Fracture-induced seismic anisotropy when shearing is involved in production from fractured reservoirs

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OUTLINE OF LECTURE

- ’OPEN’ FRACTURES // TO $\sigma_{H\ MAX.}$ The rule or an anomaly?

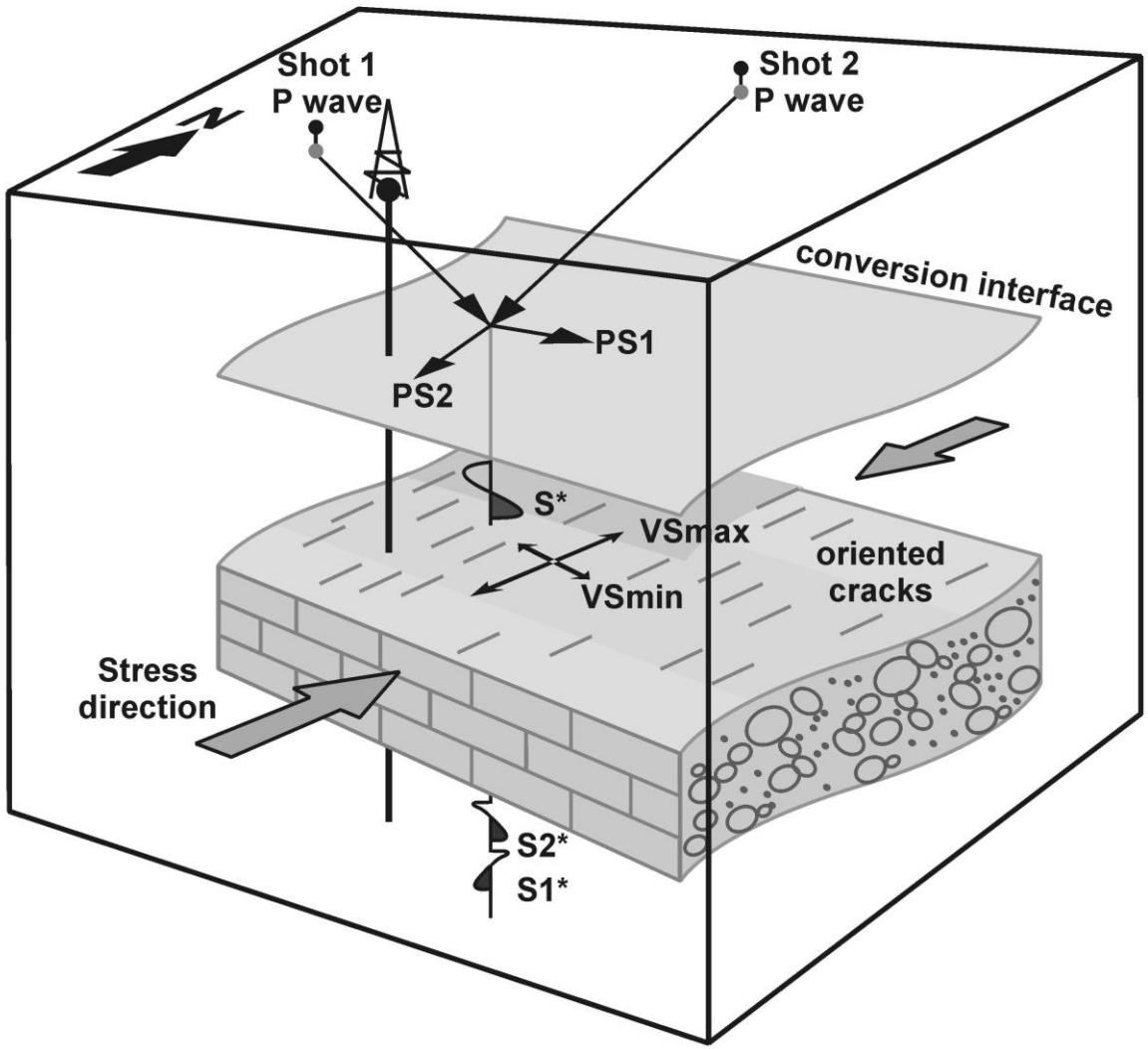
- PERMEABILITY MAY BE CAUSED BY 2-SETS?
- PERMEABILITY MAY IMPLY PRE-PEAK SHEAR
- PRE-PEAK SHEAR *IMPERATIVE* FOR PERMEABILITY ?

- TEMPORAL (4D) ROTATION OF ANISOTROPY, ATTENUATION
- POLARIZATION IN SUBSIDING OVERBURDEN *Intra-bed jointing ?*

- COMPLIANCE / STIFFNESS Z_N *and* Z_T *, Kn and Ks .....inequalities*
- INEQUALITY OF APERTURES e ≤ E ..... What aspect ratios?

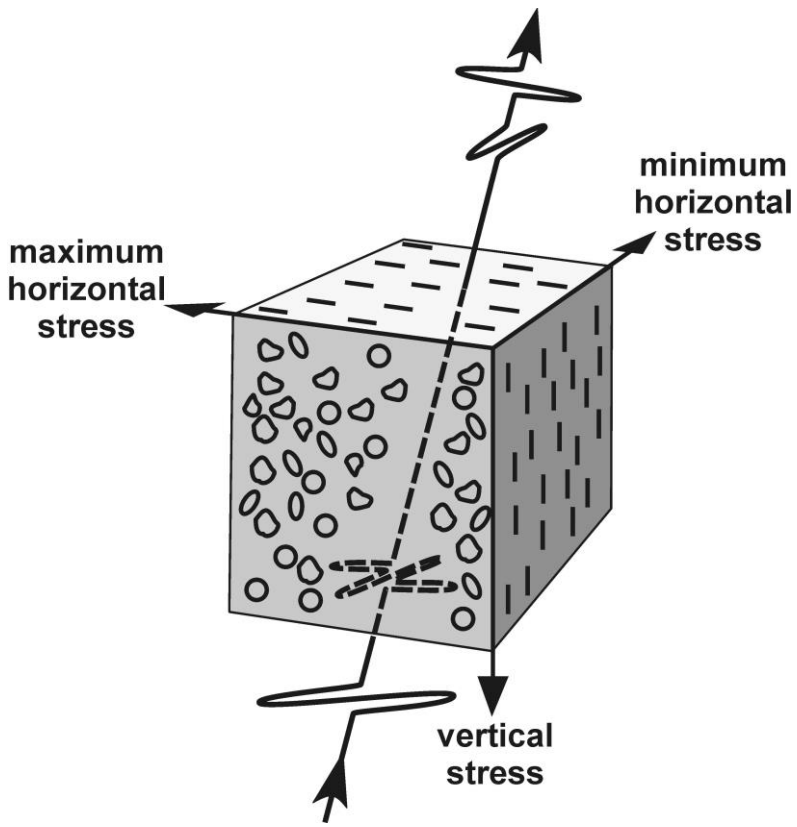
THE CLASSIC ASSUMPTION THAT $V_{S\ MAX}$ WILL BE ROUGHLY PARALLEL TO $\sigma_{H\ MAX}$ (due to oriented microcracks or fractures?)

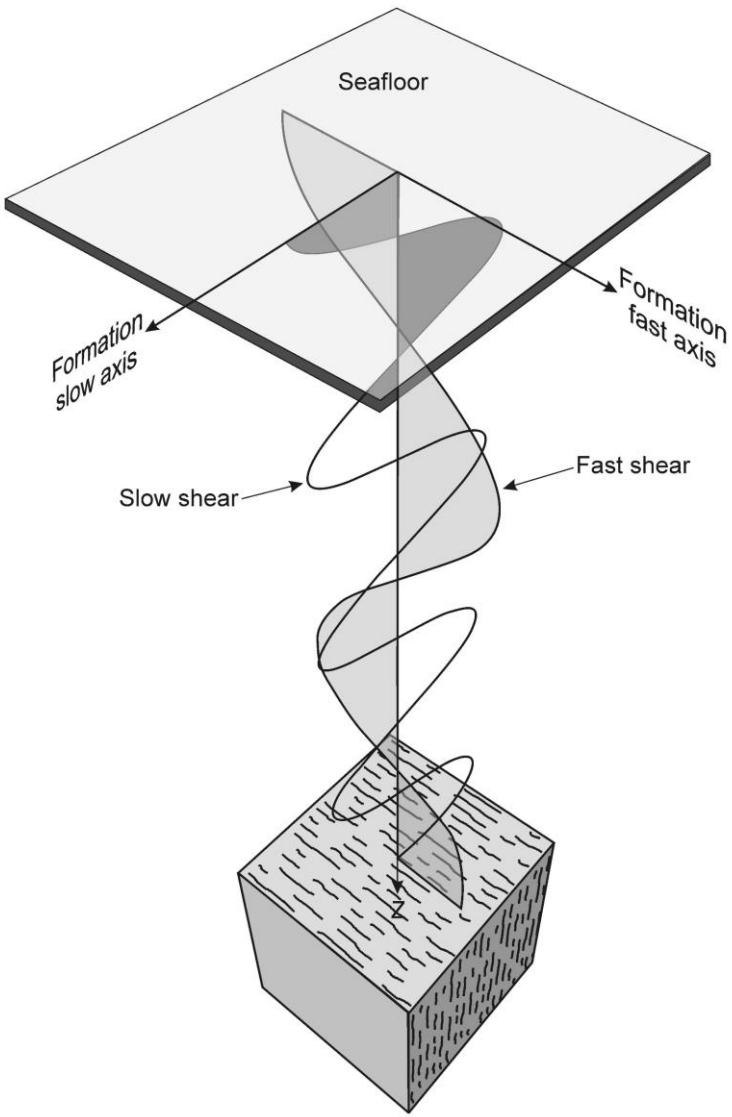
(Far-offset VSP: Stenin et al., 2002)



Shear-wave splitting .....due to microcracks sub- // to $\sigma_{H\ MAX}$?.....due to one dominant fracture set?.....due to two conjugate sets?

