL STATE)* SHEAR STRENGTH LIMIT.**

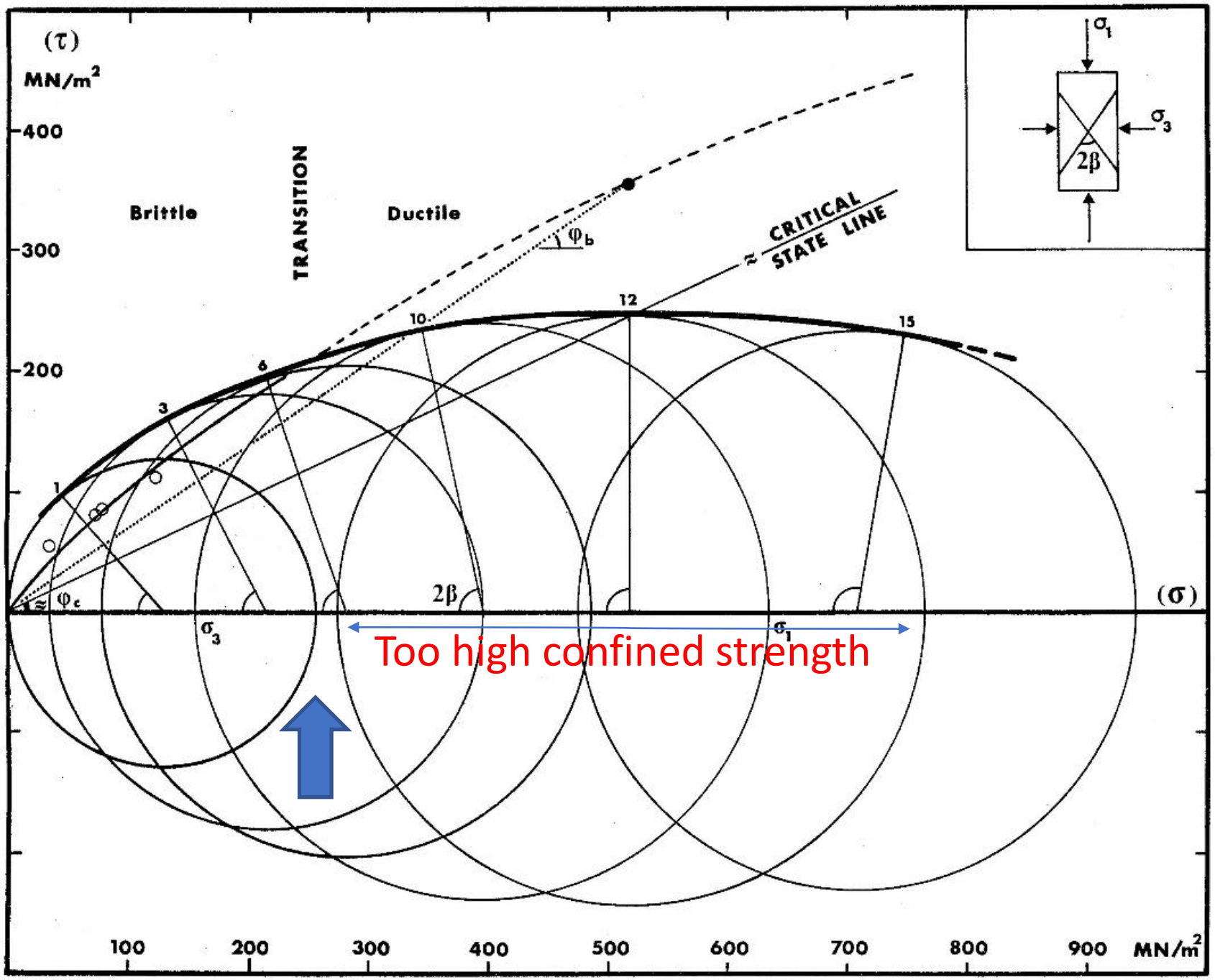


THE MAXIMUM POSSIBLE SHEAR STRENGTH AT THE CRITICAL STATE ……..

IS OF SIMILAR NUMERICAL MAGNITUDE TO UCS, SAY 200 MPa

FOR A STRONG ROCK LIKE GRANITE.

Barton, 1976,
Singh et al. 2011



SHEAR STRENGTH PROBABLY ***LIMITS*** THE HEIGHT OF THE HIGHEST MOUNTAINS

$(\tau_{max} \approx \sigma_c)$

Barton, 1976

CONCLUSIONS

1. DEEP TUNNELS IN HARD BRITTLE ROCK MAY FRACTURE/BURST DUE TO INITIATION OF *EXTENSION FRACTURING*, AND PROPAGATION IN SHEAR.

2. THE FAMILIAR '*0.4 X UCS*' FRACTURE INITIATION STRESS IS ACTUALLY DUE TO $\underline{\sigma t/\nu}$. THIS (ALSO) SIGNALS THE START OF ACOUSTIC EMISSION.

3. CLIFFS AND MOUNTAIN WALL HEIGHTS ARE LIMITED BY THE WEAKEST LINK (TENSILE STRENGTH) AND POISSON RATIO, CAUSING EXTENSION STRAIN IN (EVEN) A 3D *ALL-IN-COMPRESSION* STRESS FIELD.

4. THE 'LIMITED' HEIGHTS OF THE 15 HIGHEST MOUNTAINS (8 TO 9 km) IS CAUSED BY THE (CRITICAL-STATE) LIMITS OF SHEAR STRENGTH, *NOT BY AN IMPOSSIBLE UCS.* CONFINED COMPRESSIVE STRENGTH IS MUCH TOO HIGH.