EXTENSION FAILURE MECHANISMS EXPLAIN FAILURE INITIATION IN DEEP TUNNELS AND CRITICAL HEIGHTS OF CLIFF FACES AND NEAR-VERTICAL MOUNTAIN WALLS

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CONTENT OF LECTURE

APPLICATION of ***EXTENSION STRAIN FRACTURING THEORY*** TO:

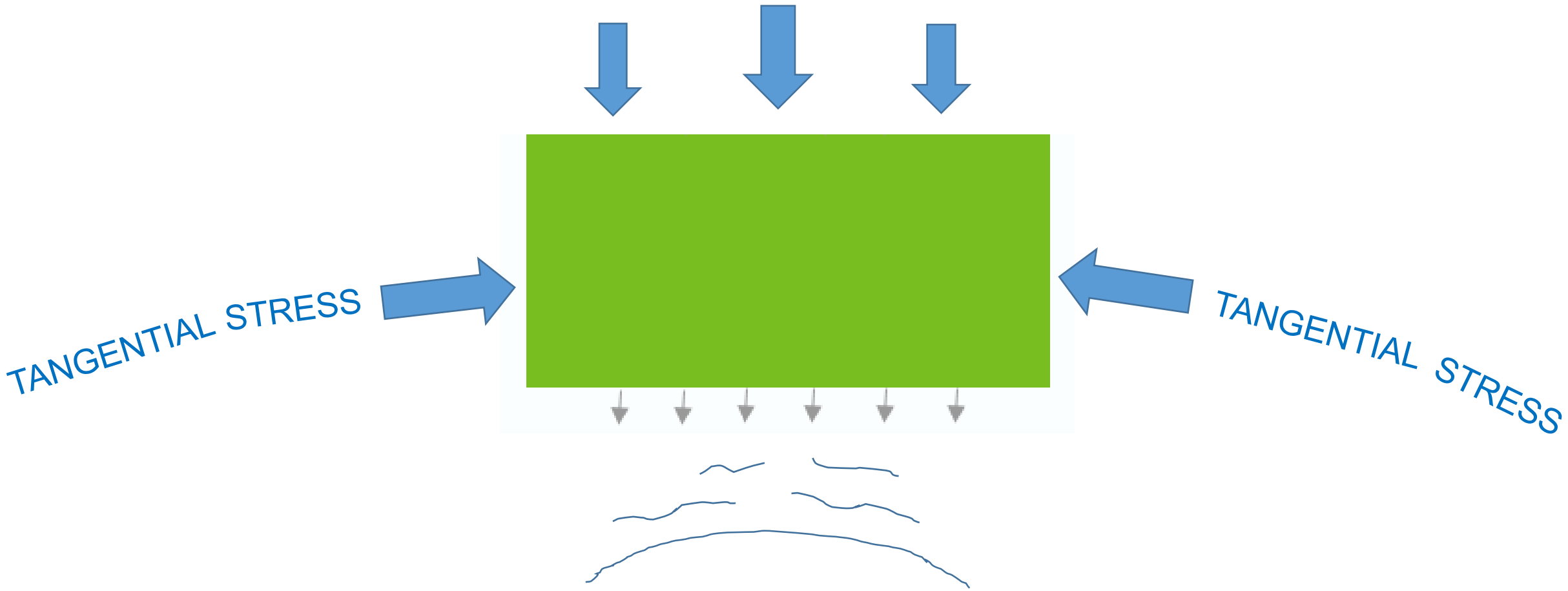
1. FAILURE AROUND TUNNELS (IN MASSIVE ROCK)
2. FAILURE BEHIND VERTICAL CLIFFS AND MOUNTAIN WALLS*
3. MOUNTAIN HEIGHT LIMIT PREDICTION *VIA CRITICAL STATE*

*(NEW *ROCK MECHANICS FORMULA* THAT IS NOT IN ERROR BY 3:1 or more, as WHEN USING CLASSIC SOIL MECHANICS FORMULÆ)