(Crampin and Lovell, 1991, Barkved et al. 2004)





UNLESS FRACTURES ARE ROUGH (or have mineral bridging), OR ARE IN VERY STRONG ROCK, THEY MAY BE ALMOST CLOSED AT RESERVOIR DEPTHS.

'OPEN' // $\sigma_{H\ MAX}$ MAY BE OPTIMISTIC !

CAN 'OPEN' FRACTURES IN RESERVOIRS BE PARALLEL TO $\sigma_{H\ max}$?

- The surface roughness of joints or fractures may help maintain permeability at high confining pressures, corresponding to depths of several kilometres.

- But smoother, more planar joints or fractures are likely to be closed at reservoir depths, when acted on by an effective normal stress = $\sigma_{h\ min} - P_w$ of 20-40 MPa in magnitude.

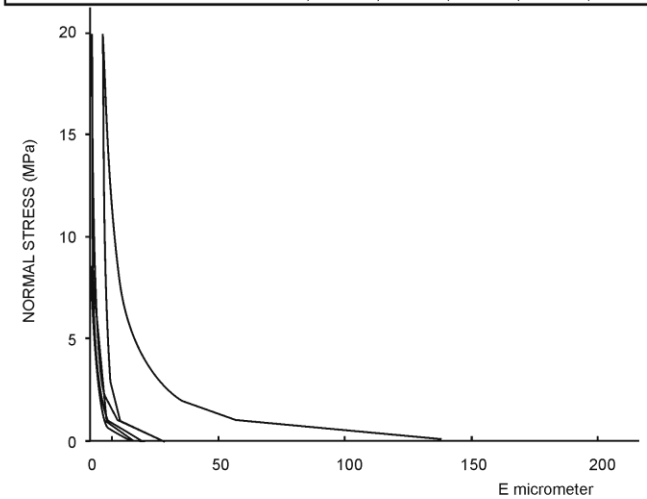
- The next figure shows Barton-Bandis models of normal closure, shearing and dilation for weak reservoir rock. Normal closure tends to *close*, shearing tends to *open*.

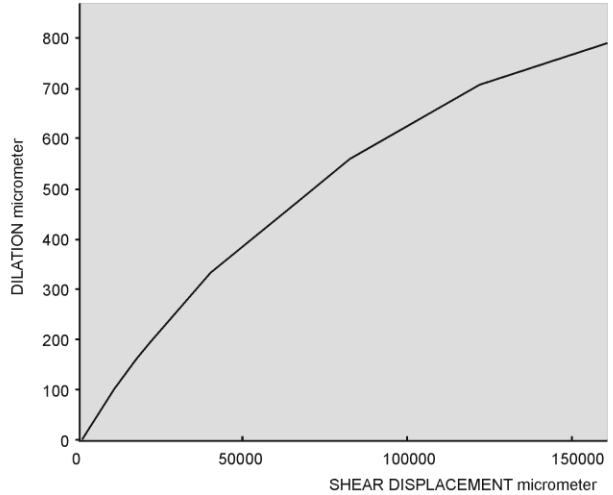
Top: input data
Left: stress-closure
Right: shear-dilation

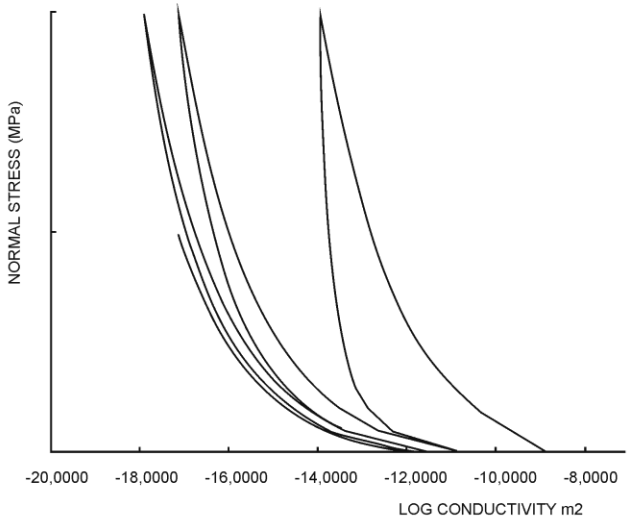
JCS = 25 MPa
JRC = 5
(weak rock,
low roughness)

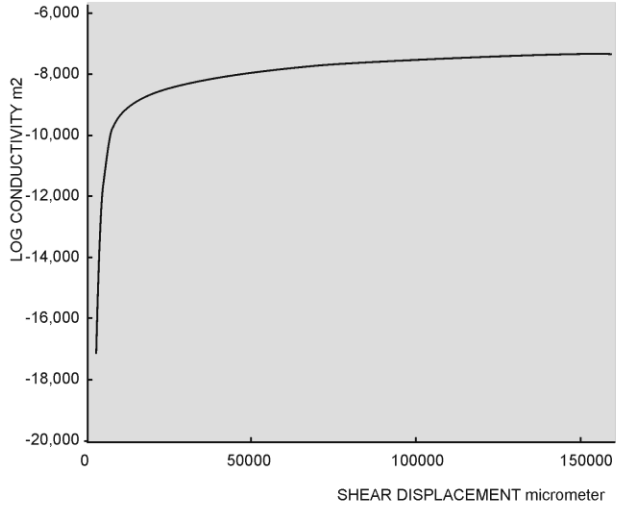
Barton Bandis Joint Model		NORMAL CLOSURE CALCULATION						
INPUT PARAMETERS		SNORM	CYCLE 1	CYCLE 2	CYCLE 3	CYCLE 4	CYCLE 5	
JRC	5	LOAD	20	20	20	10	0	MPa
JCS	25	UNLOAD	0	0	0	0	0	MPa
SIGMAC	30	APERTURE	0,140	0,030	0,020	0,016	0,015	mm
		KNP	4,60E+03	2,80E+04	4,50E+04	1,40E+04	3,00E+01	
CALCULATED PARAMETERS								
		KNI	4,76	16,42	24,13	29,18	30,42	MPa/mm
	LOAD	VMI	-0,140	-0,030	-0,020	-0,016	-0,015	mm
		AJ	0,210	0,061	0,041	0,034	0,033	
		BJ	1,499	2,030	2,100	2,125	2,130	
	UNLOAD	KNI'	16,42	24,13	29,18	30,42	23,64	MPa/mm

INPUT PARAMETRS			FULL SCALE PARAMETERS		
JRCo	5,00		JRCn	4,26	
JCSo	25,00	MPa	JCSn	19,64	MPa
Lo	0,10	M	DPEAK	2,03	mm
Ln	0,50	M	ROUGH	1,25	
PHIr	27,00	DEG	LFACT	0,01	
SIGMA n	10,00	MPa	PHIr RAD	0,47	Rad
SIGMAC	30,00	MPa	PPEAK	28,25	Degrees
APERTURE	0,000	mm	KS	2,650	MPa/mm









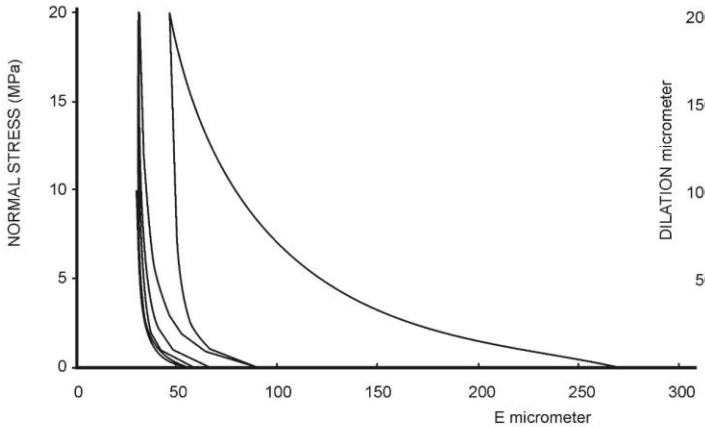
Top: input data
Left: stress-closure
Right: shear-dilation

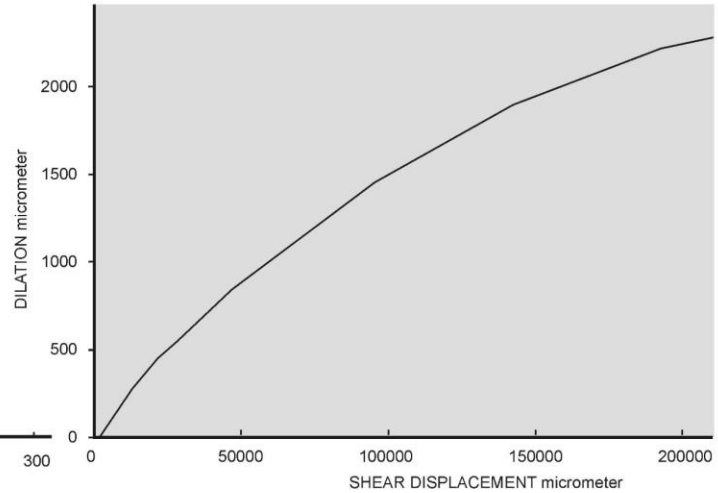
JCS = 50 MPa
JRC = 10
(stronger rock,
larger roughness)

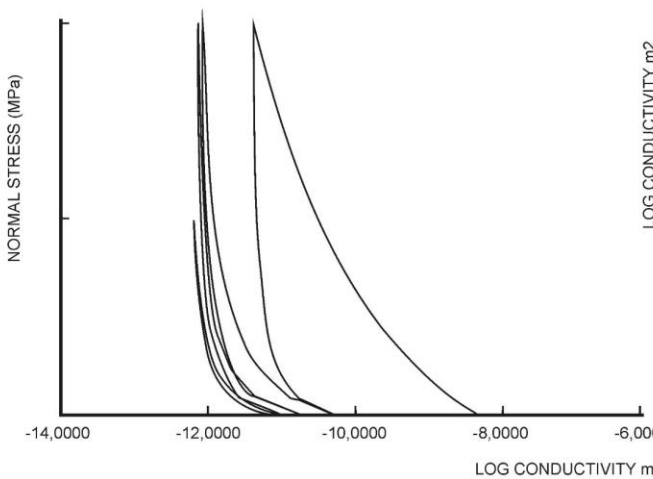
Barton Bandis Joint Model — NORMAL CLOSURE CALCULATION

