ANISOTROPY IS EVERYWHERE: TO SEE AND TO MEASURE

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(Ove Stephansson 75th anniversary)

DEFINITION(S) of ANISOTROPY

From Greek *anisos* = 'unequal'

1. Not isotropic.

2. Having properties that differ according to the direction of measurement.

3. An "axis of anisotropy" is defined as the axis along which isotropy is broken. (May take liberties with this definition later).

TYPICAL CAUSES, AND RESULTING ANISOTROPIC PROPERTIES

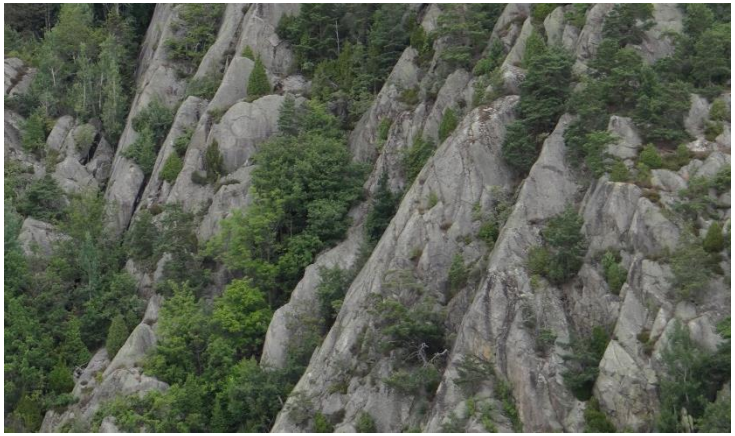
1. ***SEDIMENTARY ORIGIN*: BEDDING**
2. ***METAMORPHIC ORIGIN*: FOLIATION, CLEAVAGE, SCHISTOSITY**
3. **IGNEOUS ORIGIN: COOLING, DYKES, SILLS**

4. **UNEQUAL PRINCIPAL STRESSES (e.g. $\sigma_H > \sigma_h$)**
5. **ROCK STRUCTURE (dominant JOINTING)**
6. **MICROCRACKING (ORIENTED // to σ_1) and (conj.) SHEARING**

7. **SEISMIC VELOCITY (large azimuthal variation possible)**
8. **PERMEABILITY (huge azimuthal variation possible)**
9. **DEFORMATION MODULUS (large azimuthal variation possible)**
10. **ROCK QUALITY (Q anisotropic due to RQD, Jr/Ja, also SRF)**

ANISOTROPY

IS EVERYWHERE



Kashmir

Australia

Norway

China

ANISOTROPY INCREASED BY DIFFERENTIAL WEATHERING

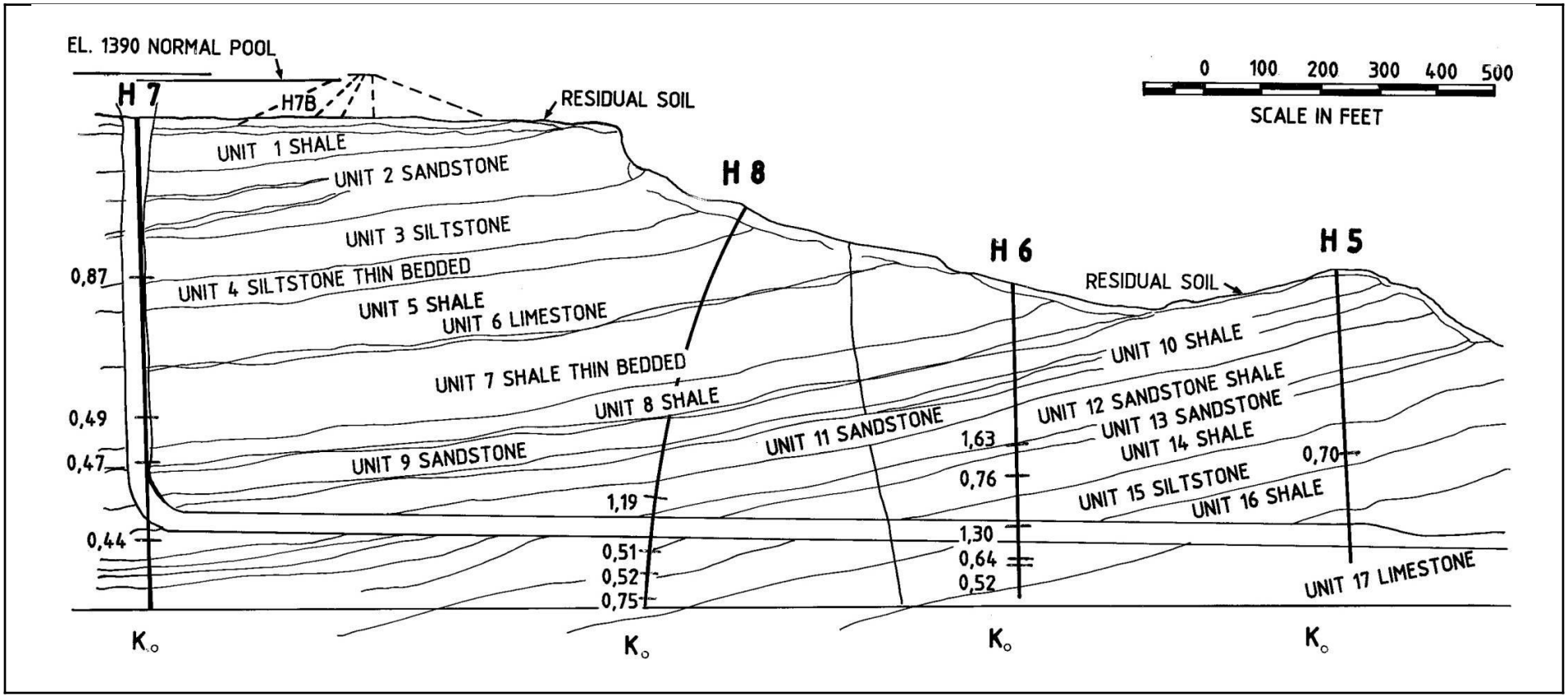
SOME OBSERVATIONS ABOUT STRESS ANISOTROPY, FROM NB/TERRATEK H-FRAC MEASUREMENTS IN THE 1980'S

K_0 values (a form of anisotropy when $K_0 \neq 1$) seem to be related to **deformation modulus** in the near-surface.

Lowest values with lowest assumed moduli.

(highest K_0) sandstone → siltstone → shale (lowest K_0)

(Rocky Mountain Pumped Hydro. Barton, 1981, 1986)



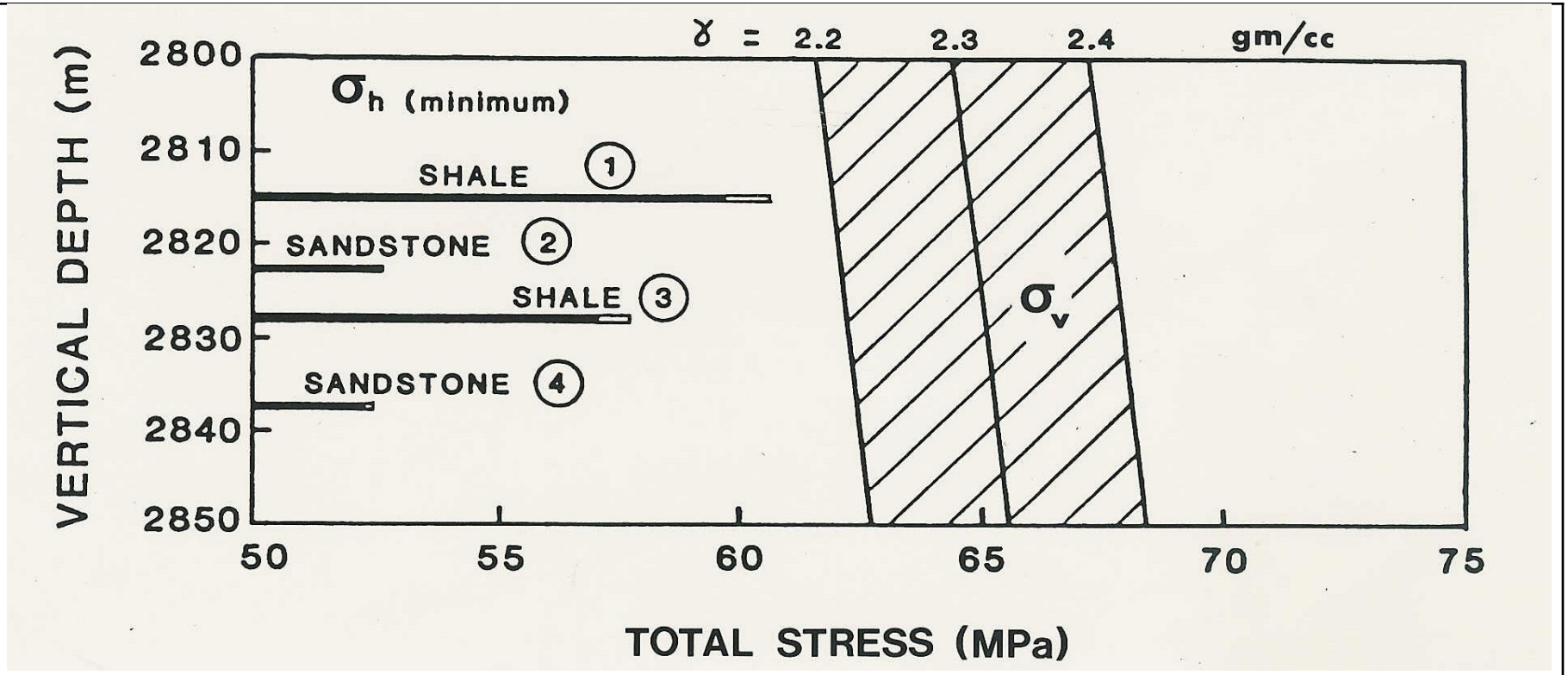
BUT : At sufficient depth the limited shear strength of the lowest modulus (cap-rock) shale/salt

IN A PETROLEUM RESERVOIR

reverses the previous anisotropic 'order'.

Shale now has highest $\sigma_{h\ min}$ (*Salt would behave likewise*)

(It is therefore that we have petroleum reserves! (Barton, 1986, 2006)



STRESS ANISOTROPY

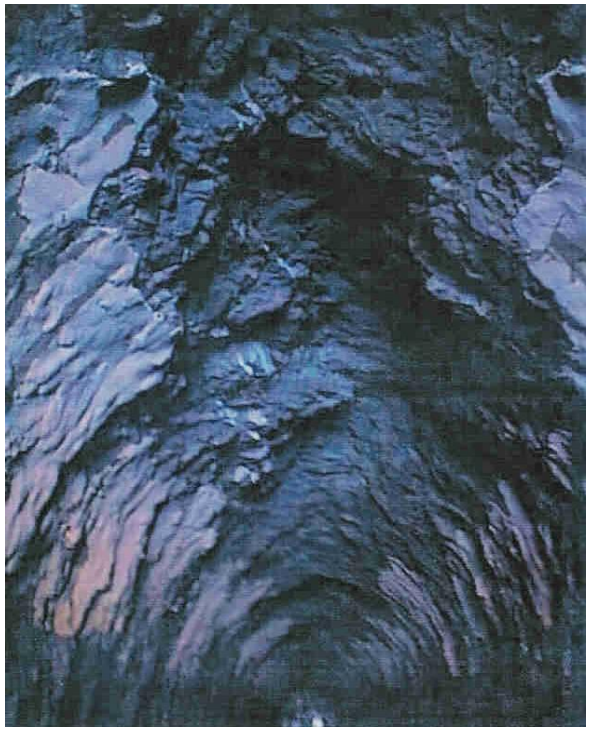
(DUE TO MODULUS CONTRASTS)

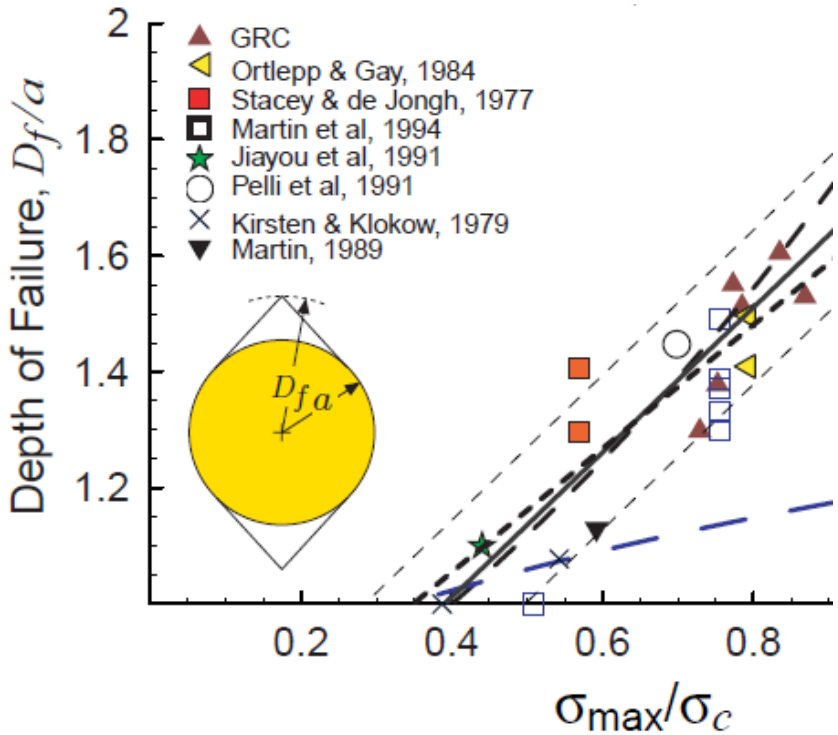
results in anisotropic behaviour in tunnelling

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

ITA hydroelectric project
1,450 MW. South East Brazil.
NNW stress orientation, parallel to diabase dyke. All tunnels crossing the most massive (Q= 30-100) HIGHEST MODULUS basalt flows, suffered *stress-fracturing*.
***$K_0 \approx 25$* (BACK-CALCULATED)**
i.e. very ANISOTROPIC BEHAVIOUR!

Stress-fracturing in arch and invert in three 14 x 16m diversion tunnels





$\sigma_\phi / \sigma_c \approx 115 / 200 \approx 0.6$

(depth of failure + radius) / radius

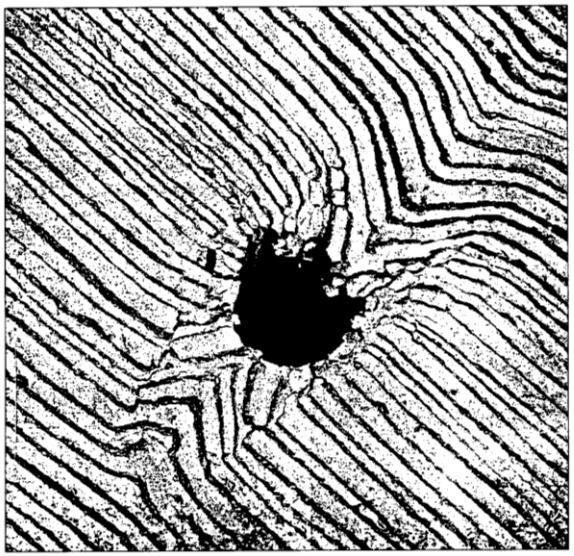
$(D_f + a) / a \approx (3+7m)/7m \approx 1.4$

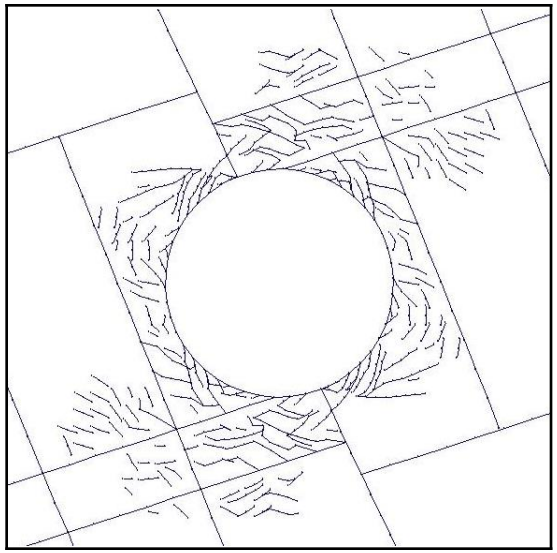
Note (also) initiation of steep SRF gradient when $\sigma_{\theta\,max}/\sigma_c$ exceeds 0.4-0.5. This deep road tunnel (civil engineering) experience of ***anisotropic-loading*** from Barton and Grimstad, 1994 is consistent with the above mining/nuclear waste experience.

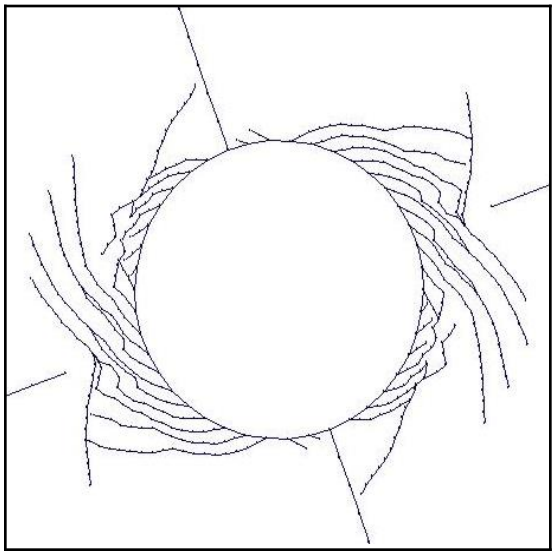
6 b) Competent rock, rock stress problems		σ_c/σ_1	σ_φ/σ_c	**SRF**
H	Low stress, near surface, open joints.	> 200	< 0.01	2.5
J	Medium stress, favourable stress condition.	200-10	0.01-0.3	1
K	High stress, very tight structure. Usually favourable to stability, may be unfavourable for wall stability.	10-5	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

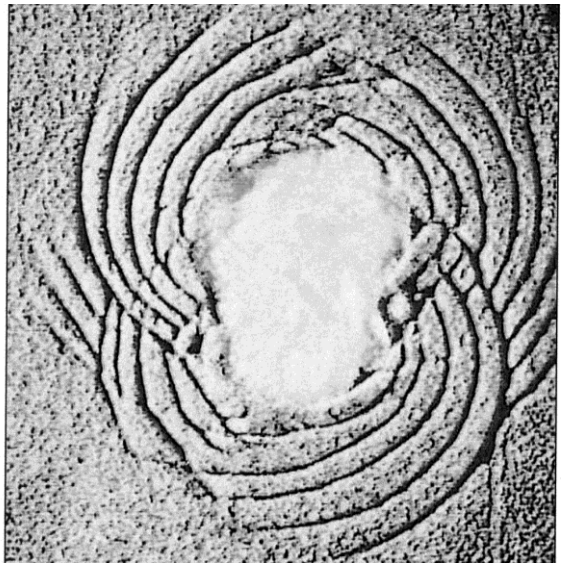
ANISOTROPIC STRESS (and / or STRUCTURE) MAY RESULT IN BEHAVIOUR/FAILURE *THAT IS ANISOTROPIC IN NATURE*

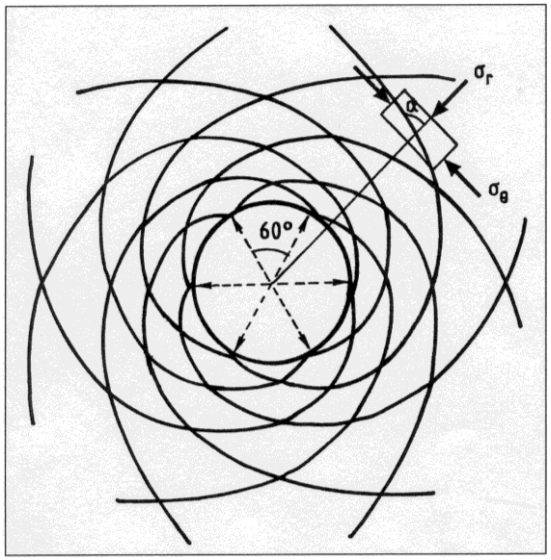
(Bandis layered model, Shen FRACOD, NGI J.I project, theory from Bray, Shen + Barton)

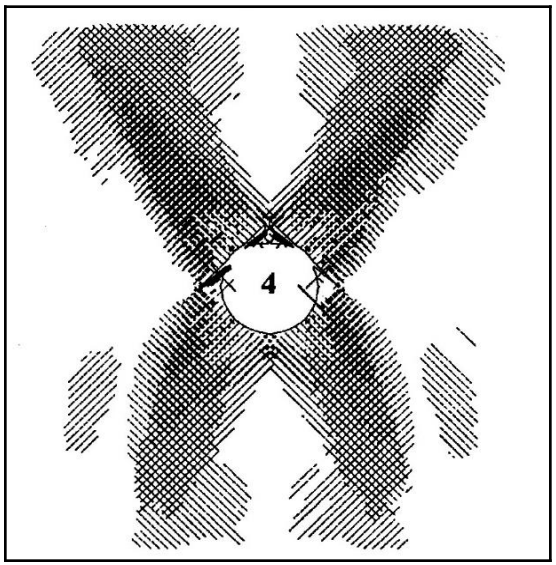






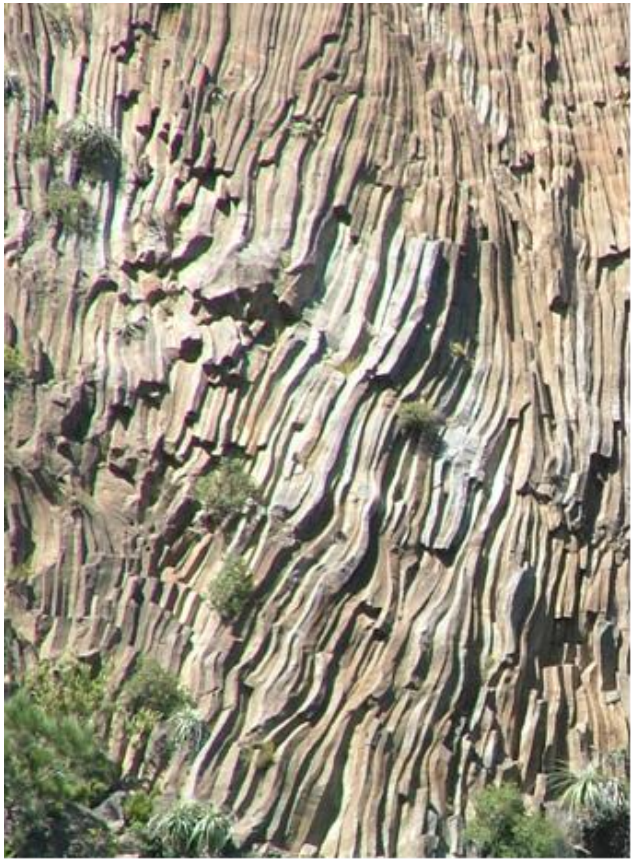


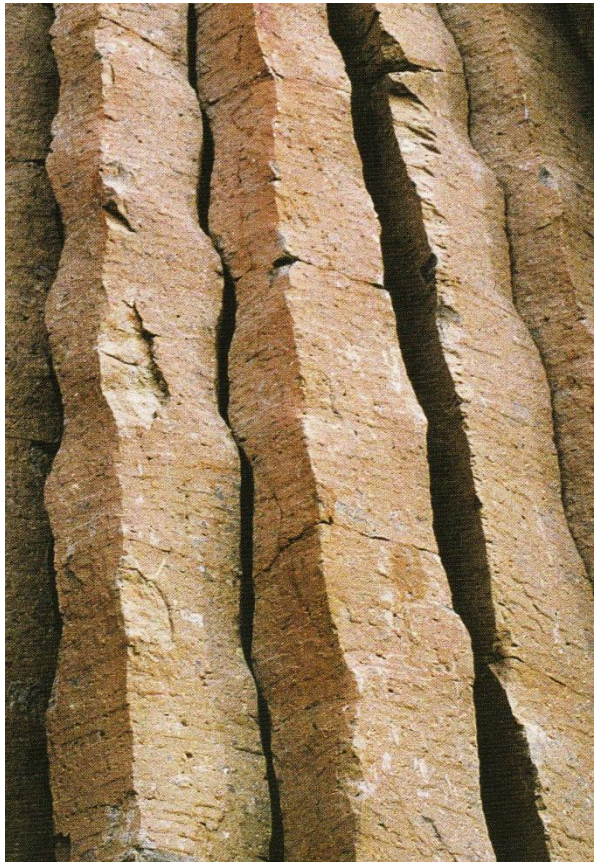




ANISOTROPY CAUSED BY JOINTING (cooling, foliation, cleavage)