1. ‘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)*

AROUND A TUNNEL: **Poisson's ratio** causes lateral strain

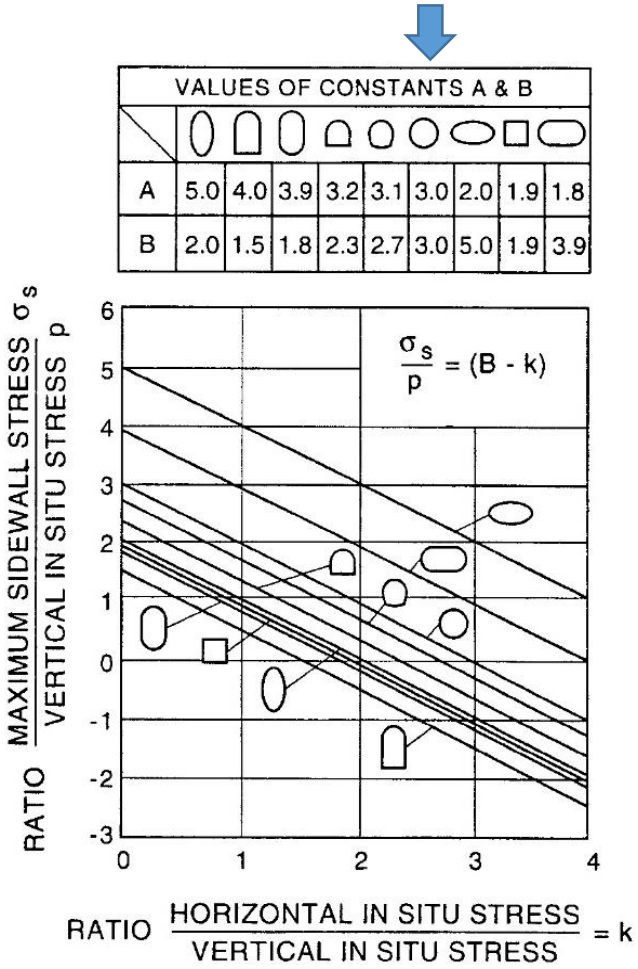


NEXT TO THE TUNNEL MAY GET (TENSILE) CRACKING

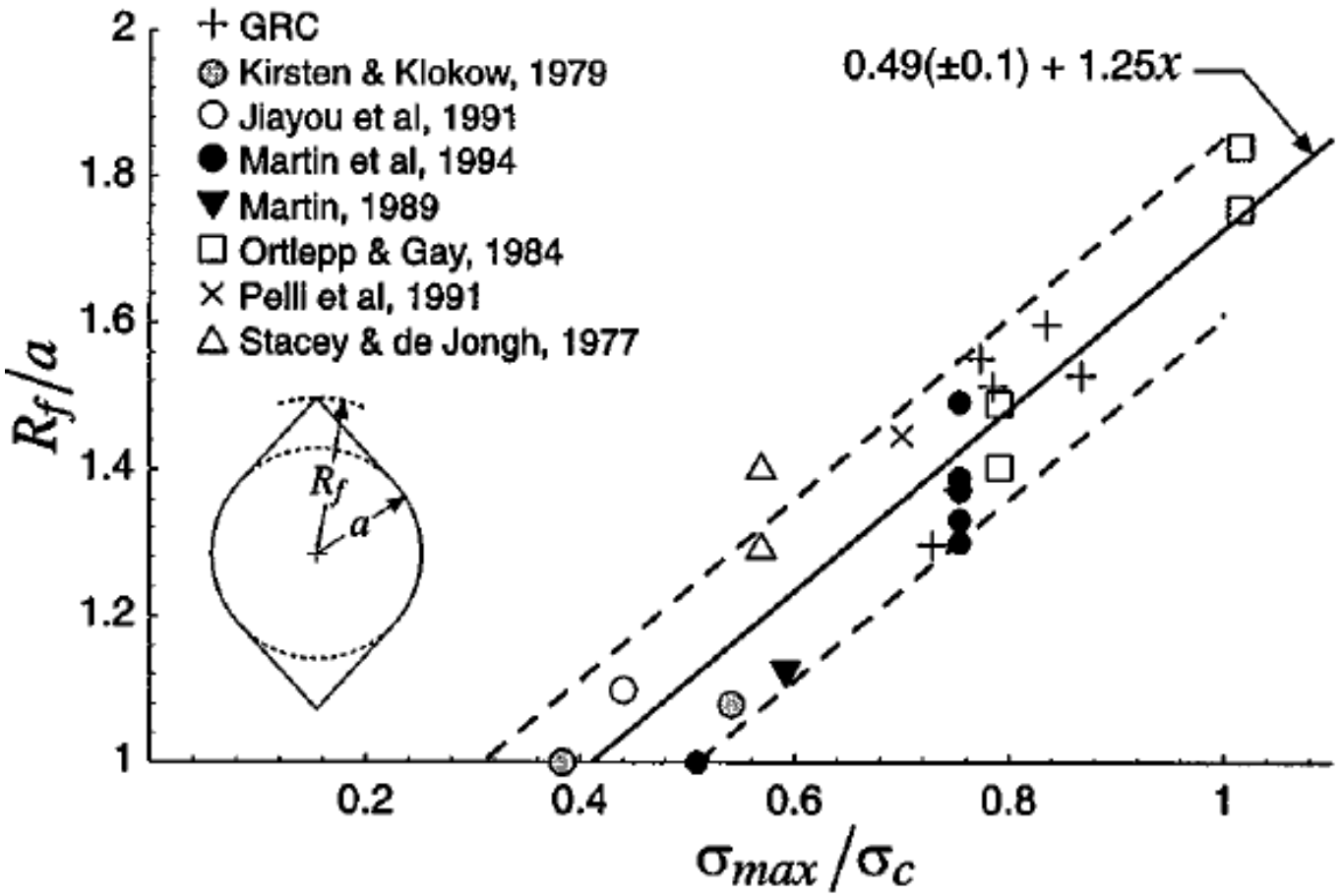
– EVEN WHEN ALL STRESSES ARE STILL COMPRESSIVE

TUNNELS IN MASSIVE ROCK: STRESS (or strain?) INDUCED FAILURE? Traditionally expect 'stress-induced' (?) failure when:

$\sigma_{\theta\,max}/\sigma_c > 0.4 +/- 0.1$ …..Maximum tangential stress from: $\sigma_{\theta\,max} = 3\sigma_1 - \sigma_3$



(Hoek and Brown, 1980)



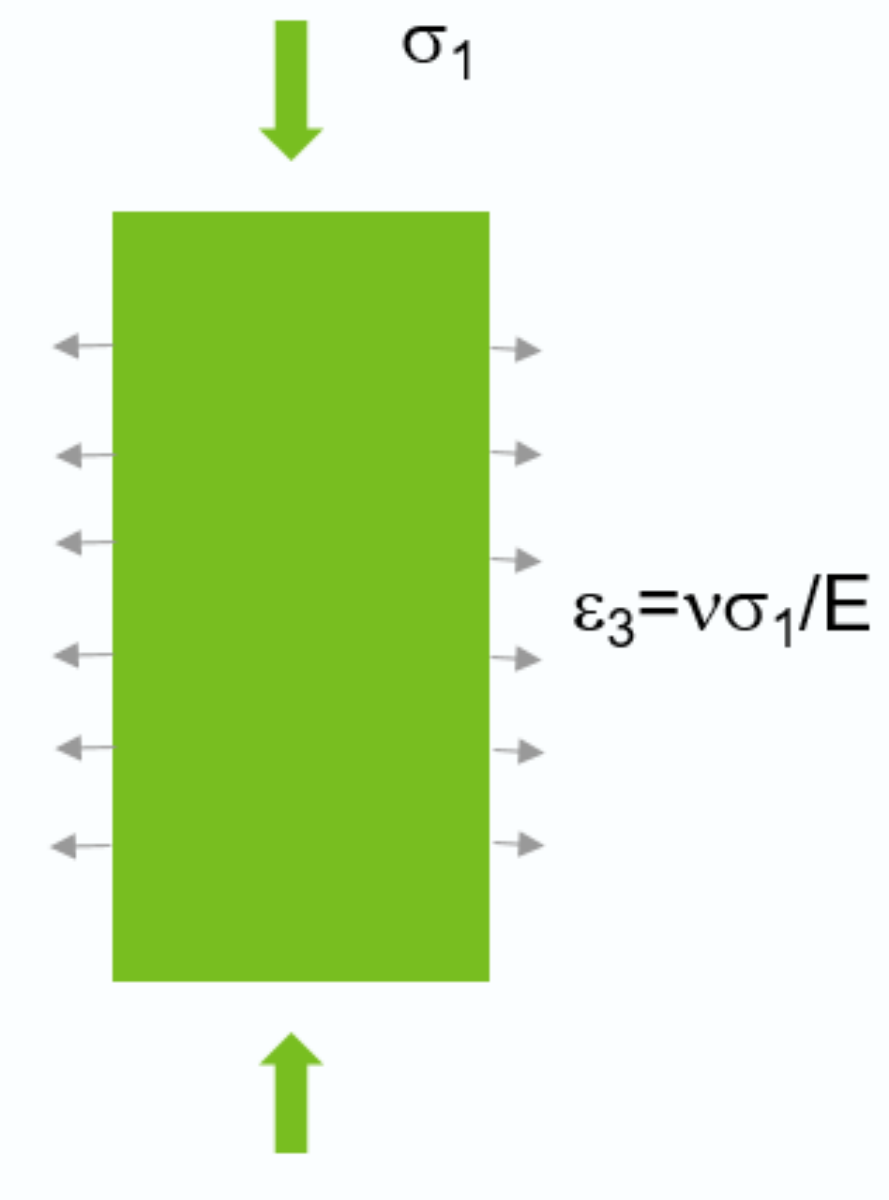
(Martin et al. 1998)