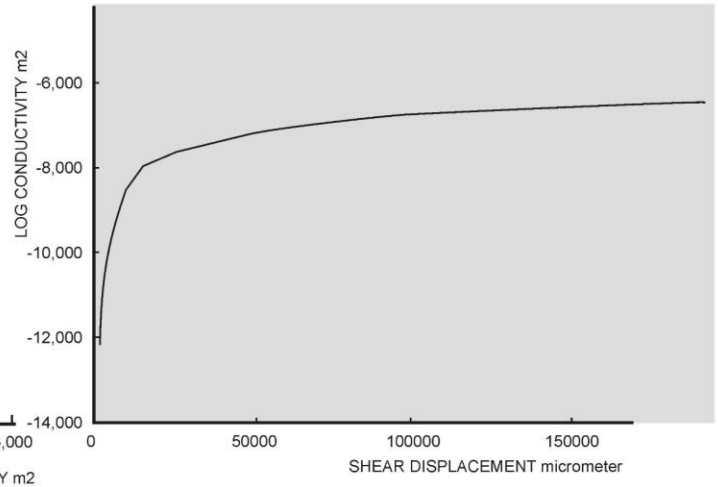
INPUT PARAMETERS		SNORM	CYCLE 1	CYCLE 2	CYCLE 3	CYCLE 4	CYCLE 5	
JRC	10	LOAD	20	20	20	10	0	MPa
JCS	50	UNLOAD	0	0	0	0	0	MPa
SIGMAC	60	APERTURE	0,280	0,090	0,068	0,059	0,056	mm
CALCULATED PARAMETERS								
LOAD		KNI	13,5	20,17	23,4	25,41	26,33	MPa/mm
		VMI	-0,277	-0,063	-0,039	-0,032	-0,029	mm
UNLOAD		KNI'	16,42	24,13	29,18	30,42	23,64	MPa/mm

INPUT PARAMETRS			FULL SCALE PARAMETERS		
JRCo	10,00		JRCn	7,25	
JCSo	50,00	MPa	JCSn	30,85	MPa
Lo	0,10	M	DPEAK	2,42	mm
Ln	0,50	M			
PHIr	33,00	DEG			
SIGMA n	10,00	MPa			
SIGMAC	60,00	MPa	PPEAK	36,55	Degrees
APERTURE	29,500	µm	KS	3,067	MPa/mm





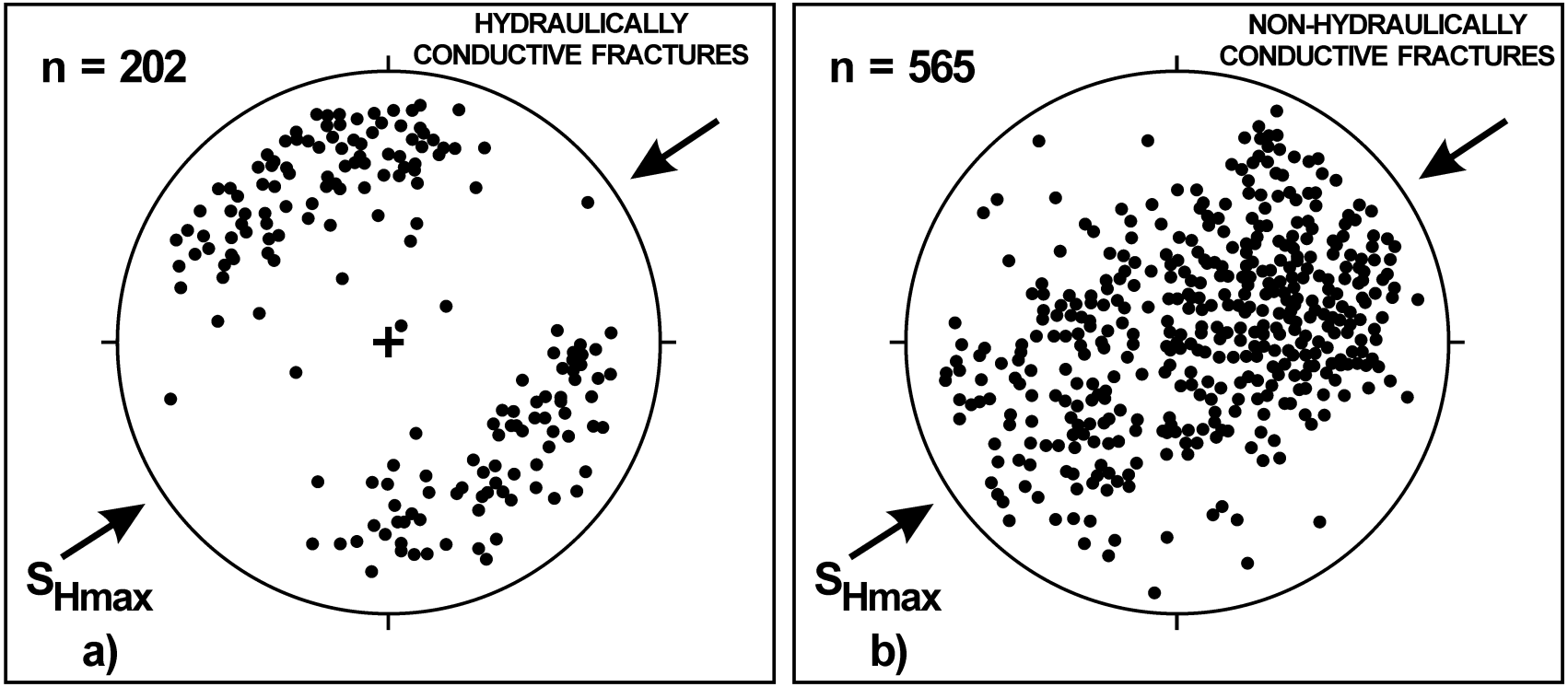


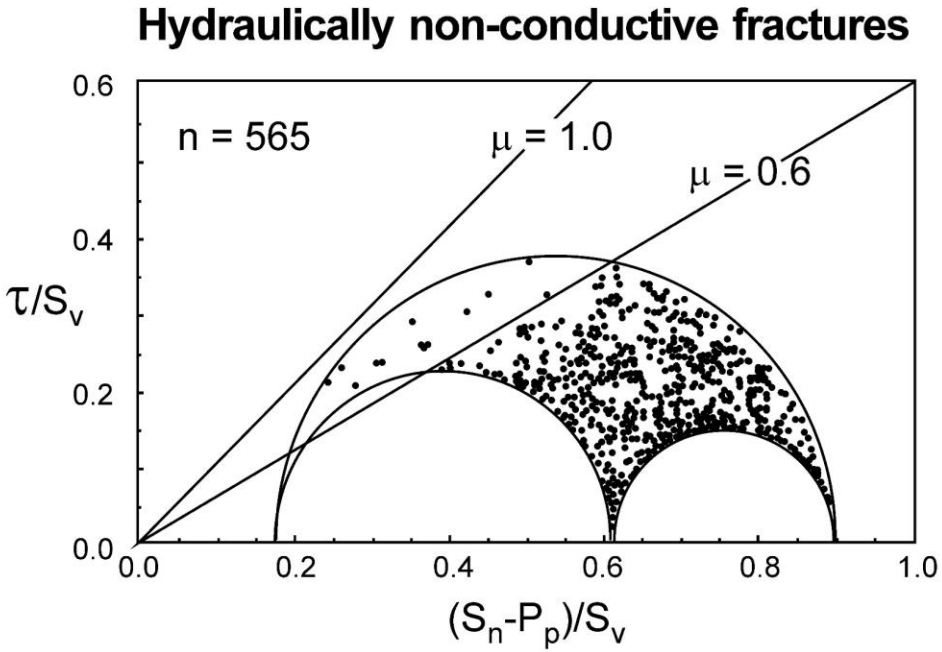


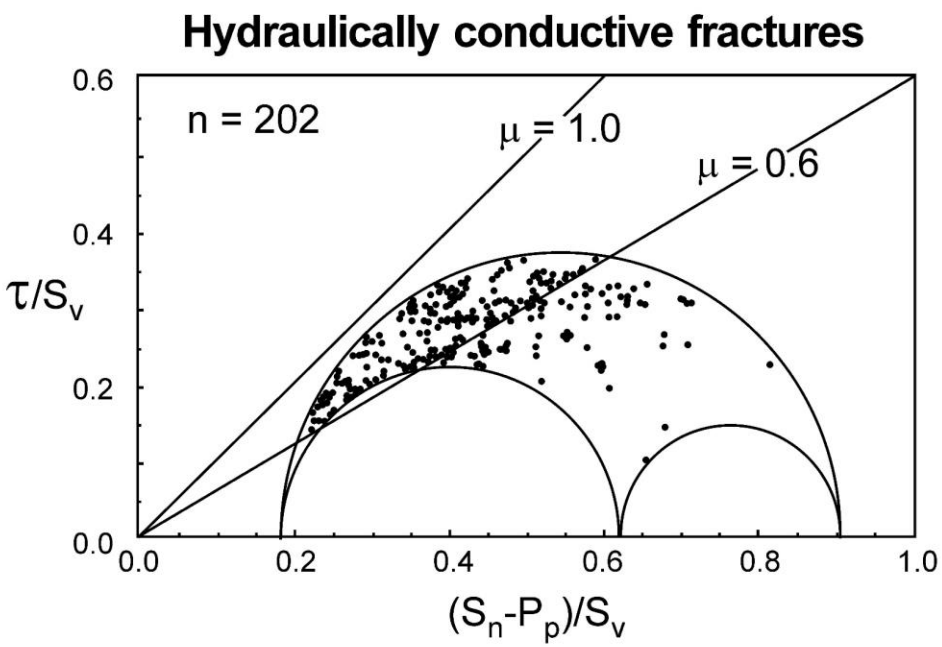
DISTINGUISHING CONDUCTIVE AND NON-CONDUCTIVE JOINTS IN DEEP BOREHOLES IN HARD CRYSTALLINE ROCKS

Geophysicists (and petroleum engineers?) often talk of 'open' fractures parallel to $\sigma_{H\ MAX}$? **There is much contrary evidence!**

(U. of Stanford authors, Colleen Barton et al., 1995).

