Low Stress and High Stress Phenomena in Basalt Flows

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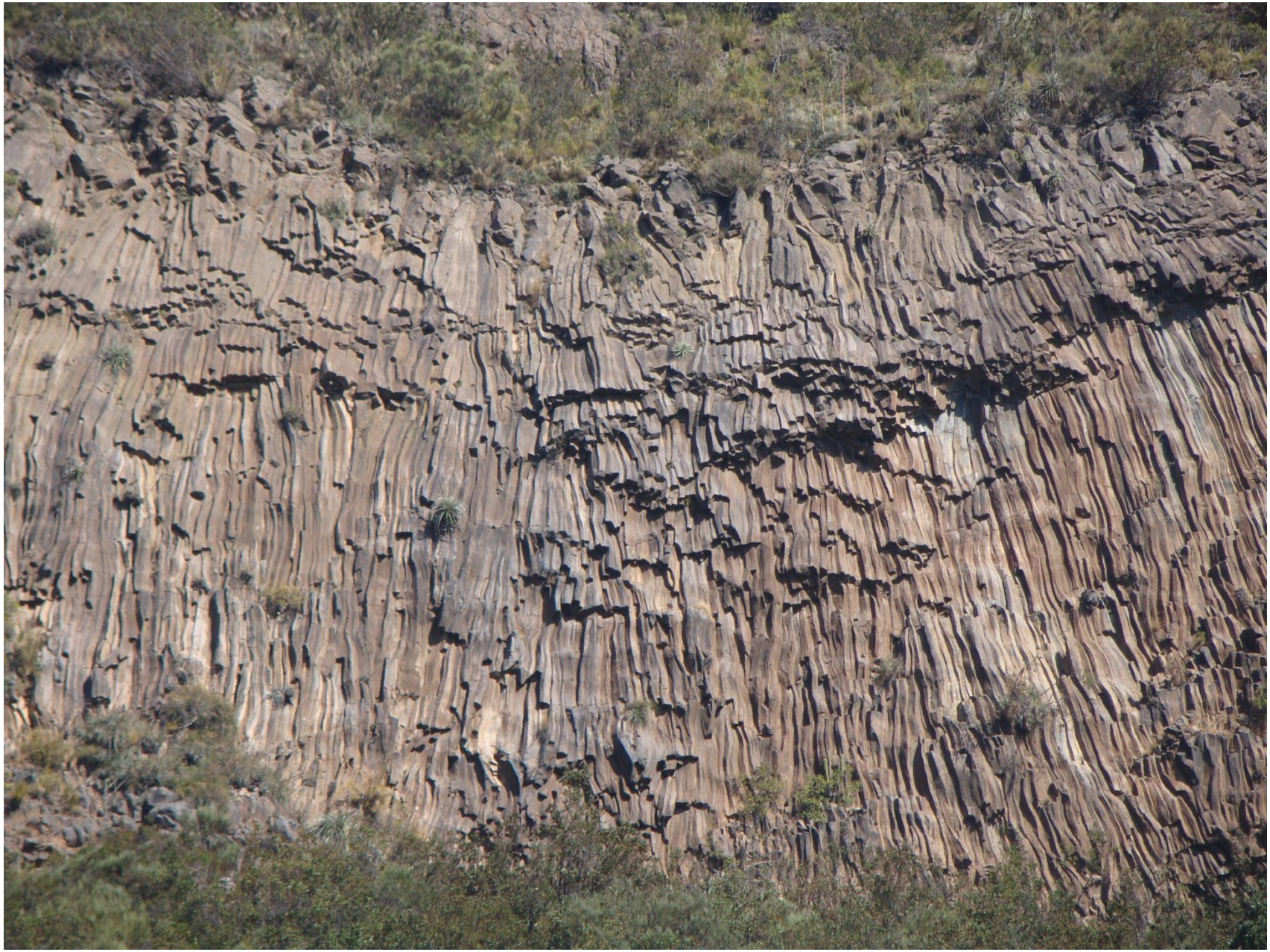
WORKSHOP ON VOLCANIC ROCKS: TENERIFE

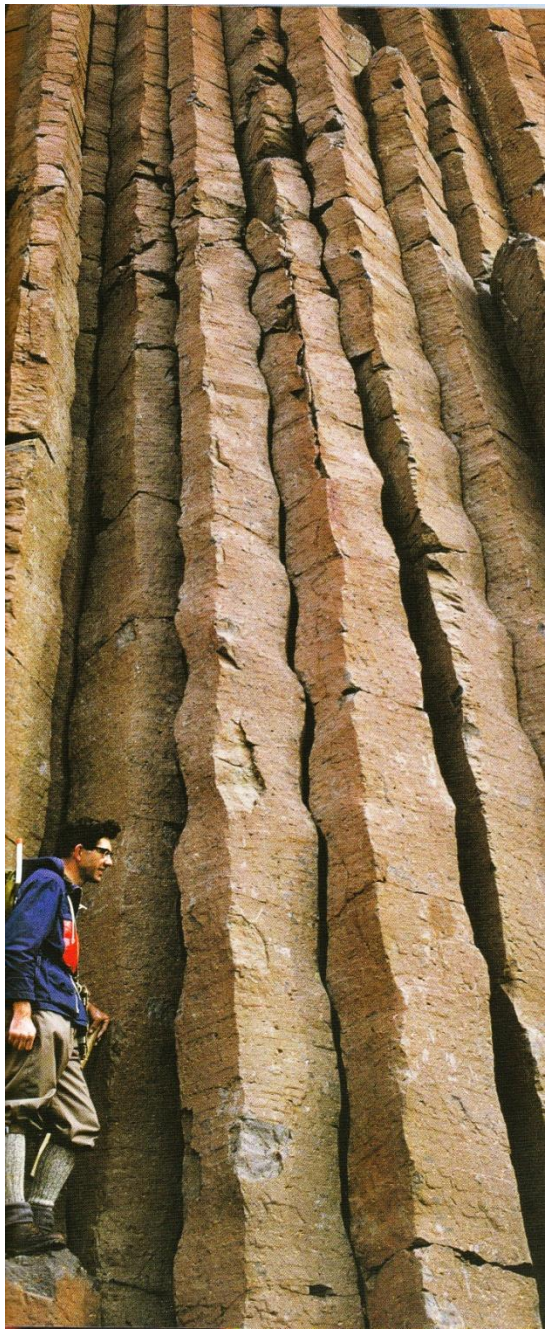
Lecture is about:

- Volcanic rock
- Rock mechanics
- Rock Engineering

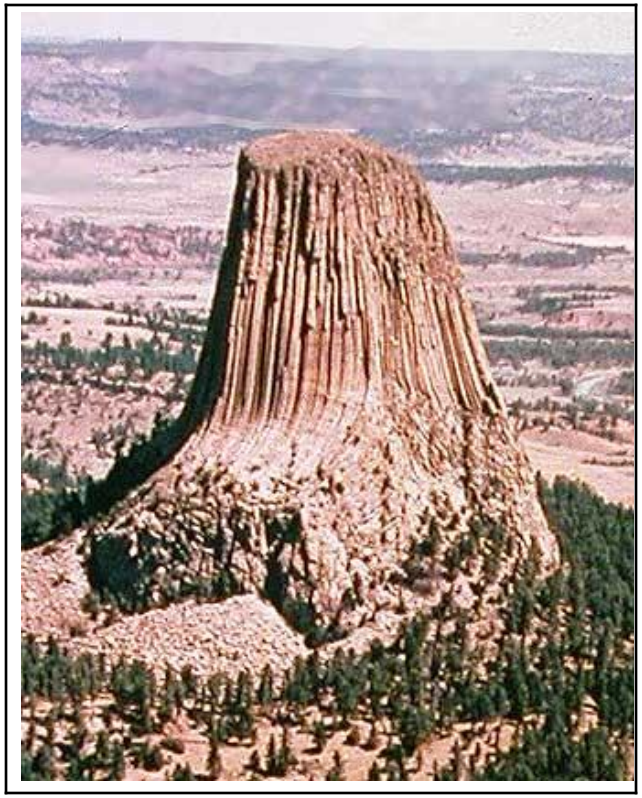
(as per workshop title)

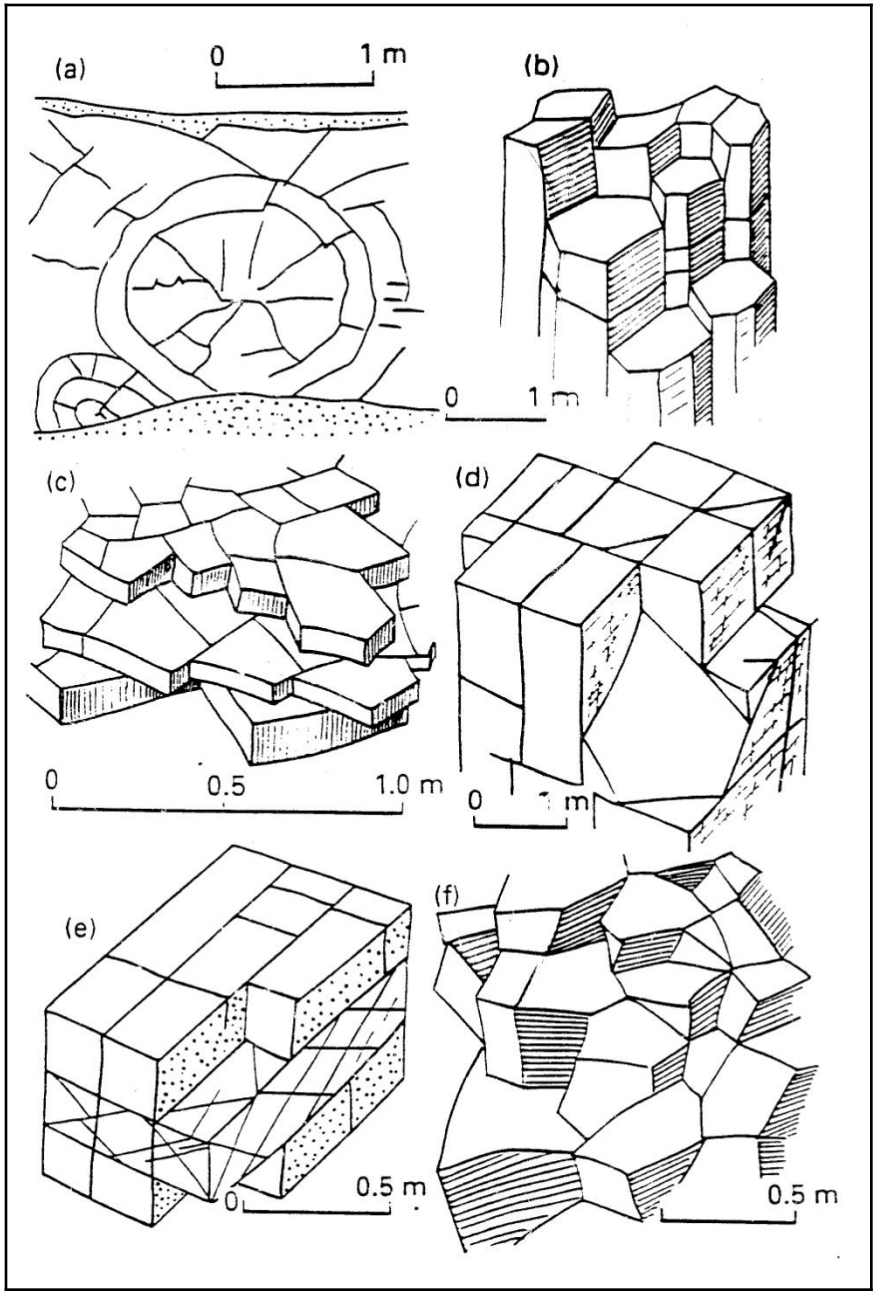
Geological beauty of basalt flows!





Close Encounters ?





One rock type takes on many forms

(source uncertain)

OUTLINE OF USA-PART OF TALK

- Cohasset flows outcrop along Colombia River.....possible ‘host rock’ (at 700-900m depth) for USA’s high level nuclear waste

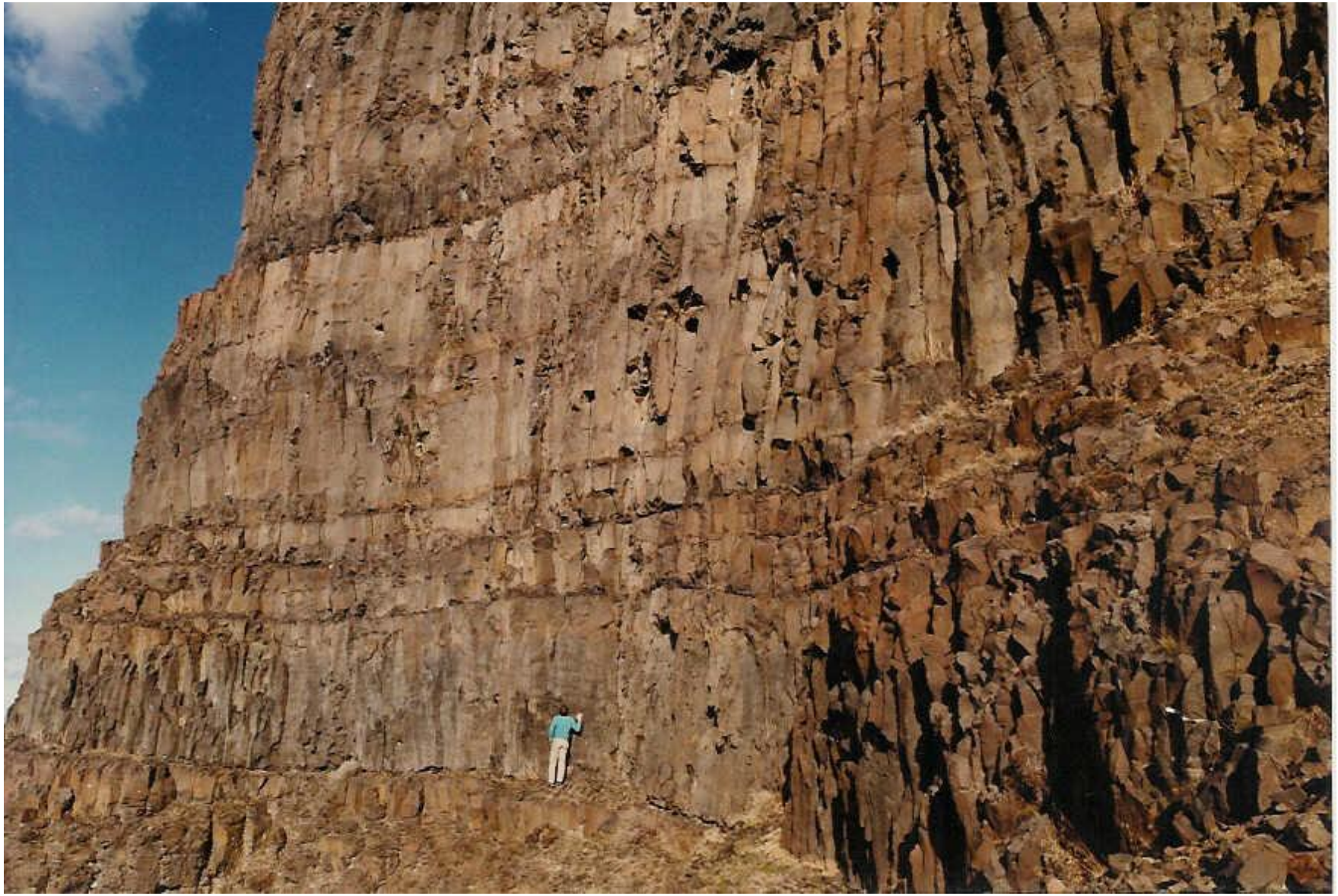
- Drilled through at 900 m depth: high anisotropic stress

- Block test in same basalt flows showed linear stress-closure
- Columnar joints closed at higher temperature