IN Q-SYSTEM, SAME EXPECTATION. If $\sigma_{\theta\,max}/\sigma_c > 0.4$, get: higher SRF – 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



TENSILE STRAIN CRITERION

(Proposed by Stacey, 1981)

From Figure: $\varepsilon_3 = \nu\sigma_1 / E$

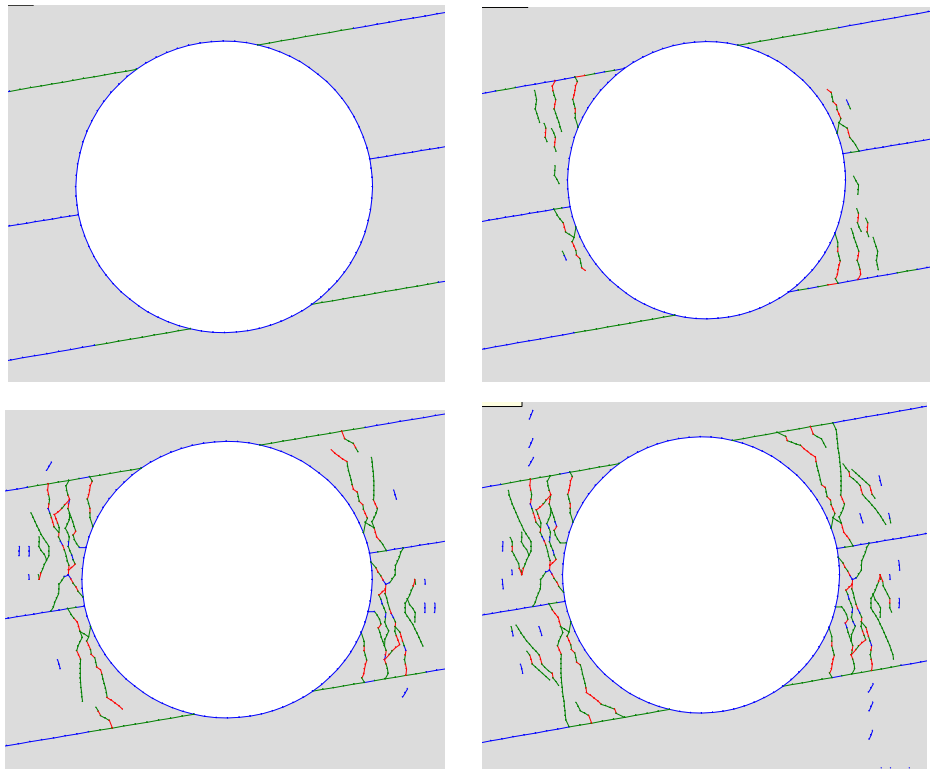
Critical tensile strain for tensile failure:

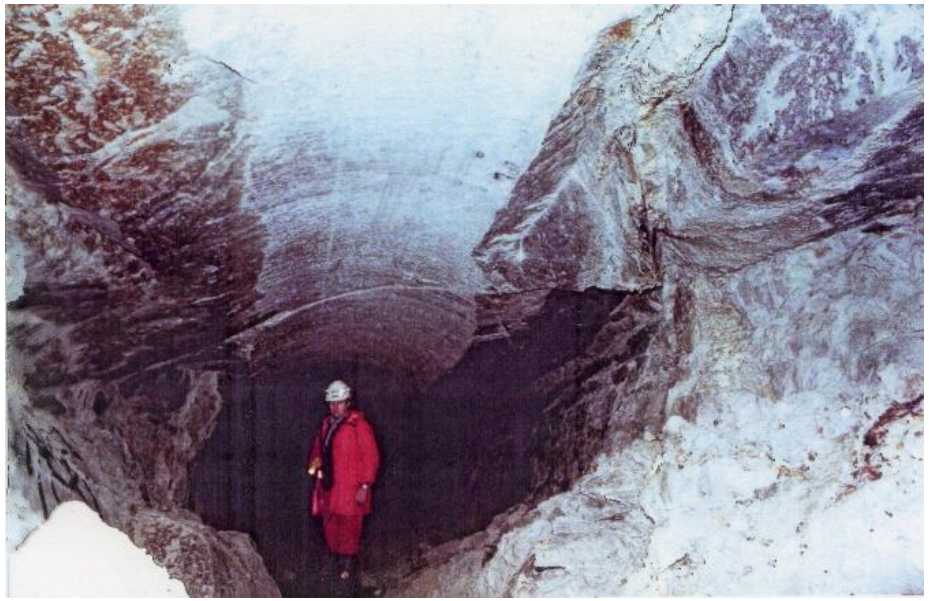
$\varepsilon_c = \sigma_t / E$

Equate strains, and eliminate E. (Shen, pers. comm. 2016). Therefore:

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

(We get '0.4' if UCS/$\sigma_t \approx 10$, and $\nu \approx 0.25$)





'CRITICAL TANGENTIAL STRESS' (WHEN $\sigma_{\theta\ MAX} \approx 0.4\ X\ UCS$) CAUSED BY REACHING (OR EXCEEDING) ***CRITICAL EXTENSION STRAIN:***

(Cracking in tension, then in shear)

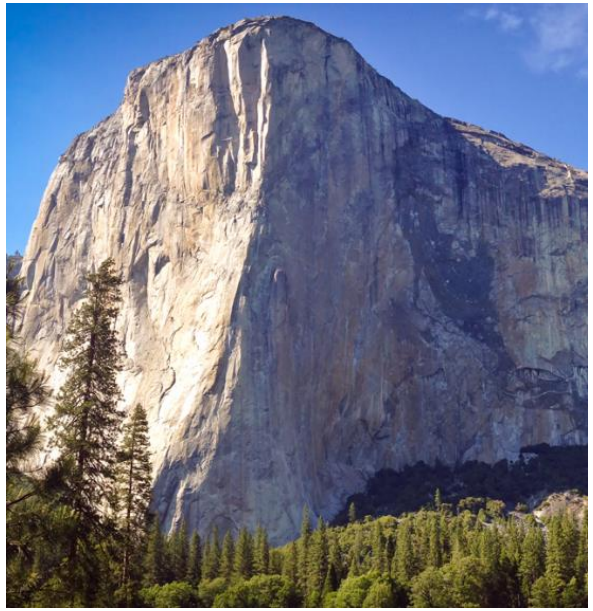
(Baotang Shen, in Barton and Shen, 2017)

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

(from $\varepsilon_3 = [\ \sigma_3 - \nu.\sigma_1]\ /E$ …. Stacey, 1981)

$$\sigma_t / \nu \approx \frac{UCS}{10\nu} = \frac{UCS}{10 \times 0.25} = 0.4 \times UCS$$

2. EXTENSION-STRAIN FRACTURING CONCEPT *NOW APPLIED* TO FAILURE OF VERTICAL CLIFFS



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.