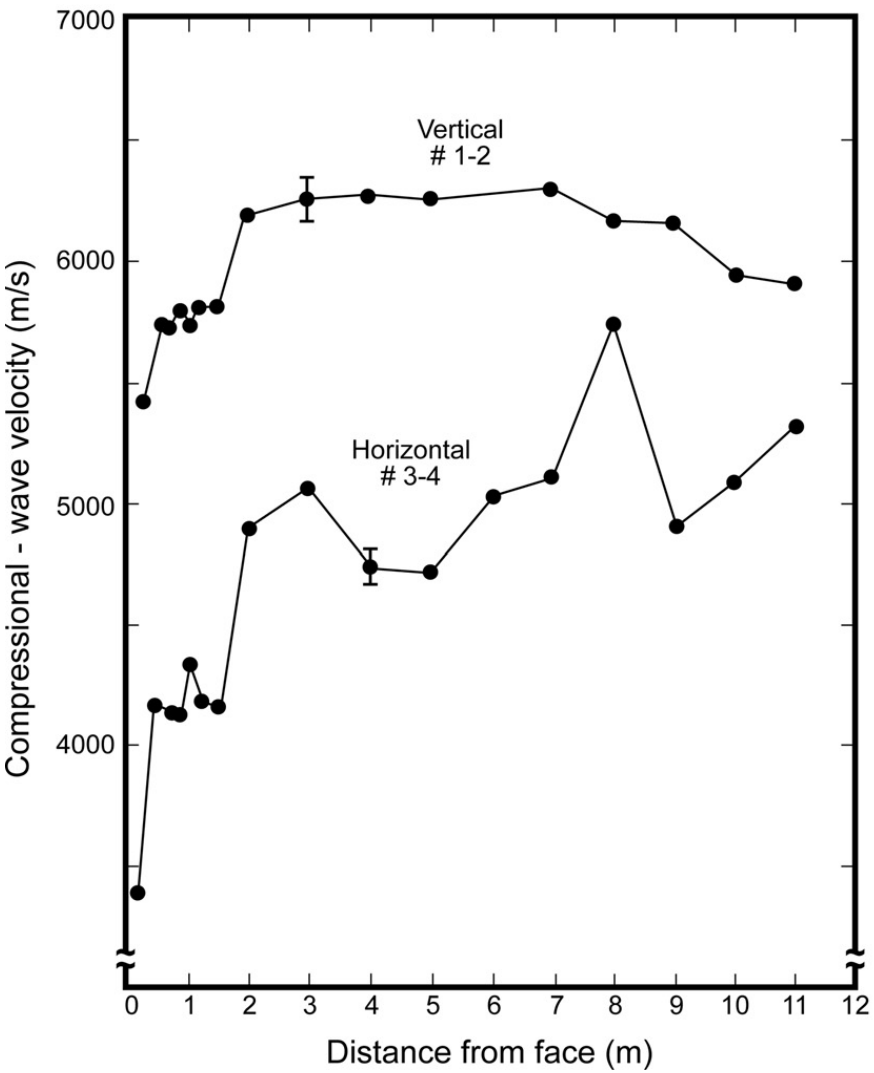
COOLING JOINTS IN BASALT CAUSING STRONG ANISOTROPY

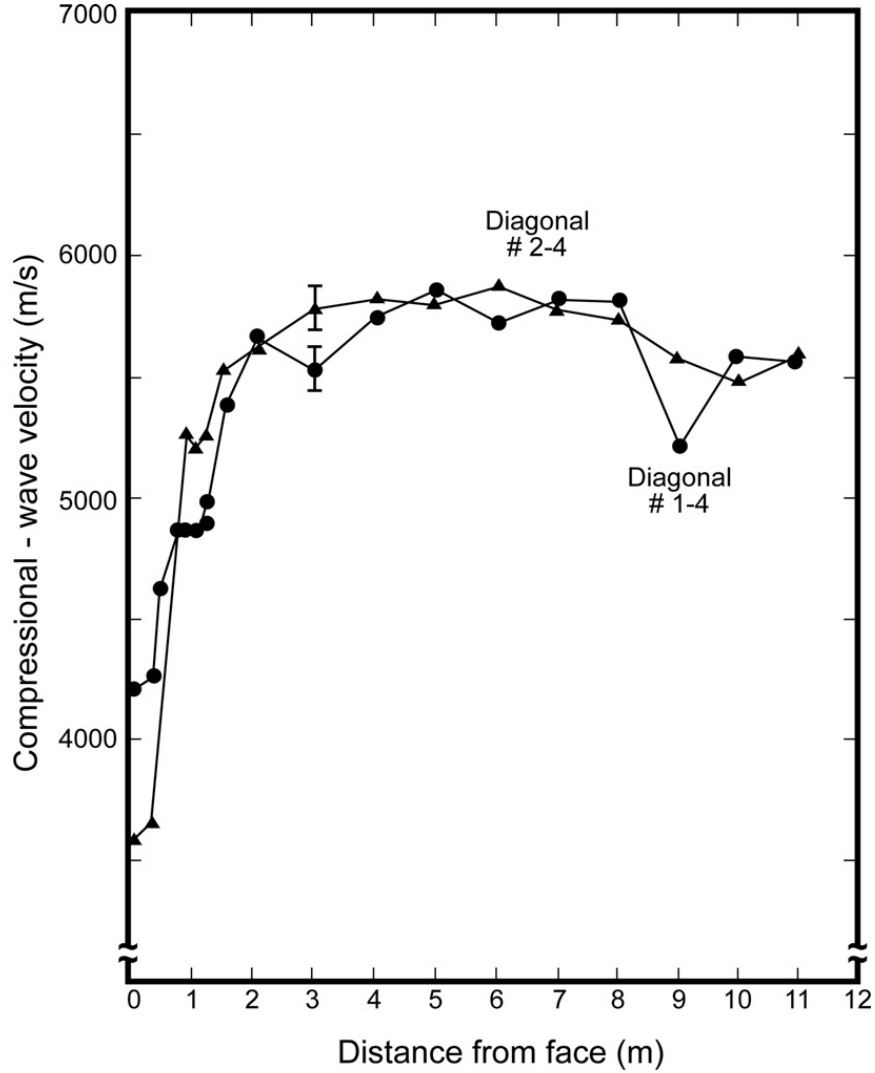




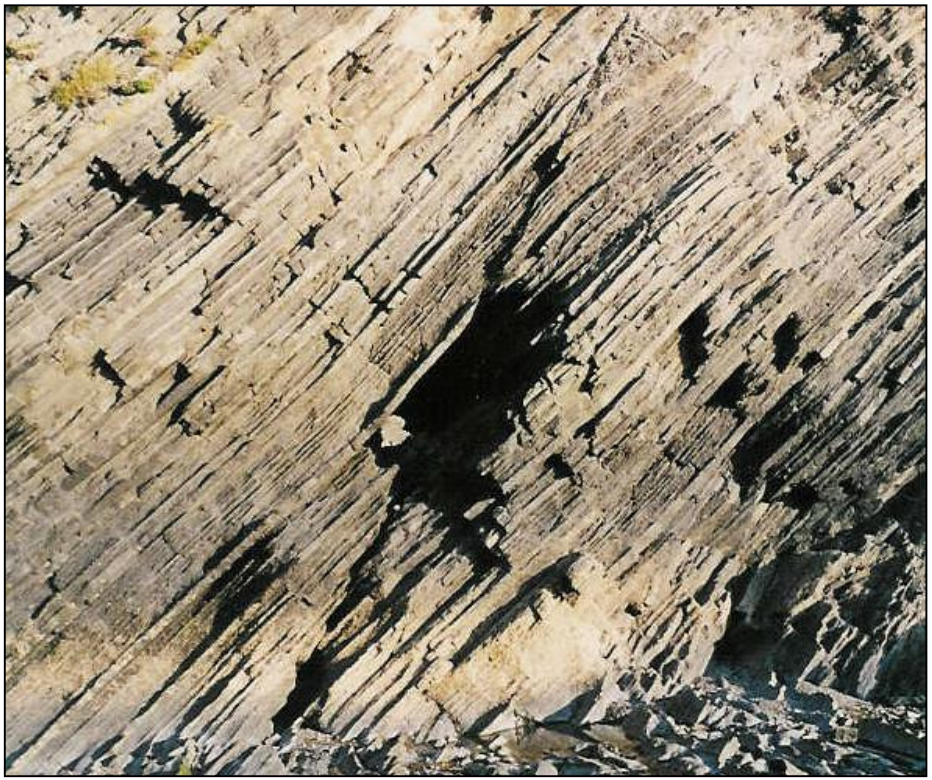
While on the subject of BASALTS.....some results of CROSS-HOLE SEISMIC IN A TEST TUNNEL

(King et al., 1984.)





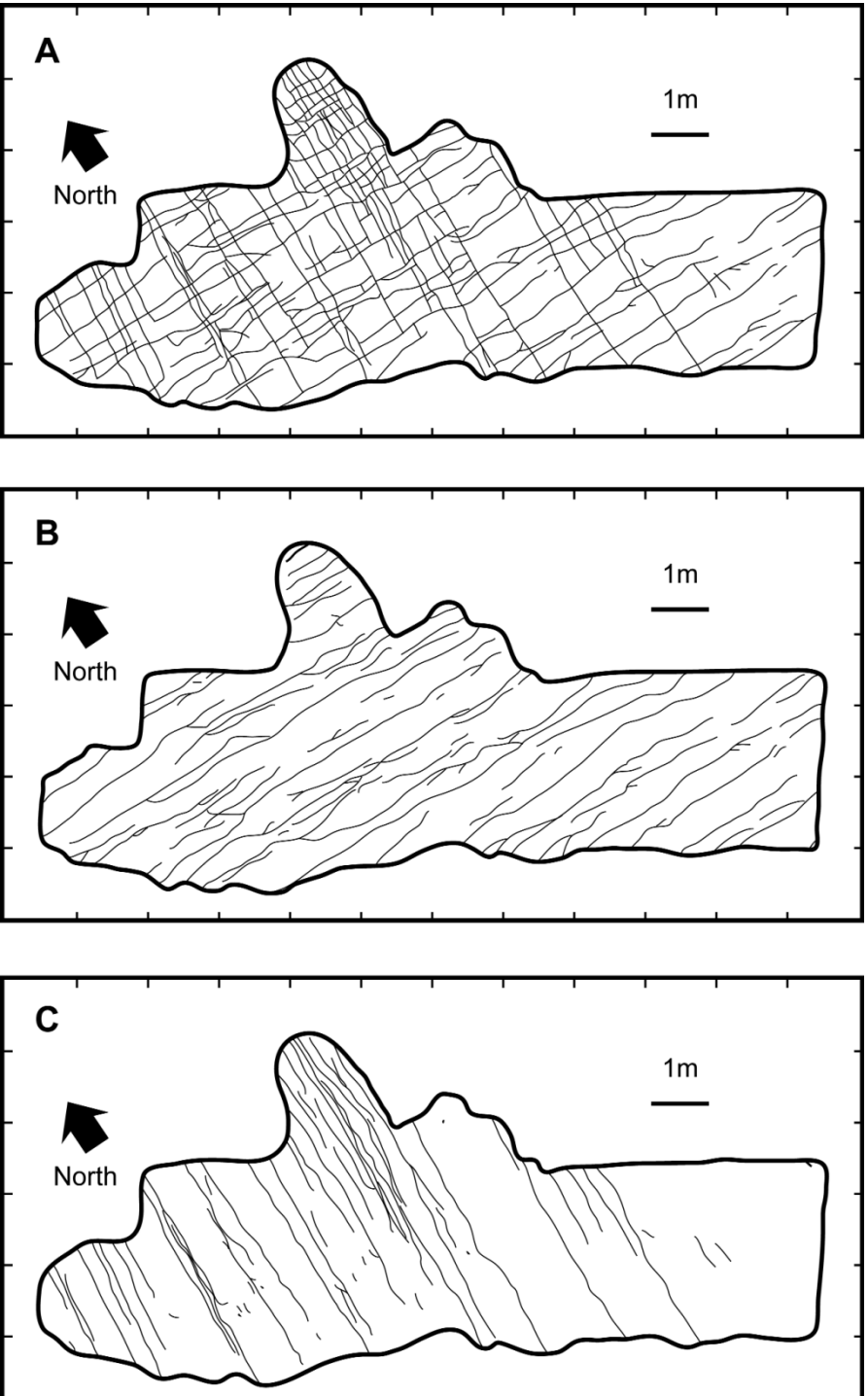
A single strike-parallel fault *(nearly)* creates blocks, and consequently a wave-cut tunnel is eventually formed. (NB photo and internet photo – from opposite ends). **Faulted grits, Aberystwyth, Wales.**



Anisotropic siltstone

(China, Jinping 1)

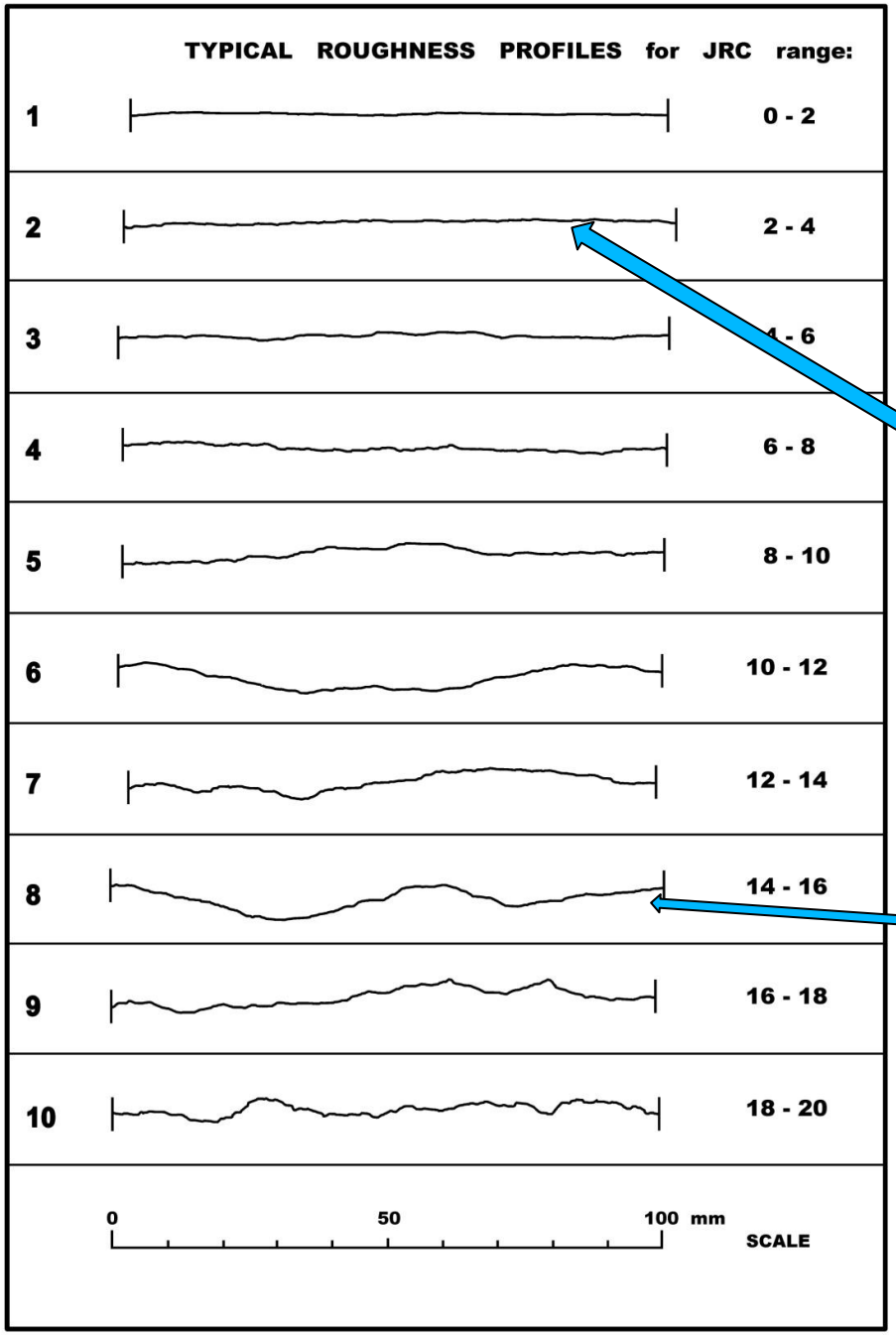
JOINT ROUGHNESS DUE TO FORMATION UNDER VARIABLE ANISOTROPIC STRESS MAGNITUDES



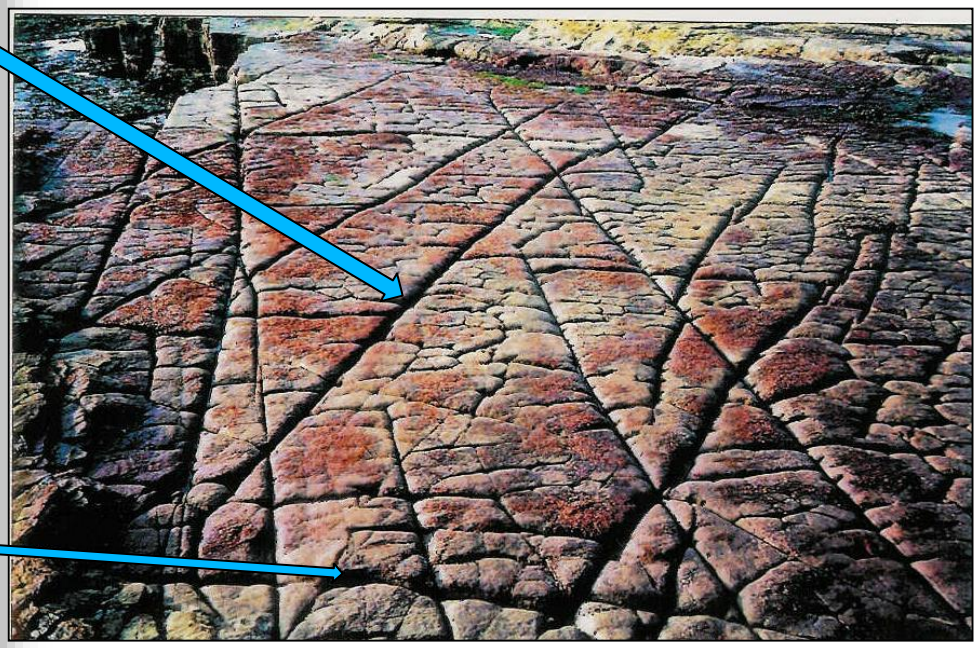
Joint traces from a 1m thick bed of limestone, 'disaggregated' in b) and c) into their two component sets.

(Olson and Pollard, 1989)

Greater stress anisotropy assumed for generation of more planar joints in C compared to B.

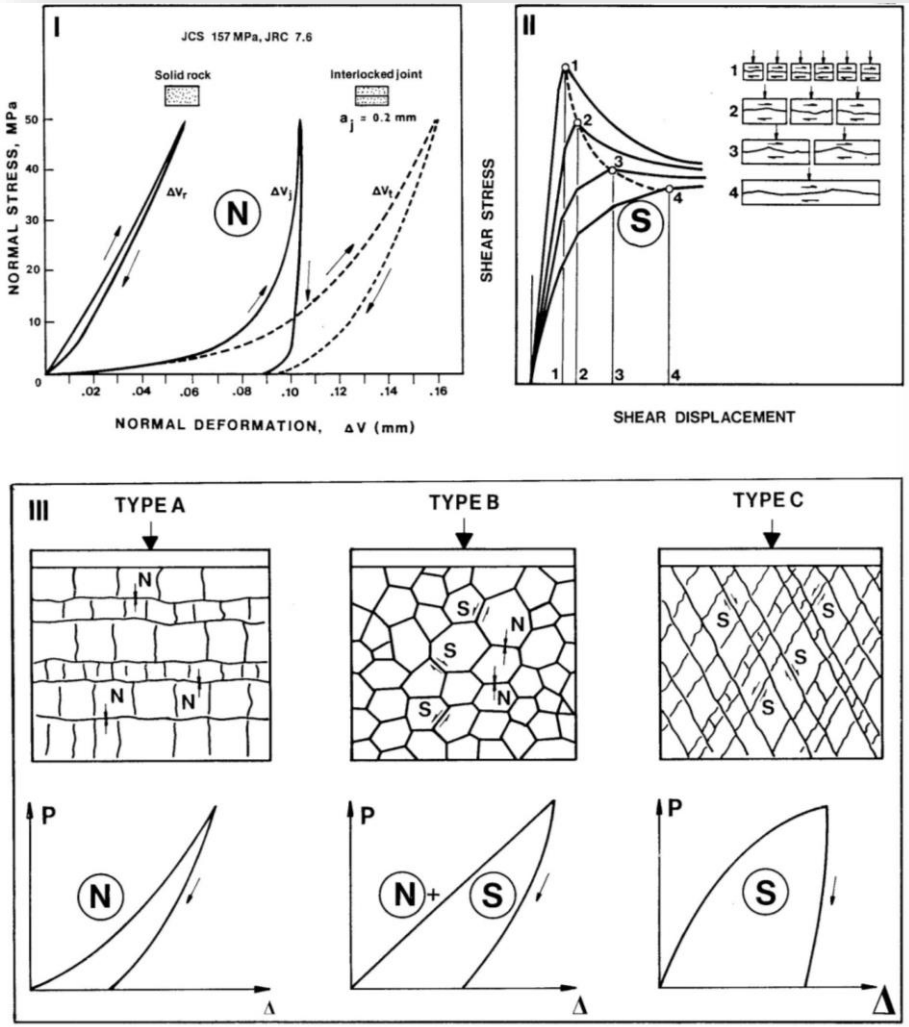


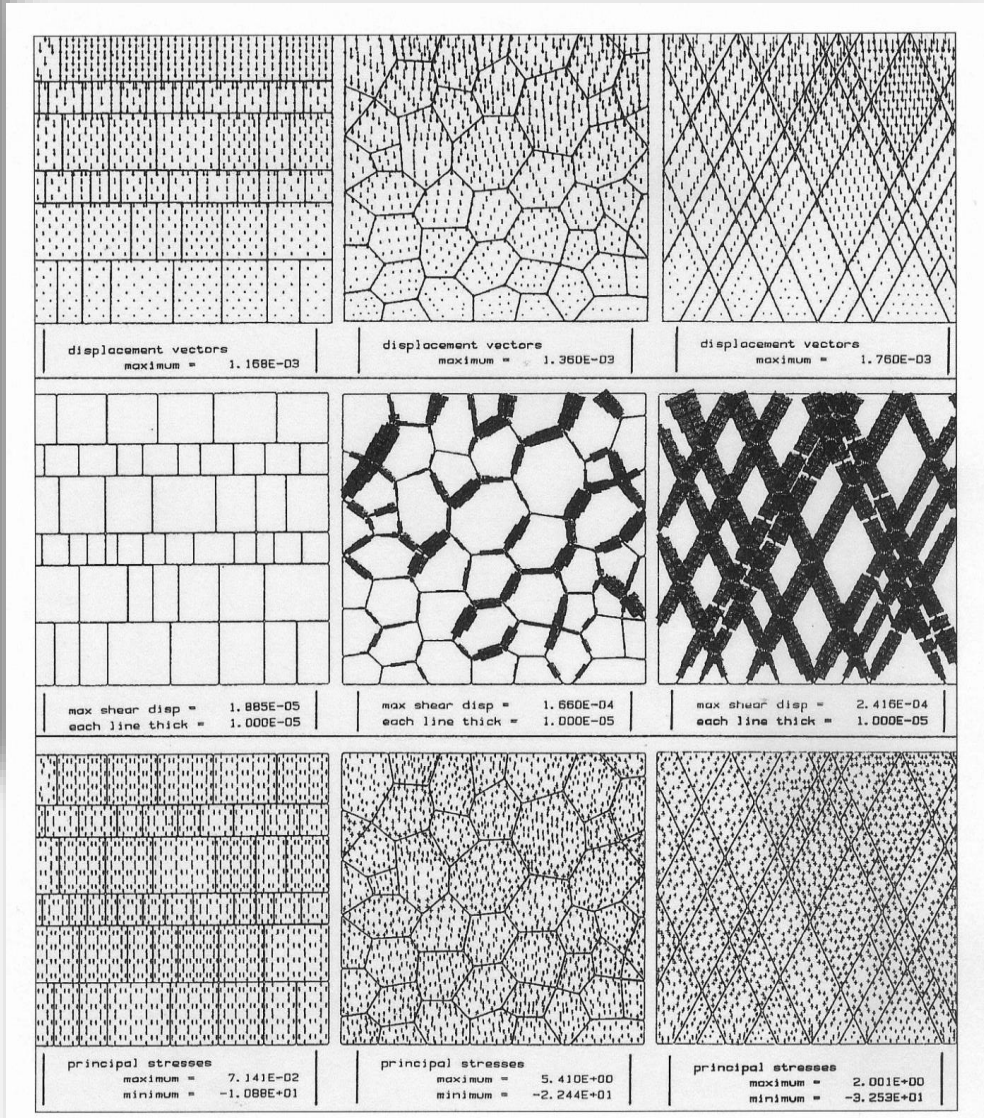
1. STRESS ANISOTROPY (K_0#1 > K_0 #2)
2. JOINT FORMATION #1
3. JOINT FORMATION #2
4. JRC#1 < JRC#2