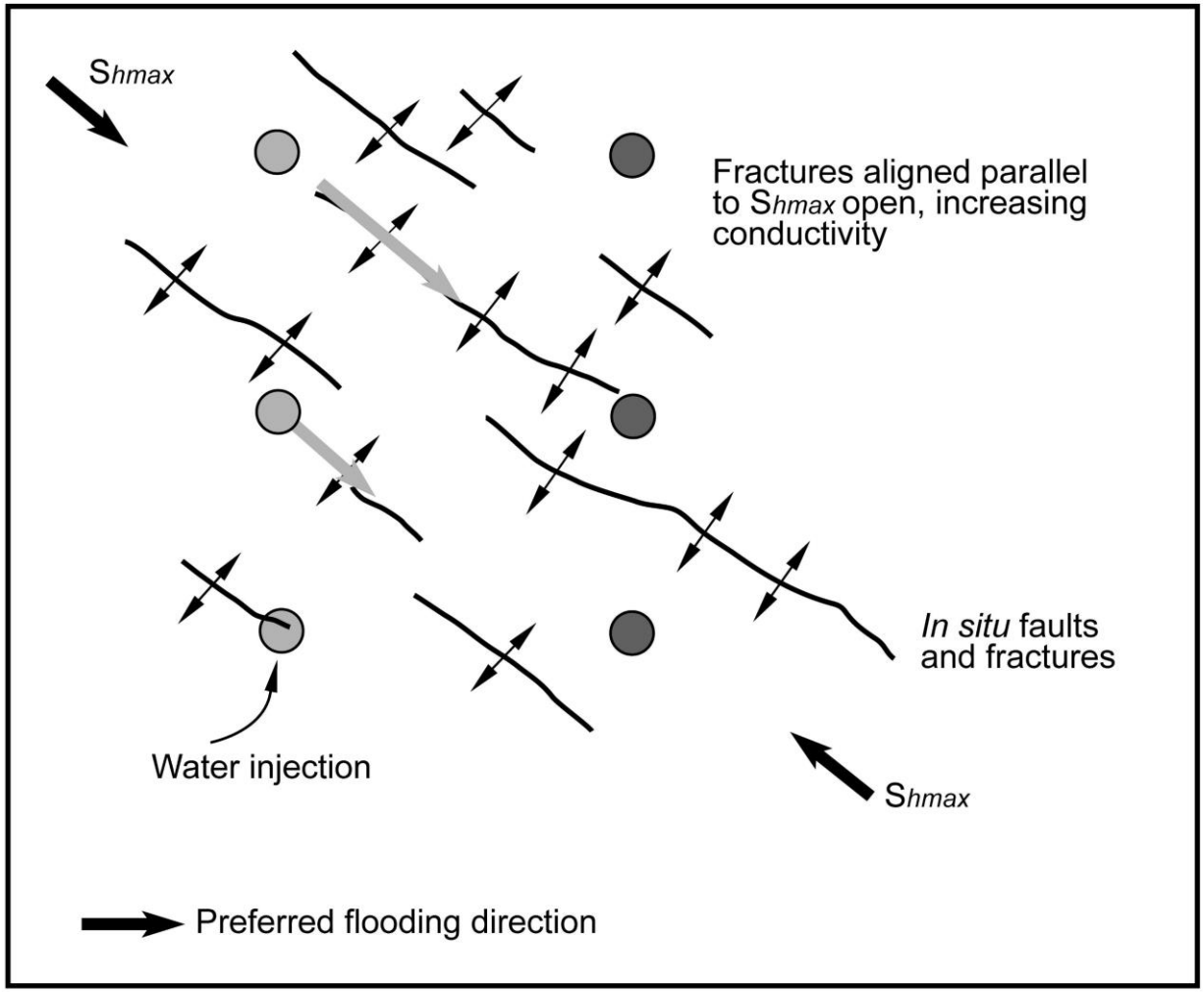






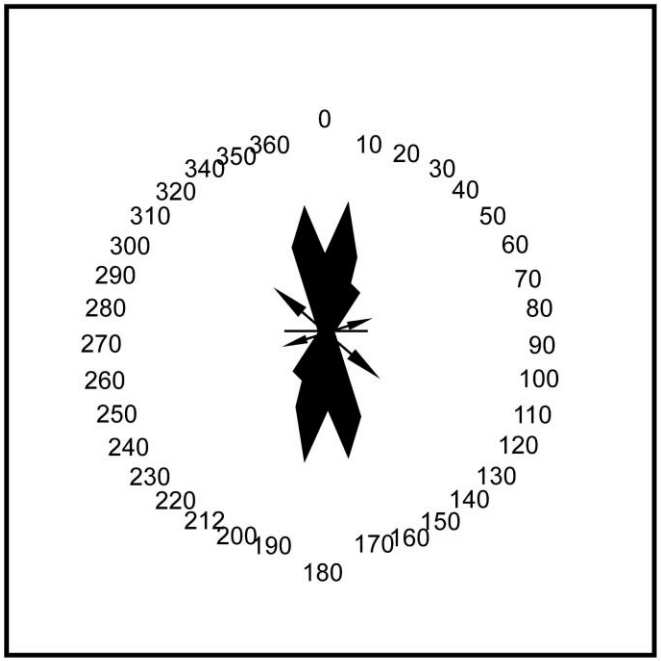
The conducting fractures are under significant shear stress, the non-conductors tend to be more normally loaded. (Colleen Barton et al. 1995)

The common fracture orientation assumption again (Heffer, 2002)



Conjugate sets bisected by $\sigma_{H\ MAX}$ seem also to be important? (Water-flood interpretations assembled by Heffer 2002)

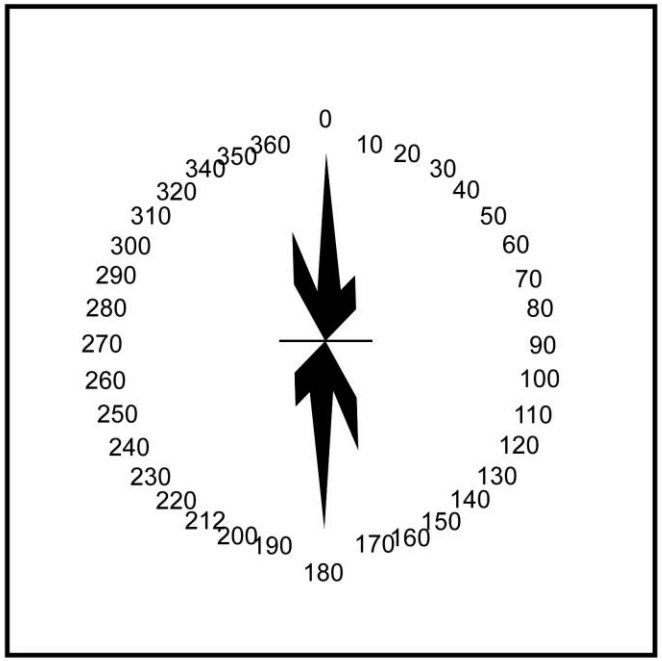
Unfractured reservoirs
(47 cases)



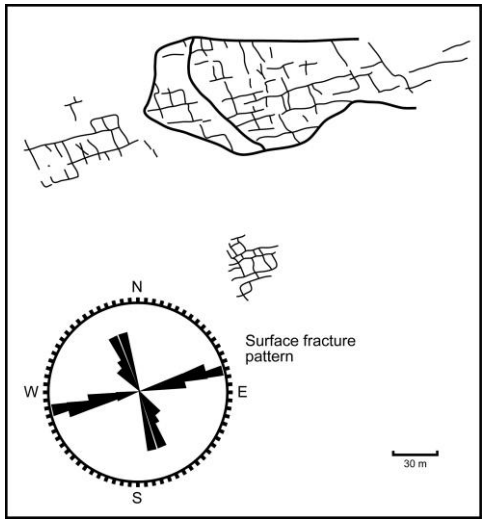
S_{hmax}

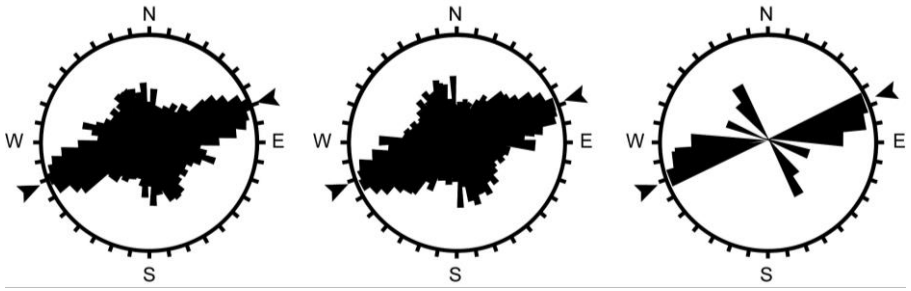
(a)

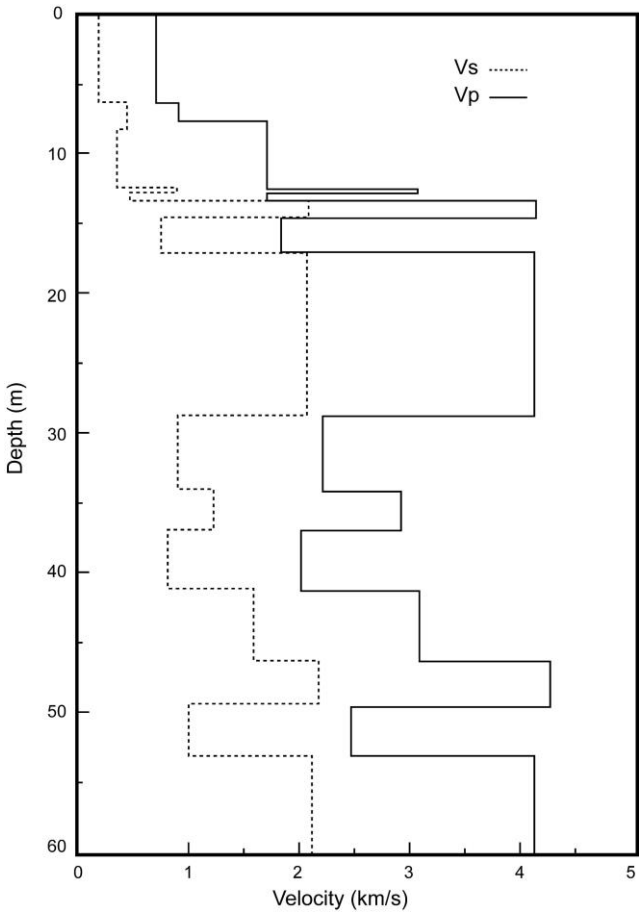
Fractured reservoirs
(33 cases)