VERTICAL HEIGHT LIMITS OF CLIFFS AND MOUNTAIN WALLS IS GIVEN BY:

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

(Assumed $\sigma_v \approx \gamma H/100$ MPa)

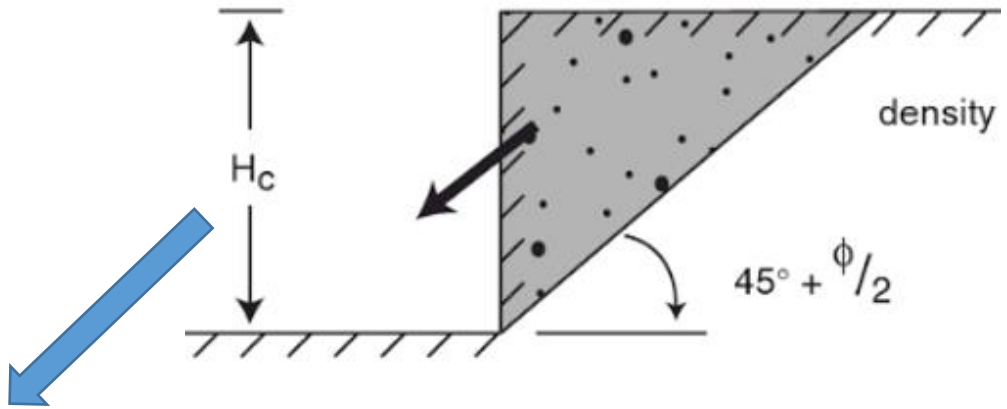
σ_t = tensile strength (MPa)

γ = density (when units are tons/m3)

ν = Poisson's ratio

Barton, 2016

$$H_{critical} \approx 100.\sigma_t / \gamma\nu$$



NOTE DIFFERENCES TO:

'SOIL MECHANICS' THEORIES:

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

(≈ 3x to ≈ 6x IN ERROR WHEN ***EXTENSION – NOT SHEAR*** FAILURE OF ROCK!)

TERZAGHI (*1962*): $H_{crit} = q_c/\gamma$ (soil) or **$H_{crit} = 100\sigma_c/\gamma$** (rock) (using MPa units)

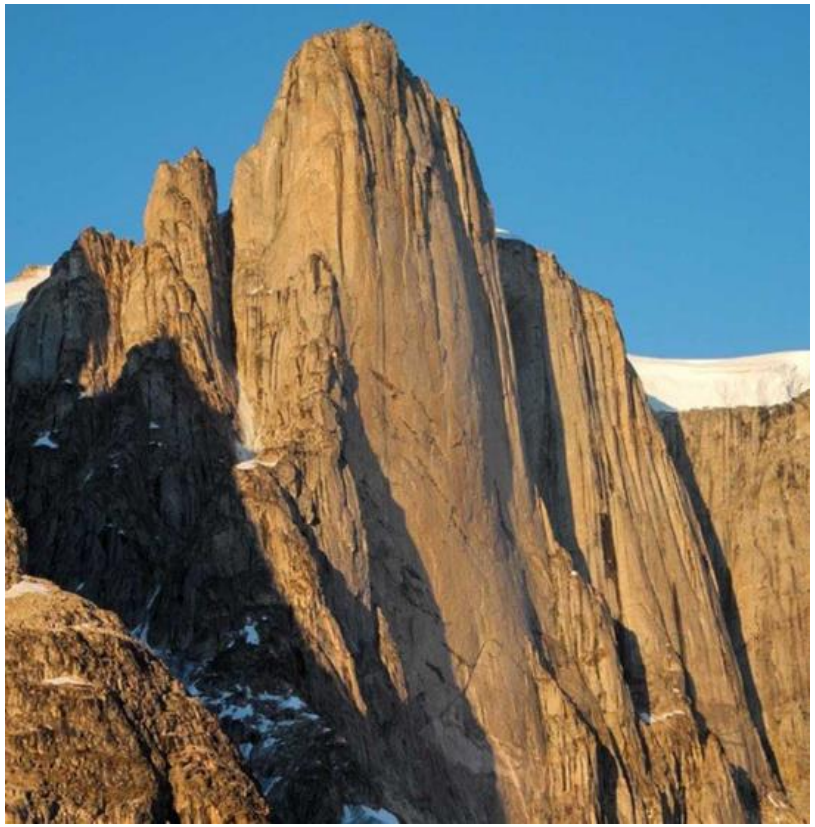
(≈ 2.5x IN ERROR FOR FAILURE OF ROCK)...IMPLIES **$\sigma_c/\sigma_t = 1/\nu \approx 4$ to 5…….NO!)**

TERZAGHI SUGGESTED *NEED FOR JOINTING – TO EXPLAIN MUCH LOWER VERTICAL MOUNTAIN WALLS* *than predicted by his own equation.*