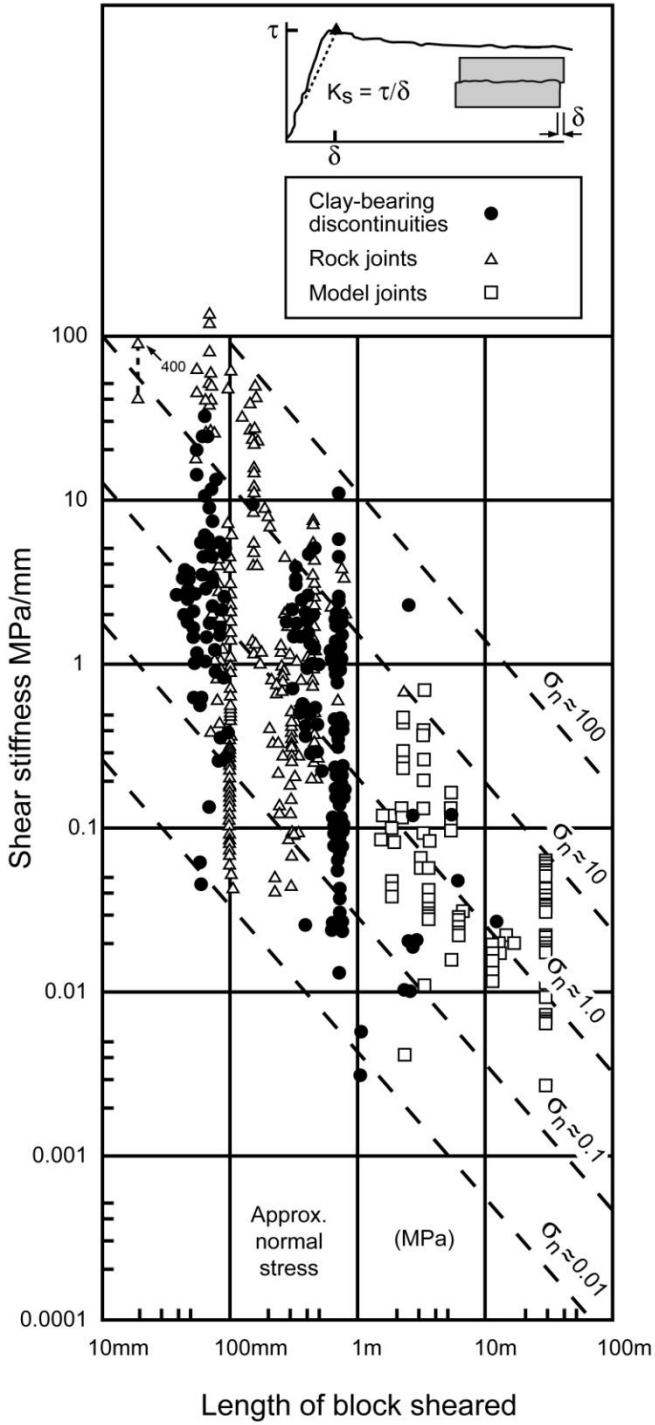
STRESS HISTORY WOULD DETERMINE TODAY'S (ANISOTROPIC) REACTION TO 'RE-LOADING'

WEAKNESS OF 'S' wrt. 'N' CAUSES ANISOTROPIC RESPONSE TO LOADING (Barton, 1986)



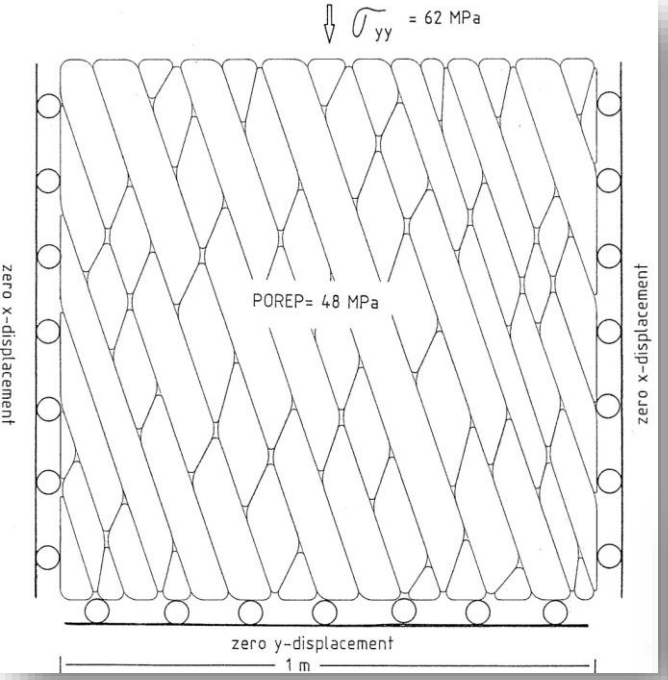


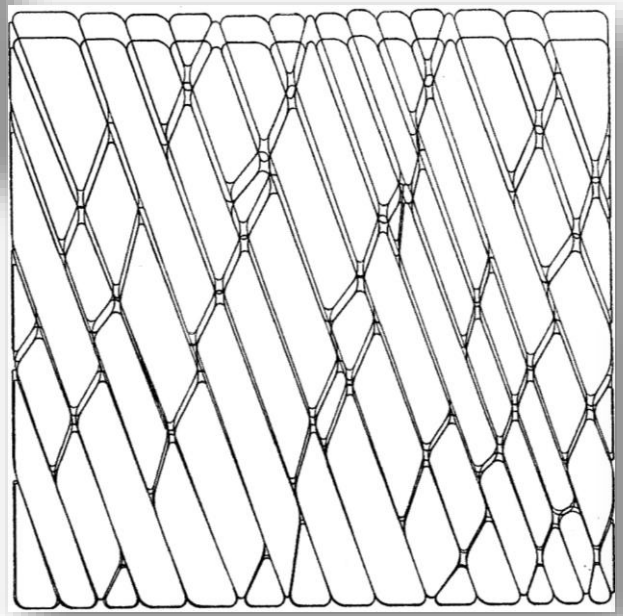
A SINGLE ROCK JOINT HAS AUTOMATIC WEAKNESS OF 'S' compared to 'N': K_S IS COMPLIANT, K_N IS STIFF

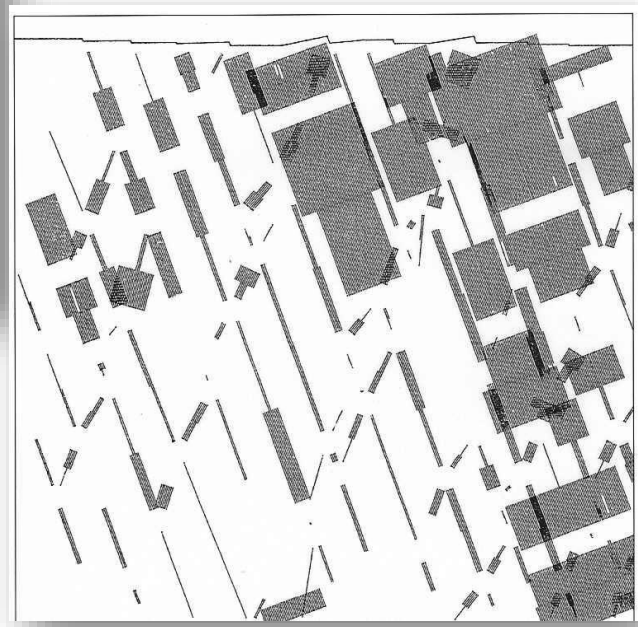


Due to scale effects on Ks, and much higher (x 100) Kn, anisotropic behaviour is automatic if considerïng jointed-rock-mass behaviour

A DOMINANT JOINT SET LEADS TO ANISOTROPIC BEHAVIOUR







DURING RESERVOIR COMPACTION MODELLING

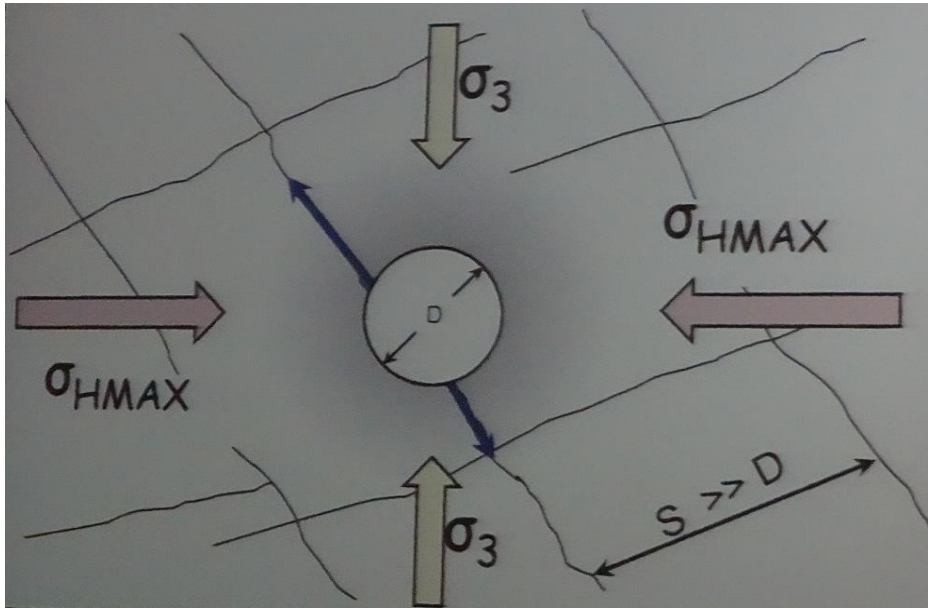
(Barton et al., 1986)

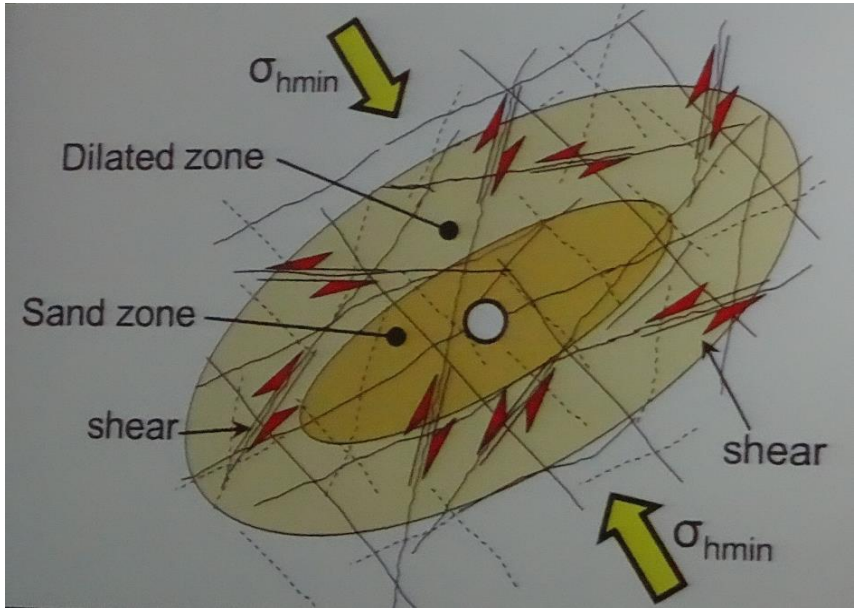
ANISOTROPY CAUSED BY (OIL-SHALE) STIMULATION (if this results in shearing)

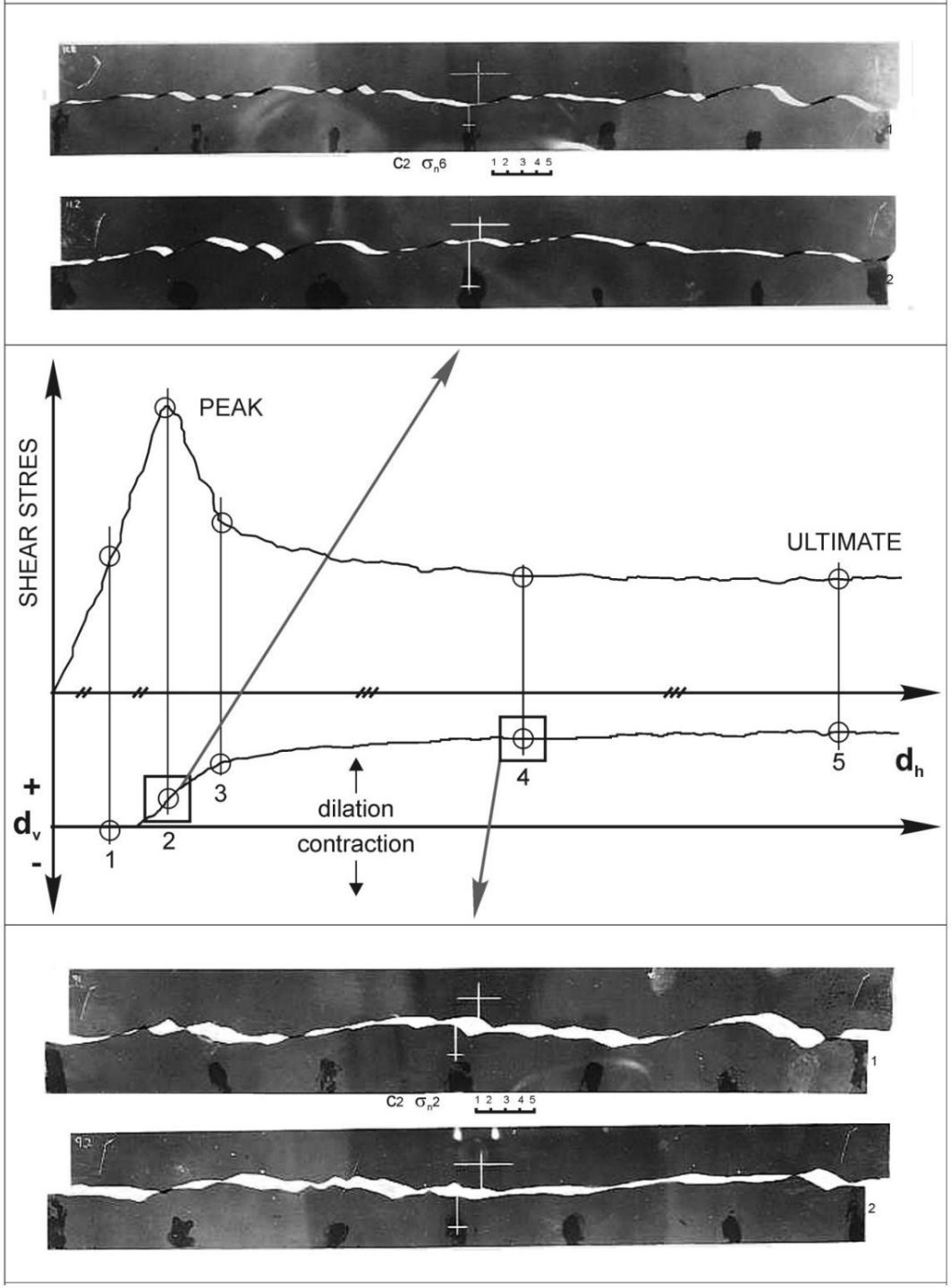
From Maurice Duffault 2013, Wroclow.

A nice illustration of anisotropic behaviour during fracing.

If the shale is strong and well jointed, less fracturing energy may be needed to propagate along pre-existing jointing, but the 'global' HFRAC direction will be perpendicular to σ min.



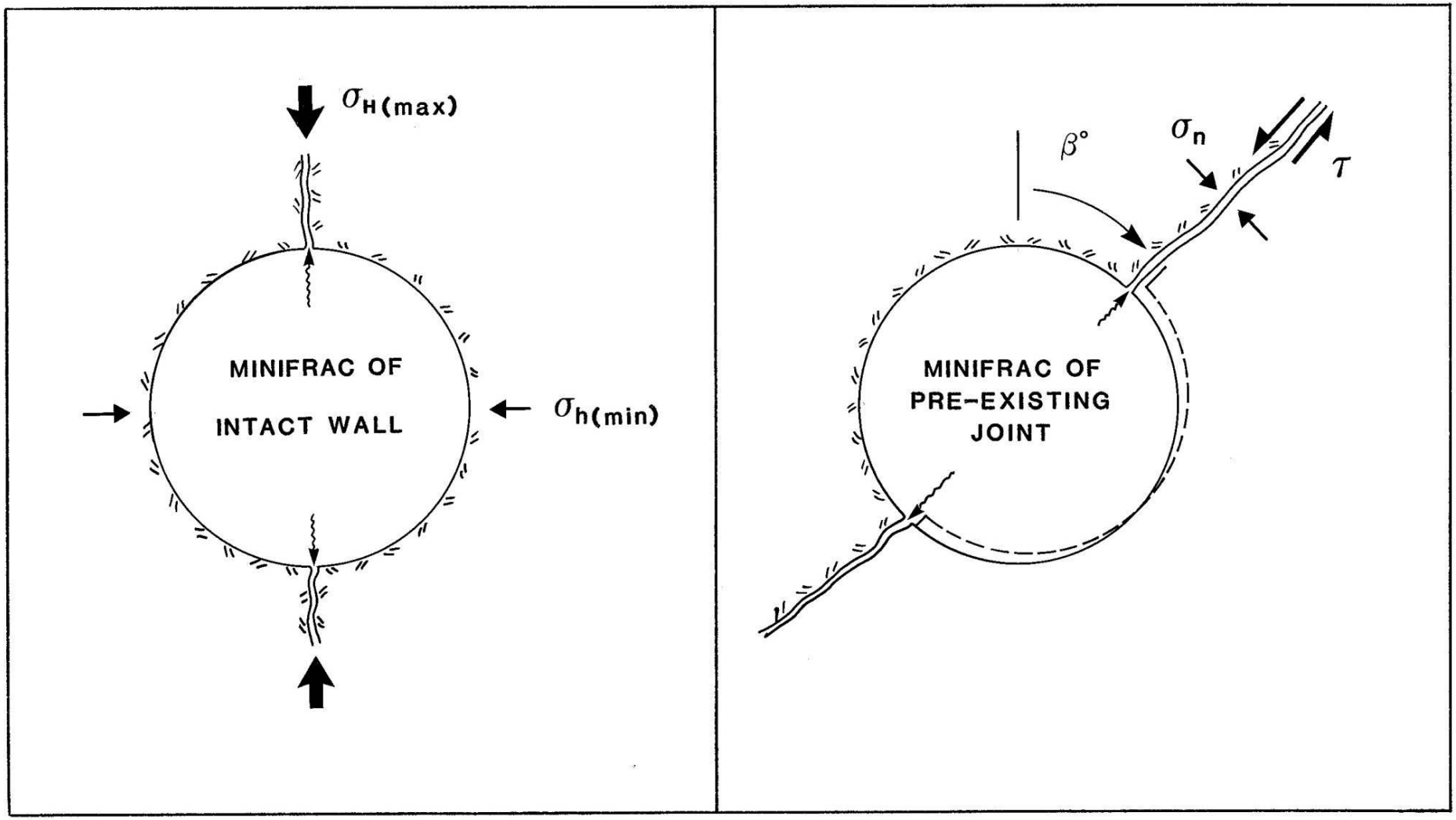




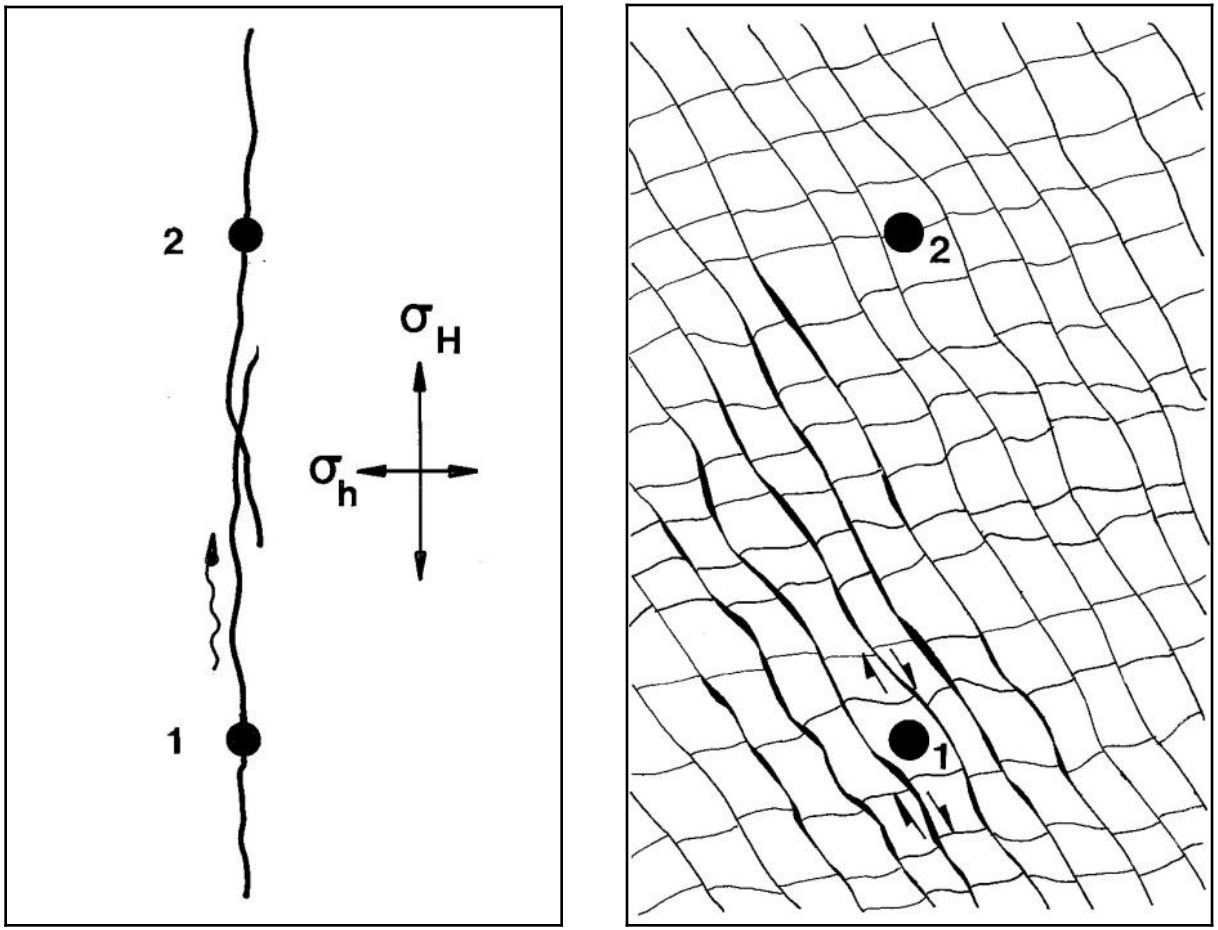
Shearing of tension fractures, joints, faults, is, in itself, an anisotropic ‘mechanism’, and creates permeability.