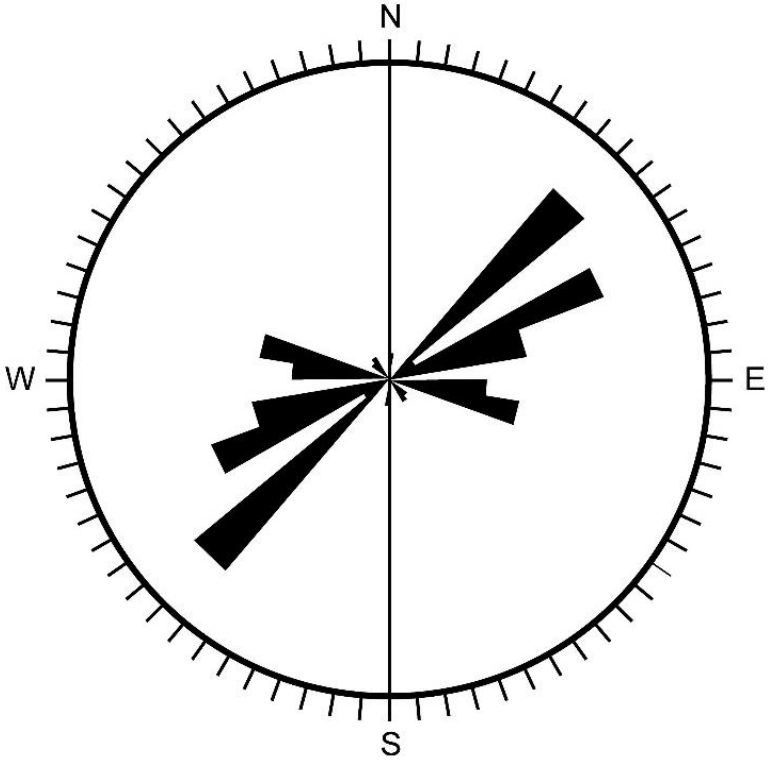
Conoco borehole site. Near-surface: the dominant fracture sets, and microcracking, and dominant polarization of shear-waves *do* tend to be // to $\sigma_{H\ MAX}$ (Liu et al. 1993, 1999)

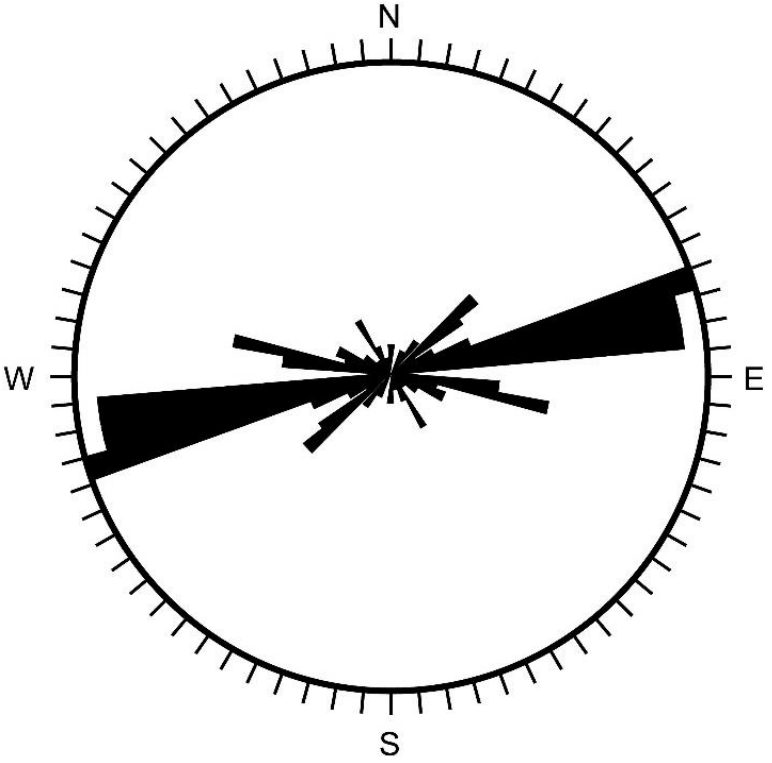






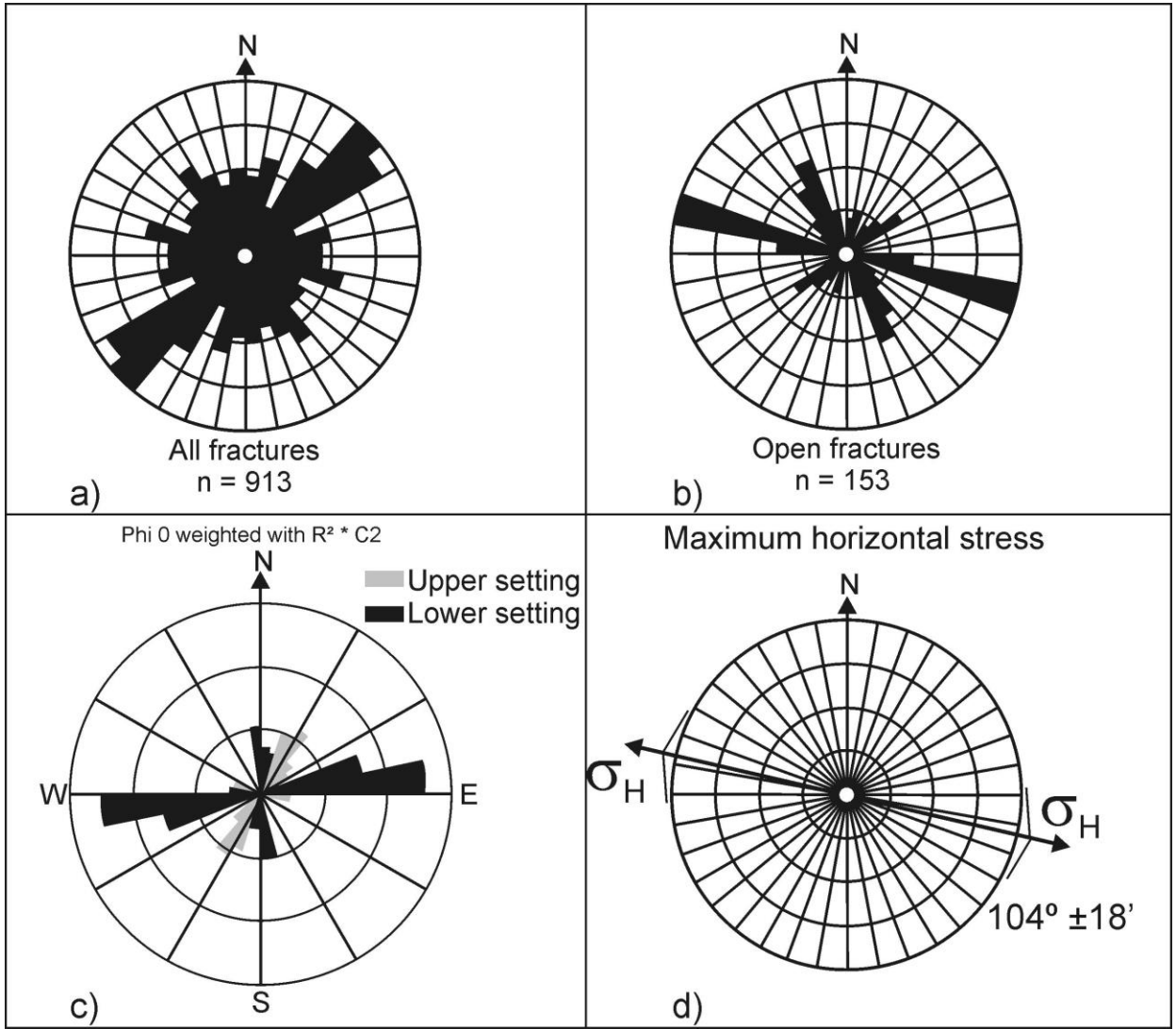
The same Conoco site: near-offset VSP from 180- 850 m depth.
Left: accumulative length of BHTV- and core-identified fracturing
Right: combined azimuths from nine-component VSP
(Queen and Rizer, 1990)