THREE OF THE HIGHEST ‘VERTICAL’ MOUNTAIN WALLS in THE WORLD

Great Trango Tower, Karakoram, Pakistan: **1,340m**

Mount Thor, Baffin Island, Canada: **1,250m**



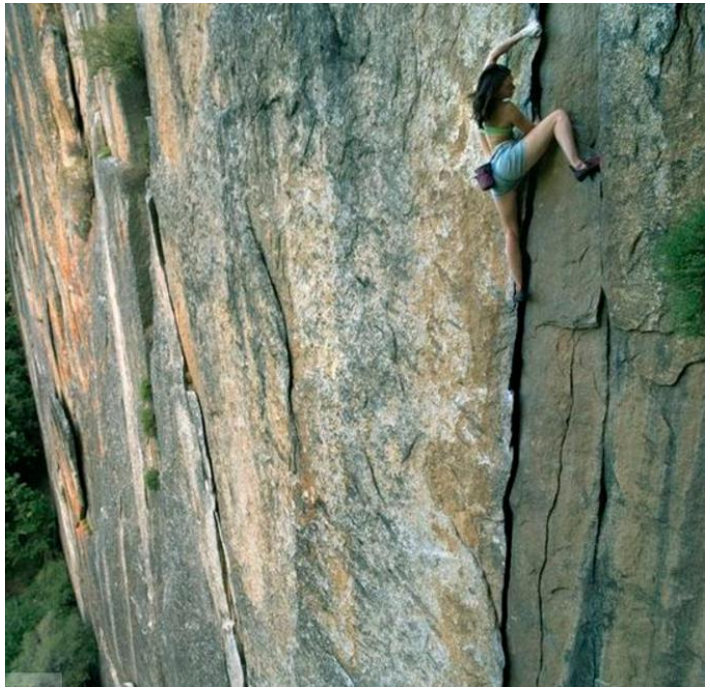
Mirror Wall, Greenland: **1,200m**

UCS 125MPa Hard rock	UCS 50MPa Medium hard rock	UCS 15MPa Low strength rock	UCS 2MPa Very low strength rock
$\sigma_t \approx 9$ MPa	$\sigma_t \approx 4$ MPa	$\sigma_t \approx 1$ MPa	$\sigma_t \approx 0.1$ MPa
$\nu = 0.25$	$\nu = 0.20$	$\nu = 0.15$	$\nu = 0.15$
$\sigma_t / \nu = 36$ MPa	$\sigma_t / \nu = 20$ MPa	$\sigma_t / \nu = 6.7$ MPa	$\sigma_t / \nu = 0.67$ MPa
$\gamma = 2.75$ tons/m^3	$\gamma = 2.5$ tons/m^3	$\gamma = 2.25$ tons/m^3	$\gamma = 2.0$ tons/m^3
$H_{crit} = 1309$m	$H_{crit} = 800$ m	$H_{crit} = 296$ m	$H_{crit} = 33$ m

$$H_c \approx (100.\sigma_t) / \gamma\, \nu$$

FOUR EXAMPLES OF ESTIMATION OF MAXIMUM CLIFF HEIGHTS

Modified from Barton, 2016



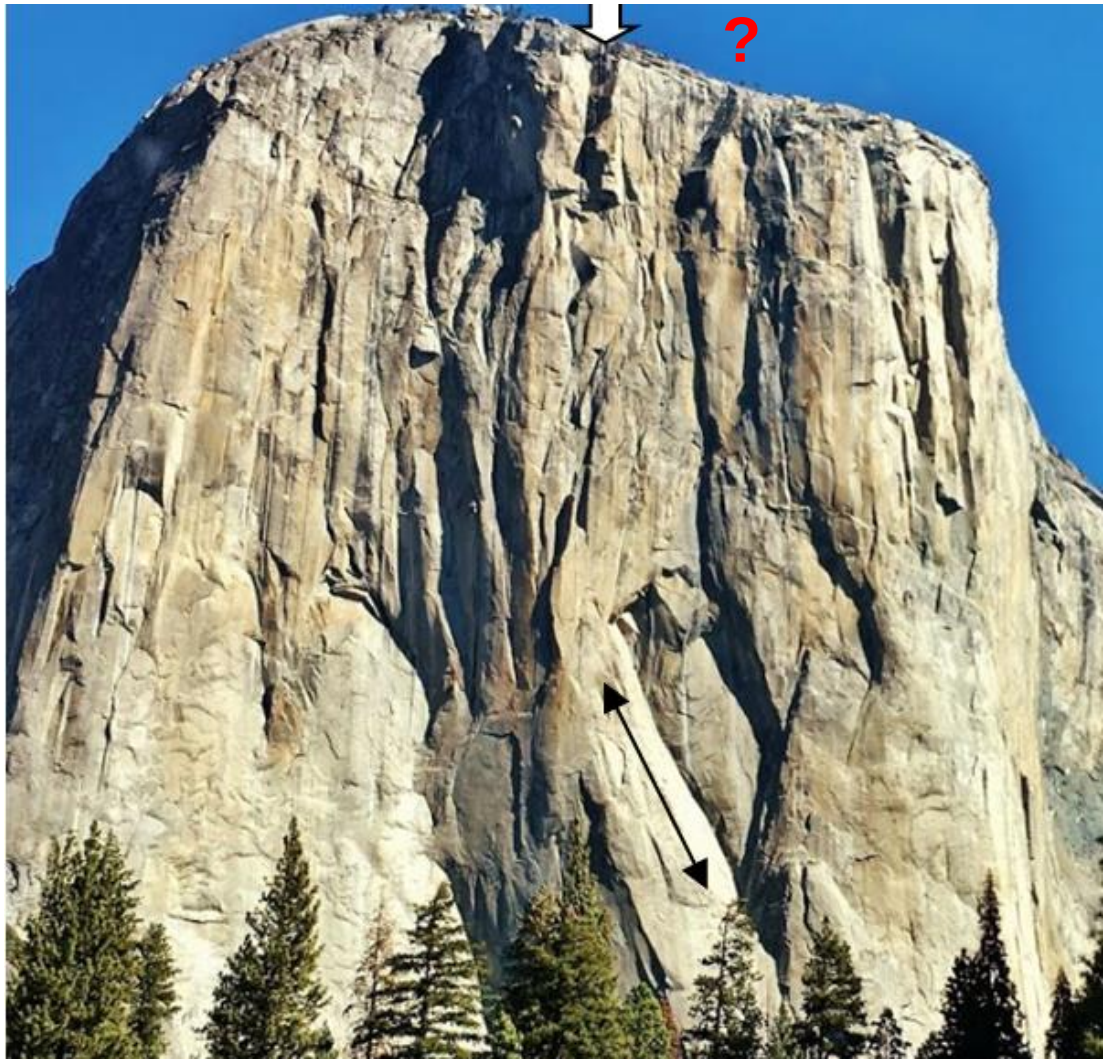
SHEETING JOINTS (AND ASSOCIATED CRACKS)

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

Free-solo rock-climbing aces:

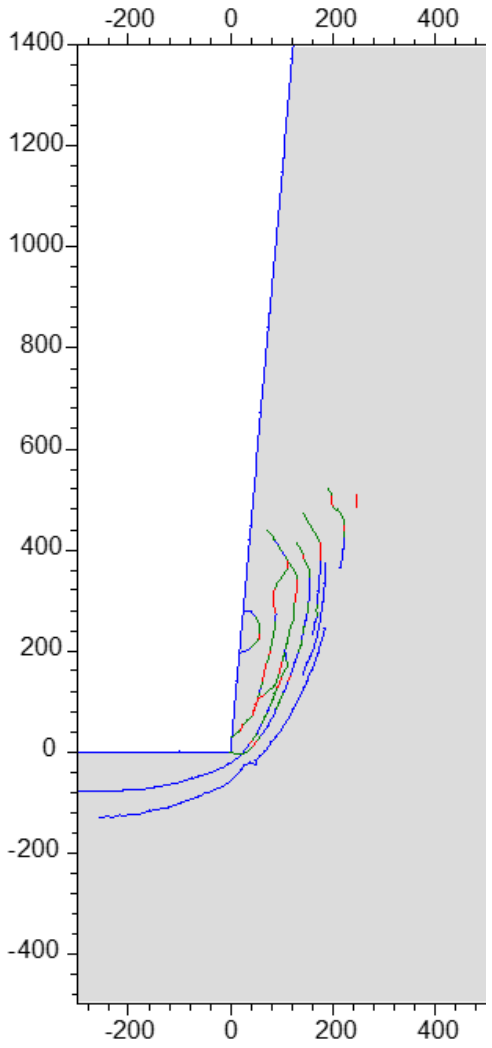
Steph Davis

Alex Honnold

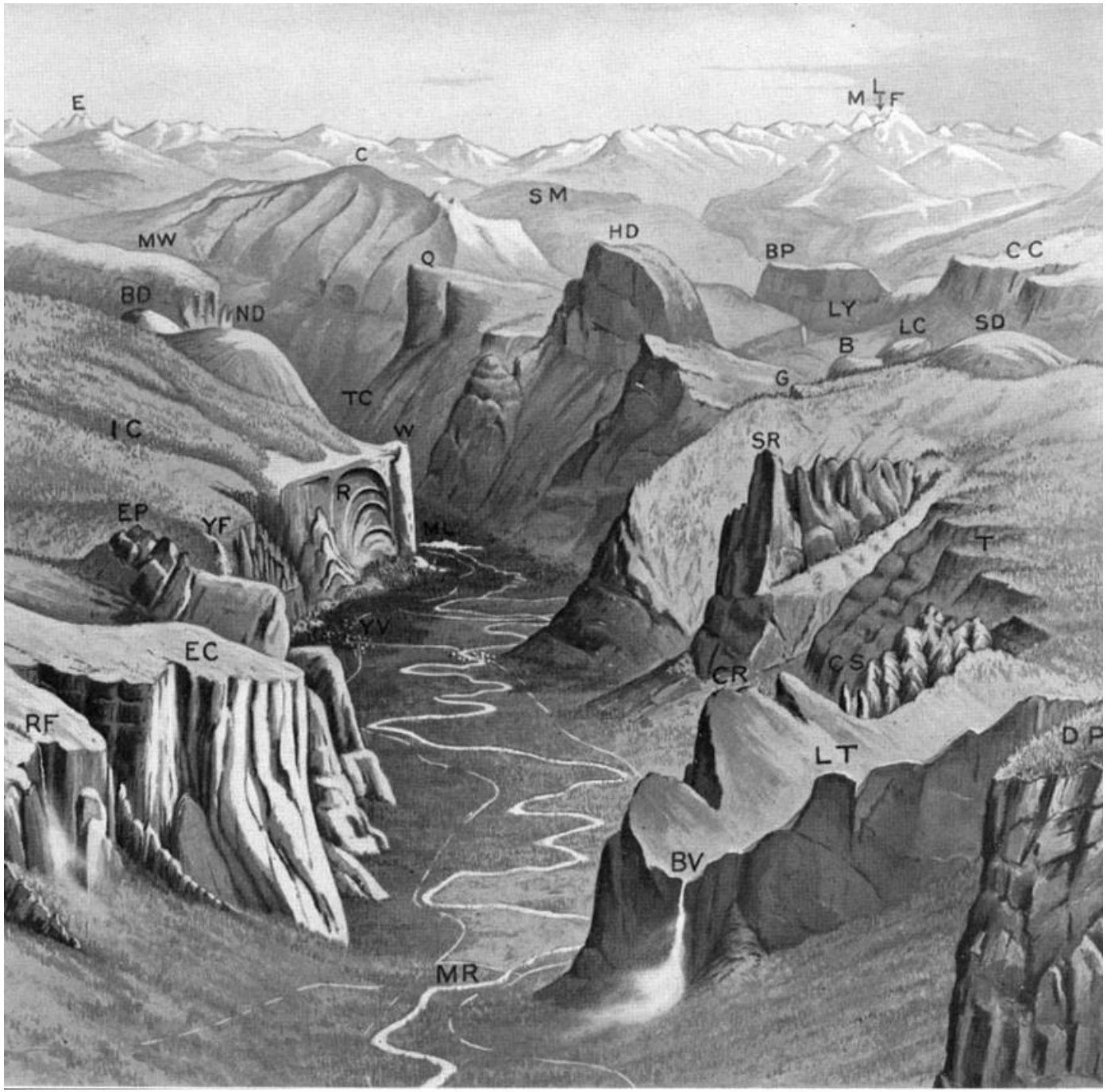


El Capitan, Yosemite.

Effect of shadows…….?