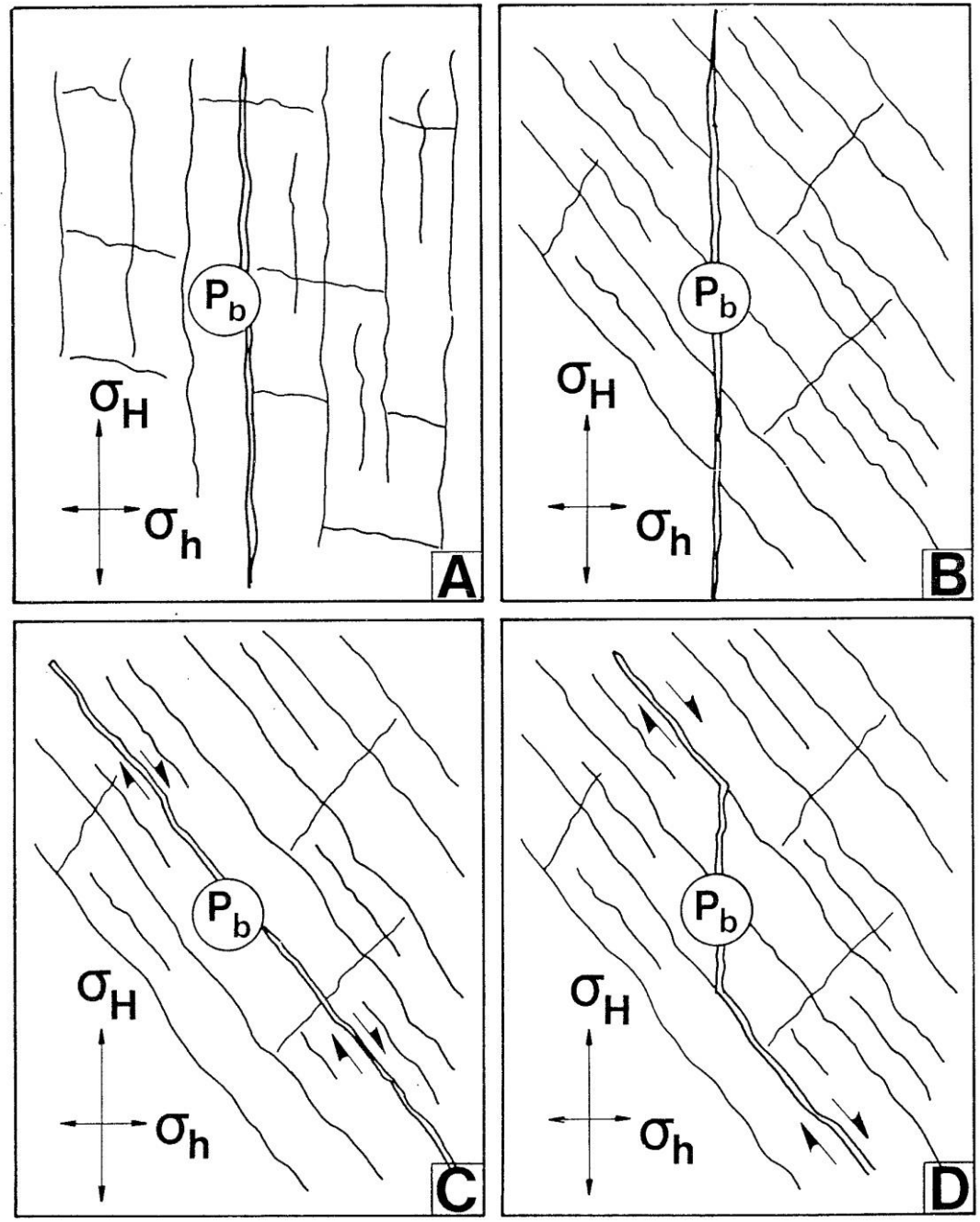
(Barton, 1971)

Barton, N. 1981. Hydraulic fracturing to estimate minimum stress and rockmass stability at a pumped hydro project. Proc. of Workshop on Hydraulic Fracturing Stress Measurements, Monterey, California.



Optimistic geothermal reservoir principle (left). Frequent anisotropic ‘joint-captured’ reality (right). Barton, 1986.





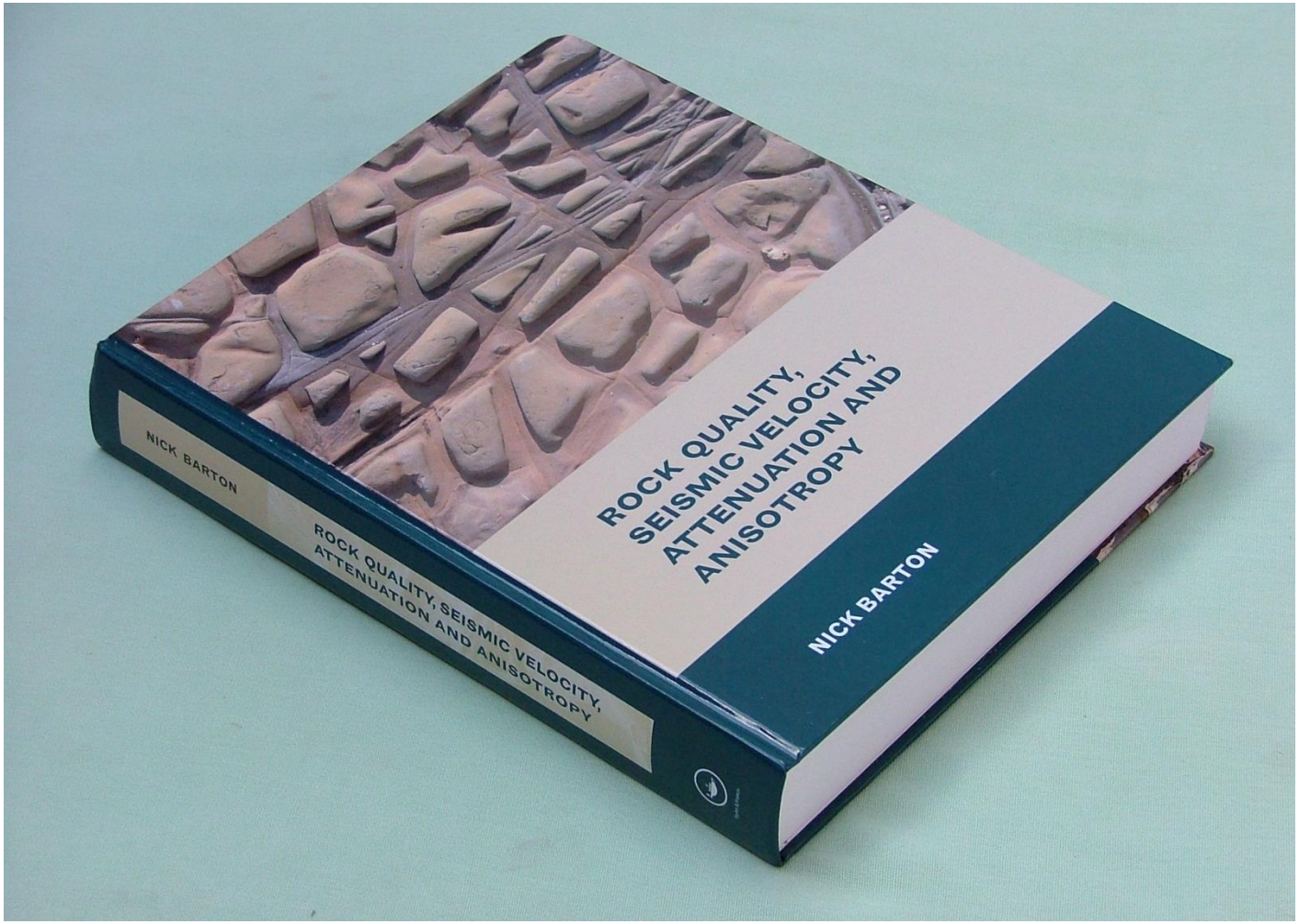
Barton, 1986.
Deformation phenomena in jointed rock.

Anisotropic HFRAC with 'sufficient' (too much) Energy (B).

Optimal (?) capture by *anisotropic* jointing if slower ramping of pressure.

SMALL-SCALE AND LARGE-SCALE ANISOTROPY MEASURED WITH *SEISMIC VELOCITY*

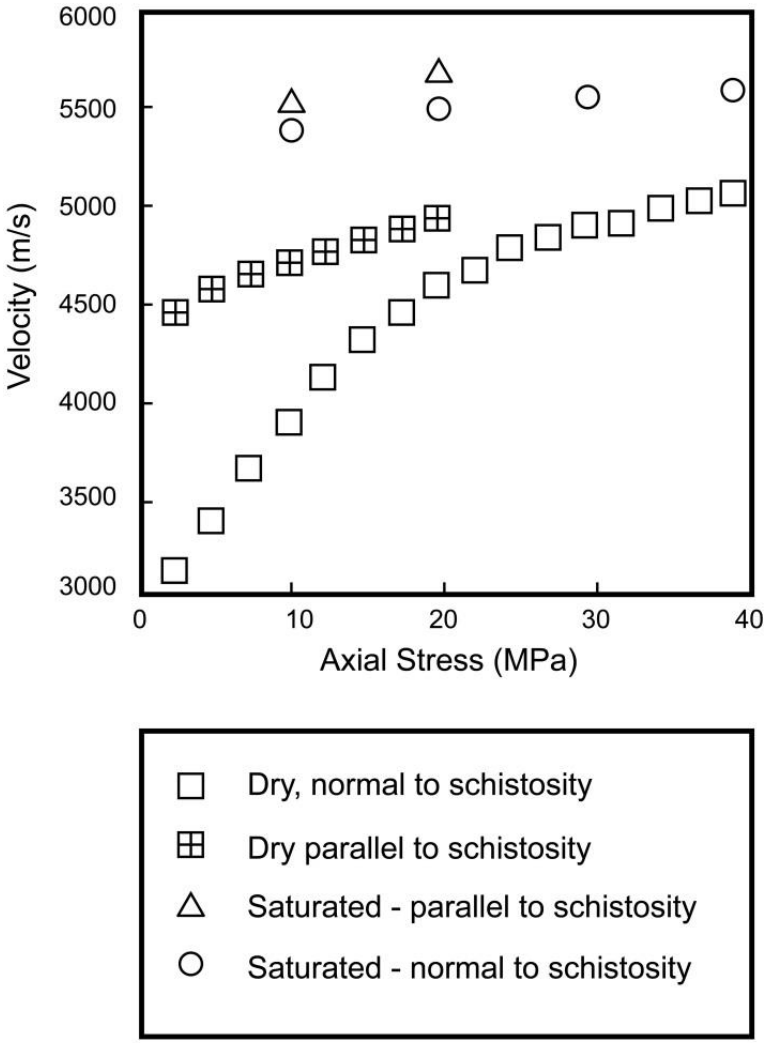
Many of the following (seismic-anisotropy) cases are from this literature review (T&F, 2006)

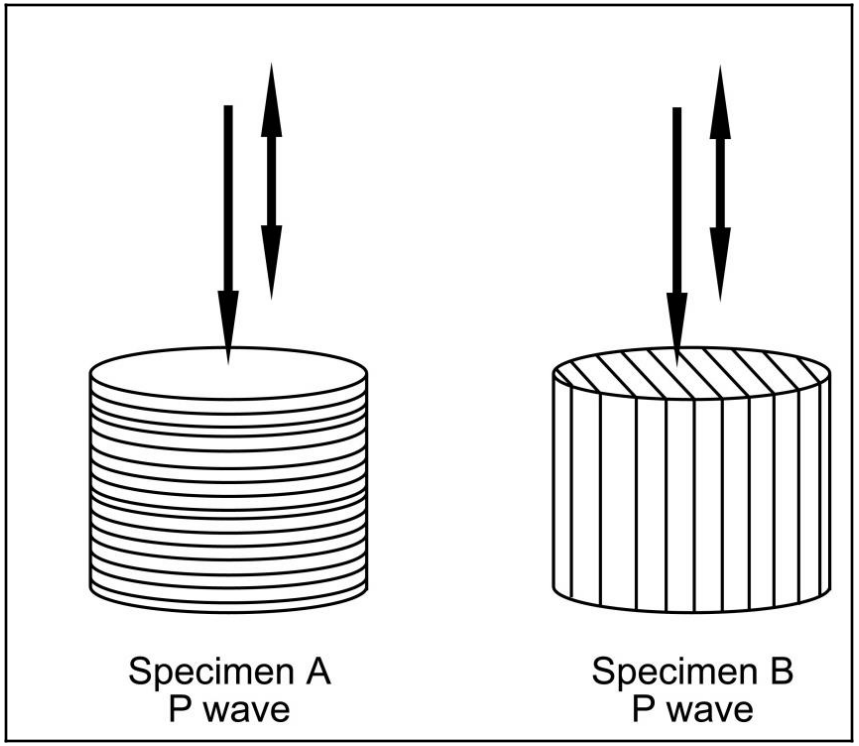


Effect of schistosity in a strongly anisotropic gneiss, loaded to 40MPa, parallel or perpendicular to the fabric.

(DRYNESS ACCENTUATES THE VELOCITY-ANISOTROPY)

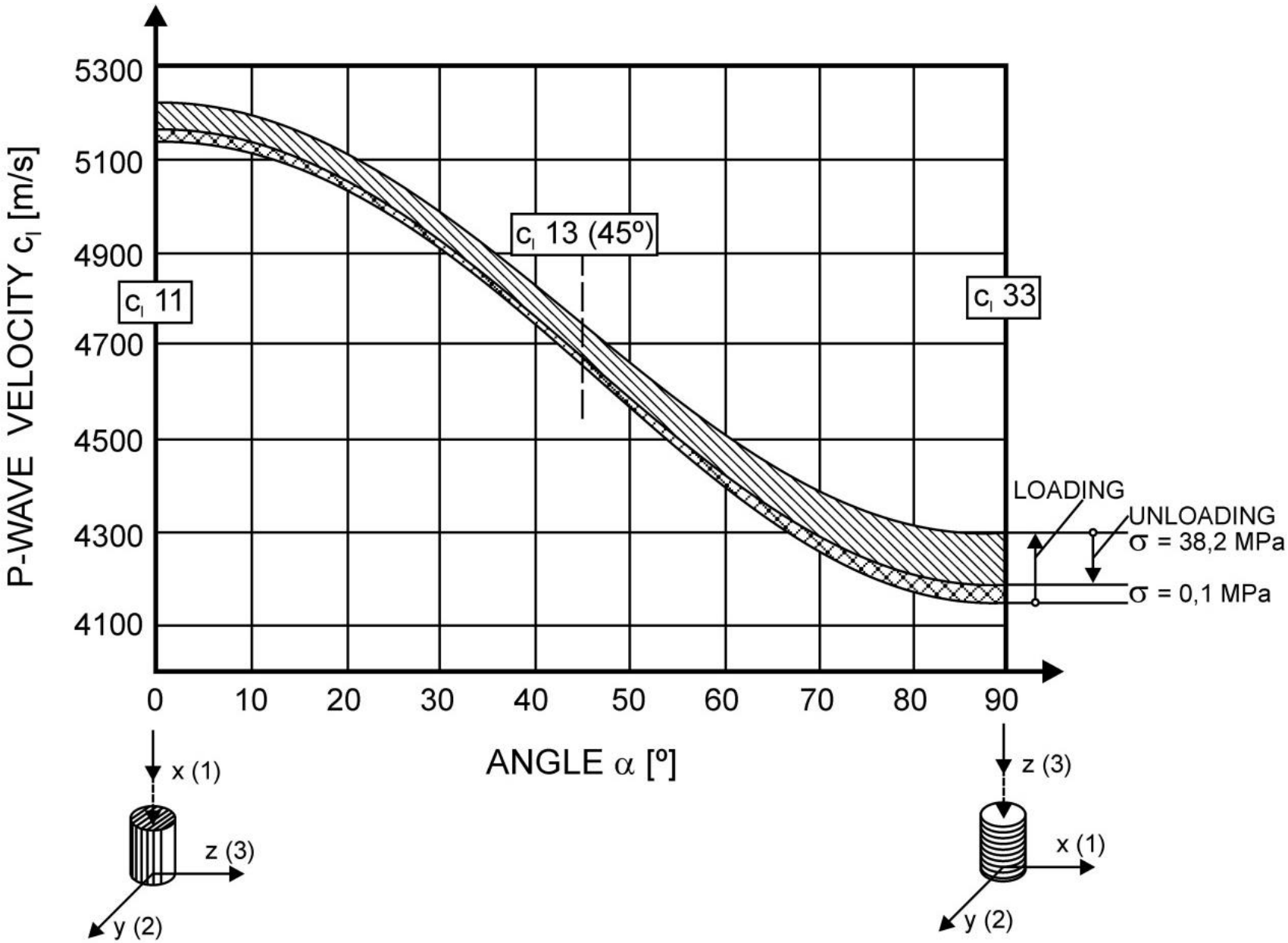
Hesler et al., 1996.

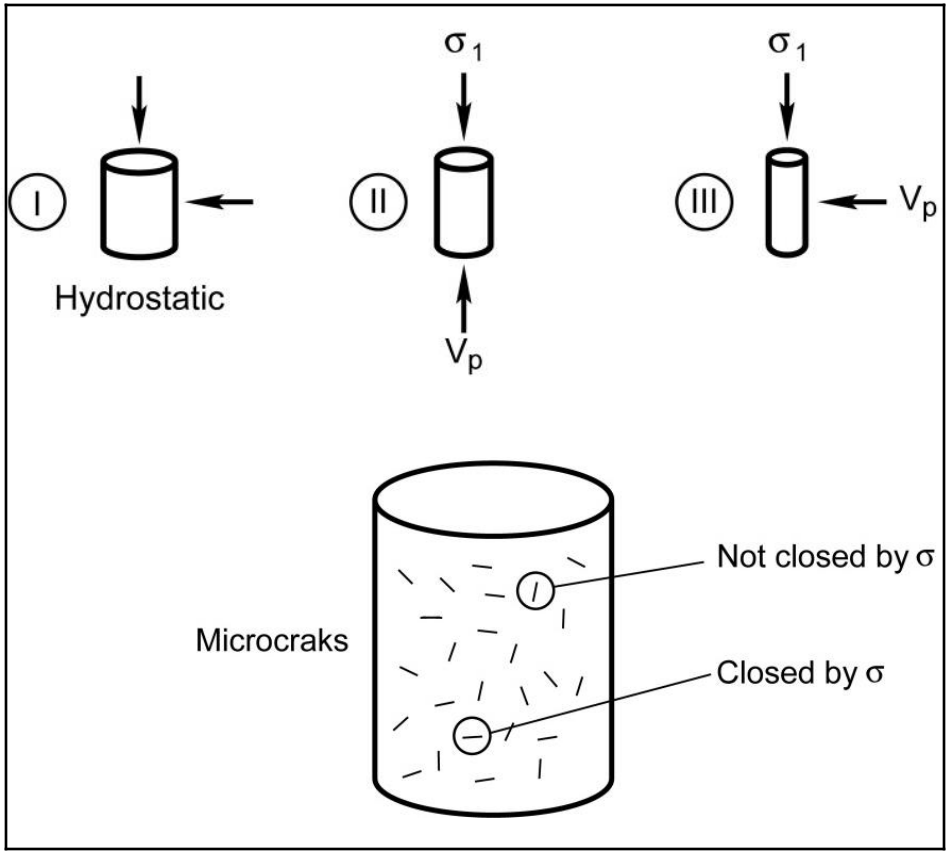


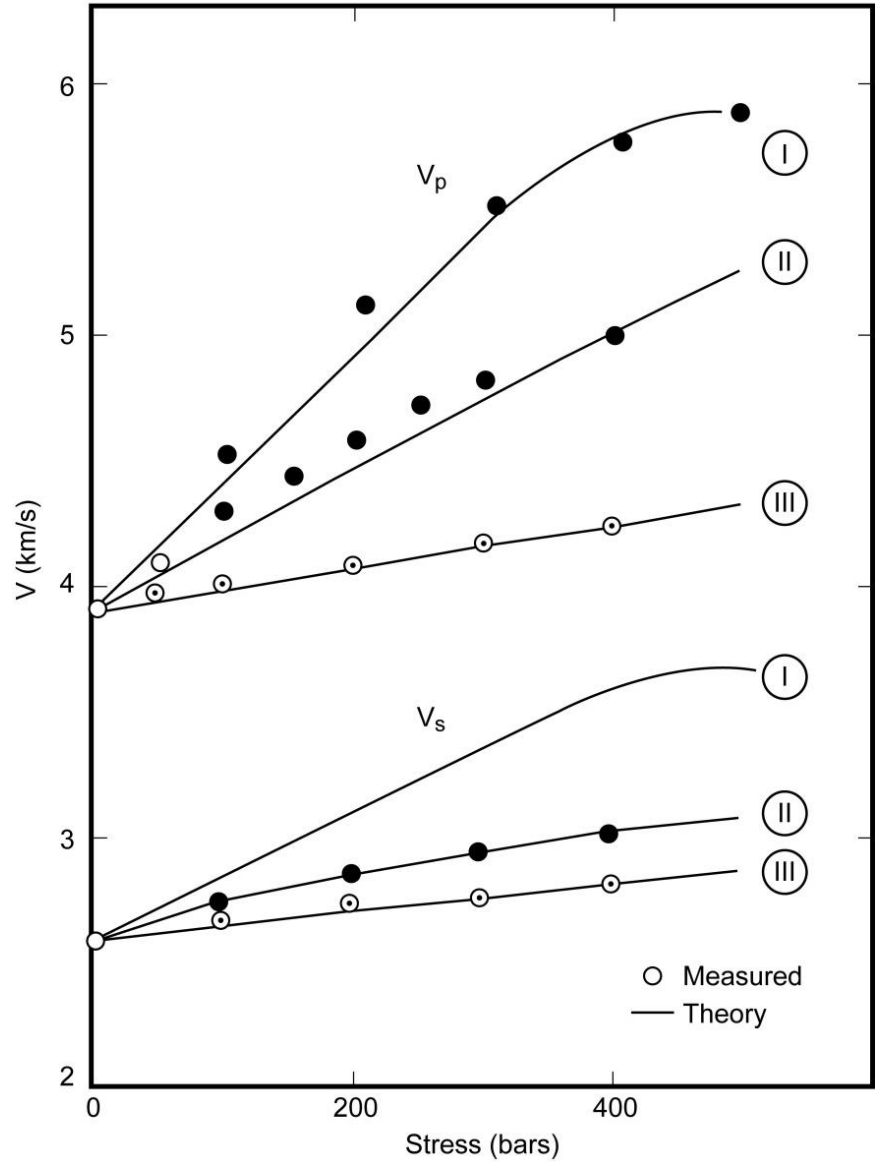


Intact samples of slate

(Duellmann and Heitfeld, 1978)





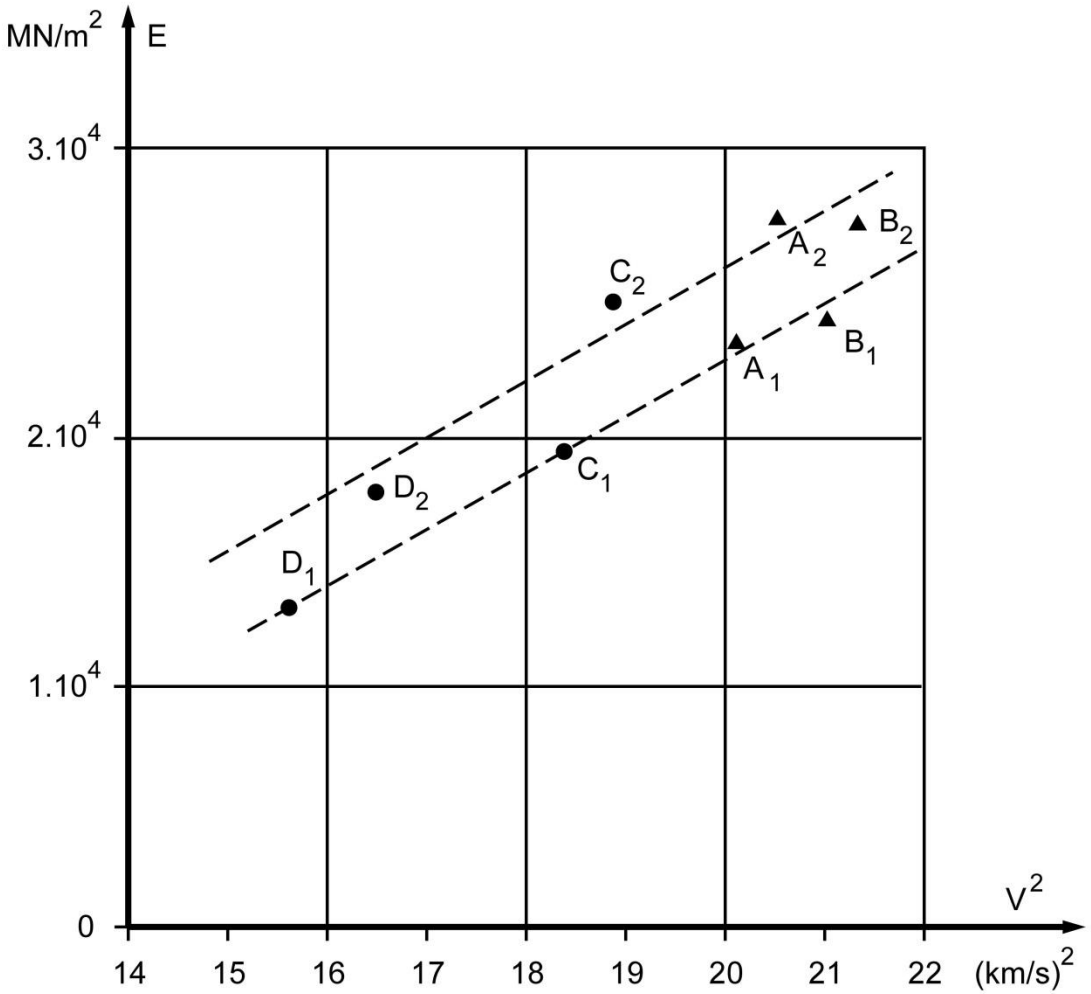


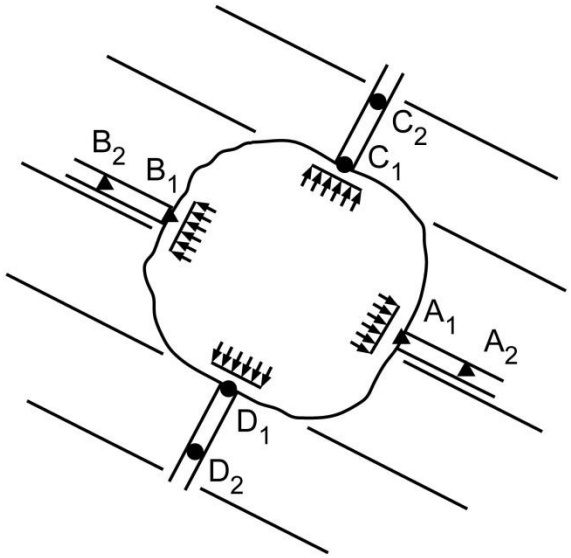
Microcracking alters the velocity

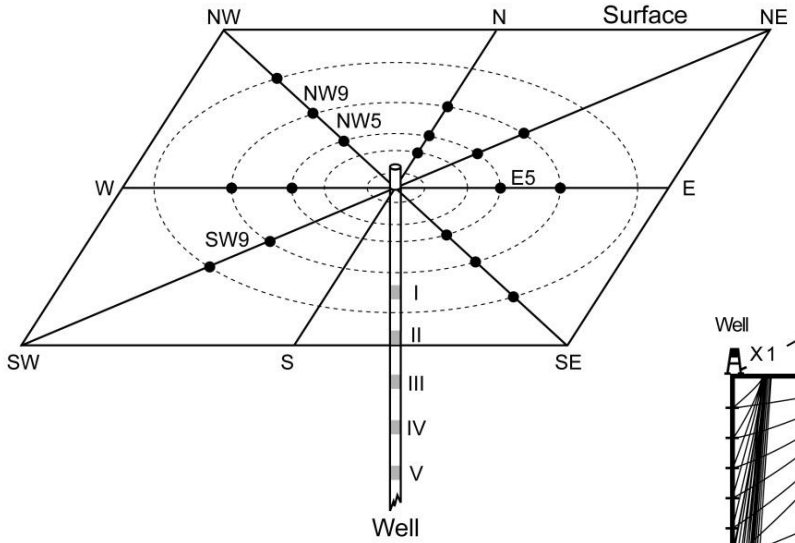
(Amos Nur, 1971)