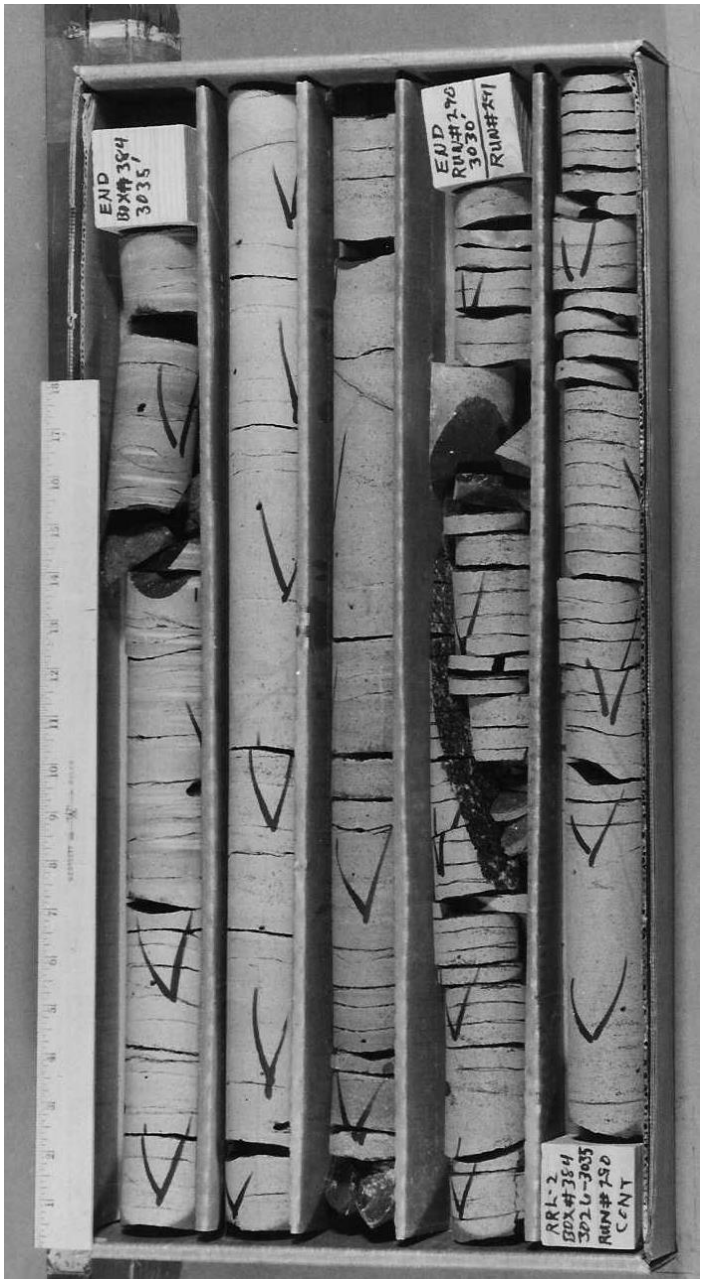
- Cross-hole seismic in tunnel wall showed anisotropic response and a strongly developed EDZ

- Deformation moduli (in GPa) resembled $Q_{seismic}$, the inverse of attenuation

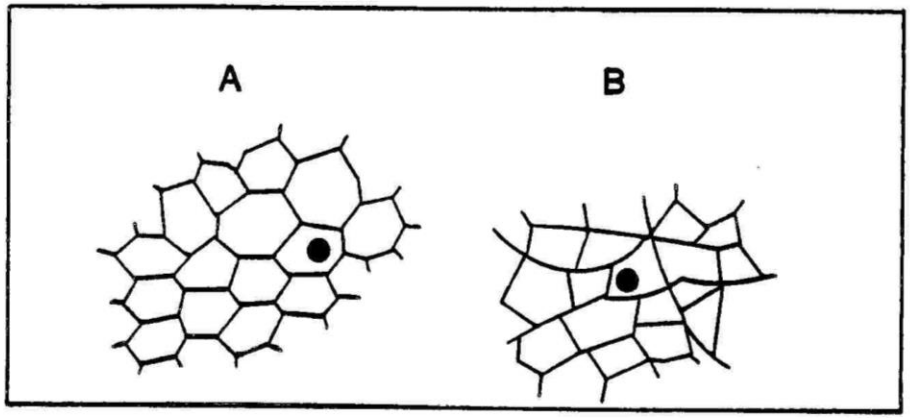
Hanford Basalts at the Colombia River



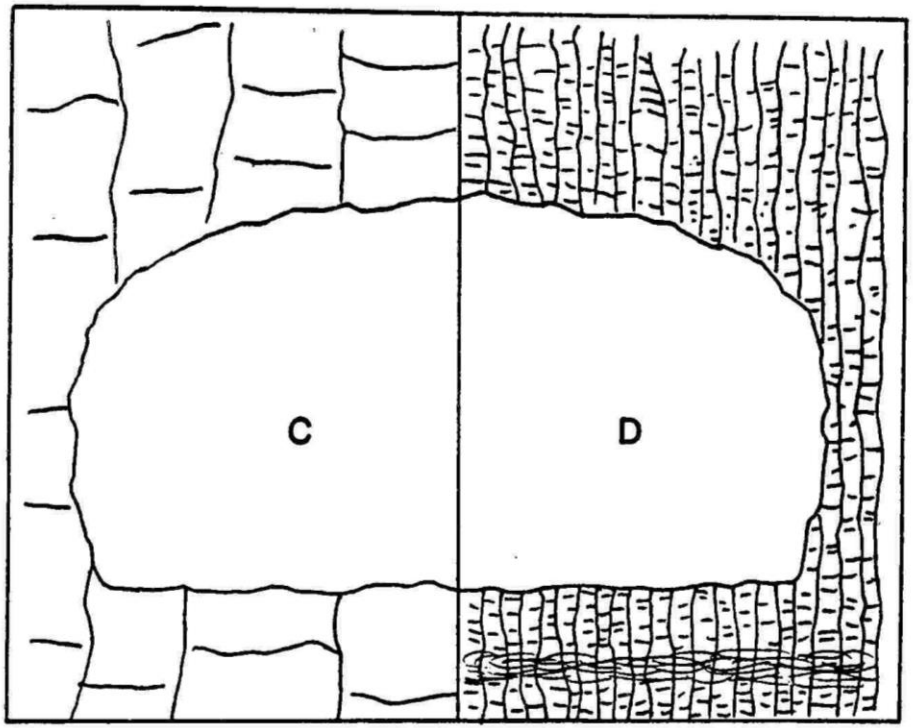
Effect of depth on the appearance of core (1880 ft, 3030 ft)



COMPARATIVE SCALES OF BOREHOLES AND TUNNELS IN COLUMNAR (and entablature) JOINTING



(a) Boreholes in "massive" rock.



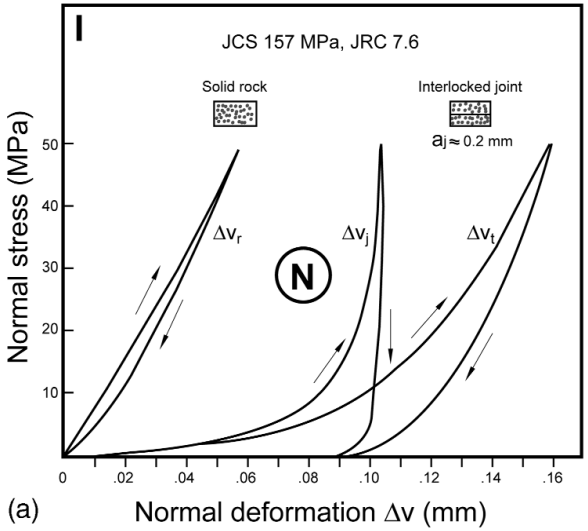
(b) Tunnels in jointed rock.

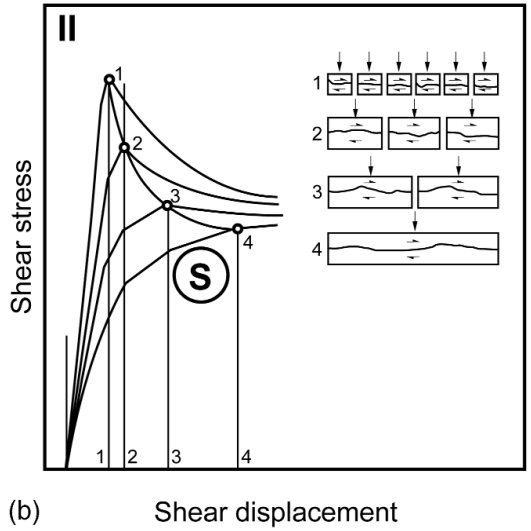
IN DEEP TUNNELS:

STRESS-FRACTURING POTENTIAL IN ‘C’

.....

DEFORMATION (ONLY) IN ‘D’

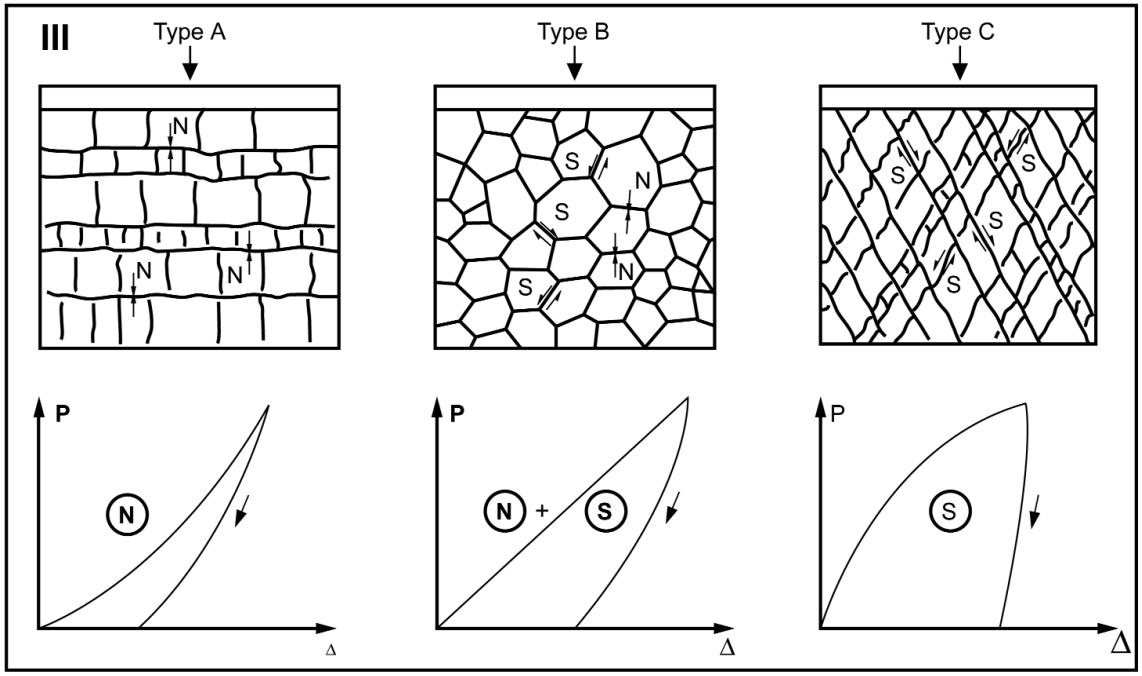




STRESS-DEFORMATION COMPONENTS

‘N’ and ‘S’

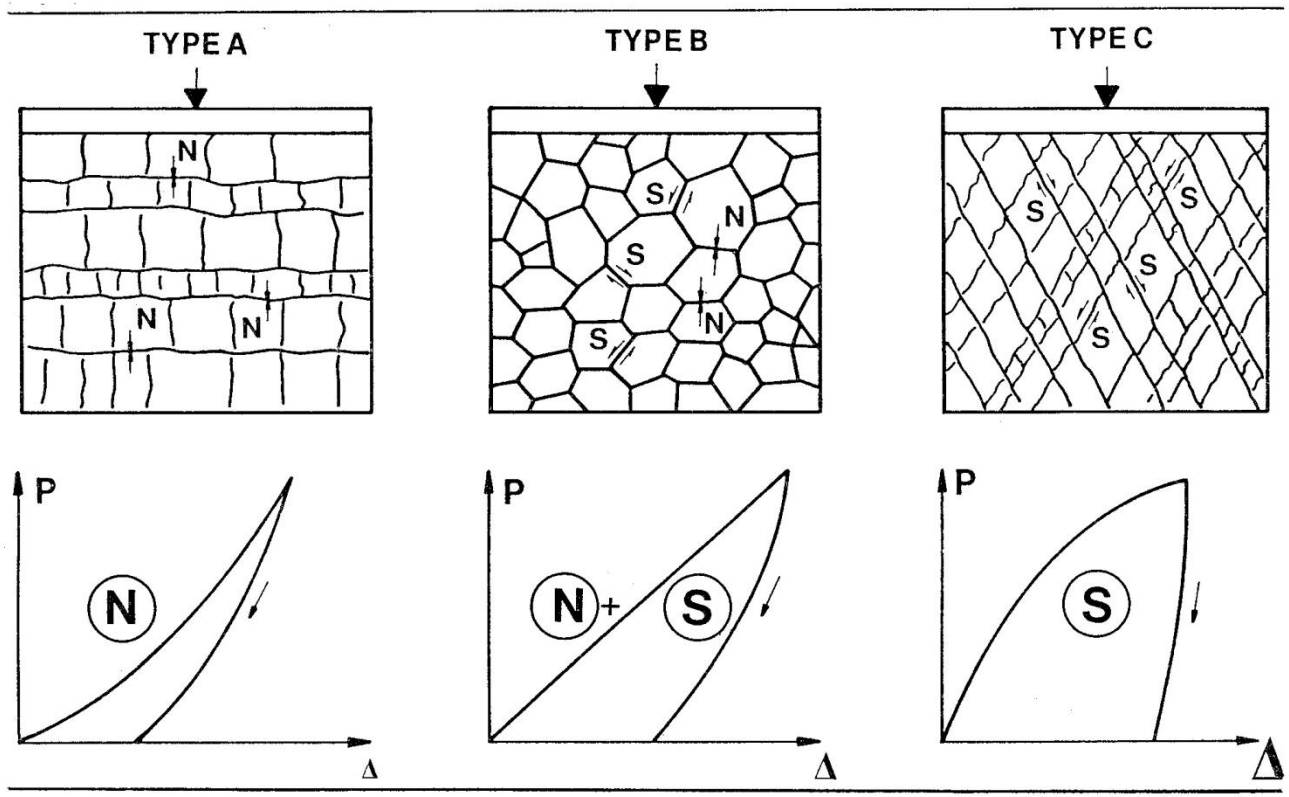
(from Bandis, 1980)



NOTE LINEAR P-Δ form for COLUMNAR JOINTING

.....