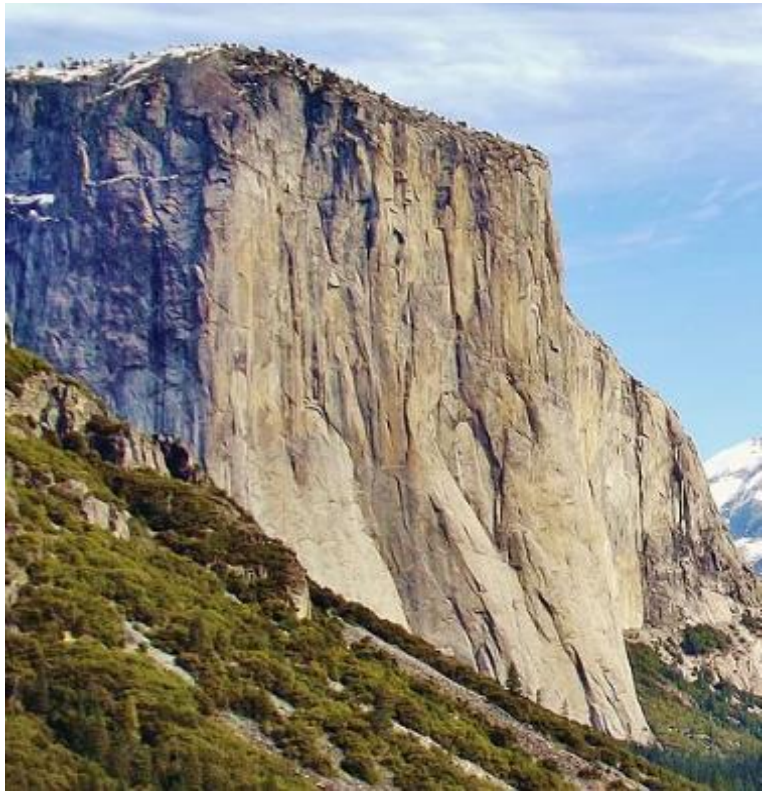


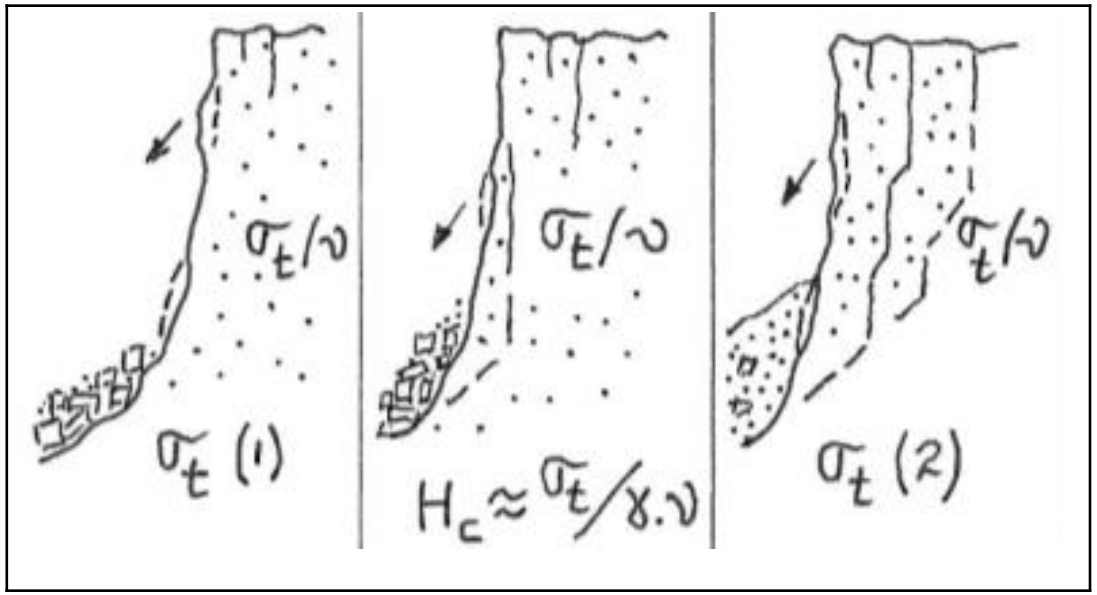
Extension fracturing, shear, and sheeting joints on El Capitan: evidence of a (slow) 'active' process. (FRACOD example, right)



USGS artist C.A.Weckerly

seems to have envisaged a future ‘failure mechanism’.

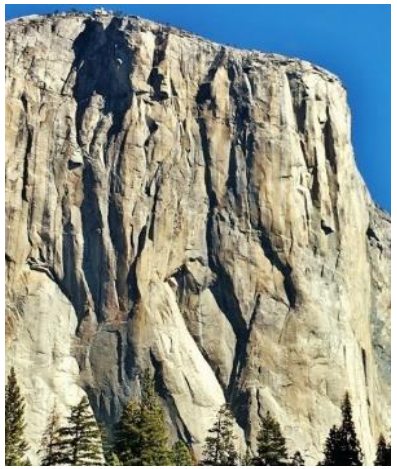




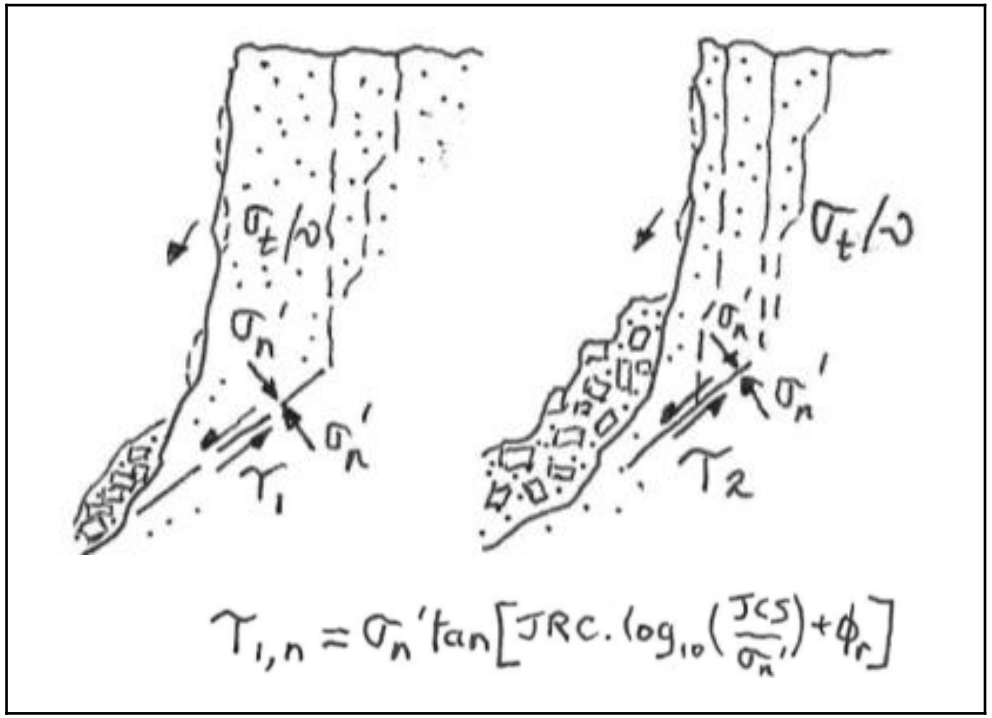
EXTENSION FAILURES CAUSE SHEETING FRACTURES, AND LIMIT ULTIMATE WALL HEIGHTS

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

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



El Capitan, CA. and Holtanna, Antarctic.