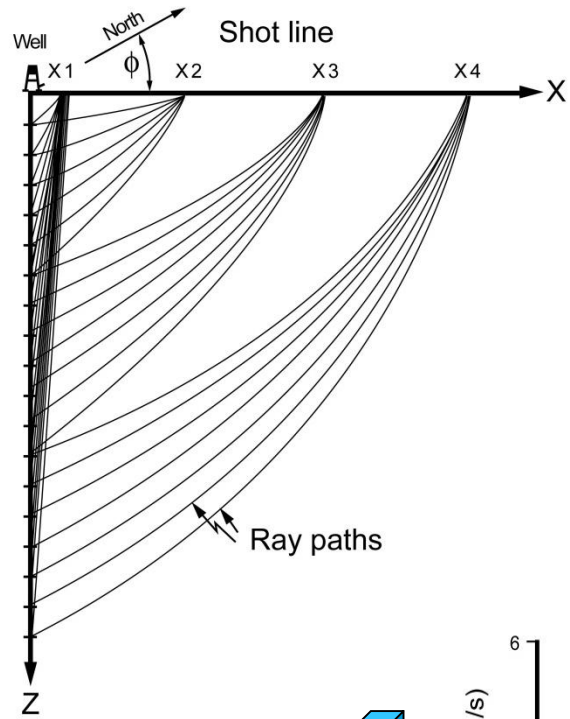
ANISOTROPY DUE TO MARL/SANDSTONE INTER-BEDS. 'CORRELATED' EFFECTS ON V_p and E_{mass}

(Oberti et al., 1979)







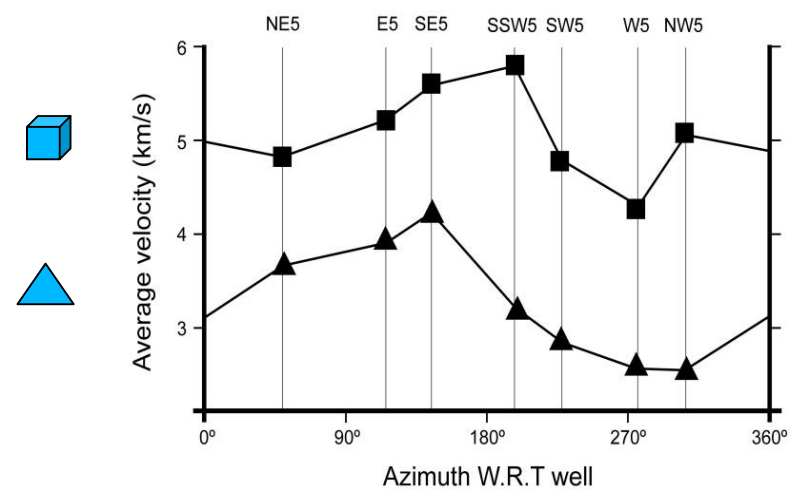


VSP with MULTI-AZIMUTH SHOT POINTS, SHOWS V_p (mean) for 0 to 300m (▲) 460-520m (■) depth ranges

ROCK MASS SURROUNDING THE WELL HAS **DOMINANT JOINTING** AND/OR **STRESS-INDUCED ANISOTROPY**

(Leary and Henyey, 1985)

STRONG EFFECT OF DEPTH on V_p

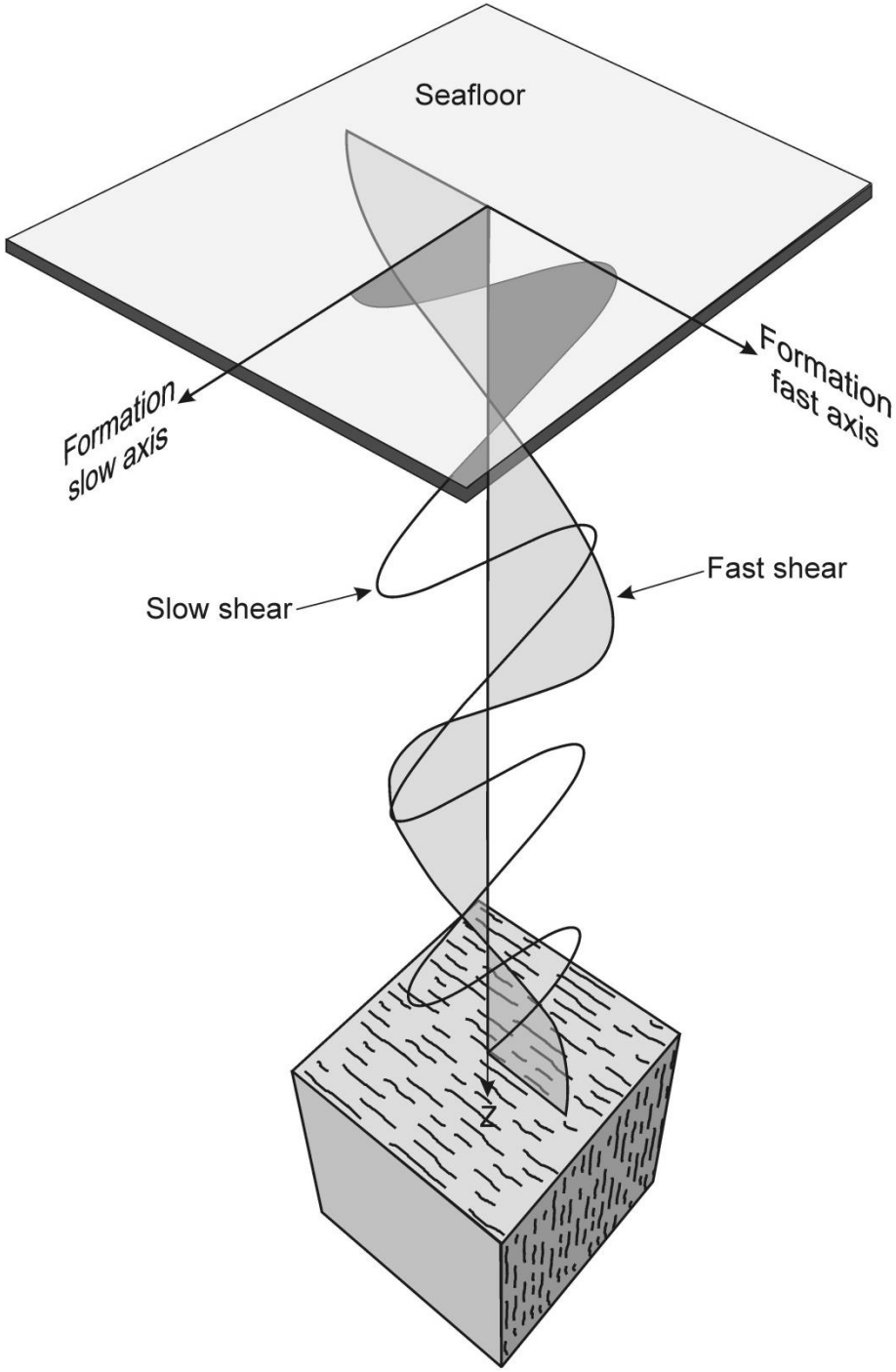


SHEAR WAVE SPLITTING

(POLARIZATION INTO FAST AND SLOW AXES)

DEMONSTRATES ANISOTROPIC RESPONSES AT MANY KILOMETER (RESERVOIR) DEPTHS

…….in response to ‘fracturing’ caused by principal stress anisotropy. (May be oriented microcracking and/or oriented joint sets



SHEAR WAVES SPLIT INTO FAST AND SLOW AXES

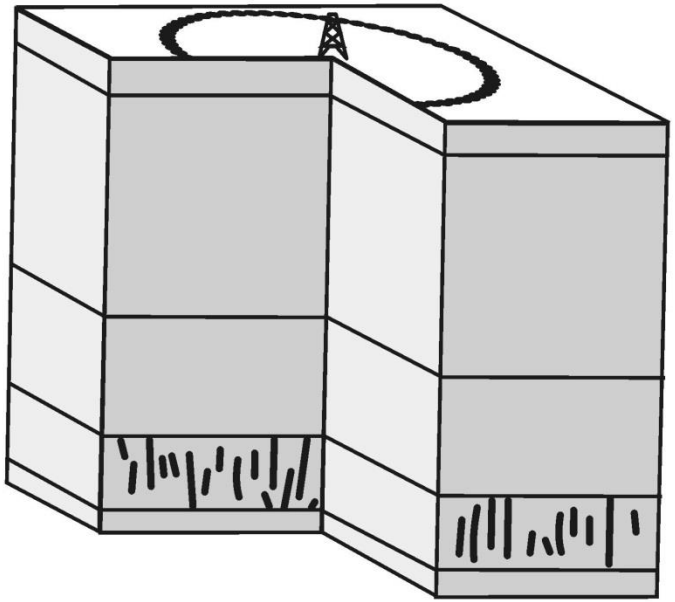
Barkved et al., 2004.

THE CONVENTIONAL IDEA IS THAT IT IS CAUSED BY ONE SET OF DOMINANT JOINTS (even just by microcracks, if agreeing with Crampin)

……

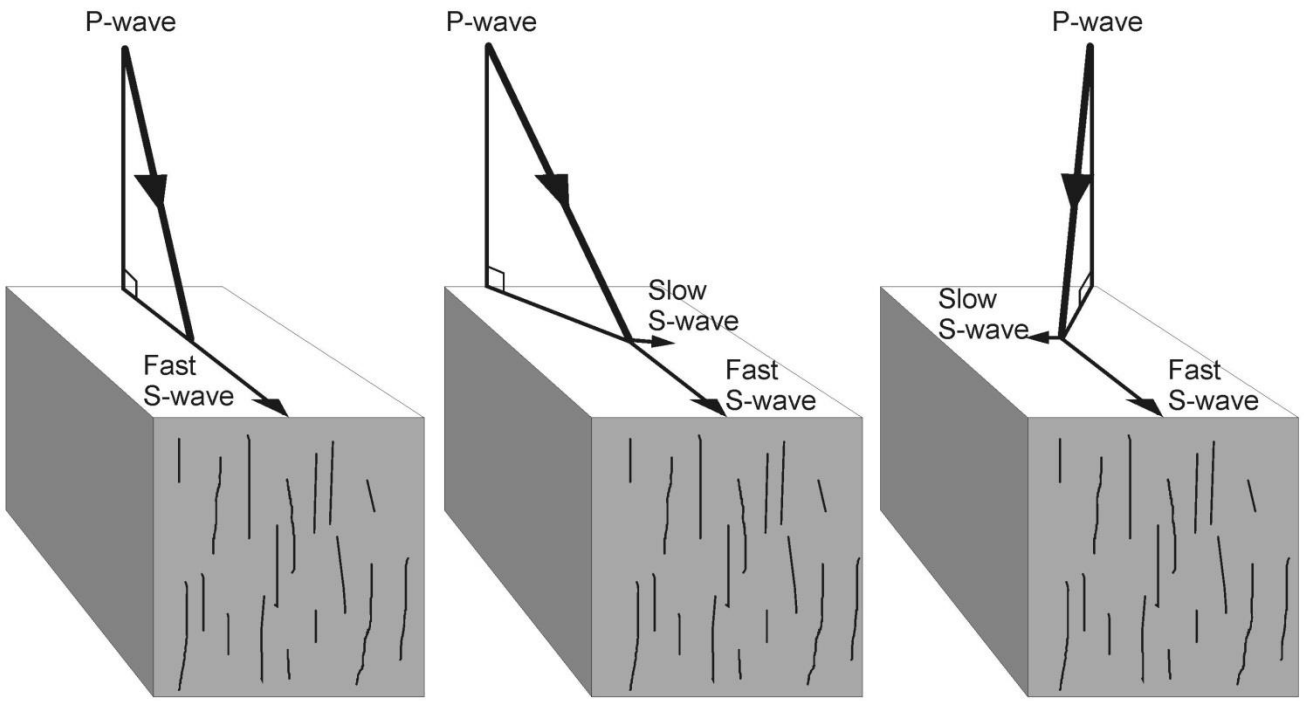
BUT ONE SET OF JOINTS MAY NOT MAKE A VERY PRODUCTIVE RESERVOIR

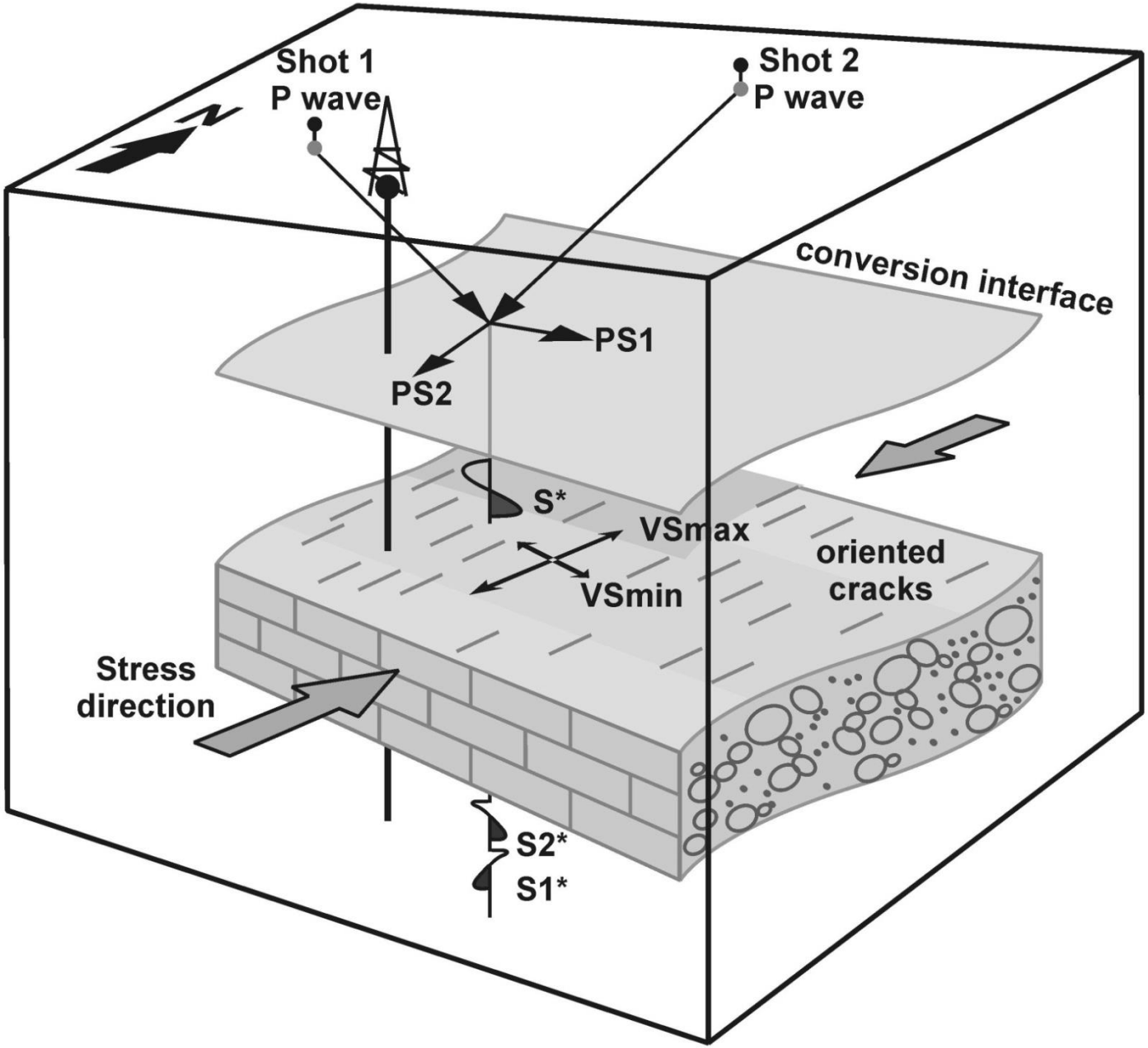
(See alternatives in Barton, 2006)



A ONE JOINT-SET PETROLEUM RESERVOIR?

Horne, 2003.





THE CONVENTIONAL GEOPHYSICS VIEW OF FAST AND SLOW AXES

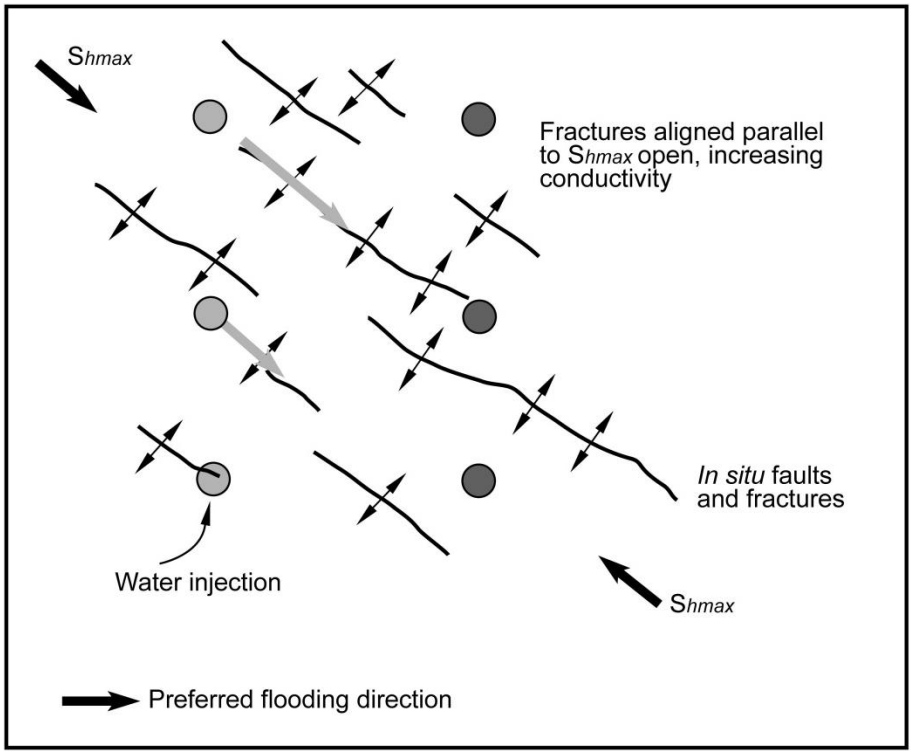
AS IF CAUSED by just one set of STRESS-ALIGNED FRACTURES

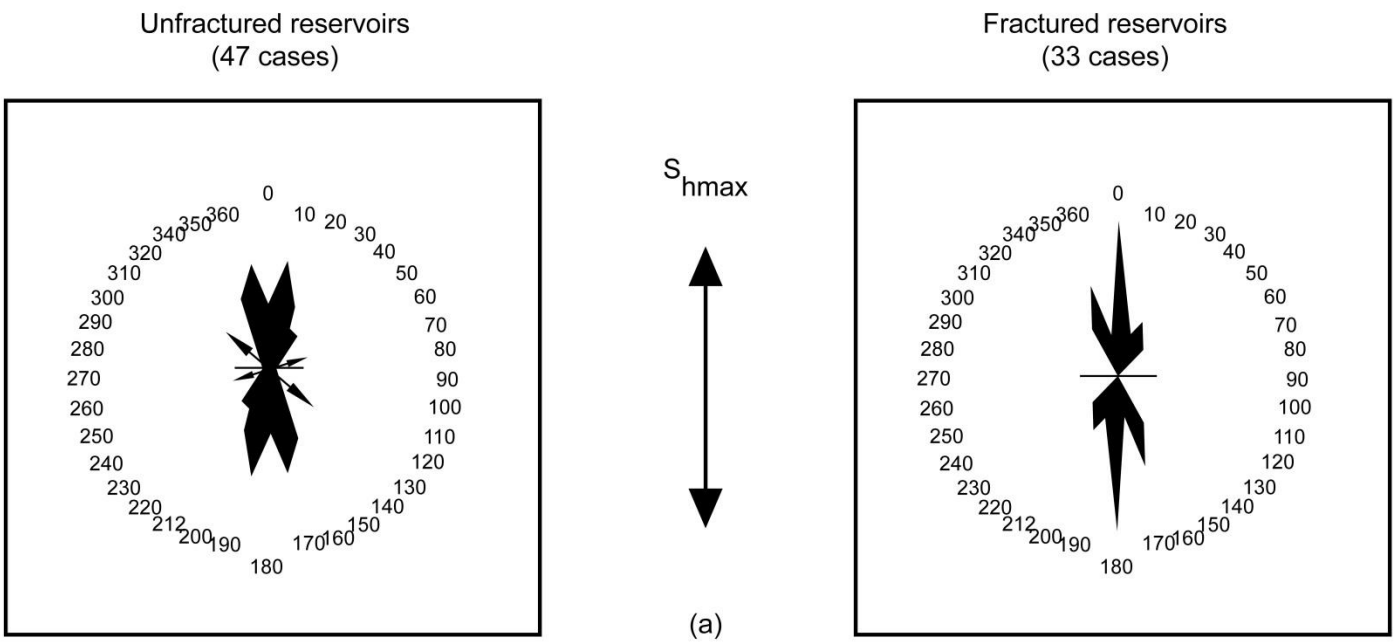
(or by stress-aligned micro-cracks)

(Stenin et al., 2002)