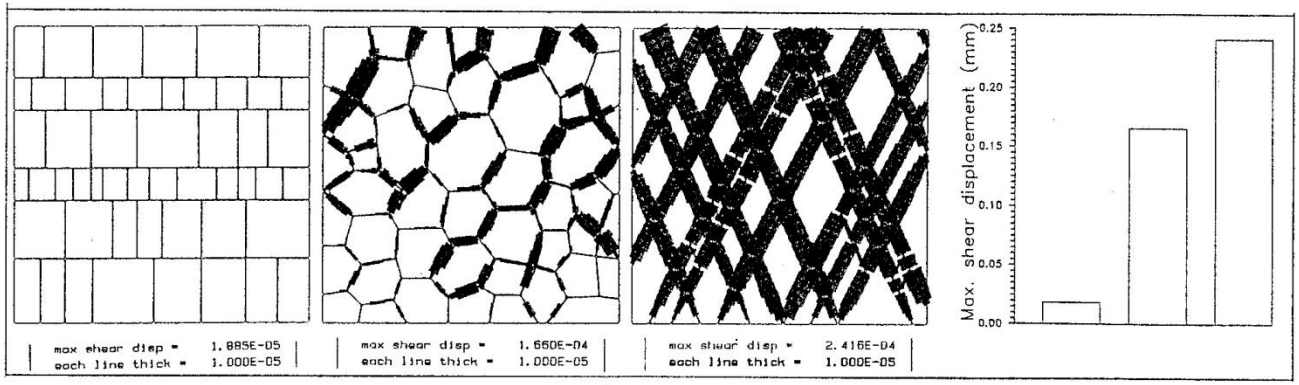
(if loaded ⊥ to jointing)



‘N’ and ‘S’

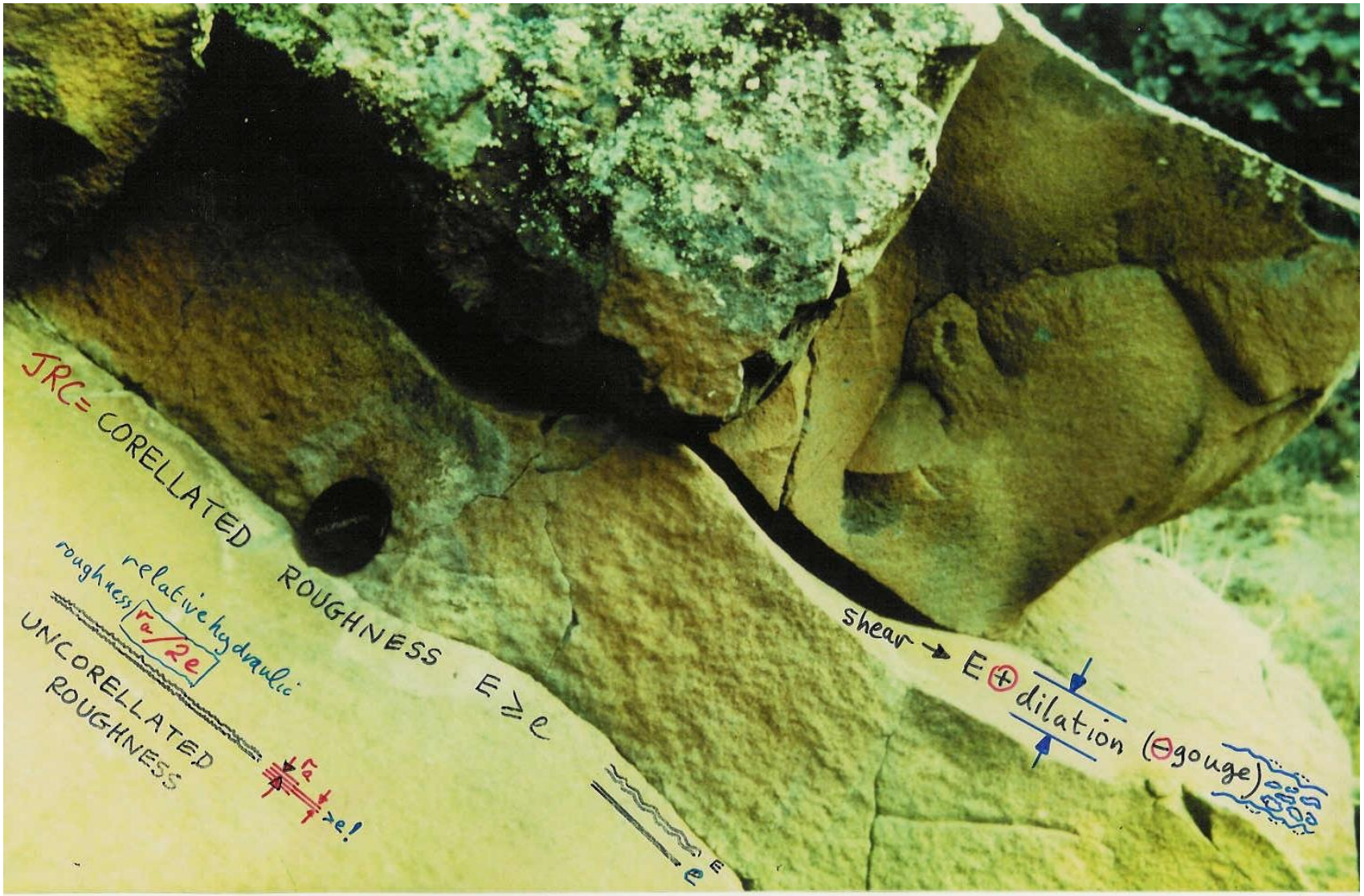
as explanation of loading curve form

(Barton, 1986)

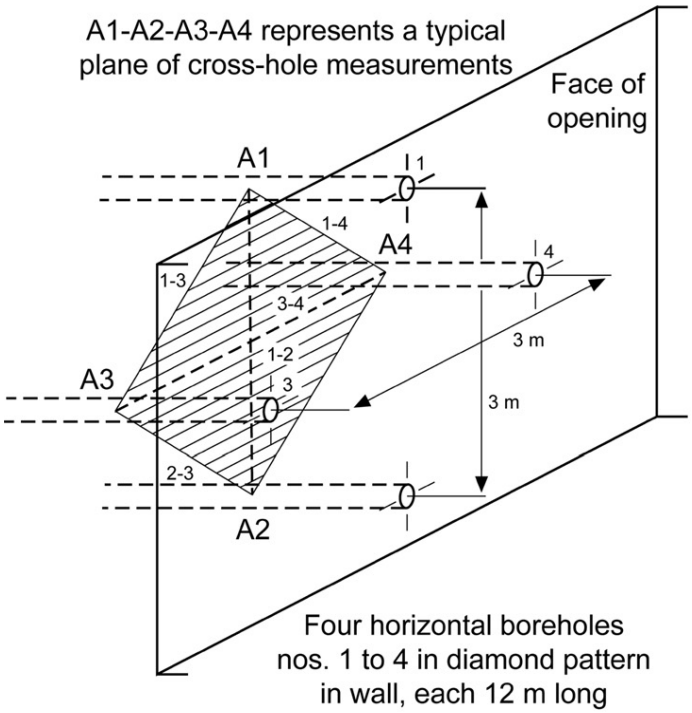


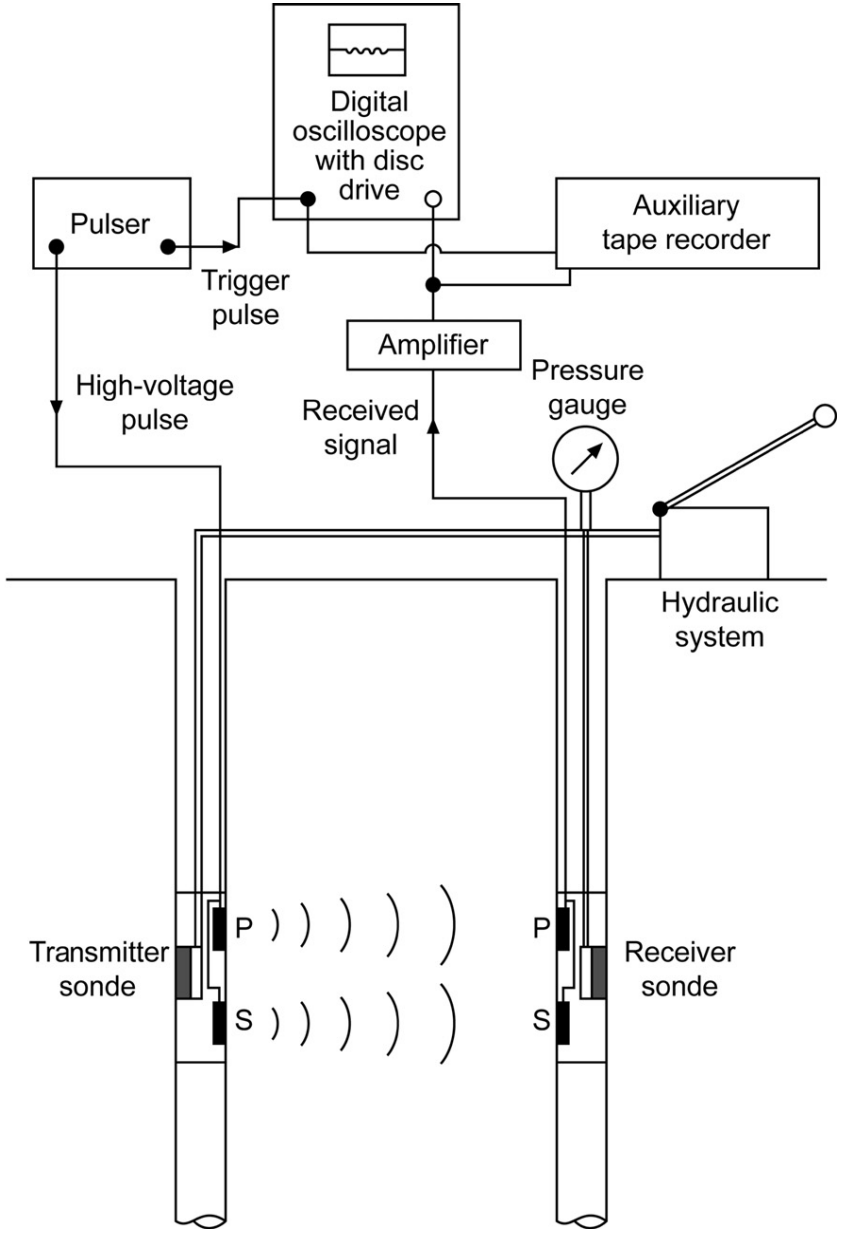
SEE MATCHING UDEC-BB ***SHEAR DISPLACEMENTS***

The waviness of columnar joints has pedagogic uses also .....here the effect of dilation on aperture is illustrated.

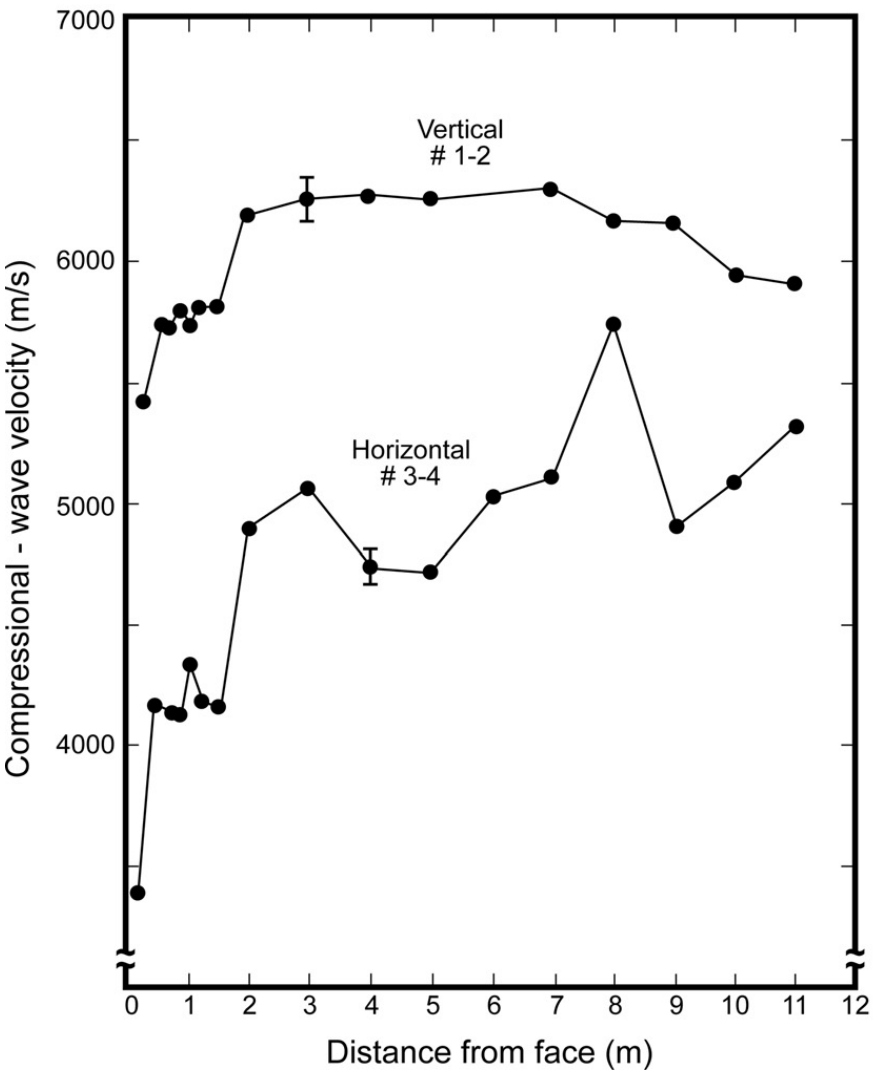


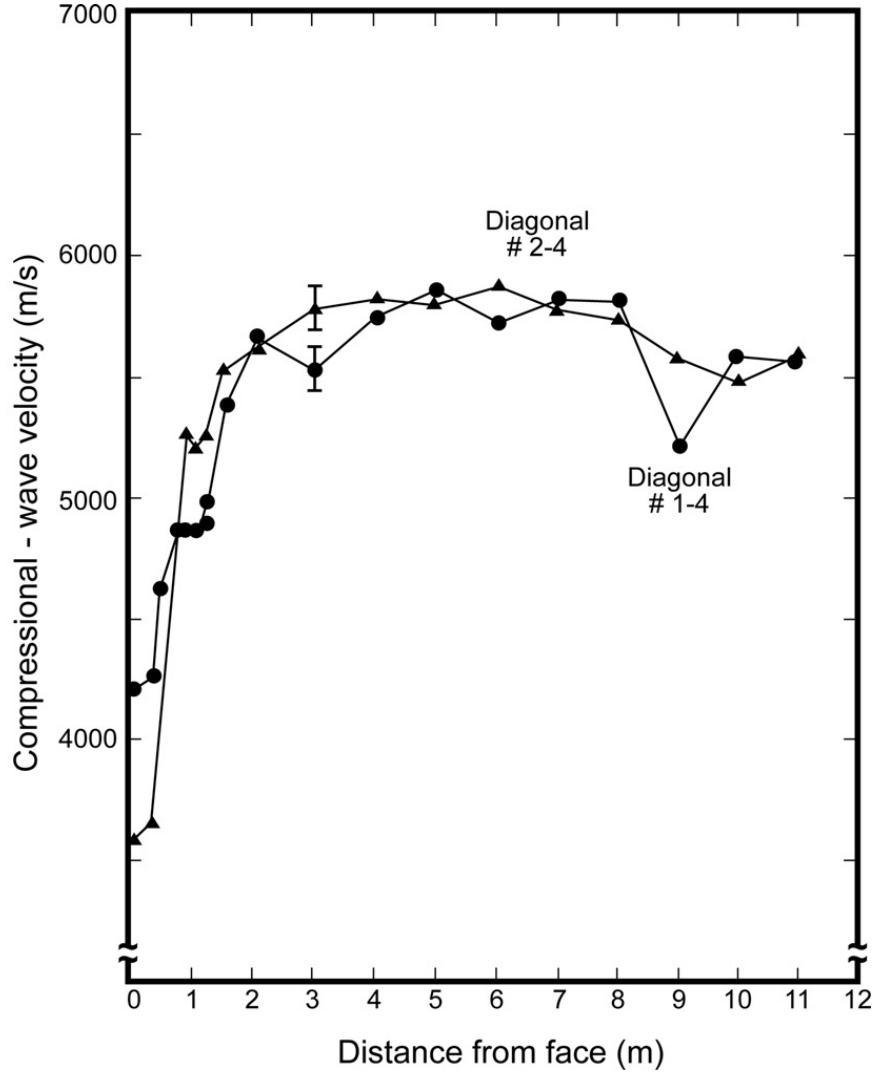
CROSS-HOLE SEISMIC CHARACTERIZATION OF EDZ AT HANFORD SITE....four holes in tunnel face





Four of the selected ray paths and the effect of the EDZ on the P-wave velocities. (King et al., 1984.)