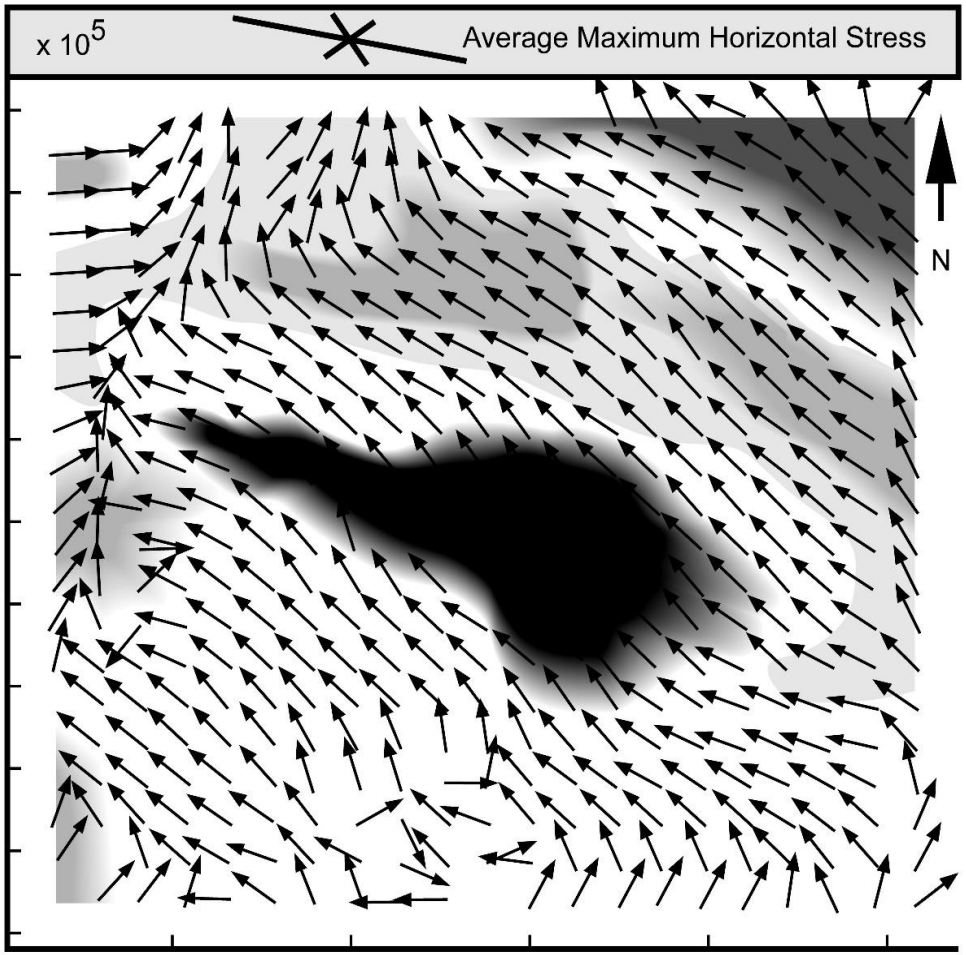


Claire Field (Smith and McGarrity, 2001, Maultzsch et al. 2005)

c) Minimum attenuation from multi-azimuth walk-away VSP, in reservoir (black) and in overburden (grey). Note rotations.



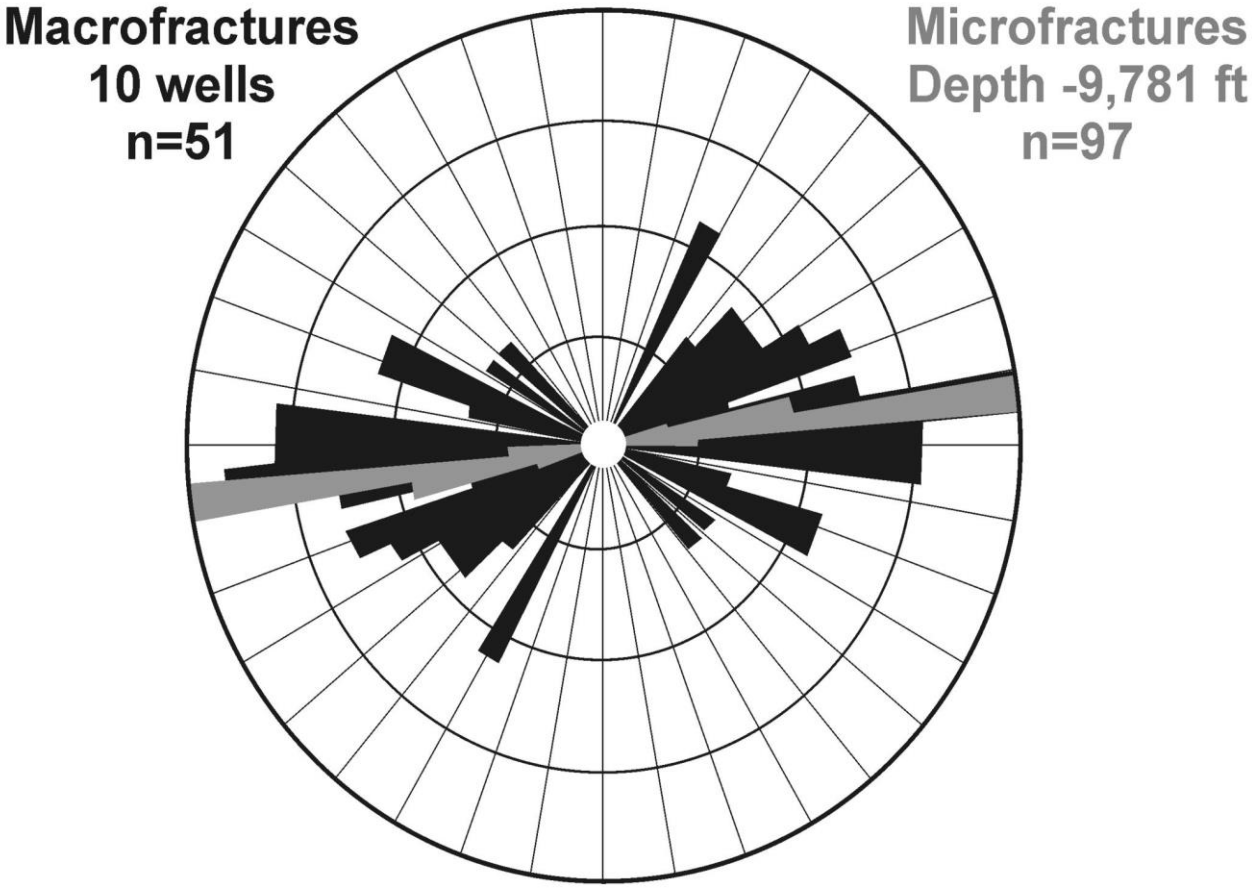
Fractured limestone reservoir at 3 km depth. Converted P-S shear-wave analysis of dominant fracture (or fracture-component ?) directions. Pérez et al. 1999.



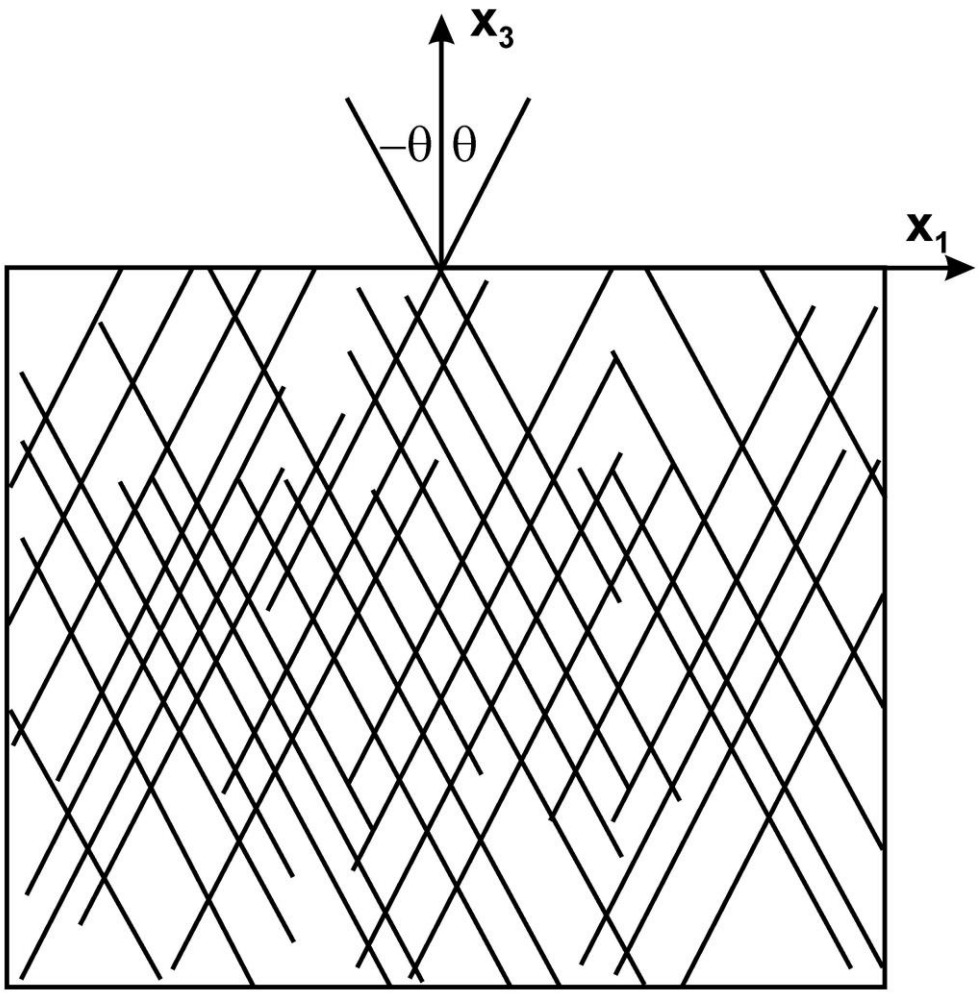
EAST TEXAS WELL DATA (Laubach et al. 2000)

It may be reasonable to assume that the microcracks are sub- // to $\sigma_{H\ MAX}$?