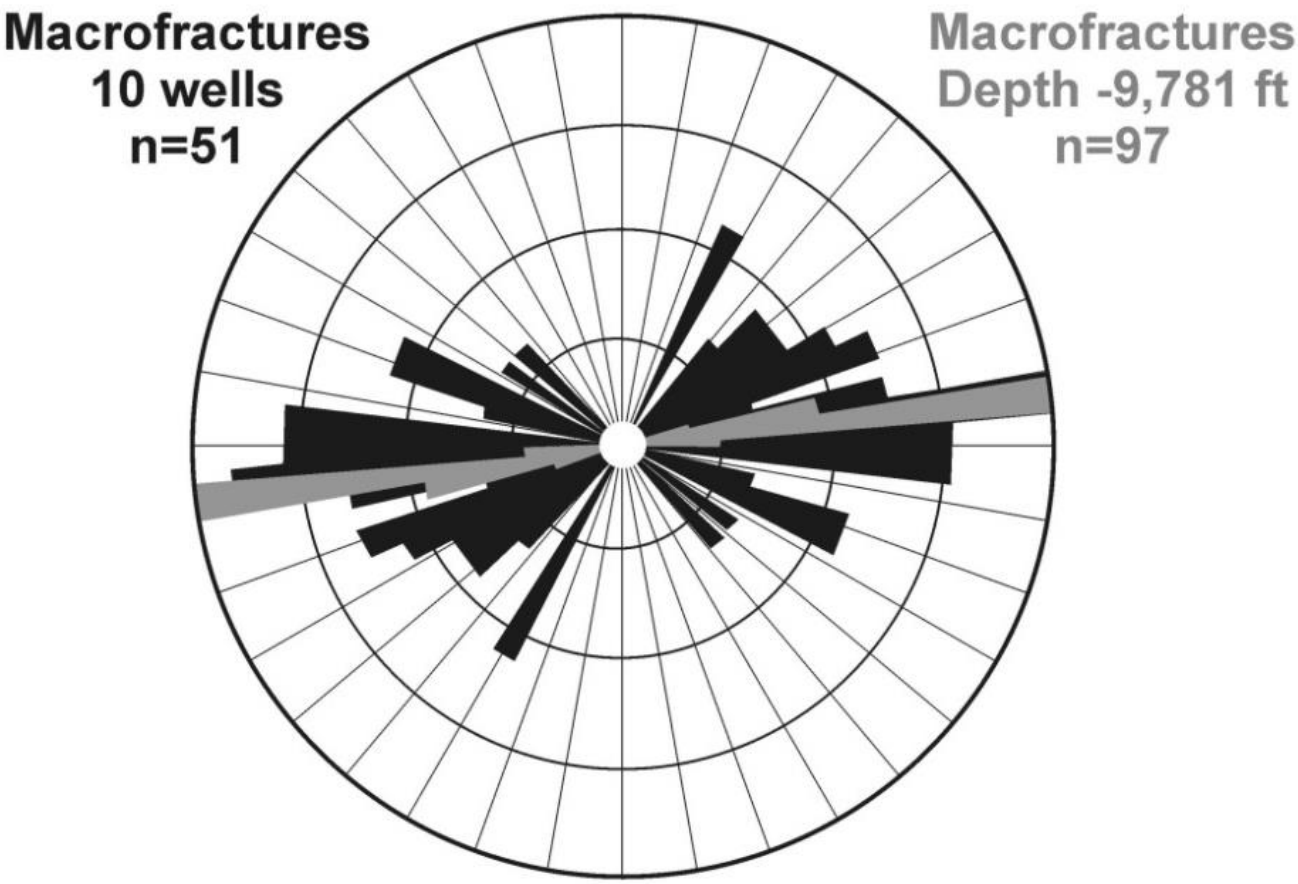
The theory (top)
The mixed-mode reality (bottom)

(Heffer et al., 1997, Heffer, 2002)



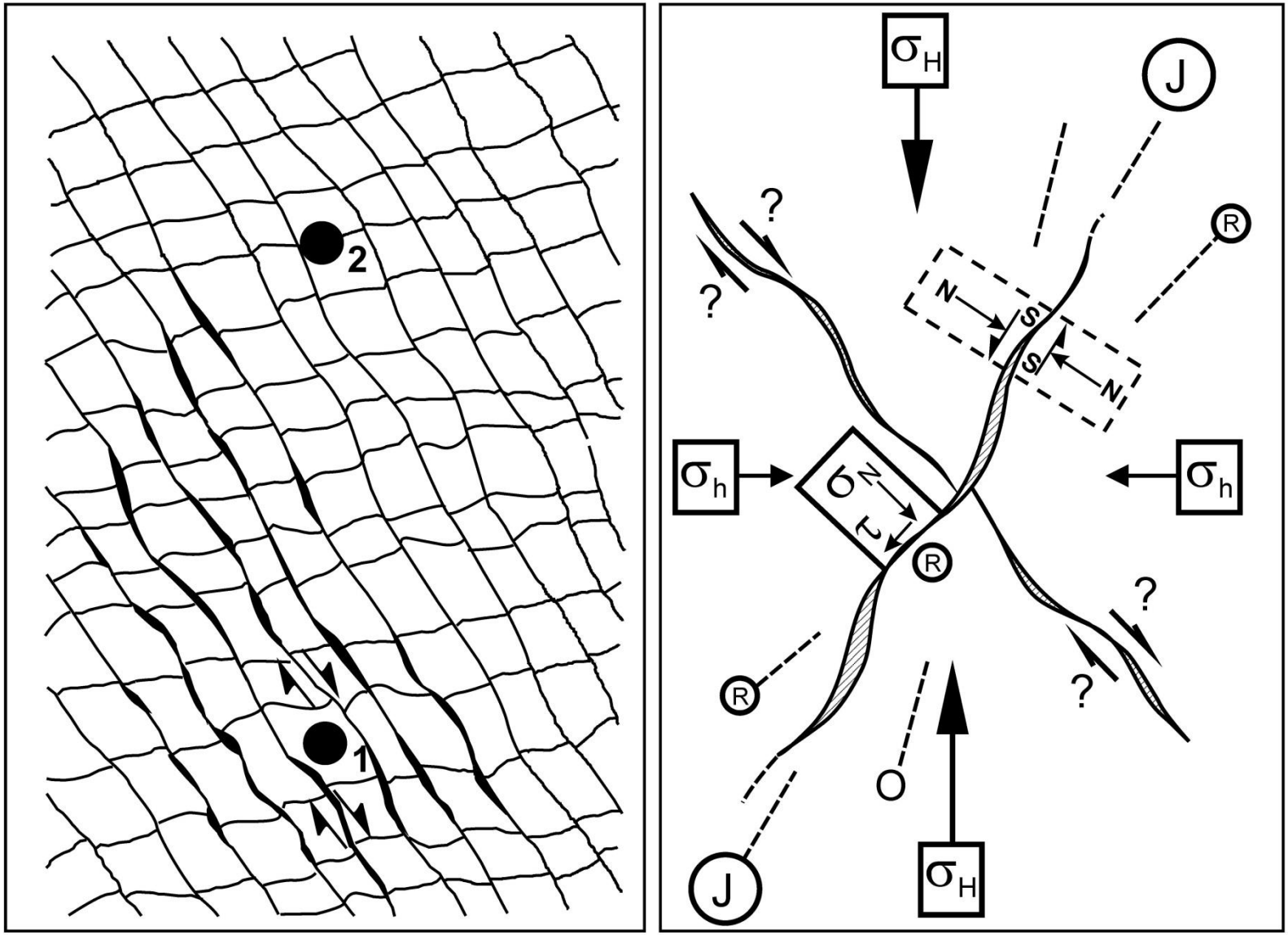


***Microcracks* appear to be (anisotropically) stress-aligned. Reservoir *fracture sets* may be conjugate (with potential shear stress component).** Laubach et al., 2000.



SHEAR-WAVE SPLITTING MAY BE DUE TO MORE THAN ONE SET

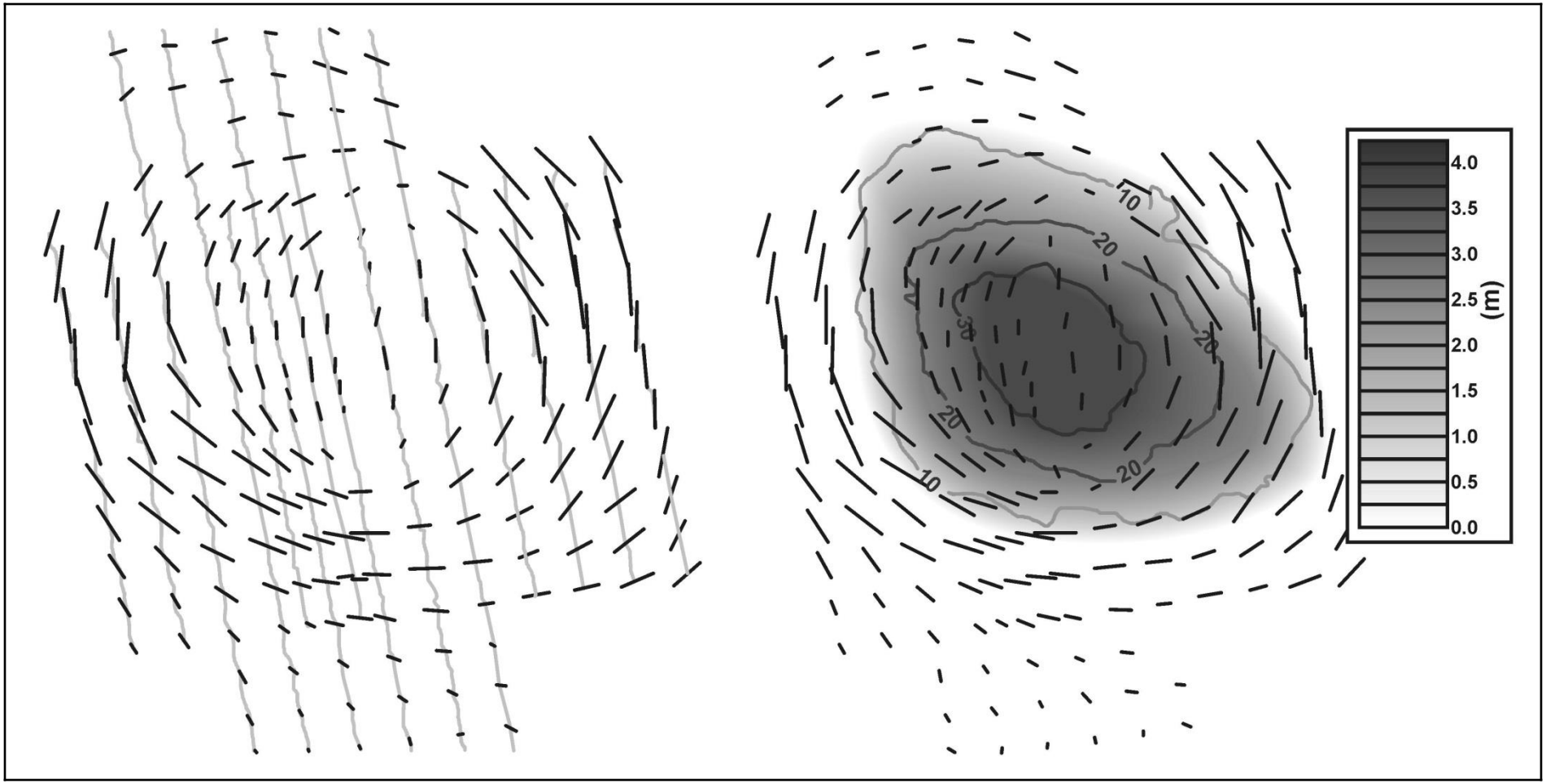
(MODEL FOR A CONDUCTIVE RESERVOIR, Barton, 2006)



SEABED SUBSIDENCE SUPERIMPOSED ON SHEAR-WAVE SPLITTING IN THE OVERBURDEN

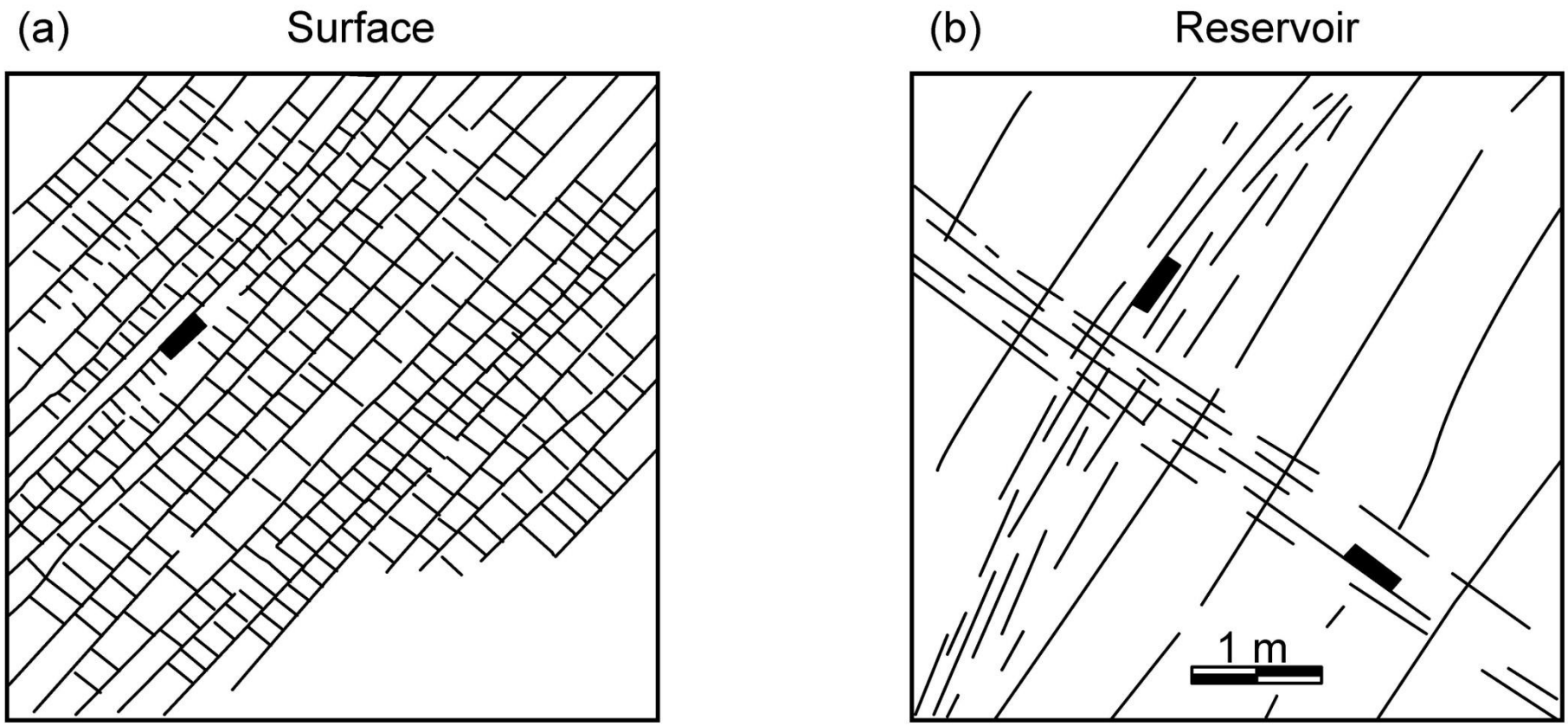
.....TWO SETS OF JOINTS? ('N-S' dominance?)

Olofsson and Kommedal, 2002.



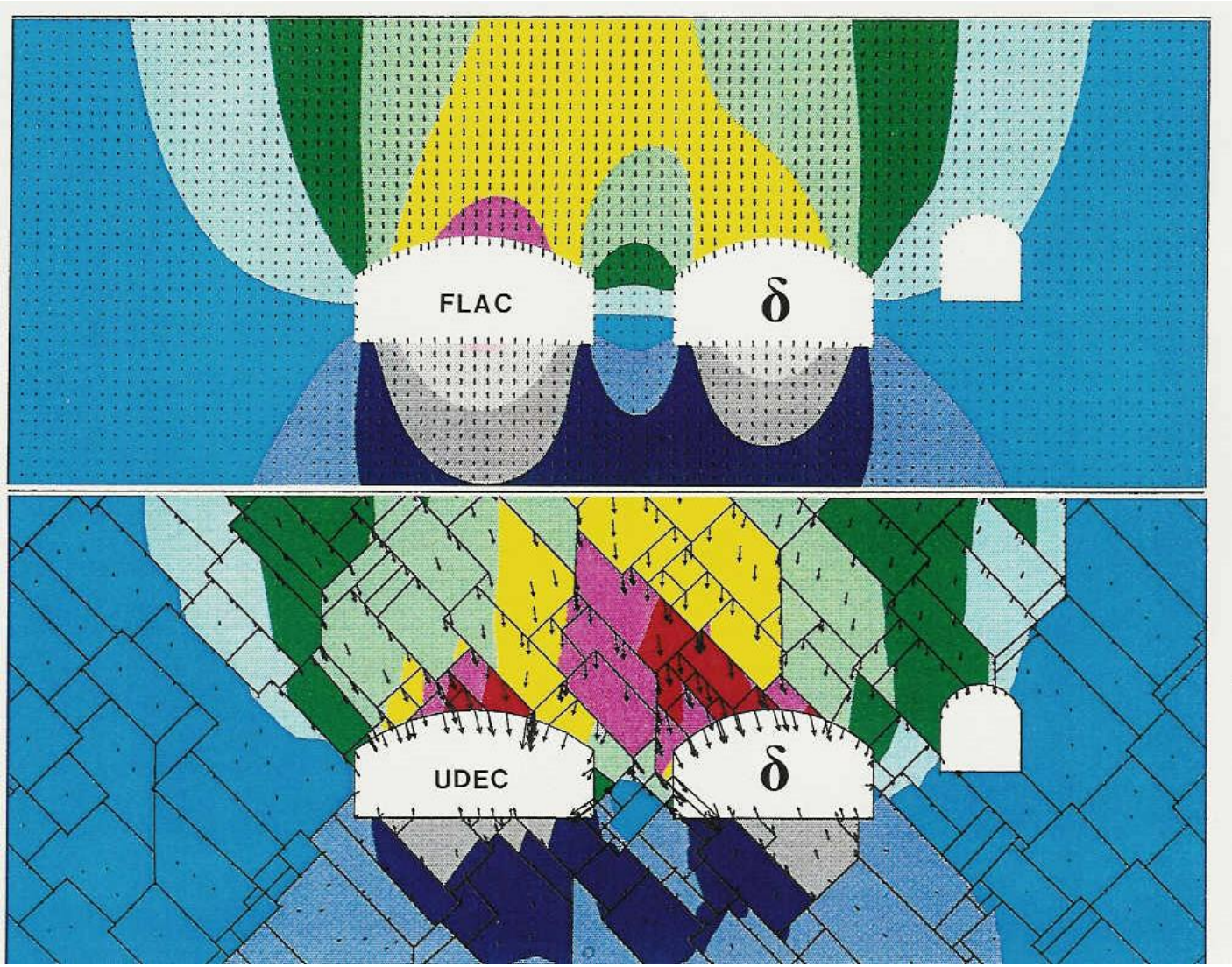
A MORE VIABLE (two sets of joints) RESERVOIR STRUCTURE

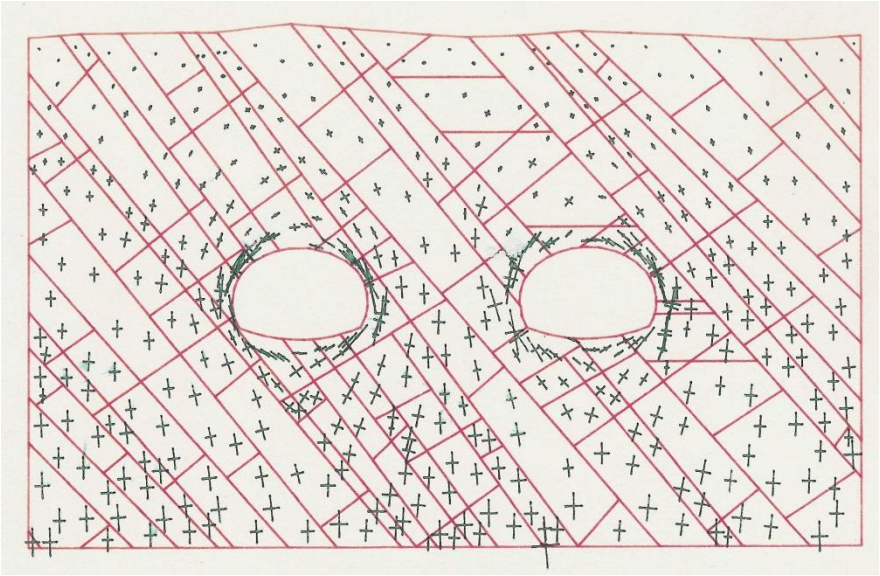
Natih reservoir, Oman. (Van der Kolk et al., 2001)

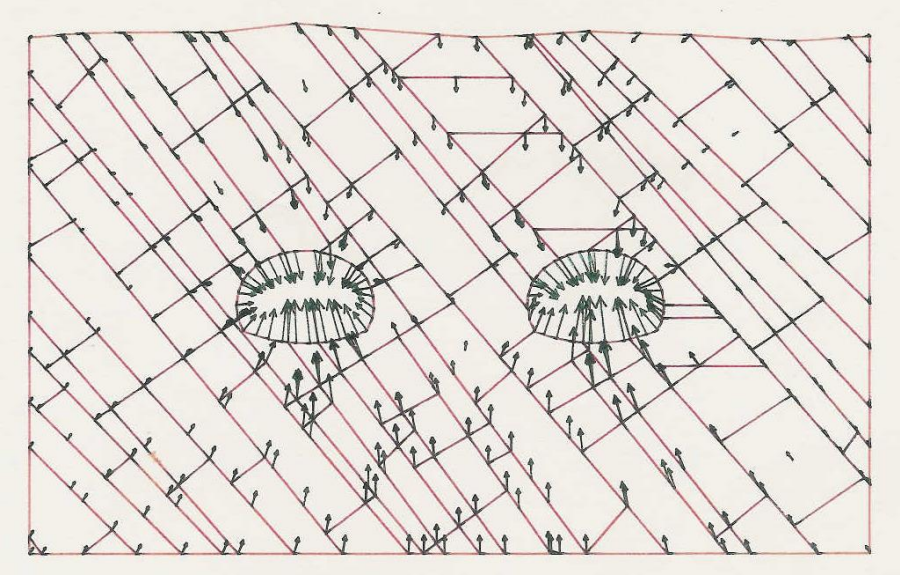


ANISOTROPY MODELLED DISCRETELY IN UDEC-BB

THE CHOICE OF ISOTROPIC BEHAVIOUR (USUALLY NON-REALITY) *or ANISOTROPY (FREQUENTLY THE REALITY) WHEN MODELLING ROCK MASSES (Backer, NGI)*

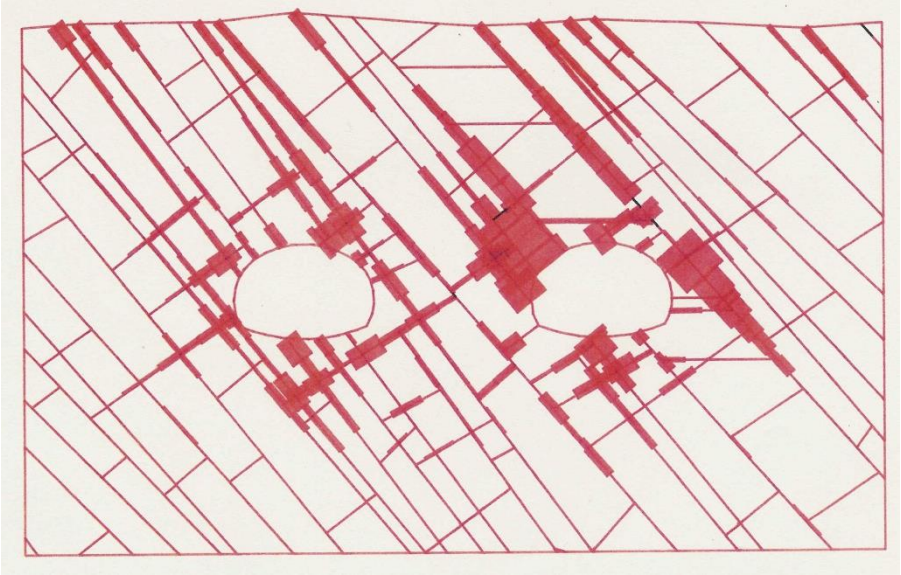


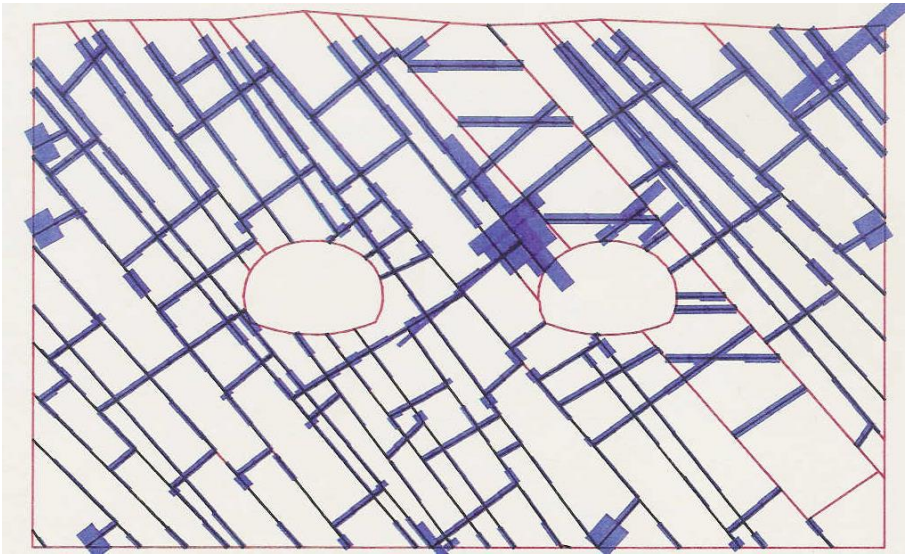




BUILT-IN ANISOTROPY DUE TO MODELLING OF DIPPING BEDS OF LIMESTONE AND SHALE. UDEC-BB.