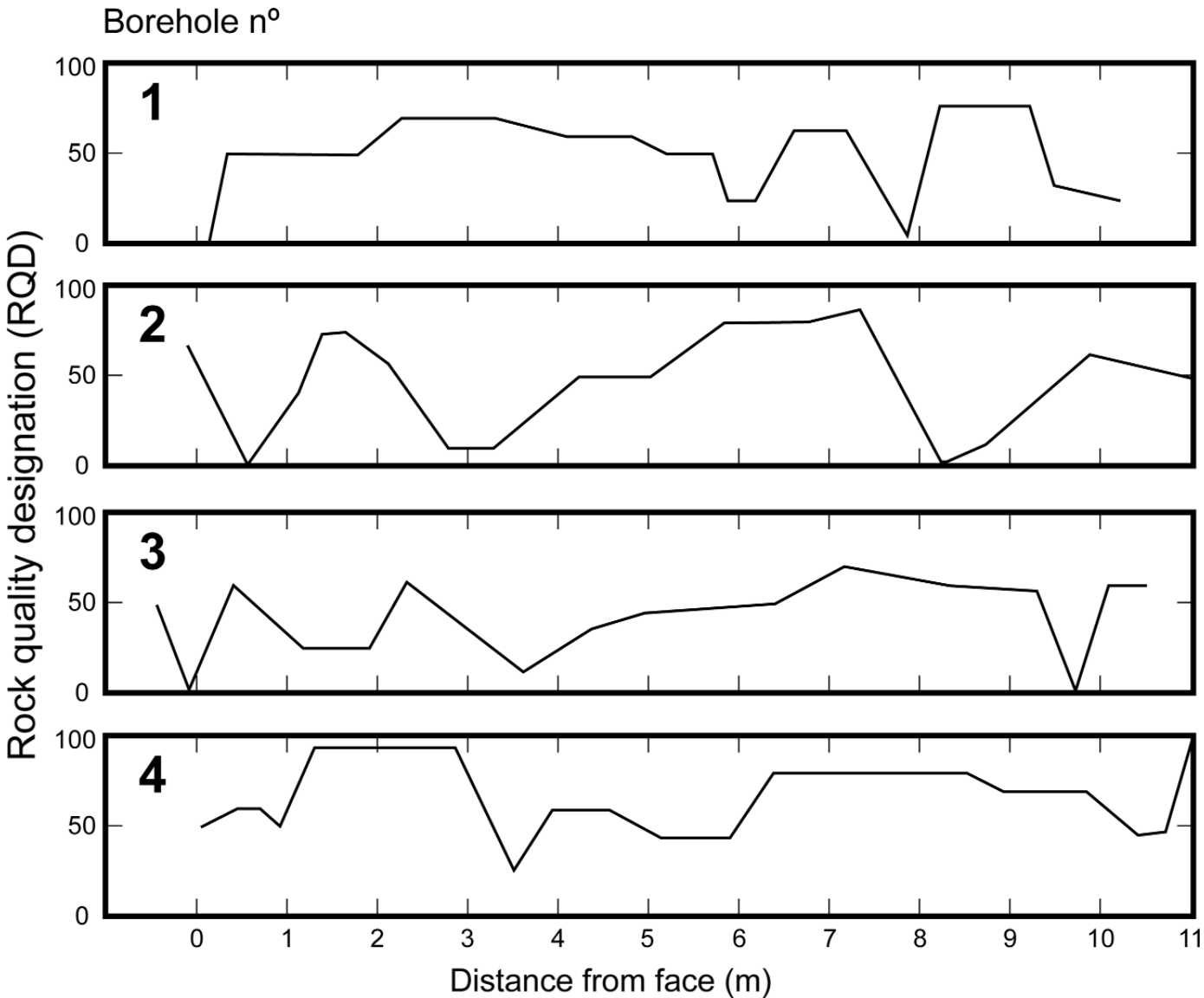




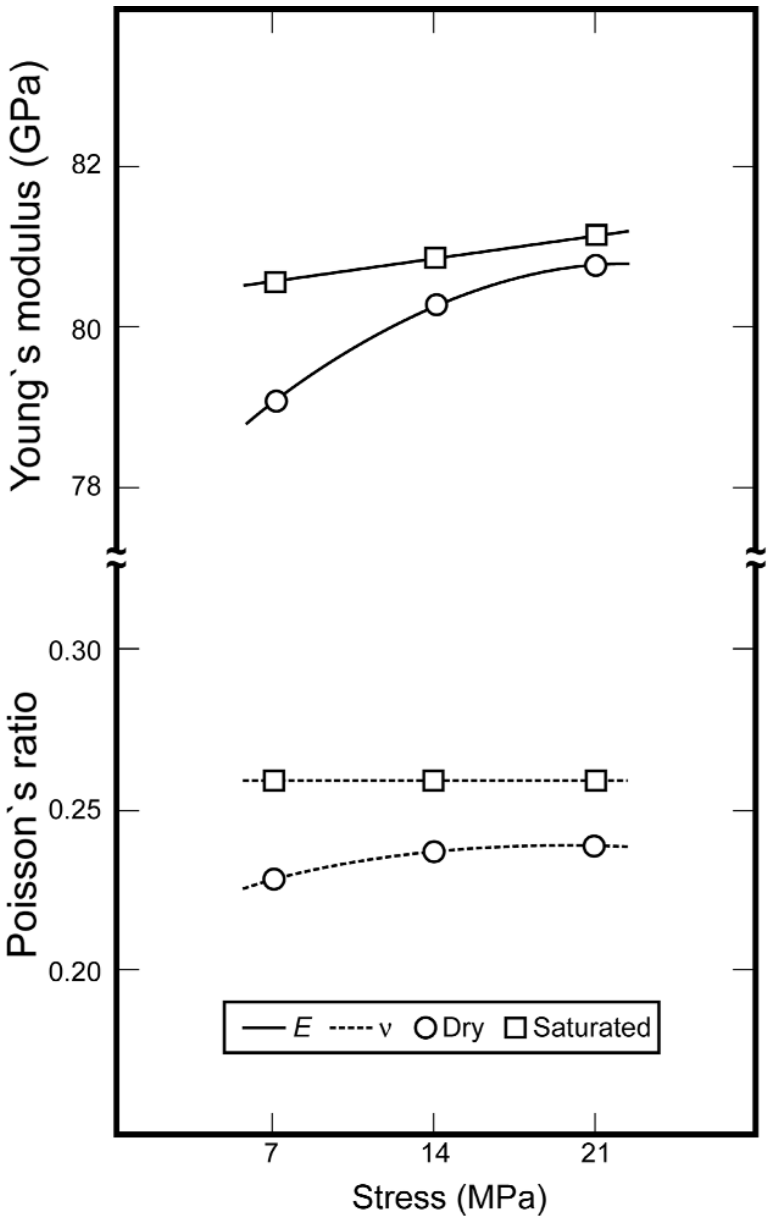
- Signs of loosening effects *across* the sub-vertical joints (columnar joints) were evident in the *horizontal velocity reductions*.

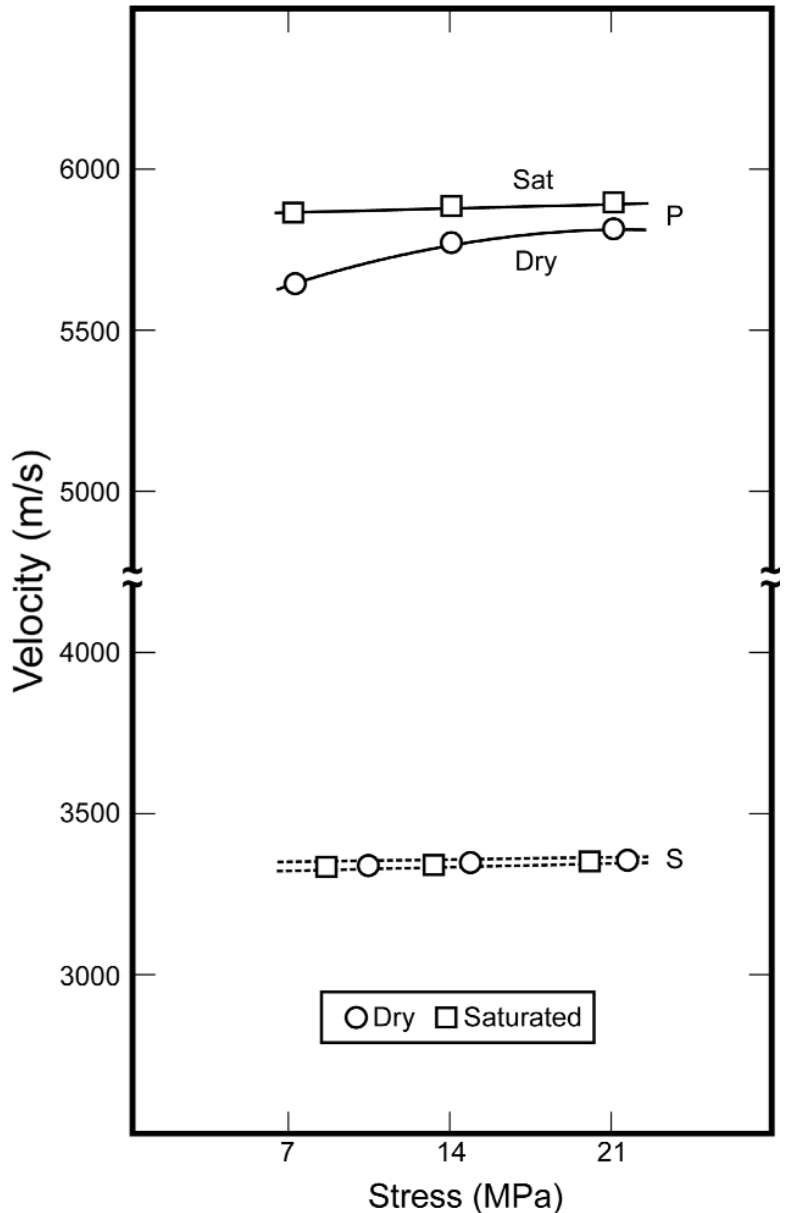
- The additional effects of stress anisotropy and joint anisotropy (and tangential stress) were illustrated in the different seismic paths.

RQD variation in the boreholes in the basalt *showed no marked EDZ effect*. (King et al., 1984).



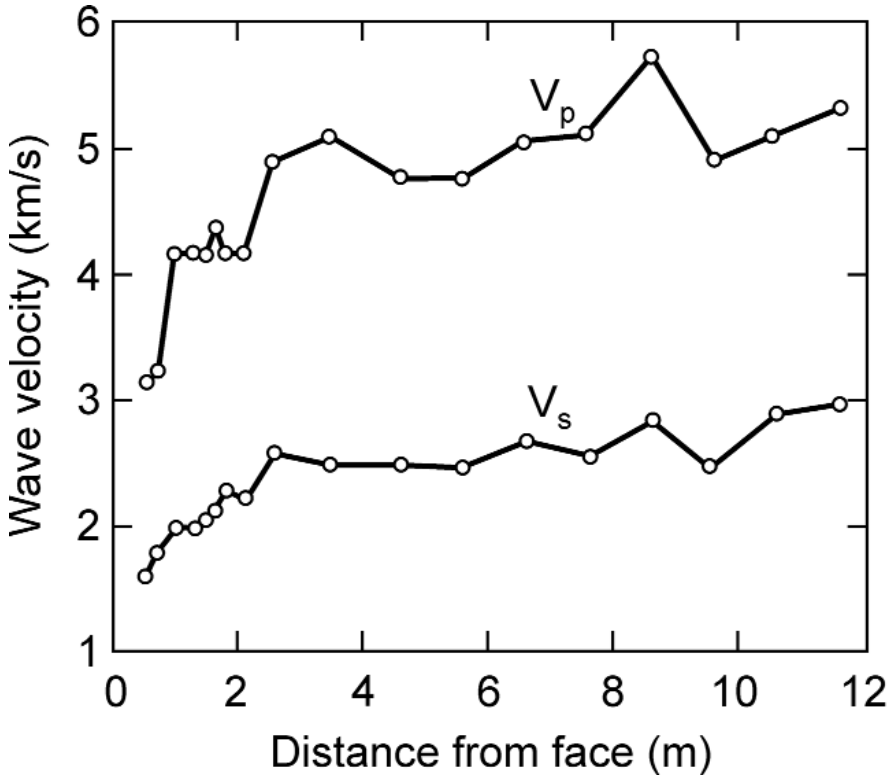
Effects of stress on *laboratory samples* of the basalt, in the dry and saturated states. King et al., 1984

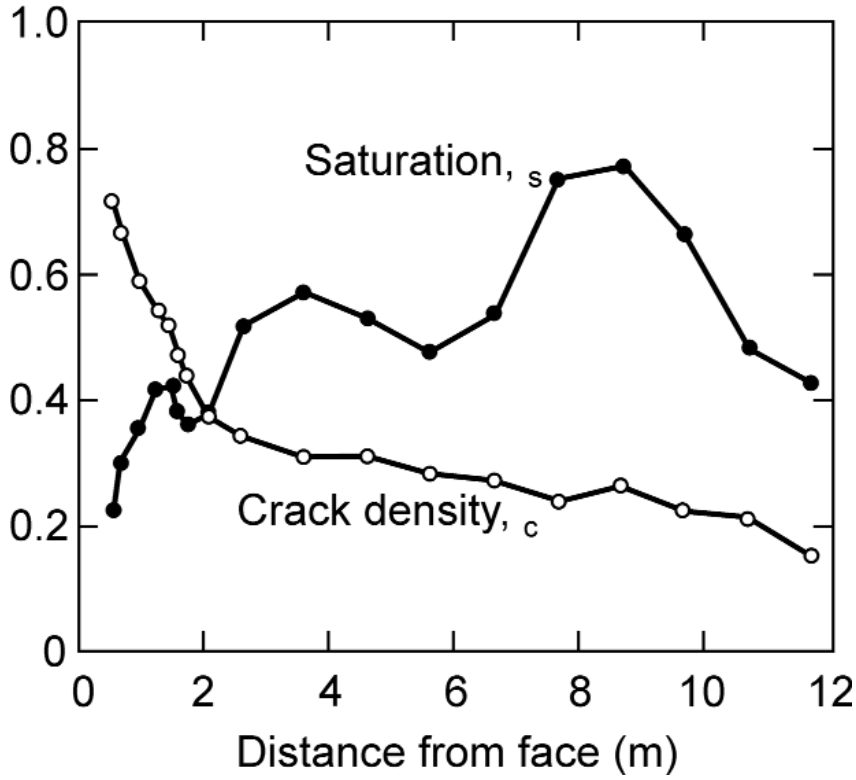


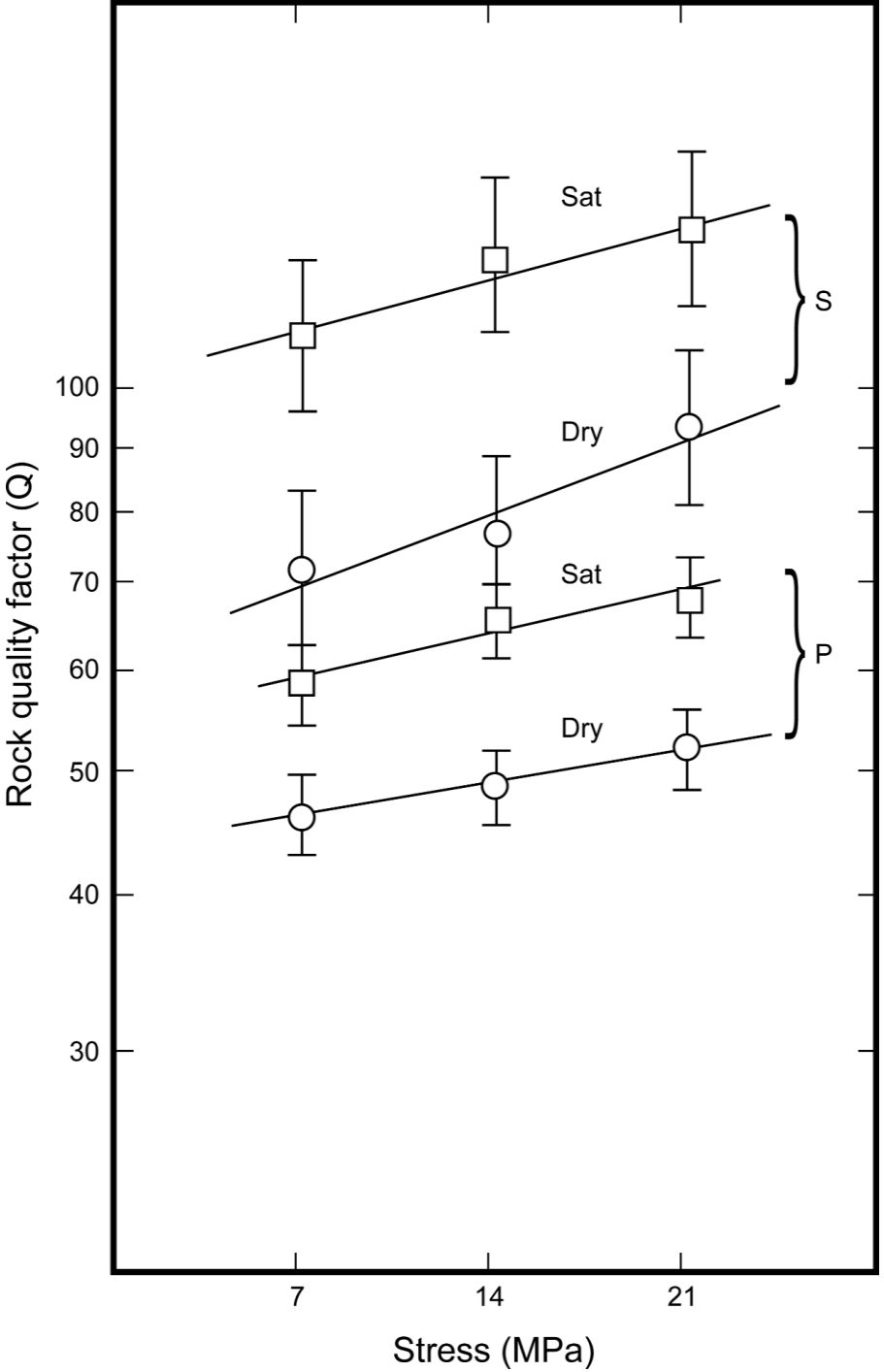


V_p and V_s as a function of depth in the tunnel face

Partial explanations of 'EDZ phenomena' (?) via *saturation level* and crack density variations in the EDZ in the BWIP basalt. (Zimmermann and King, 1985).