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

Mount Everest
8,864m

(Wikipedia photo)

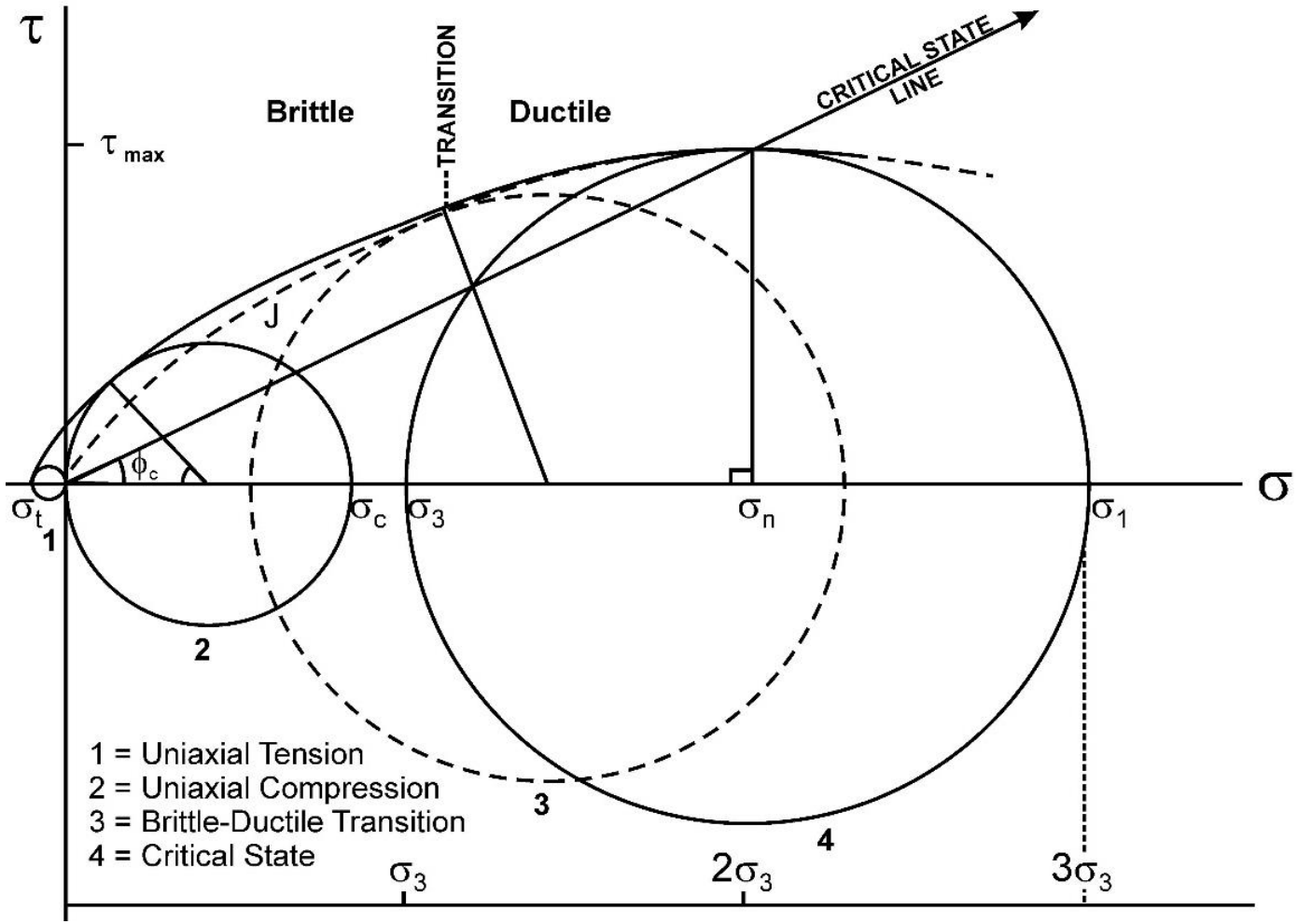
MISUSE OF 'TERZAGHI' FORMULA: GIVES $H_c = 100\ \sigma_c / \gamma$ e.g. 100 x 250/2.75 = 9.1km?

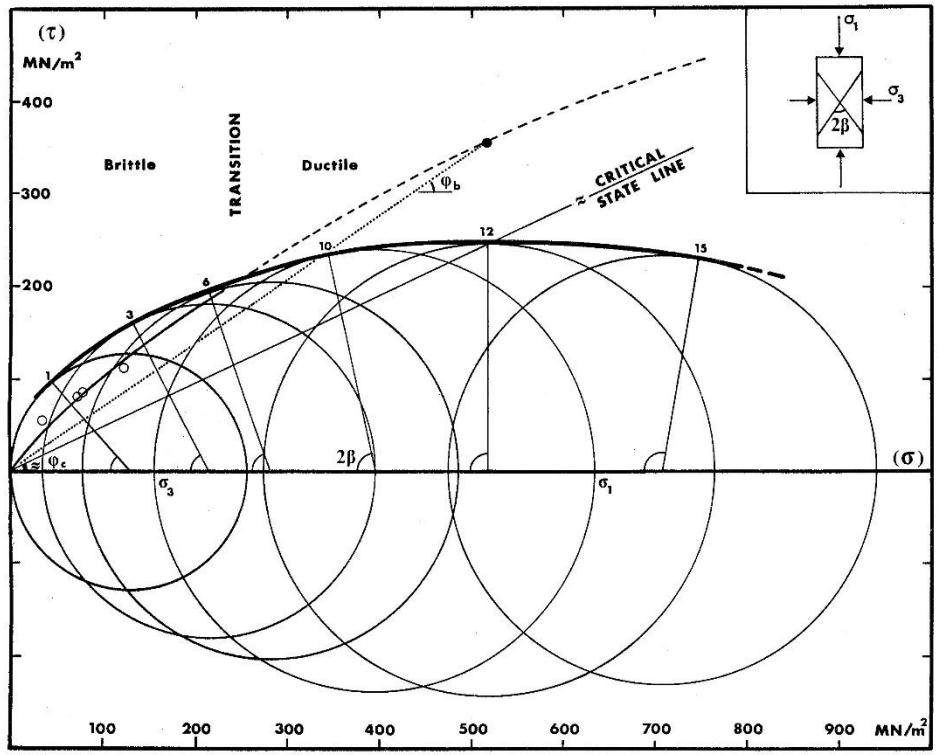
BUT ***HAS TO BE*** *CONFINED STRENGTH AT 9 KM* DEPTH (!) AND THIS IS TOO HIGH!

CORRECT LOGIC SUGGESTS A LOWER *(CRITICAL STATE)* SHEAR STRENGTH LIMIT.

SHEAR STRENGTH LIMITS THE HEIGHT OF THE HIGHEST MOUNTAINS

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





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

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.