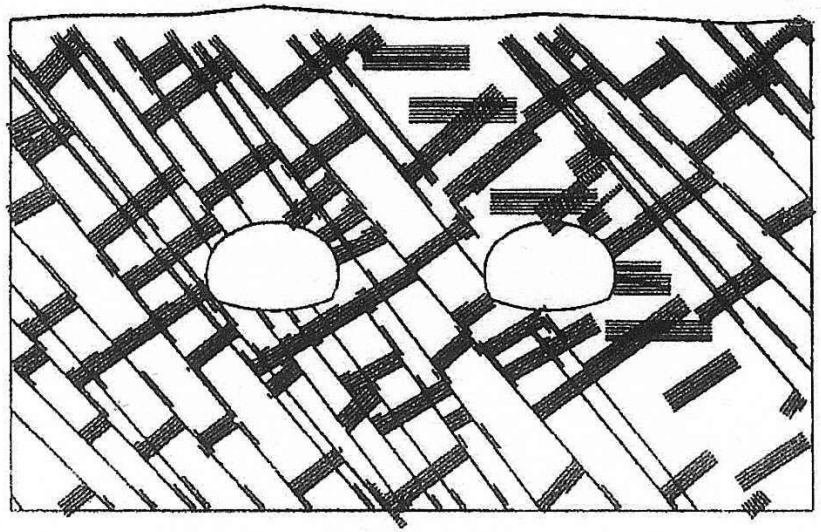
(Makurat and Barton, 1989).



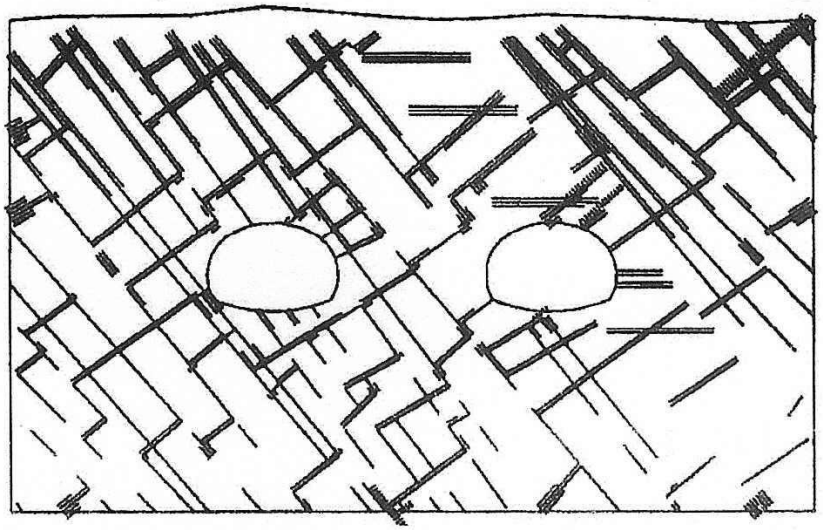


APERTURE ANISOTROPY CAUSED BY **MEASURED ANISOTROPY OF Kn AND Ks** BASED ON SCHMIDT HAMMER (JCS) AND ROUGHNESS (JRC) MEASUREMENTS

UDEC-BB (Makurat and Barton, 1989)



joint mech. aper.
max mech aper = 1.160E-03
each line thick = 2.000E-05



joint hydr. aper.
max hydr aper = 1.160E-03
each line thick = 2.000E-05

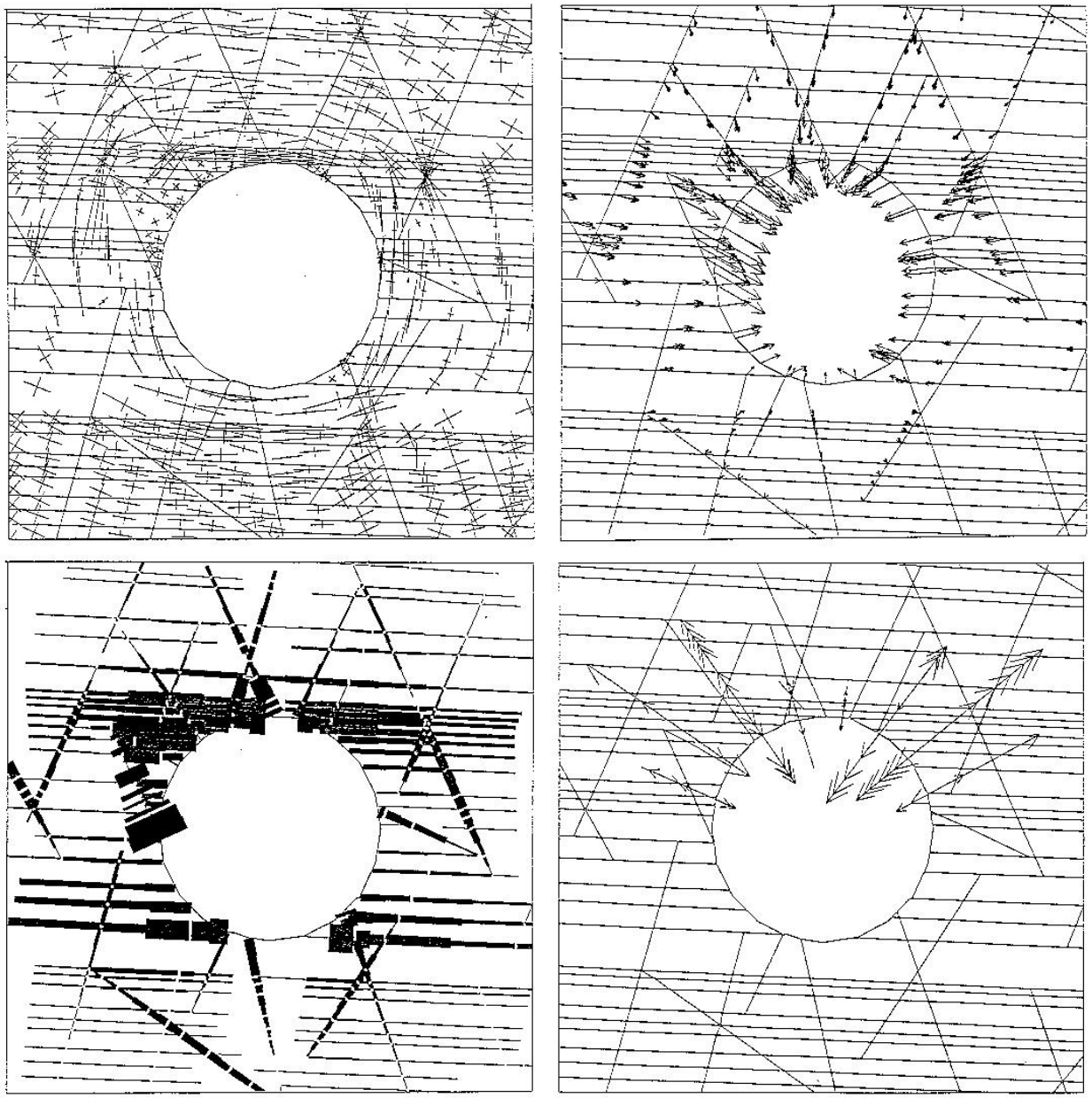
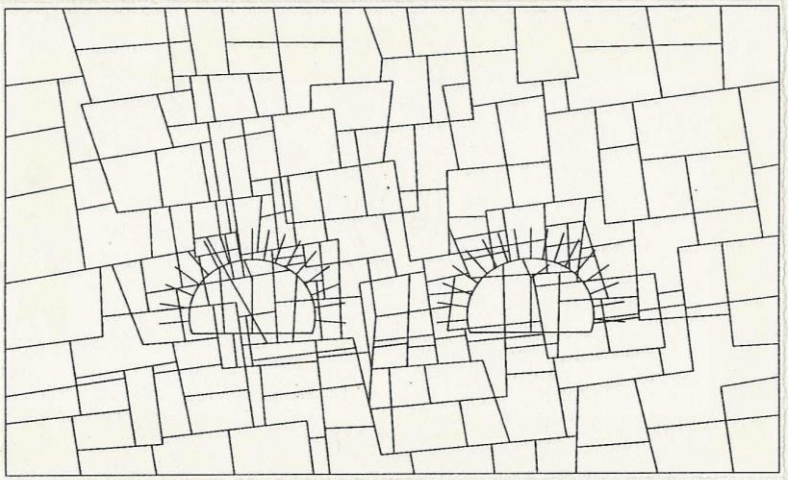


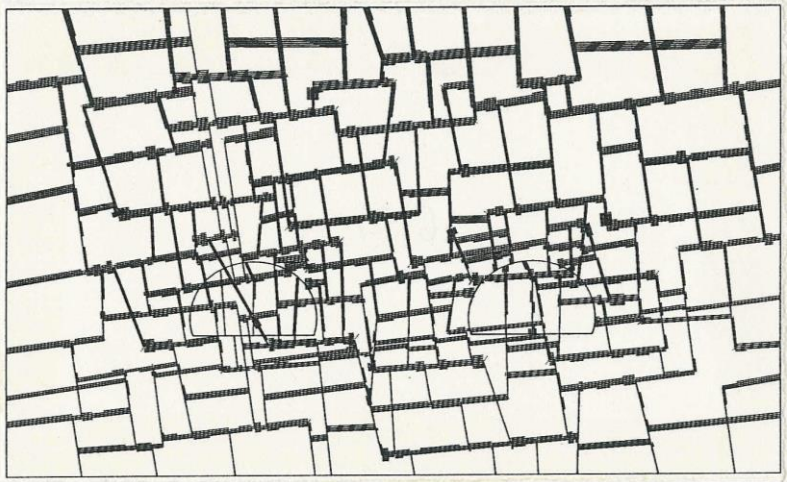
Fig. 63 Stresses (max. 55.1 MPa), displacements (max. 15.0 mm), joint shearing (max. 8.0 mm) and bolt loadings (max. 15.0 tnf) in 8 m diameter TBM model using UDEC-BB. Chryssanthakis, NGI, 1991.

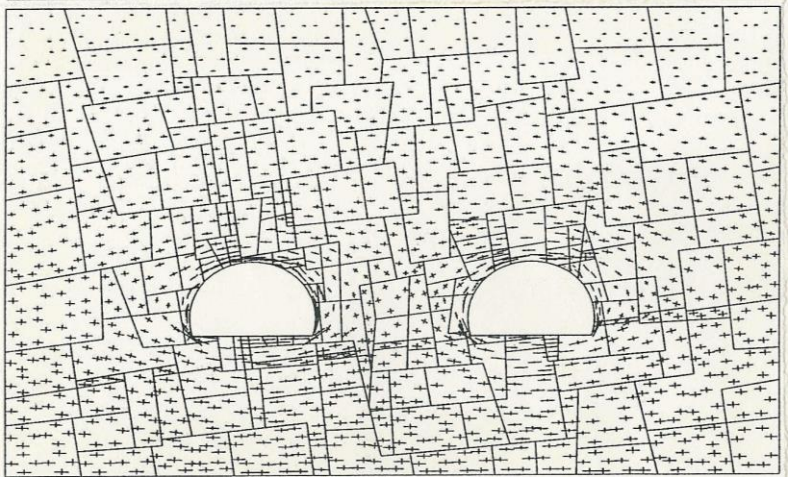
ANISOTROPIC RESPONSE CAUSED BY INTER-BEDDED SANDSTONE/SHALE SEQUENCE.

Max. deformation 15 mm, max. joint shearing 8 mm.

Chryssanthakis, 1991
UK Nirex, NGI report.



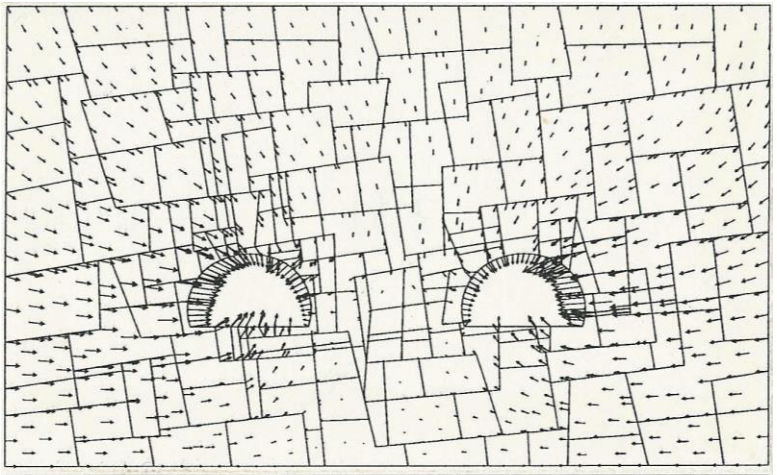


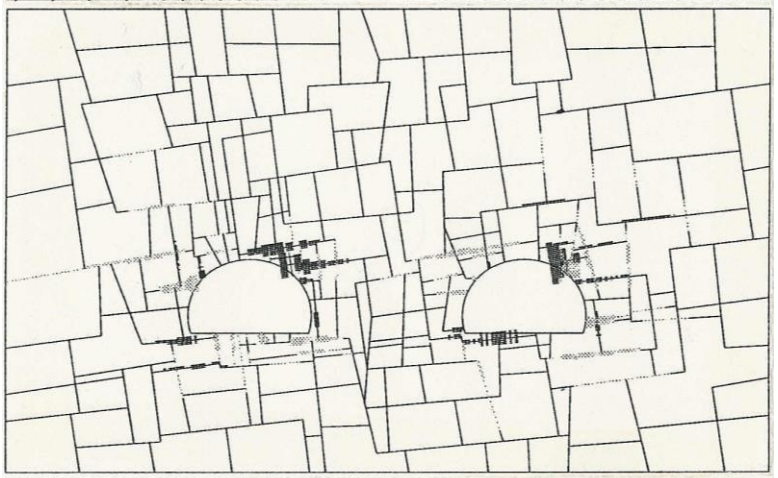


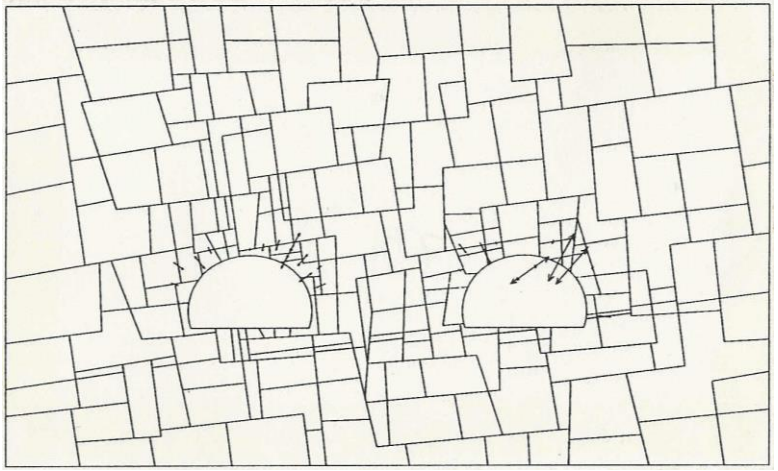
NGI UDEC-BB model of tunnels in Hong Kong granites. (Tsing Yi)

Note anisotropic $K_0 > 1$ and *therefore anisotropic:*

stress σ_θ
apertures
shear deformation
bolt forces



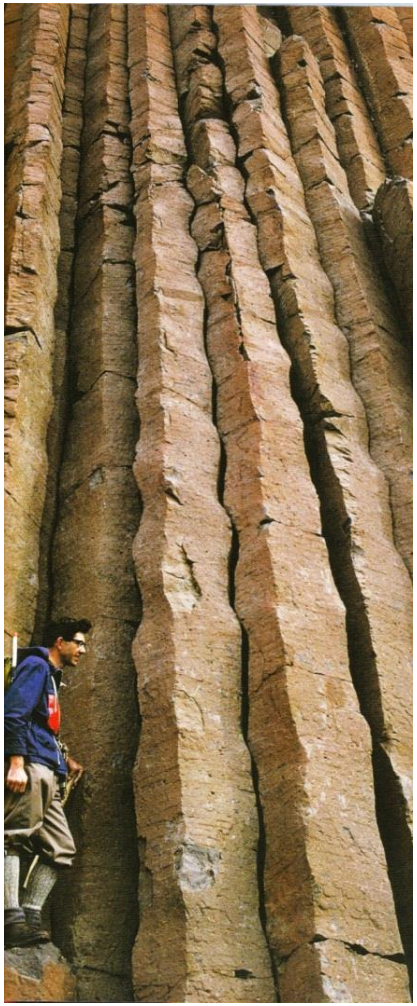


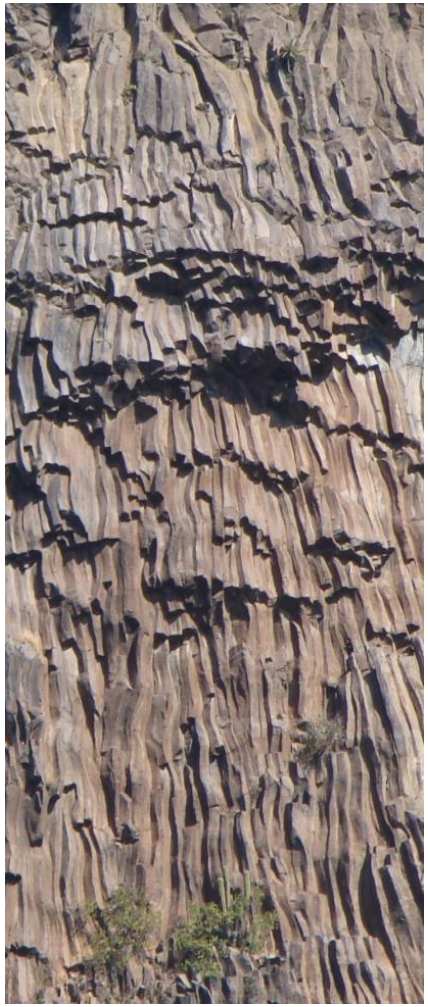


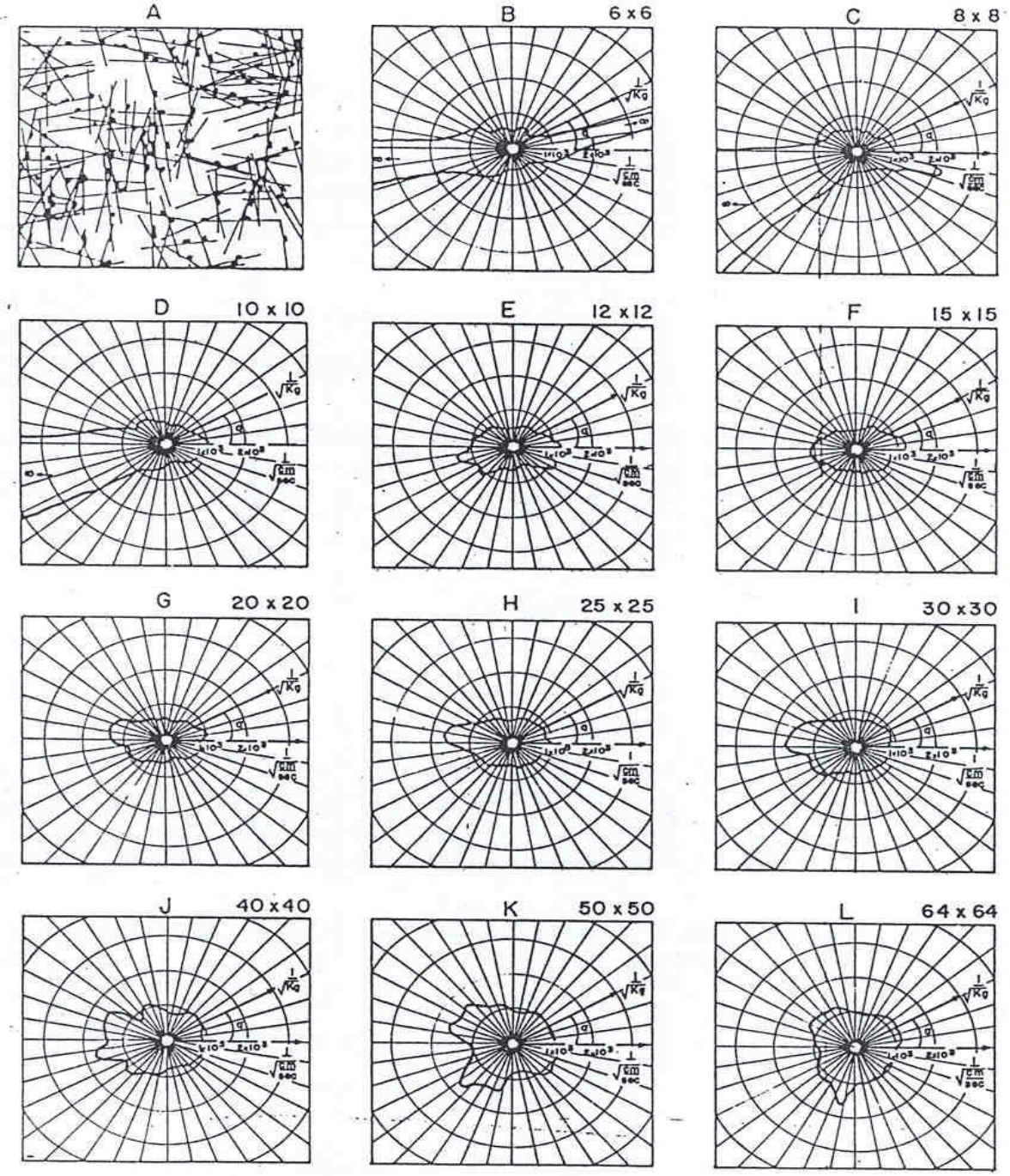
2D MODELLING, AND 3D PERMEABILITY MEASUREMENTS, MAY EACH SHOW ANISOTROPIC TENDENCIES, WHICH ARE ALSO SCALE-DEPENDENT

Zion National Park, S.Utah. ($K_{vert} >> K_{//\ bedding}$?)