The effect of stress on the ***seismic quality Q***, the inverse of attenuation, for the *intact* basalt samples.

Note that the authors' incorrect use of the term *'rock quality factor'* is left unchanged in this reproduction of their drawing.

There are numerical similarities between *rock quality* Q and *seismic quality* Q, *but* *deformation modulus in GPa* is closer numerically to $Q_{seismic}$

$Q_{seismic}$ (= 1/attenuation)

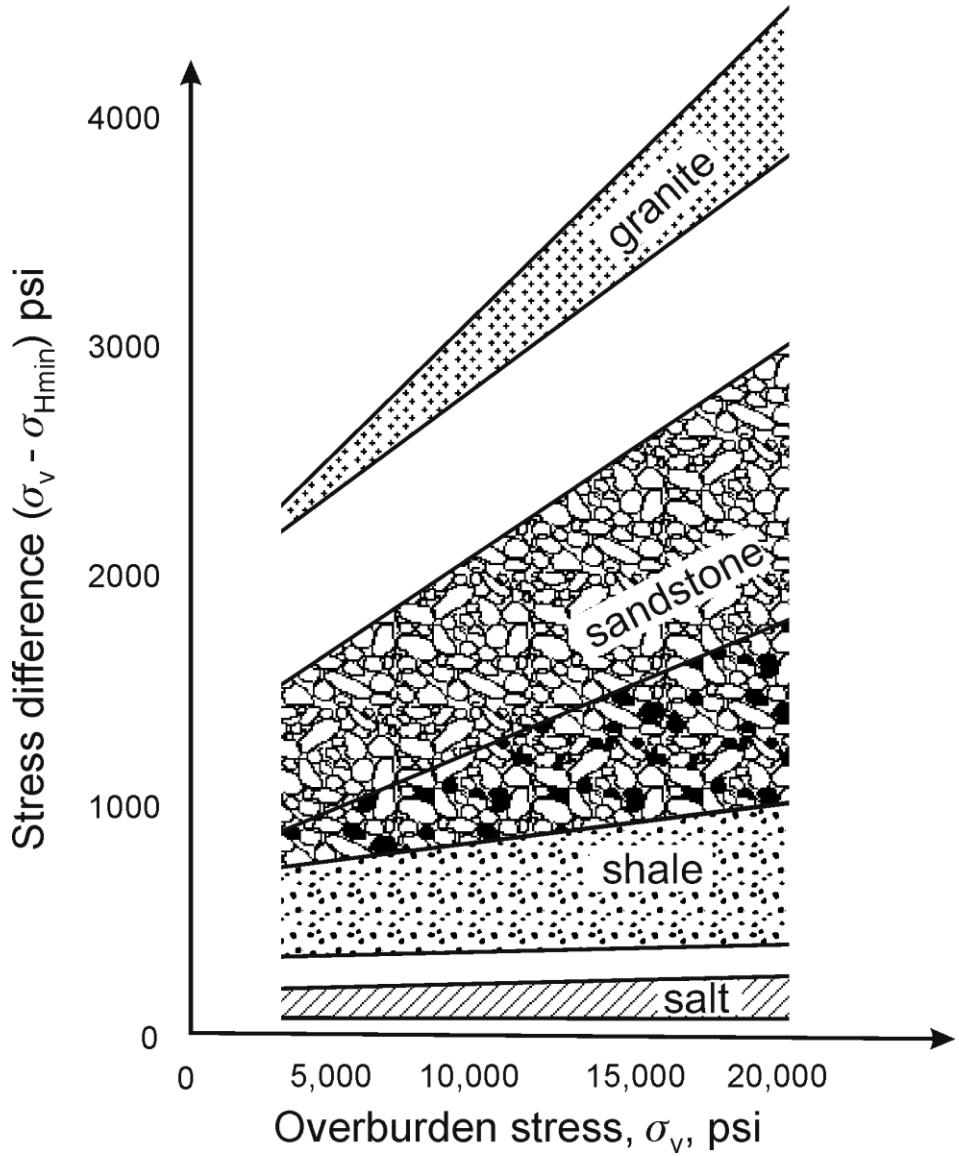
Table 10.1 Some examples of Q_{seis} for longitudinal or bending excitation of various solids, selected from Knopoff, 1964, sorted by magnitude.

Material	Q_{seis}
Steel	5000
Copper	2140
Silica	1250
Glass	490
Diorite	125
Limestone	110
Lead	36
Sandstone	21
Shale	10
Celluloid	7

OUTLINE OF BRAZIL-SECTION OF TALK

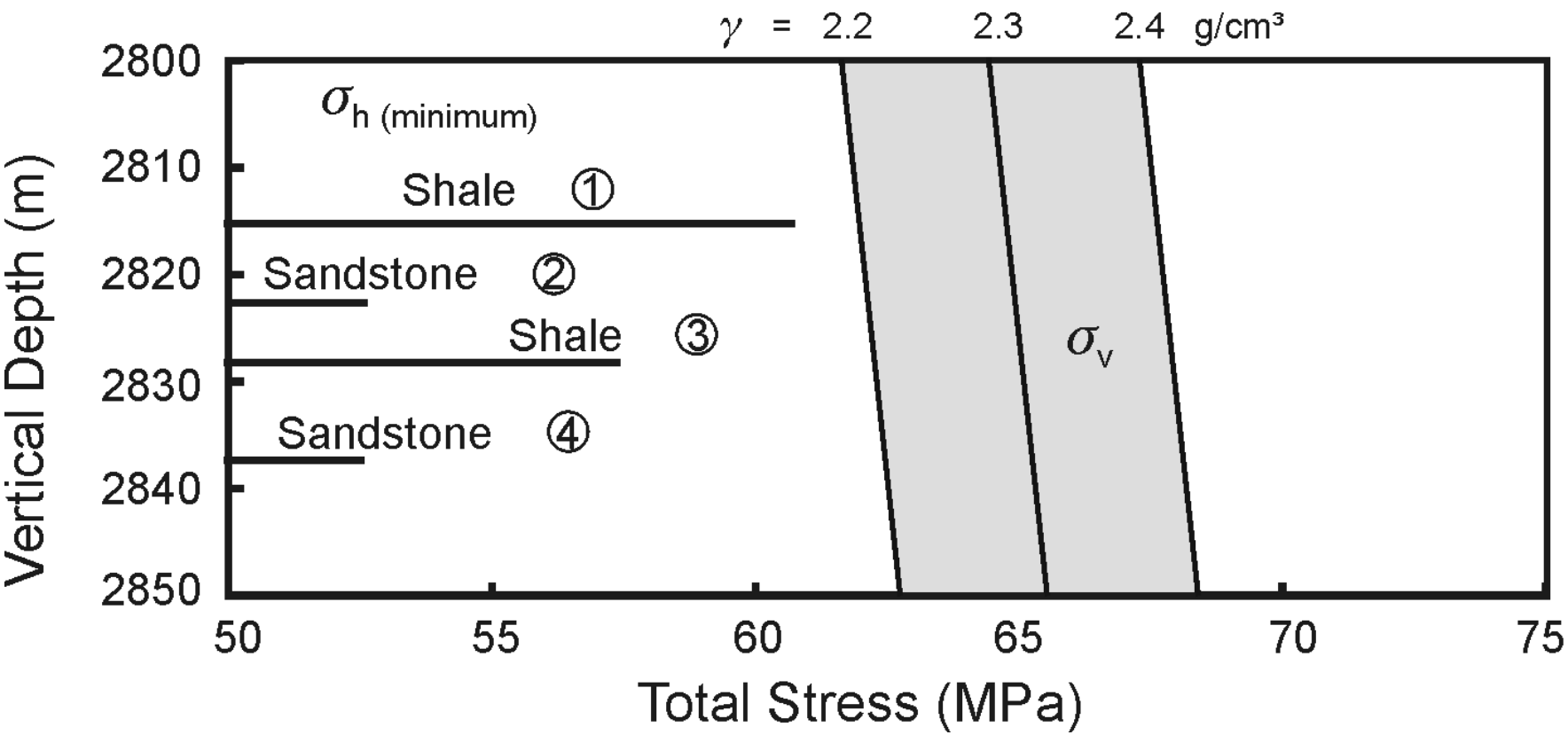
- Tolerance of *stress difference* in soft and hard rock types: at depth and near-surface
- The ITA Hydro Electric Project layout and geology
- Massive and jointed basalt flows alternated
- Possible (additional) reasons for stress concentration
- Empirically-based back-*analyses* of stresses
- Different types of stress-induced failure at ITA HEP

Tolerance of shear stress is rock-type and depth-dependent (Petroleum reservoir data from Swolfs,1977)



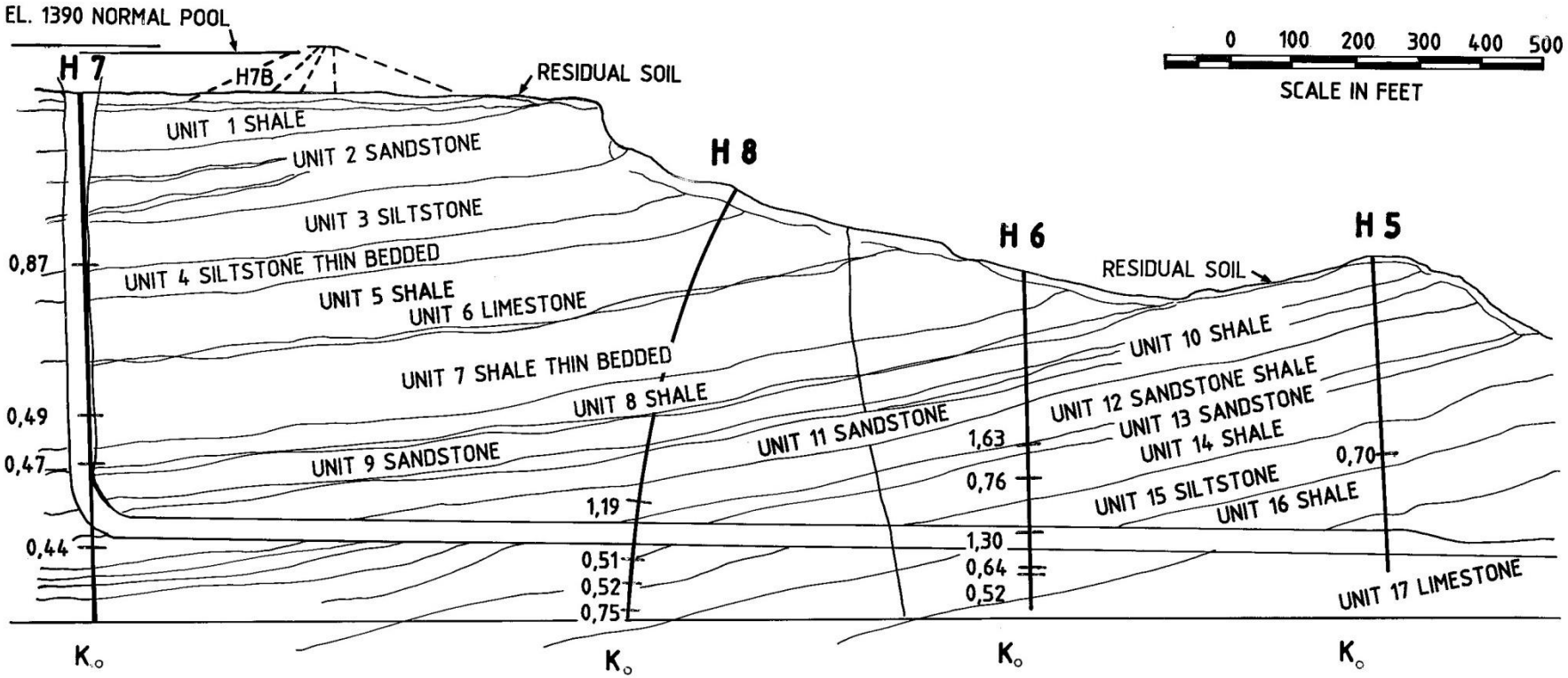
Example of deeply buried sandstone/shale sequencies (mini-HFRAC for Shell, 1982)

(Higher $K_o = \sigma_{h\,min}/\sigma_v$ in the *weakest rock, while the stronger sandstone tolerates a stress difference easily.....**also true for basalt!***



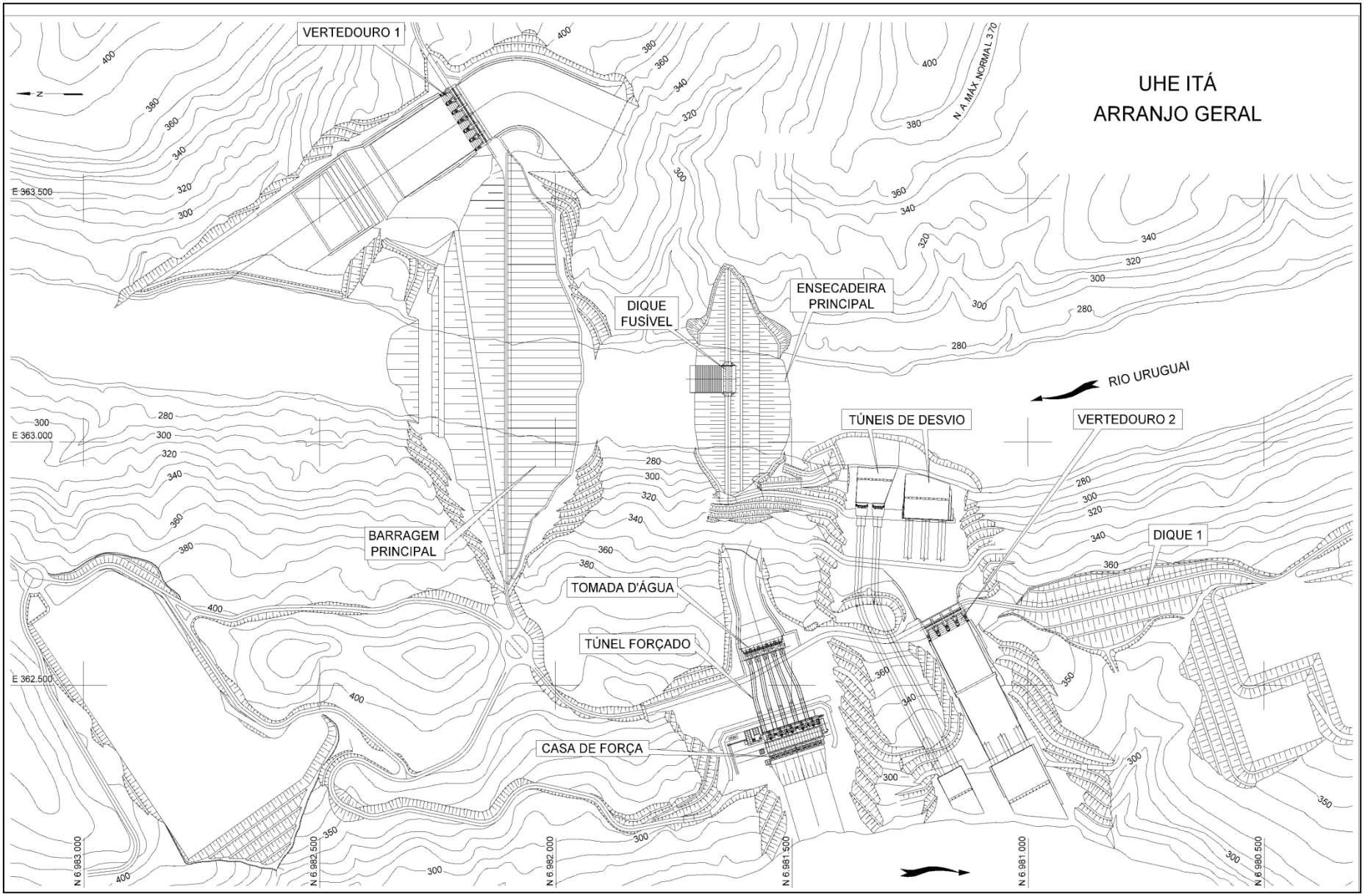
Mini-HFRAC for pumped-hydro,Georgia Power, USA (1980)

(Near-surface: higher magnitudes of $K_o = \sigma_{h\ min}/\sigma_v$ in *stronger* rocks.....as also for basalt which may tolerate an extreme $\boldsymbol{\sigma_{H\ max}/\sigma_V}$!)