So the fractures may be bisected by $\sigma_{H\ MAX}$



Sayers, 2002 investigation of shear-wave polarization when incident waves are no longer parallel to vertical fracturing

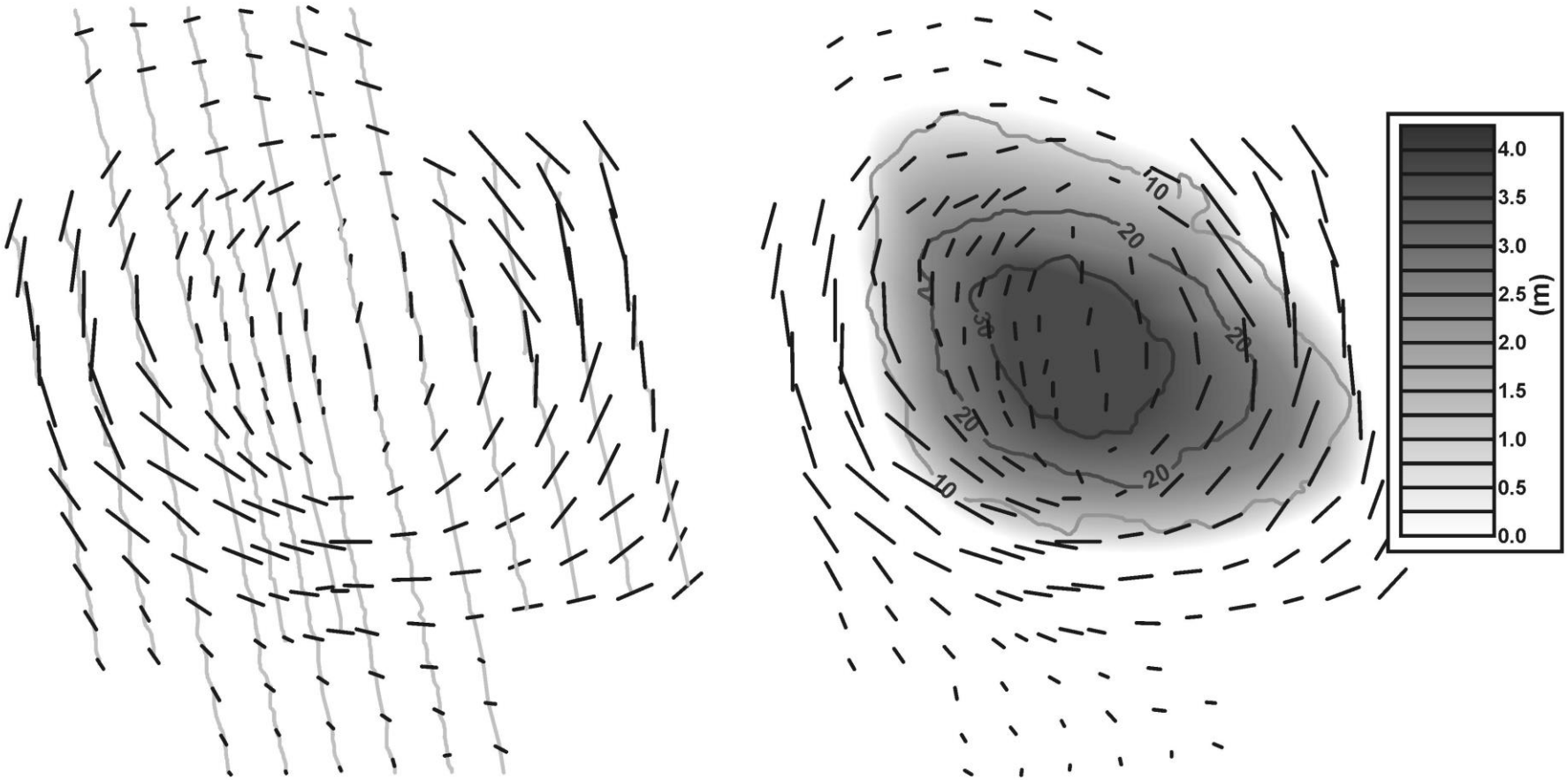


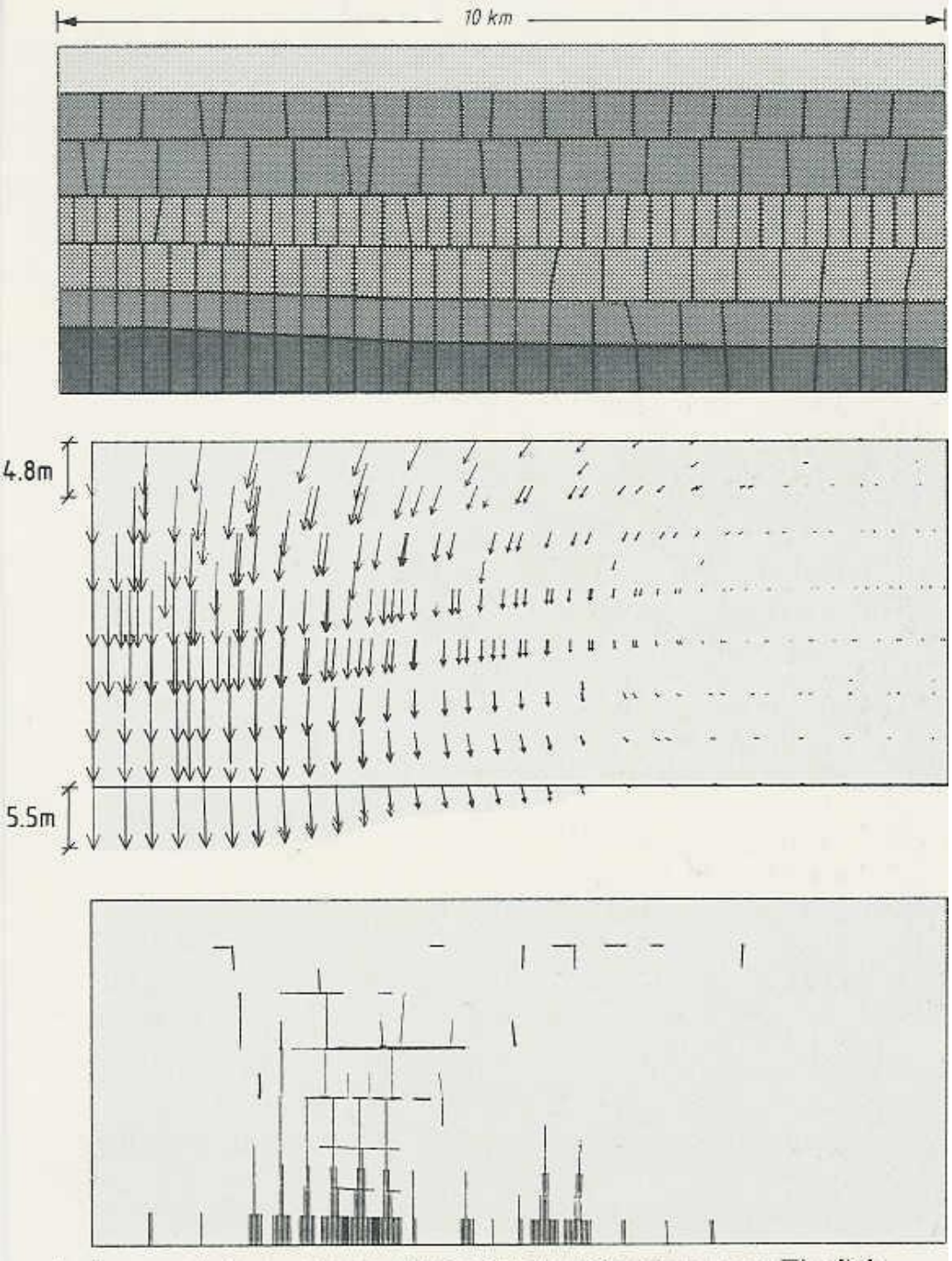
VERTICAL SHEAR WAVES SPLIT BY DOMINANT FRACTURE OR JOINT SETS.

ARE WE REGISTERING THE RESULTANT OF TWO SEPARATE COMPLIANCE MAGNITUDES (AND THEIR CONJUGATE ORIENTATION – roughly bisected by $\sigma_{H\ max}$)?

SHEAR WAVE POLARIZATION IN A SUBSIDING OVER-BURDEN (VALHALL: Olofsson and Kommedal, 2002, Gaiser and Van Dok, 2003, Barkved et al. 2004)

Note 'squareness' of pattern...due to polarization on two sets of *intra-bed* jointing ??