COLUMNAR JOINTING IN BASALTS, AND WEATHERED FLOW-TOPS. EACH GENERATE THEIR OWN (PERMEABILITY) ANISOTROPY



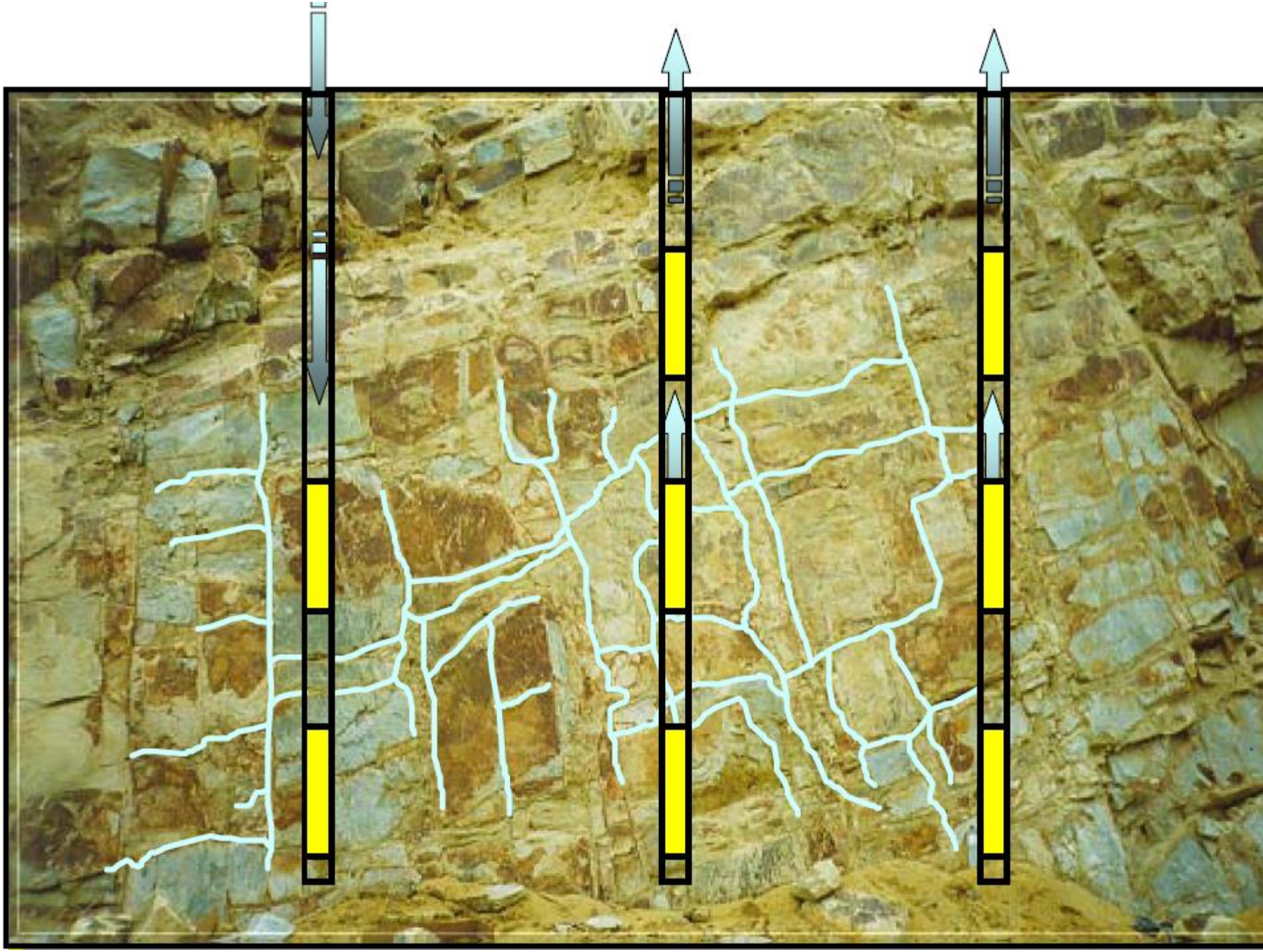




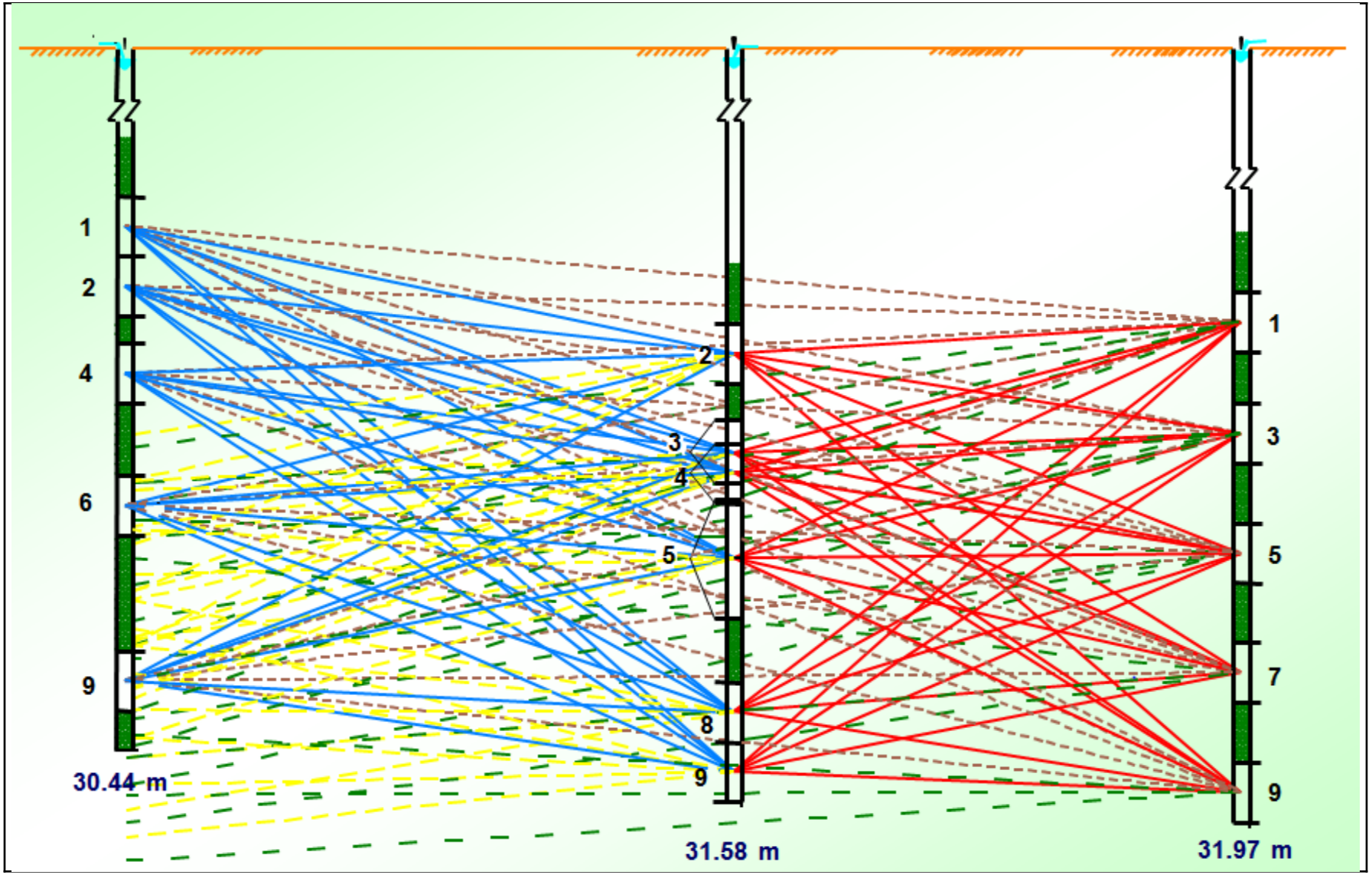
ANISOTROPY AS A FUNCTION OF (NETWORK) SAMPLING SIZE

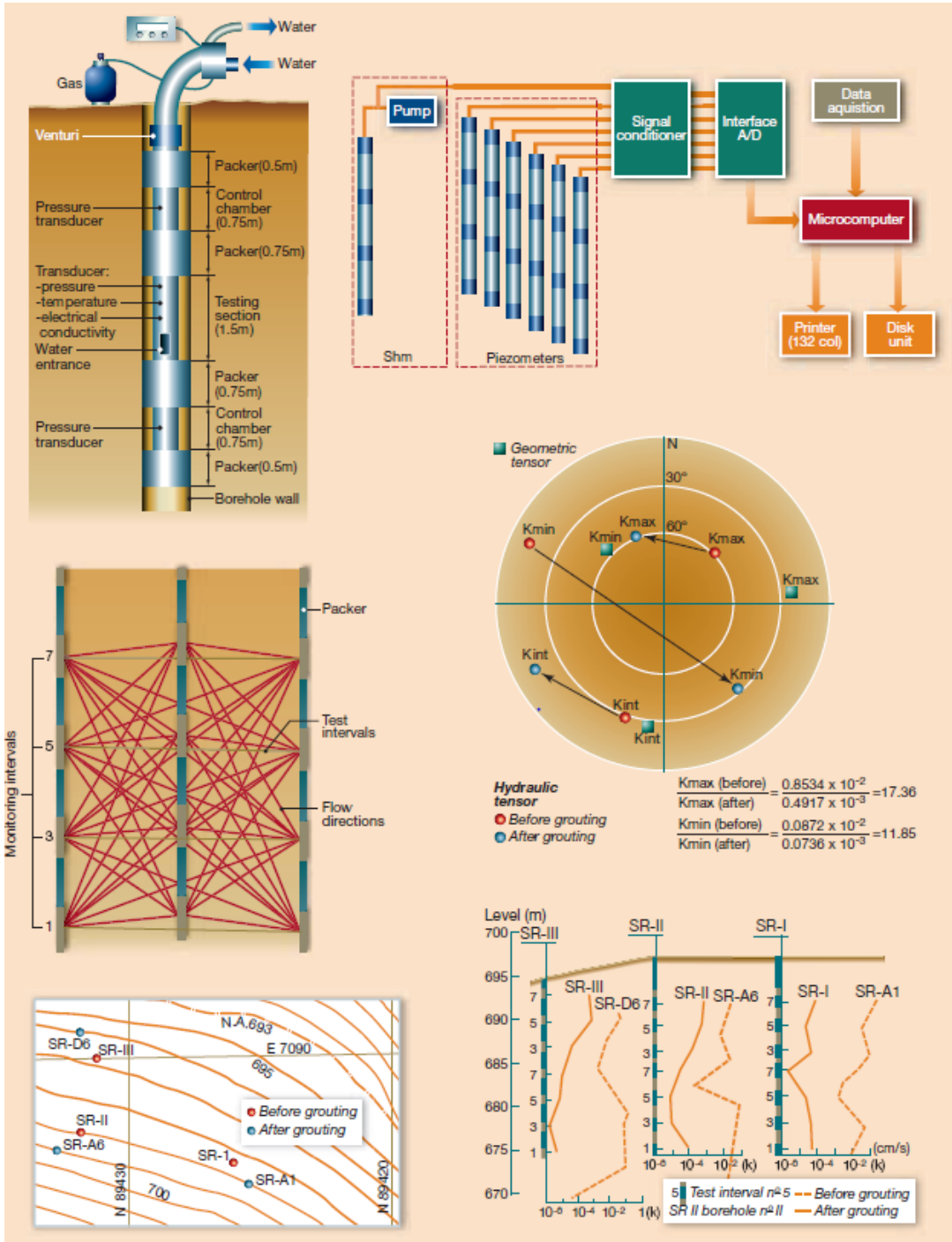
Jane Long et al., 1982

3D HYDROTOMOGRAPHY



PUMPING OUT FROM ONE PACKERED SECTION (….SUCCESSIVELY MOVED…) WHILE MONITORING PRESSURE IN ALL PACKERED SECTORS OF THE SURROUNDING BOREHOLES.





3D PERMEABILITY TESTING (HYDRO-TOMOGRAPHY) FREQUENTLY (ALWAYS?) DEMONSTRATES ANISOTROPIC PERMEABILITY (e.g. 10:1 up to e.g. 200:1) Kmax/Kmin).

MEASUREMENT BEFORE and AFTER GROUTING: *ROTATION OF PERMEABILITY TENSORS*

(Quadros & Correa Filho, 1995)

MANY CHANGES CAUSED BY THE GROUTING

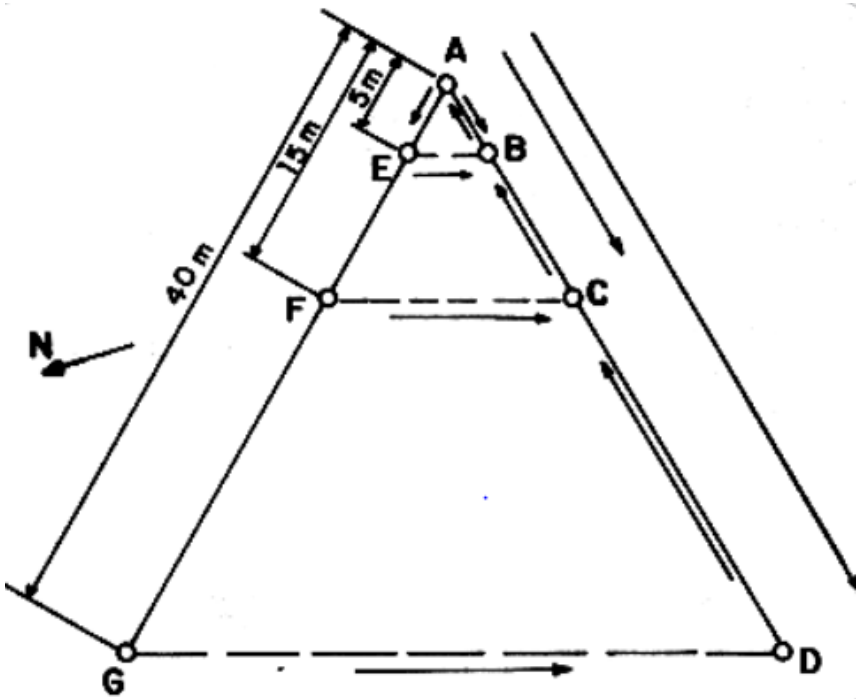
Characteristics of the hydraulic conductivity tensor before cement grouting

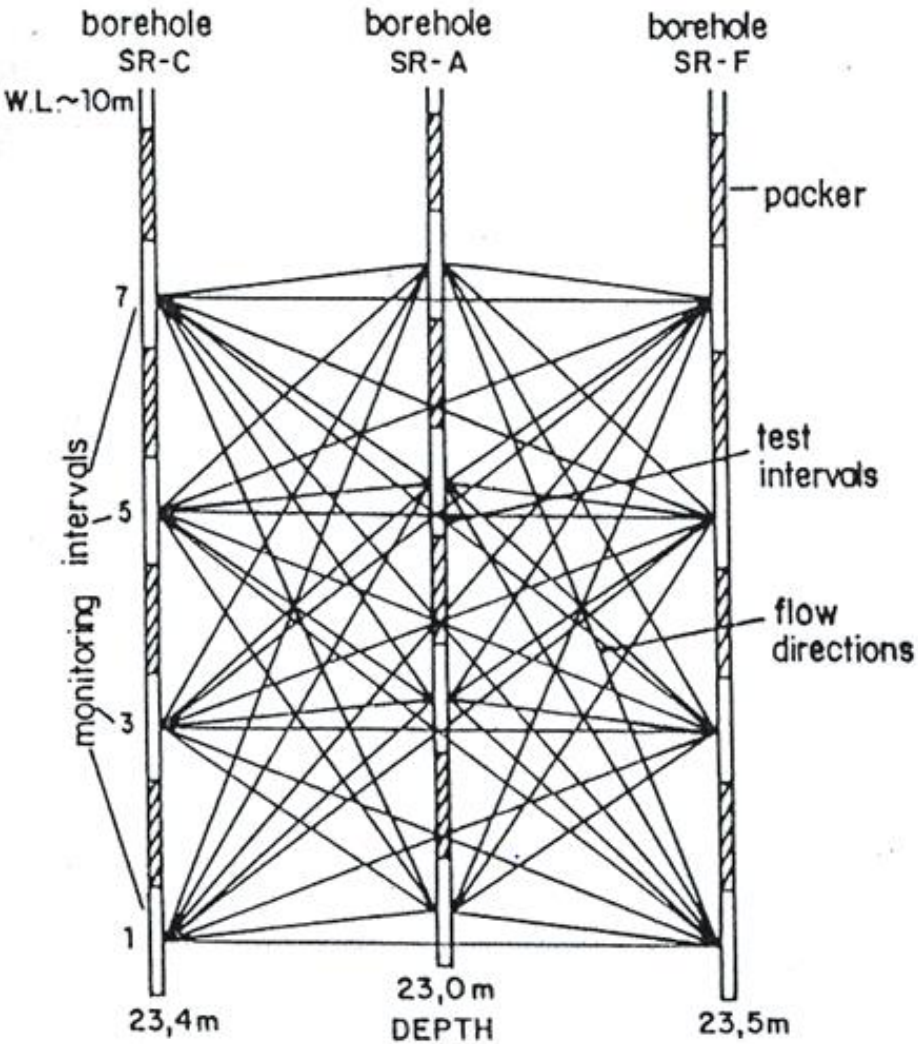
TENSOR COMPONENTS	EINGENVALUES (x 10^{-2} cm/s)	ANISOTROPY RELATIONS	ATITUDE	
			STRIKE (degrees)	DIP (degrees)
K_{max}	0.8534	9.79	N 46.13	57.34
K_{int}	0.1912	2.19	N 197.86	29.44
K_{min}	0.0872	1	N 295.26	12.85

Characteristics of the hydraulic conductivity tensor after cement grouting

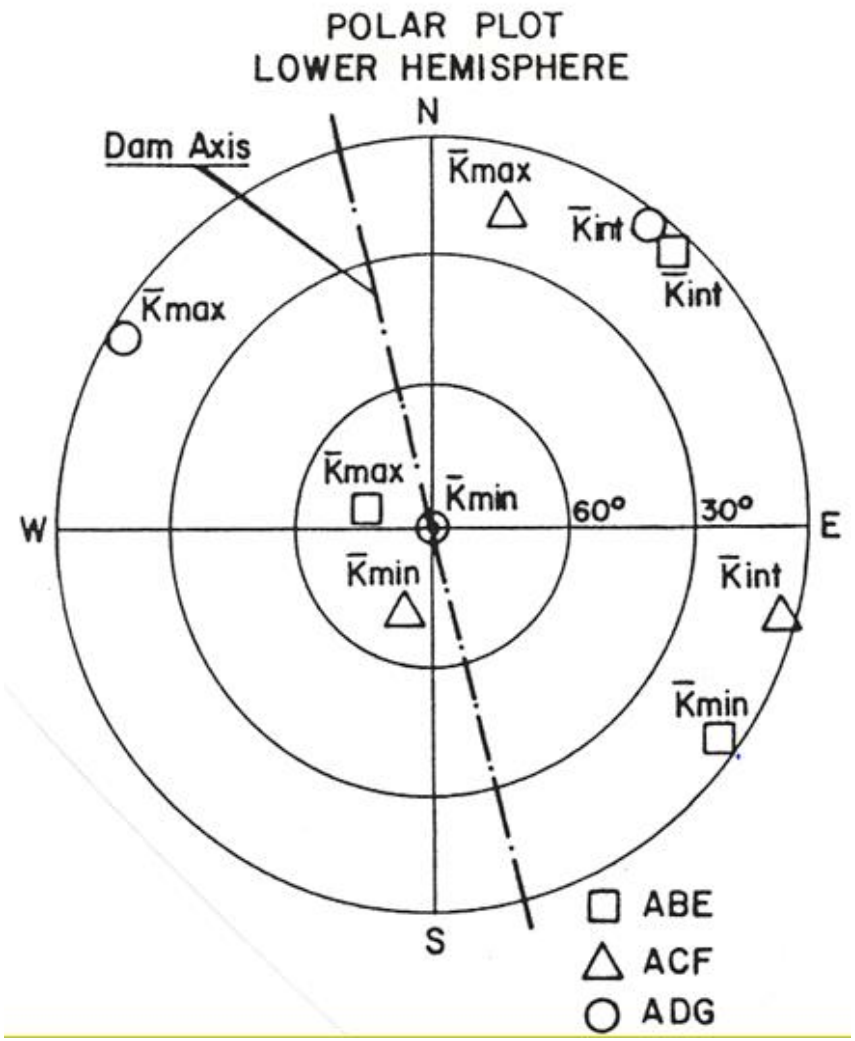
TENSOR COMPONENTS	EINGENVALUES (x 10^{-2} cm/s)	ANISOTROPY RELATIONS	ATITUDE	
			STRIKE (degrees)	DIP (degrees)
K_{max}	0.4917	6.68	N 339.68	58.75
K_{int}	0.2157	2.93	N 240.68	5.43
K_{min}	0.0736	1	N 147.45	30.67

Plan layout and scales ABE, ACF and ADG used in the hydraulic (3-D) tests in Porto Primavera dam. (Quadros & Correa Filho, 1995)





Characteristics of the Hydraulic Conductivity Tensor



A) Scale ABE

Tensor Comp.	Eigenval. cm/s(10^{-3})	Anis. Ratio	Orientation	
			Dir.(0°)	Inclin.(0°)
$\bar{K}$max	10.52	33.93	N 284.5	76.31
$\bar{K}$int	7.1	2.29	N 35.5	3.34
$\bar{K}$min	3.1	1	N 125.7	3

B) Scale ACF

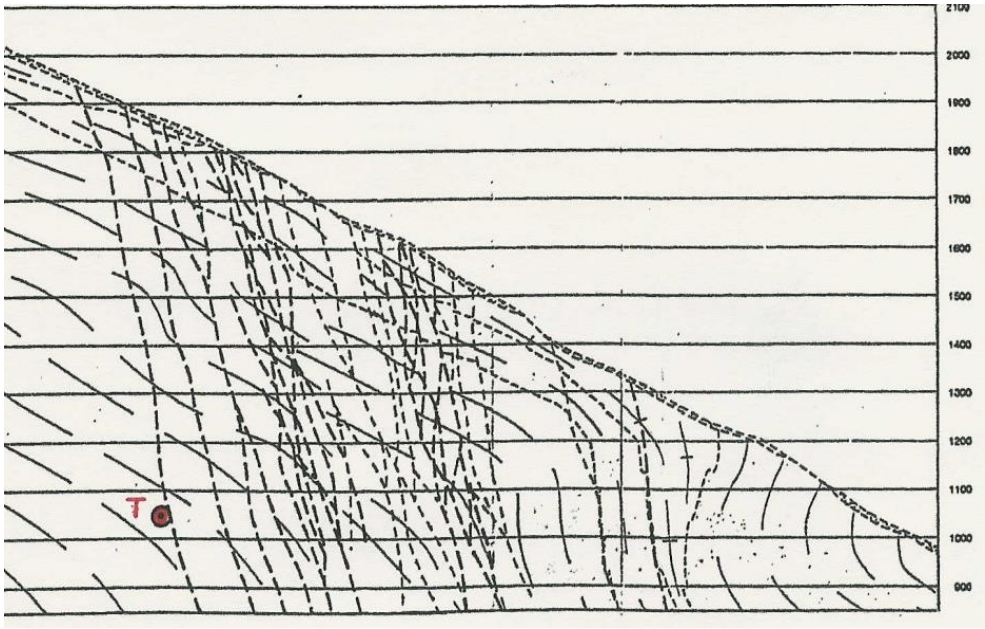
Tensor Comp.	Eigenval. cm/s(10^{-3})	Anis. Ratio	Orientation	
			Dir.(0°)	Inclin.(0°)
$\bar{K}$max	65.67	12.9	N 13.03	19
$\bar{K}$int	16.07	4.15	N 103.50	1.35
$\bar{K}$min	5.1	1	N 197.42	70.91

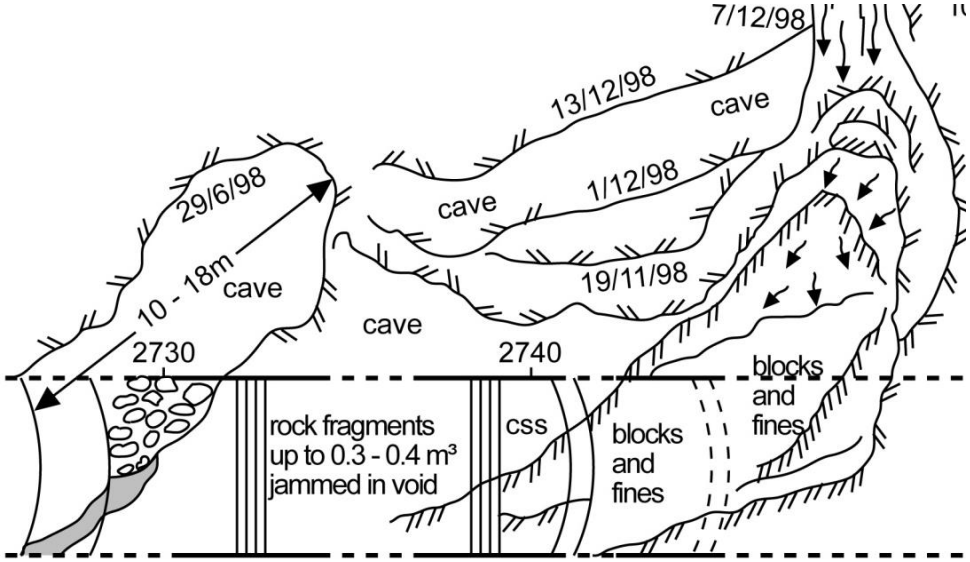
C) Scale ADG

Tensor Comp.	Eigenval. cm/s(10^{-3})	Anis. Ratio	Orientation	
			Dir.(0°)	Inclin.(0°)
$\bar{K}$max	64	213	N 302.3	1
$\bar{K}$int	17.88	59.6	N 32.34	1
$\bar{K}$min	0.3	1	N 166.35	90

Hydraulic Conductivity Tensor

ANISOTROPIC STRUCTURE CAUSING ANISOTROPIC PERMEABILITY, HAS CAUSED THIS TBM TO BE PERMANENTLY BURIED 800m UNDER THIS VALLEY-SIDE





CONCLUSIONS

ANISOTROPY IS SO WIDESPREAD THAT WE SHOULDN'T NEED A WORKSHOP TO DISCUSS IT, AS IF IT WAS SOMETHING SPECIAL !

NEVERTHELESS, THERE ARE HUGE NUMBERS OF CONSULTING OFFICES, EVEN PH.D. STUDENTS AND THEIR PROFESSORS, WHO USE ISOTROPIC CONTINUUM MODELS TO 'SOLVE' ROCK ENGINEERING PROBLEMS. (The 'colourful appendices brigade').

THIS HAS BEEN ENCOURAGED BY PRESENT-DAY 'DOWNLOADABLE' ROCK MECHANICS, APPARENTLY THE ONLY SOURCE FOR MANY.

Q AND RMR (AND GSI) SHOULD NOT ACTUALLY BE USED TO OBTAIN ISOTROPIC 'PROPERTIES' OF ROCK MASSES, BECAUSE Q and RMR ACTUALLY VARY WITH DIRECTION.

WHEN WILL THOSE PRACTICING 'ROCK MECHANICS' RETURN TO DESCRIBING THE ACTUALLY MOST FREQUENT BEHAVIOUR OF ROCK MASSES? ANISOTROPIC: stress, deformability, velocity, permeability.