SATTELITE IMAGE OF RIVER URUGUAI AND FUTURE ITA *HEP* SITE

THE NARROW RIDGE was THE SITE CHOSEN for the *ITA Hydropower Project*

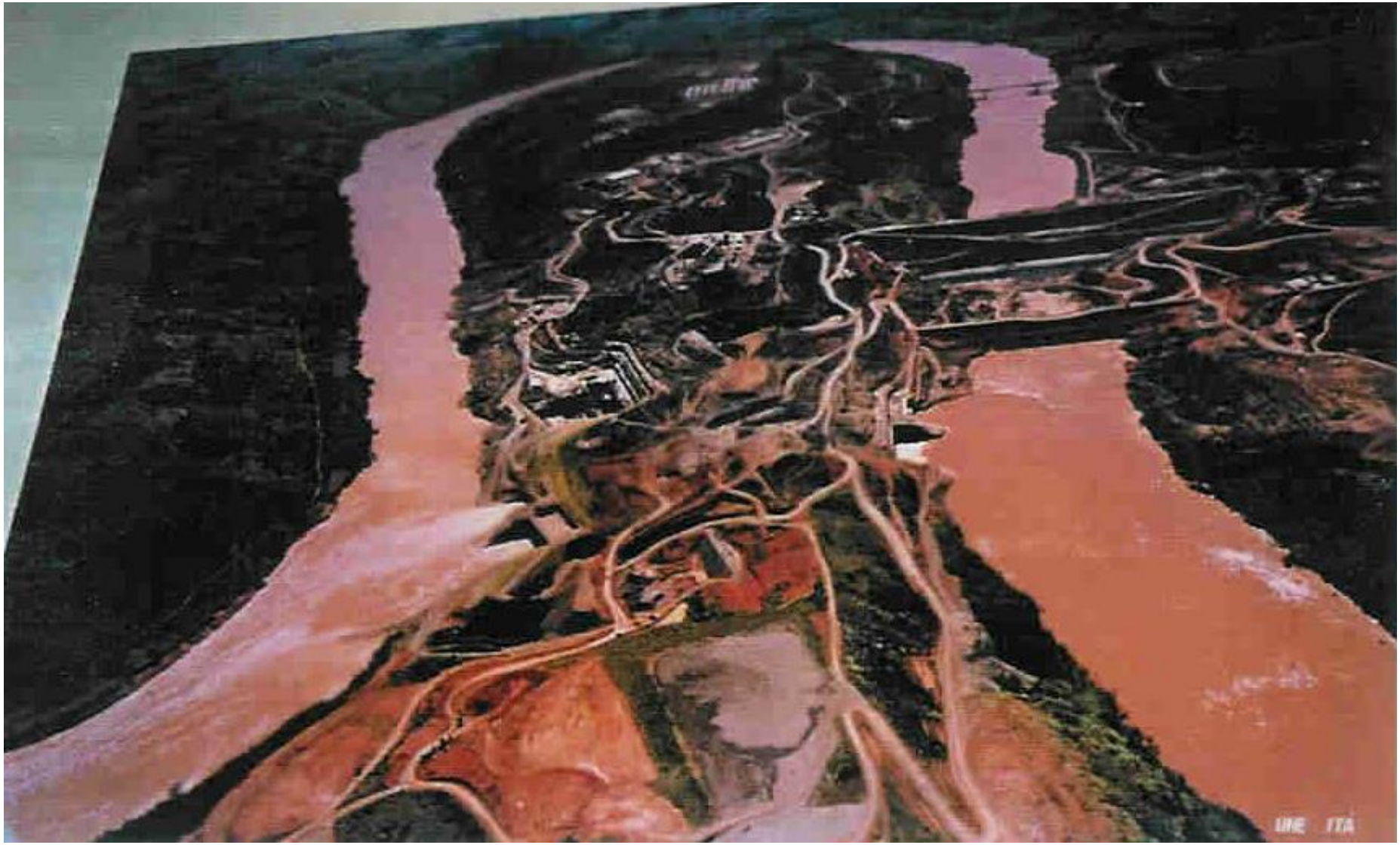


LAYOUT OF THE ITA HYDRO-ELECTRIC PROJECT

INSTALLED CAPACITY AT ITA HEP is 1450 MW

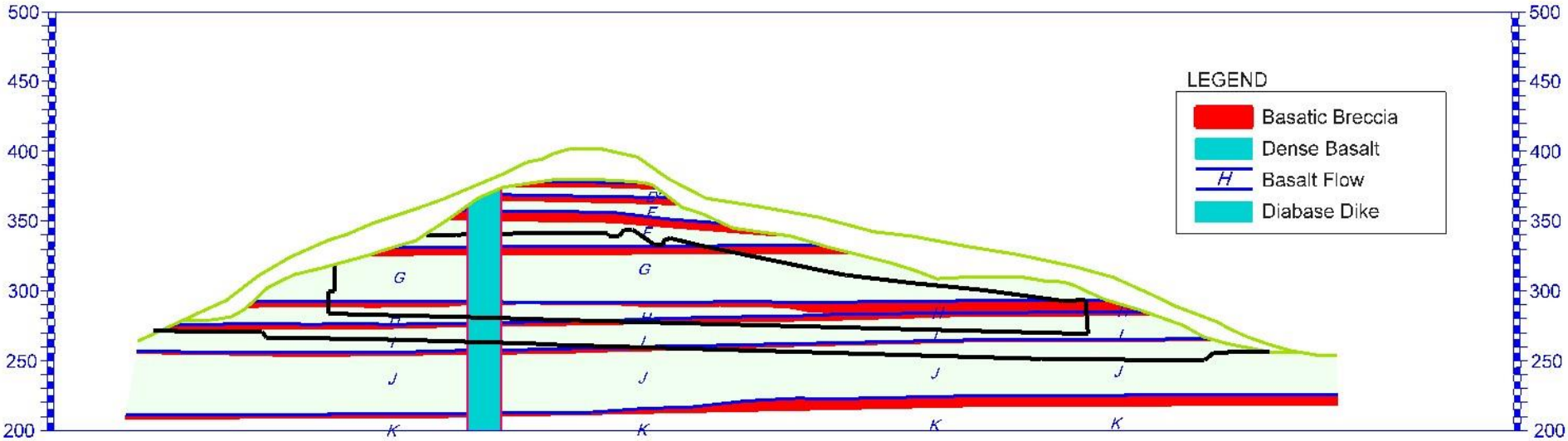
STRESS-INDUCED PROBLEMS IN ALL OF THESE !!

- **River diversion tunnels: *two* main tunnels (1 and 2) 14,0m x 14,0m (with control gates)**
- ***Three* auxiliary tunnels (3, 4 and 5) 15,0m x 17,0m high, (no control gates, operate during floods)**
- **Pressure tunnels 5 x 120m, 9 m diameter, 53º inclined (concrete lined: lower section: steel penstock)**
- **Emergency spillway**
- **Exploratory boreholes?**



RIVER DIVERSION DURING CONSTRUCTION OF *UHE ITA*
Coffer dam in foreground (right), main rockfill dam behind

- *THE THREE AUXILLIARY DIVERSION TUNNELS LOCATED BENEATH THE EMERGENCY SPILLWAY (see still dark water)*
- *THE TWO MAIN TUNNELS (with control gates) ARE FLOWING WATER*



AT THE SITE THERE ARE 4 SPECIFIC BASALT FLOWS

TWO ARE MASSIVE……HIGH Q-value……HIGH E $_{MODULUS}$

TWO ARE JOINTED……LOWER Q-value……LOWER E $_{MODULUS}$

(THE 'H' AND 'I' FLOWS ARE MASSIVE….and attract higher stress...a sandwich with hard filling))

The relative magnitudes of the Q-parameters in the two pairs of flows were as follows:

FLOWS G and J (jointed flows)

$$Q = \frac{70-90}{6-9} x \frac{1.5-2}{1-2} x \frac{.66}{1}$$ **= 5 to 13**

Flows H and I: (massive flows)

$$Q = \frac{90-100}{3-6} x \frac{1.5-4}{.75-1} x \frac{1}{1}$$ **= 30 to 100**

Prior to assumption of <u>significant stress difference</u> **between the two pairs of flows, these were the Q-ranges of 5 to 13, and 30 to 100 respectively.**

Now *assume <u>general high stress</u>* for all these flows, and a preliminary SRF ranging from 0.5 to 2, the above ranges are extended to 2.5 to 26, and 15 to 200 respectively.

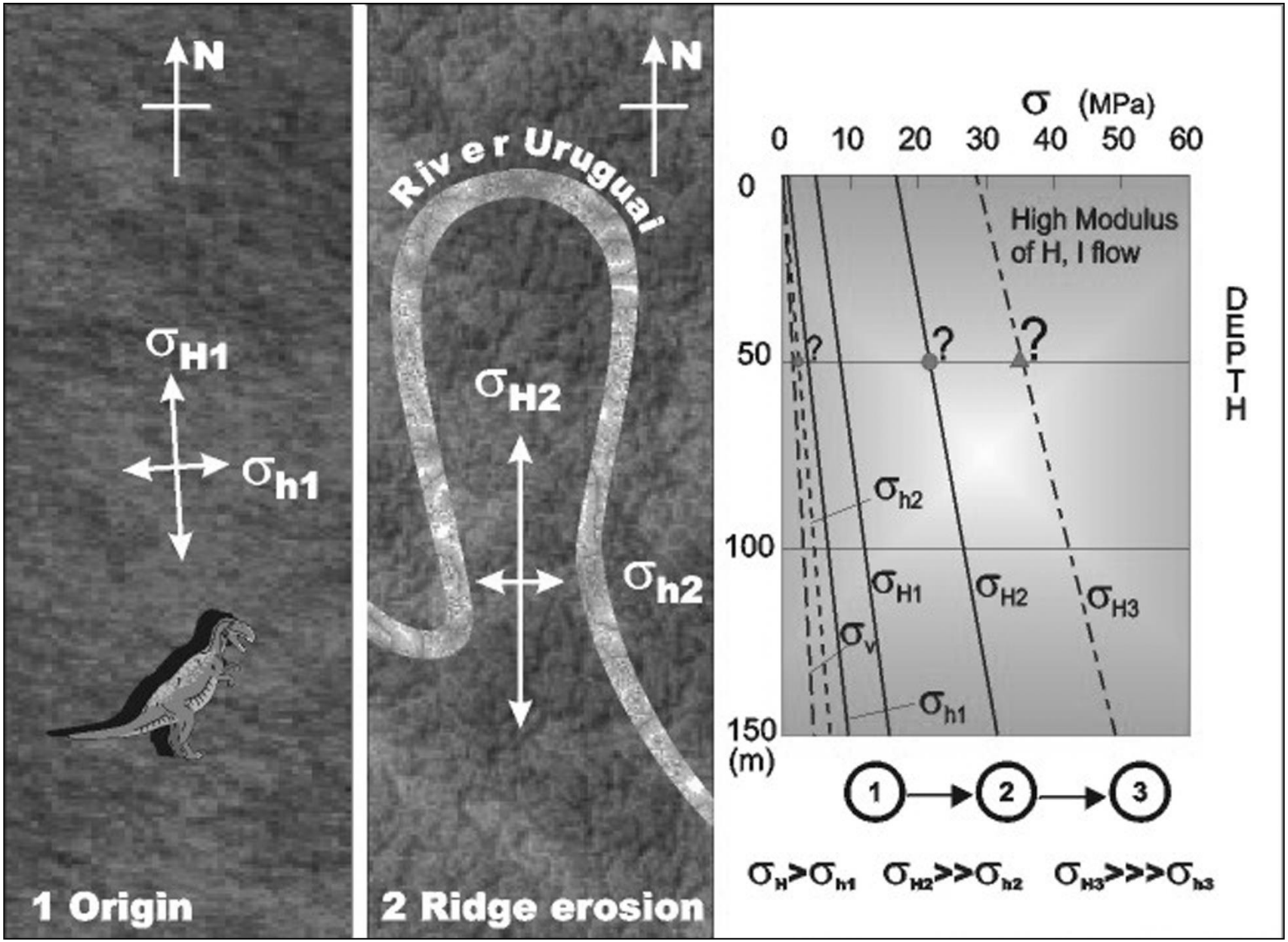
It soon became clear that stresses were higher than expected in these supposedly well known S.E. region Brazilian basalts.

At depths of between 50 and 100m in the tunnels there were:

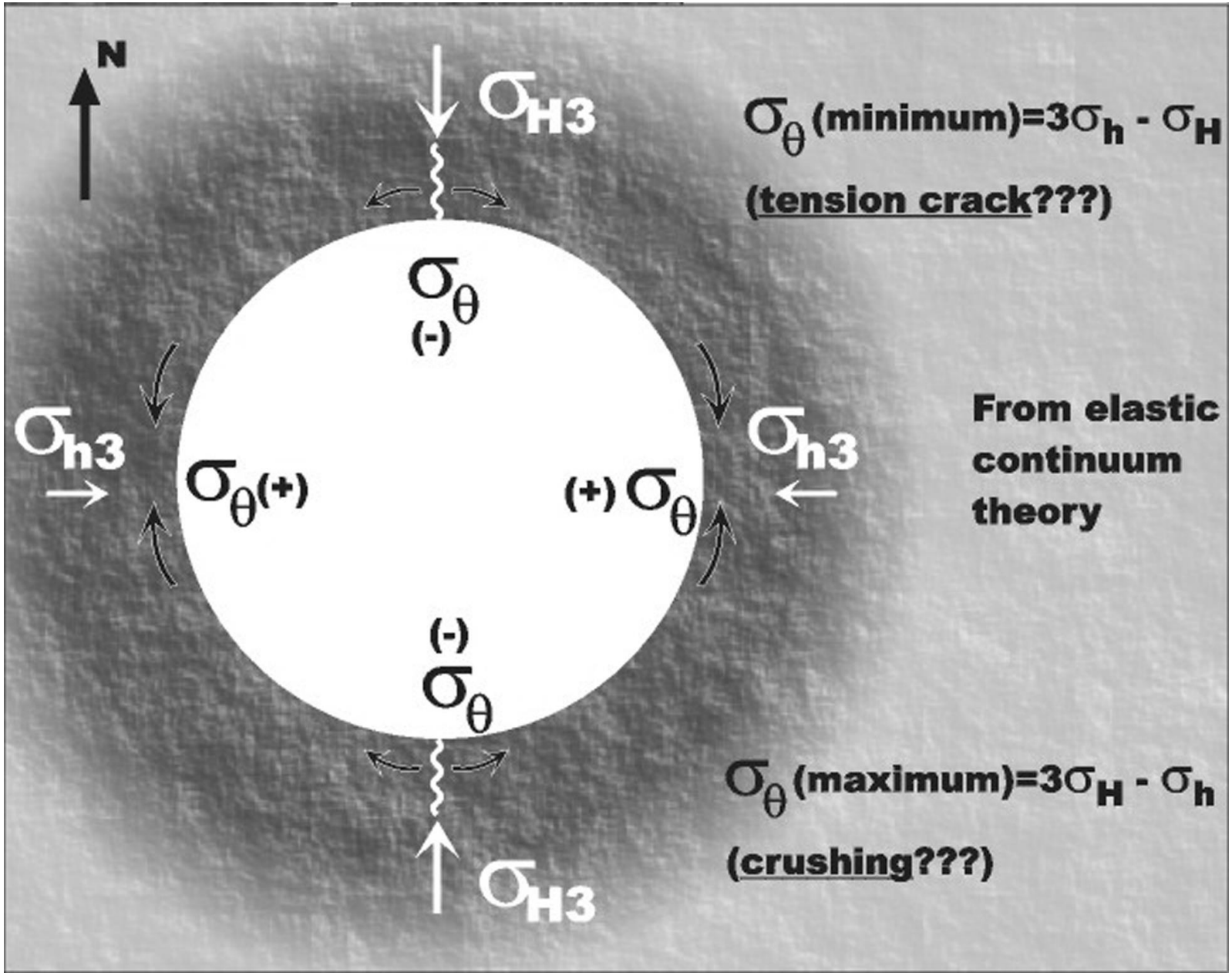
- **popping noises**
- **thin slab ejections**
- **larger than expected deformations**

The stress problems were concentrated in the massive flows ……

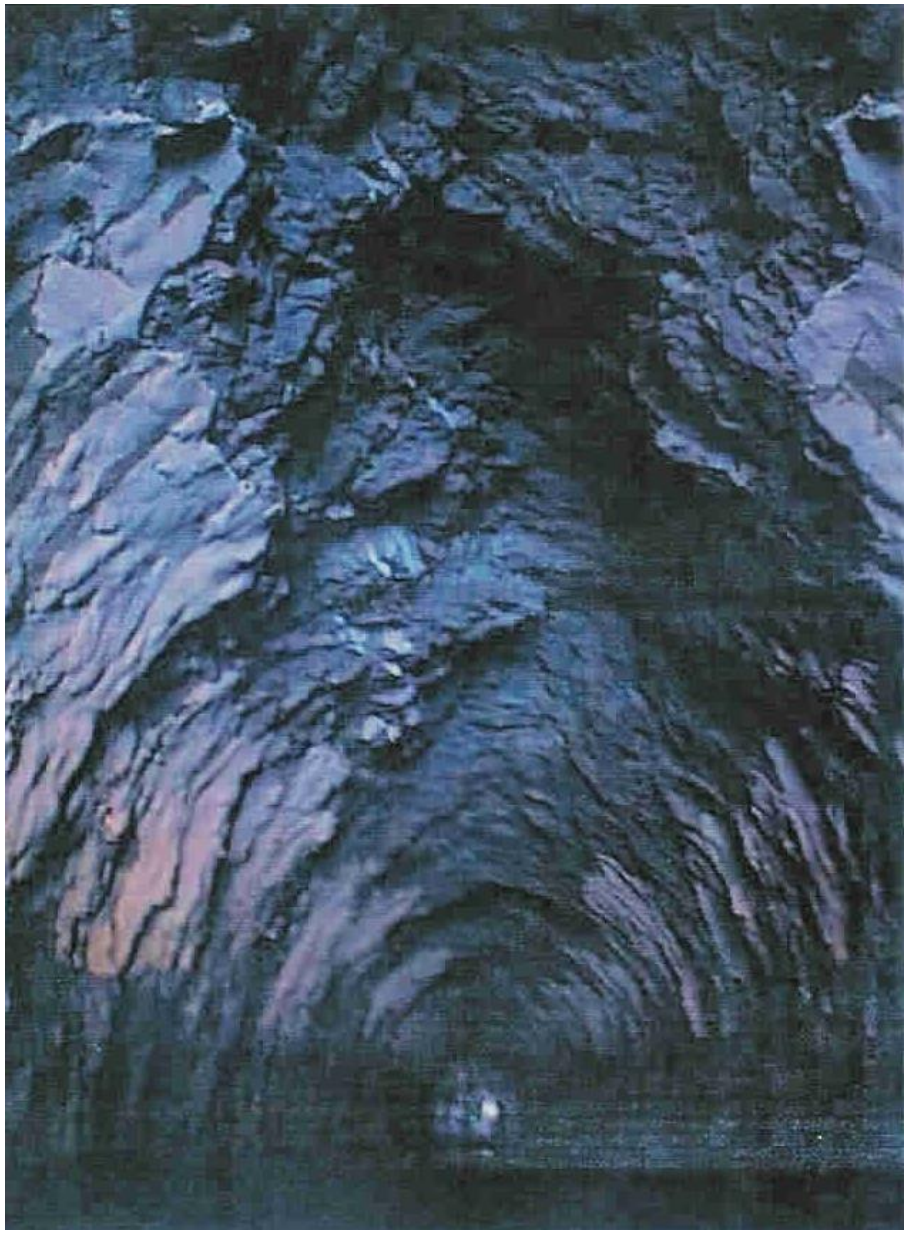
due to their higher modulus, higher stress, and lack of jointing for stress-concentration release)



AN INTERPRETATION OF STRESS CONCENTRATION MECHANISMS



THE CLASSIC ASSUMPTIONS OF TANGENTIAL STRESS CONCENTRATION



THE REALITY OF STRESS-INDUCED FAILURES IN THE ARCHES (AND INVERTS) OF THE DIVERSION TUNNELS. MANY THOUSAND M^3 OF ROCK FAILED…and more was eroded by the water – most in the invert.

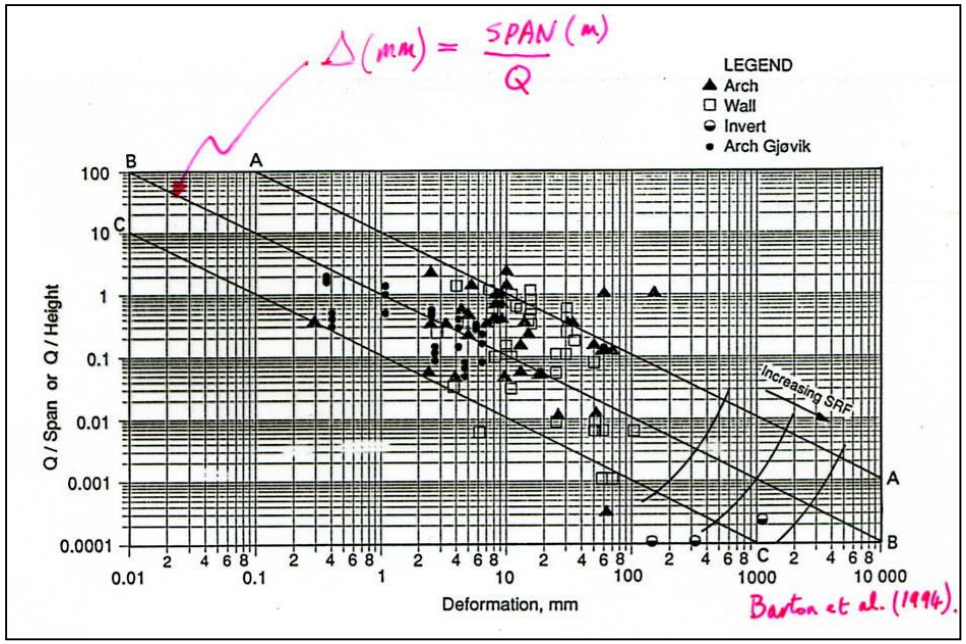
BACK-CALCULATION OF POSSIBLE STRESS LEVELS

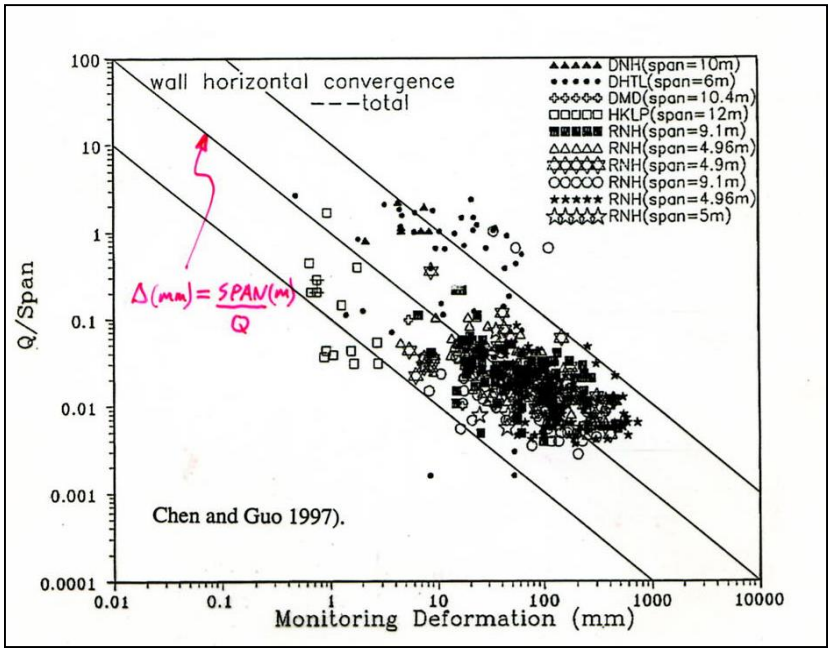
1. <u>from deformation measurements</u>

- **Twenty measurement locations along each of the five diversion tunnels.**
- **Convergences plotted in the $\log_{10}$ Q/ (span or height) versus $\log_{10}$ (convergence) format of Barton et al. 1994 *(see next screen!)***
- **Δ(mm) ≈ SPAN(m) or HEIGHT(m) / Q**
- **In top headings, deformations ranged from 0.5 to 13mm (already mostly higher than expected from central empirical trend of data:**
- **In tunnel TD-5, ten instrument locations also monitored after benching down to the full 17m height**
- **Magnitudes of convergence from 13 to 50mm, with a median value of 22mm, and a mean of 25mm.**

A CRUDE EMPIRICAL METHOD OF DEFORMATION ESTIMATION

Chen and Guo collected hundreds of tunnel deformation data from difficult tunnelling projects in Taiwan, using the same plotting format of logQ / SPAN and log *convergence*.





- **Back-calculation suggested much lower 'stressed' Q-values. 20 mm deformation implied Q ≈ 0.8, and 50mm implied Q ≈ 0.3**

- **(C*haracterization*** prior to tunnel excavation *had* suggested Q-values for massive H and I flows of 15 to 200)

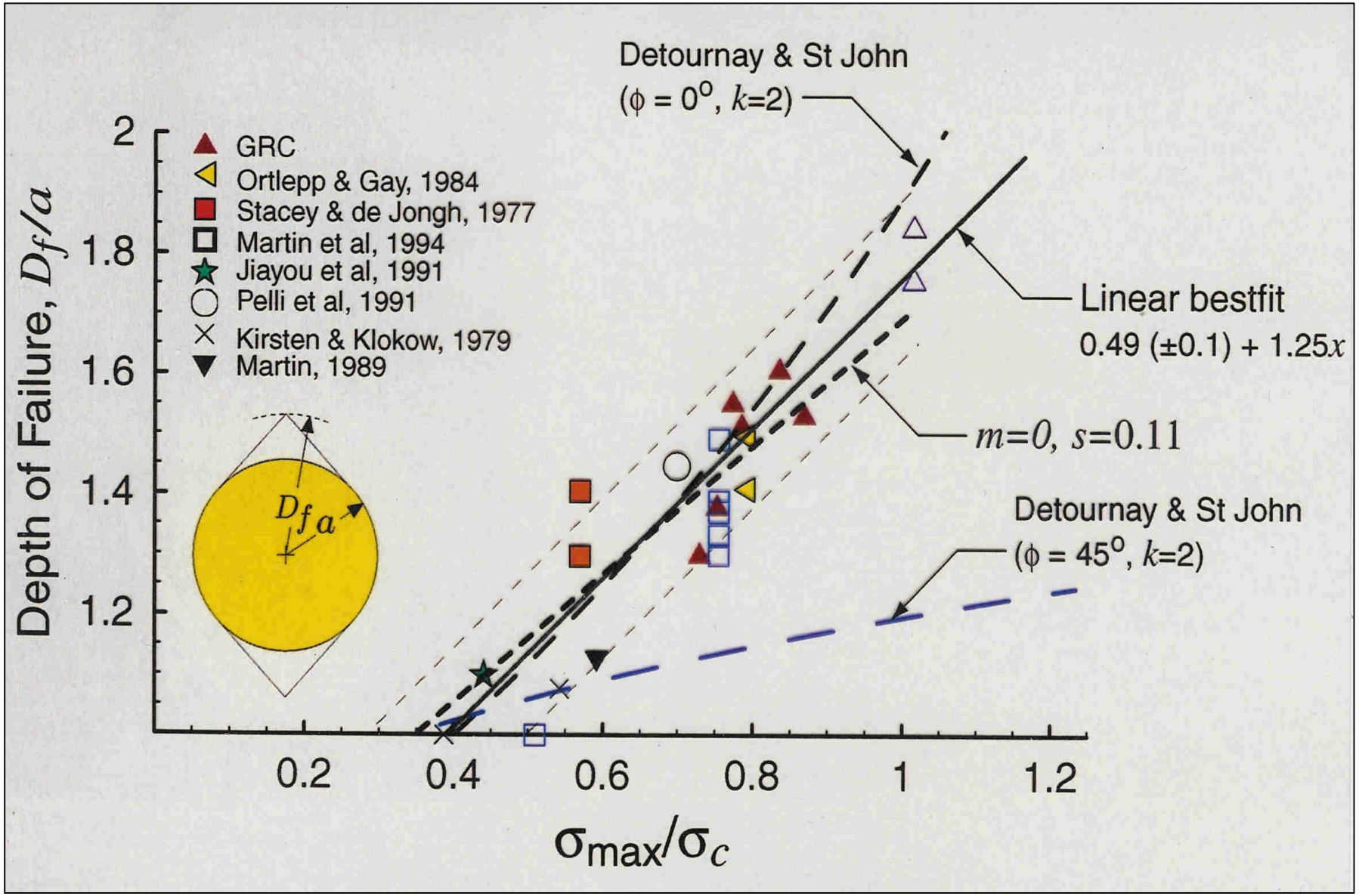
- **C*lassification* for tunnel design through back-calculation from deformations suggested Q-values in the approximate range of 0.3 to 1.5.**

- Need 'stress-slabbing' SRF class of 5-50 (Grimstad and Barton, 1993) to 'explain' these low Q-values, implying σ_c/σ_1 ratio of 5 to 3, or 'elastic behaviour' tangential stress ratio (σ_θ / σ_c) = 0.5 to 0.66

- i.e. a tangential stress high enough to cause failure with rock strength scale effects considered

- **Above ratios suggest σ_H *value might be 47 to 56 MPa* (with $\sigma_c \approx$ 200MPa)**

2. **<u>Next from depth of stress-induced failure (refer to next figure)</u>**



Empirical data for stress-induced depths of failure in relation to stress/strength ratios. (e.g. Martin et al. 2002).

- **Depths of failure are in the range 2 to 3m for average tunnel 'radius' of 8m.**

- Implies ratios of σ_{max}/σ_c of 0.6 to 0.7 when Df /a is in range of (8 + 2 or 3m) / 8 = 1.25 to 1.38.

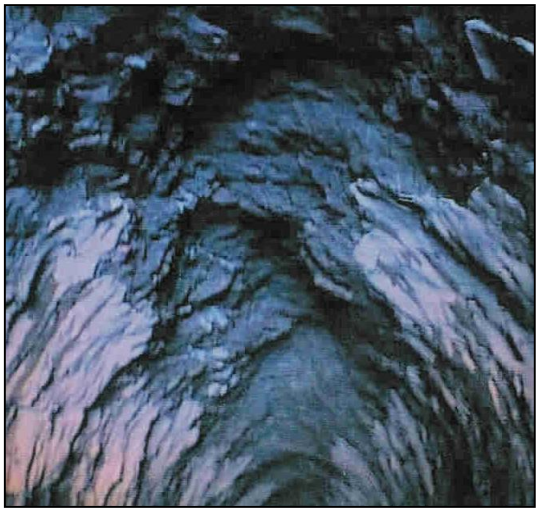
- Taking σ_C as an average 200 MPa, the above implies maximum tangential stress as high as 120 to 140 MPa.

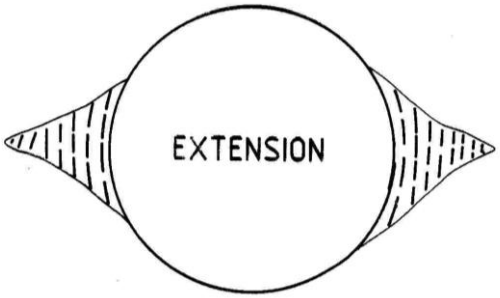
- **Assume relevant vertical stress of 1 to 3 MPa from 50 to 100m overburden depths.**

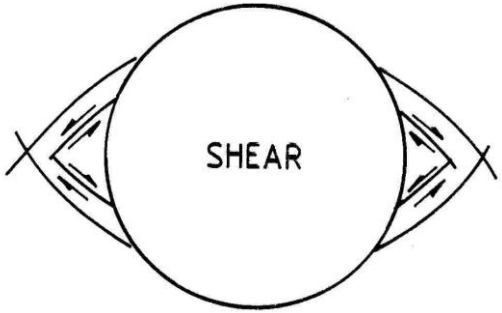
- Assume elastic isotropic theoretical $\boldsymbol{\sigma_\varphi(max) = 3\sigma_H - \sigma_v}$

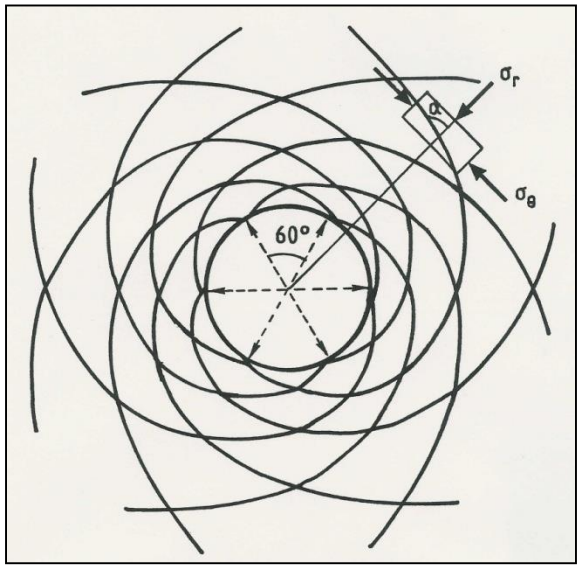
- Therefore $\sigma_H \approx$ 39 to 46 MPa (Previous estimate = 47 to 56 MPa).

- *The implication is therefore that the ratio of principal stresses (σ_H/σ_V) may be as high as 20 to 25……..in the central massive basalt flows*



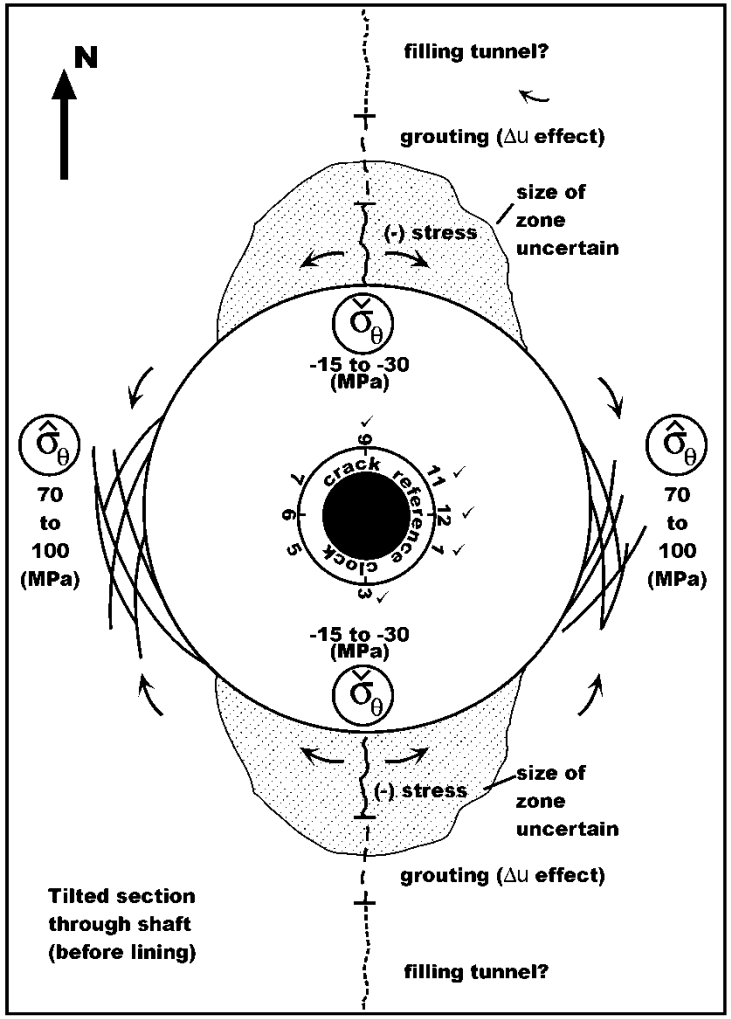


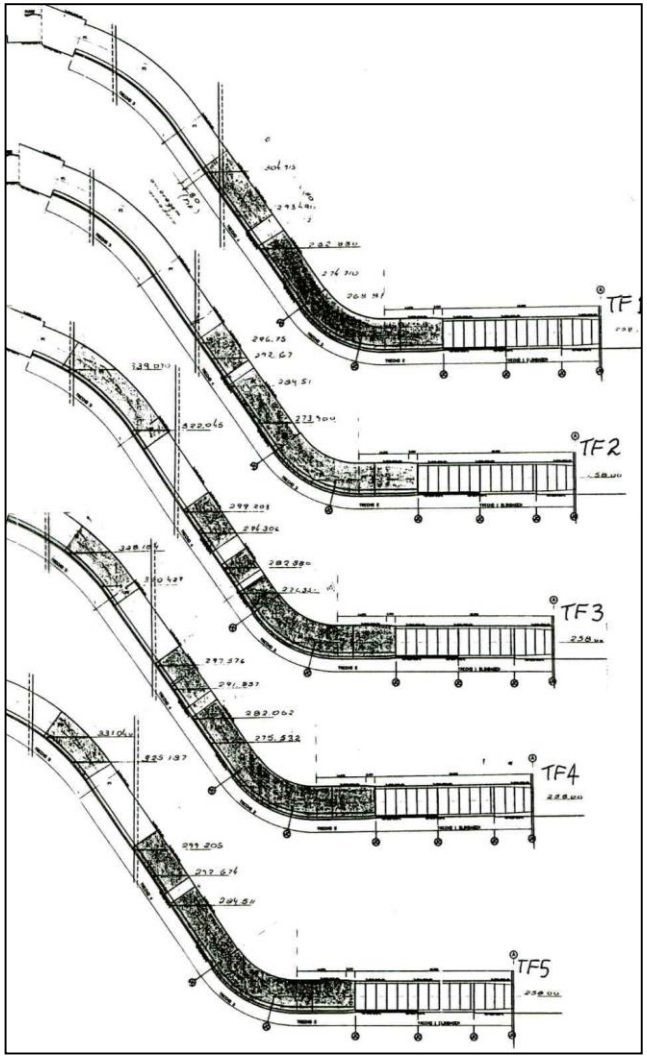




Stress-induced failures in tunnels, in a model and in theory

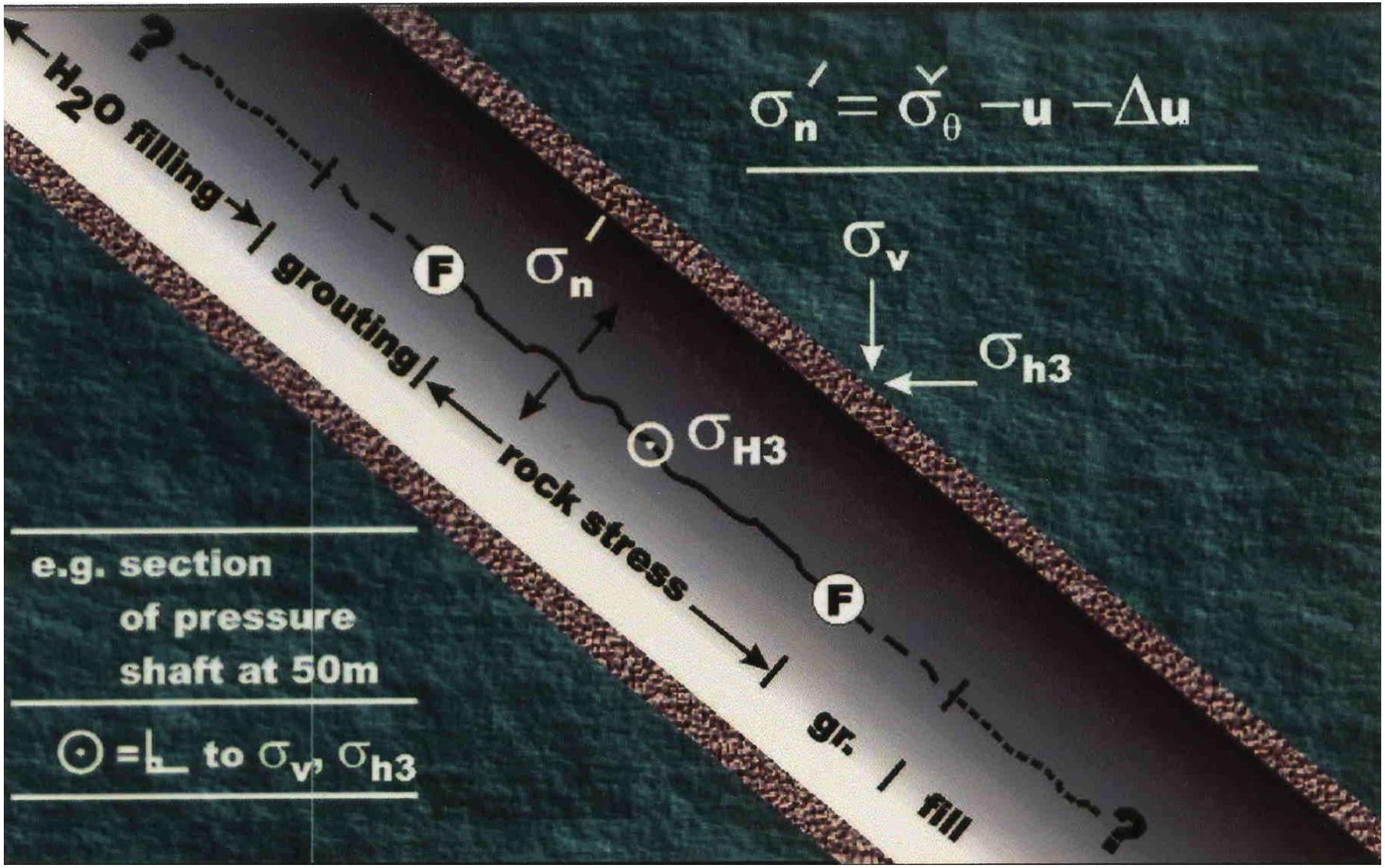
THE PRESSURE TUNNELS….
5 of them, inclined at 53˚



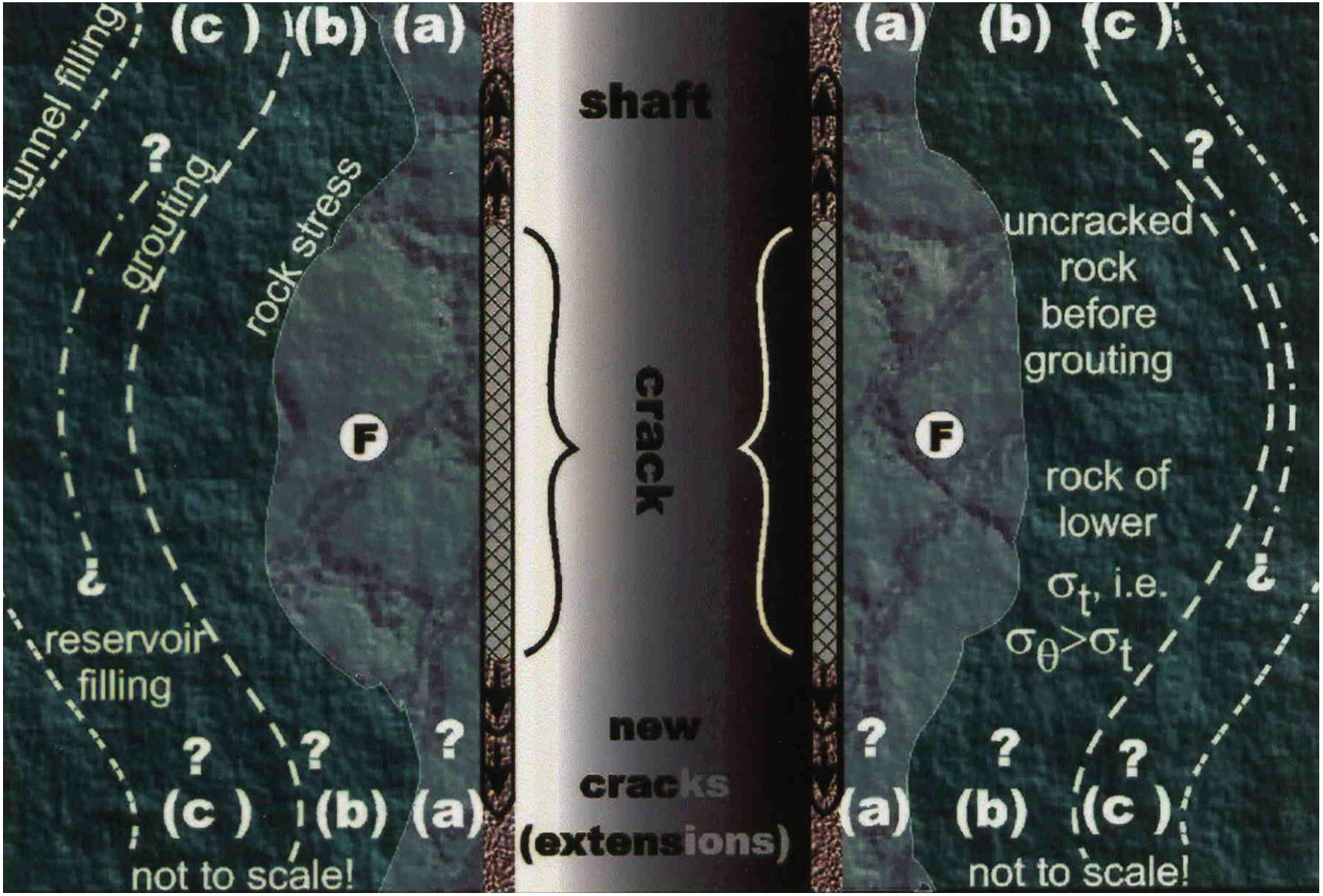


EACH SHAFT WAS CRACKED (SHADED)

Quite linear, sometimes sporadic, sometimes semi-continuous cracking stretched for some 60 to 90 m down each concrete lined pressure shaft



CRACKING DUE TO ROCK STRESS, GROUTING, TUNNEL FILLING



The 125 m-high Itá concrete-faced rockfill dam and 1450 MW powerplant in Brazil

CONCLUSIONS

1. Do not neglect the possibility of surprises…….at any site.

2. ‘Over-coring’ by a river, stress concentration due to modulus contrast , human intervention – i.e. tunnelling…….EACH caused stress problems:

   a) in boreholes
   b) in diversion tunnels
   c) in pressure tunnels
   d) in the rock spillway

3. Even stress measurements would have been problematic with $\sigma_H / \sigma_V \approx 20$ to 25 !