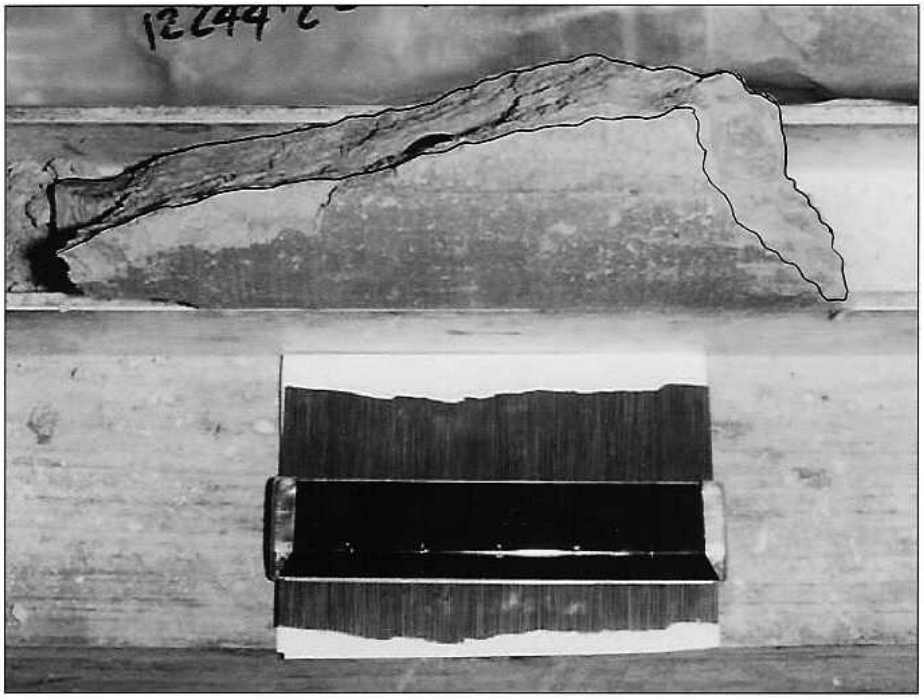


AT EXAGGERATED BLOCK-SIZE: SEE JOINT SHEAR/OPENING DUE TO OVER-BURDEN STRETCH

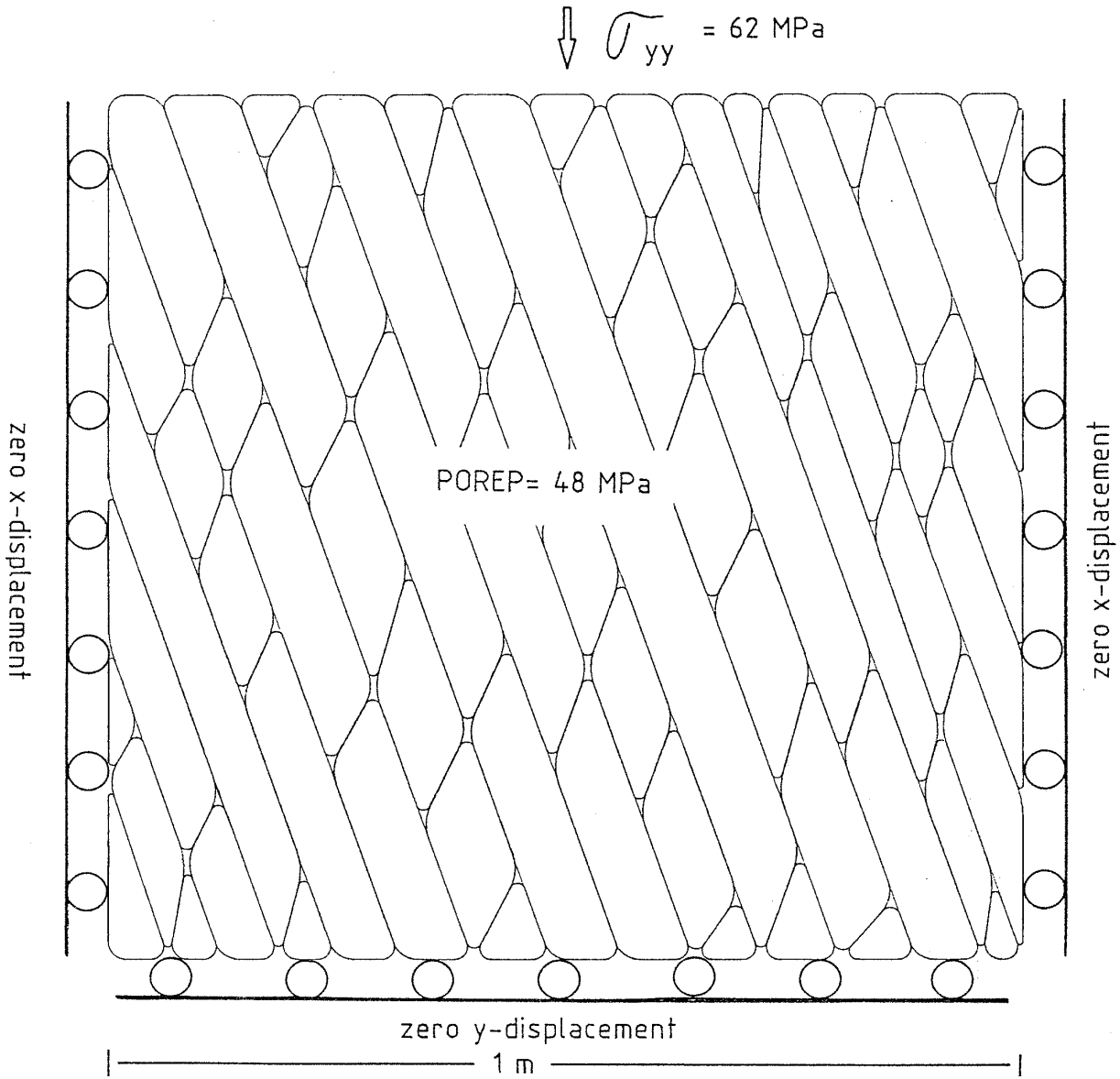
(Barton et al. 1988)

Conjugate joints from Ekofisk chalk reservoir, prior to characterization for roughness,
wall strength, and subsequent
UDEC-BB modelling
(Barton et al., 1986)

Note that fracture density is about 1.4 for portions of this reservoir. See next screen.

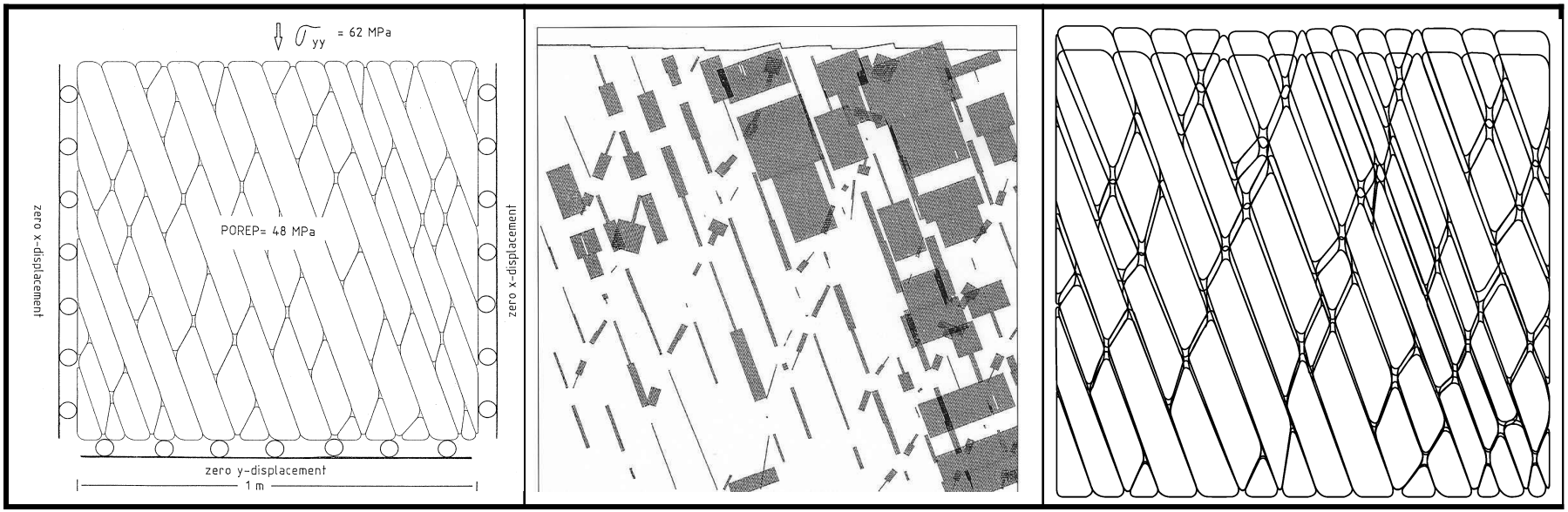


ONE-DIMENSIONAL COMPACTION MODELLING OF AN EKOFISK '1m window '



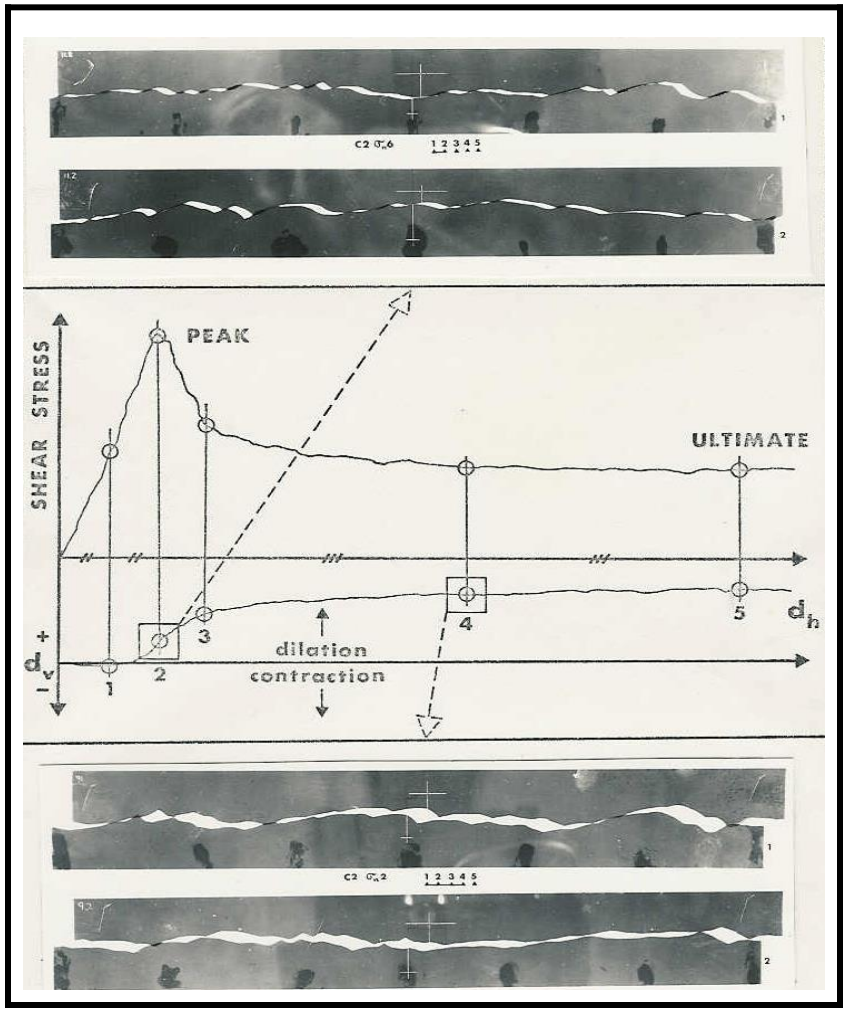
SMALL-SCALE JOINT-SHEARING MECHANISMS from UDEC-BB modelling. Note: slickensided fractures were discovered for the first time since exploration, when drilling water injection holes in the mid-eighties.

(matrix compaction due to ΔP' makes space for down-dip shear (Barton et al., 1986)



Pre-peak shear-displacement with limited dilation on unequal, non-planar sets of fractures could explain frequent deviation from the ‘classic’ but perhaps anomalous $\sigma_{H\ max}$ direction for deep, yet conductive reservoir fracturing.

(Barton, 1973)

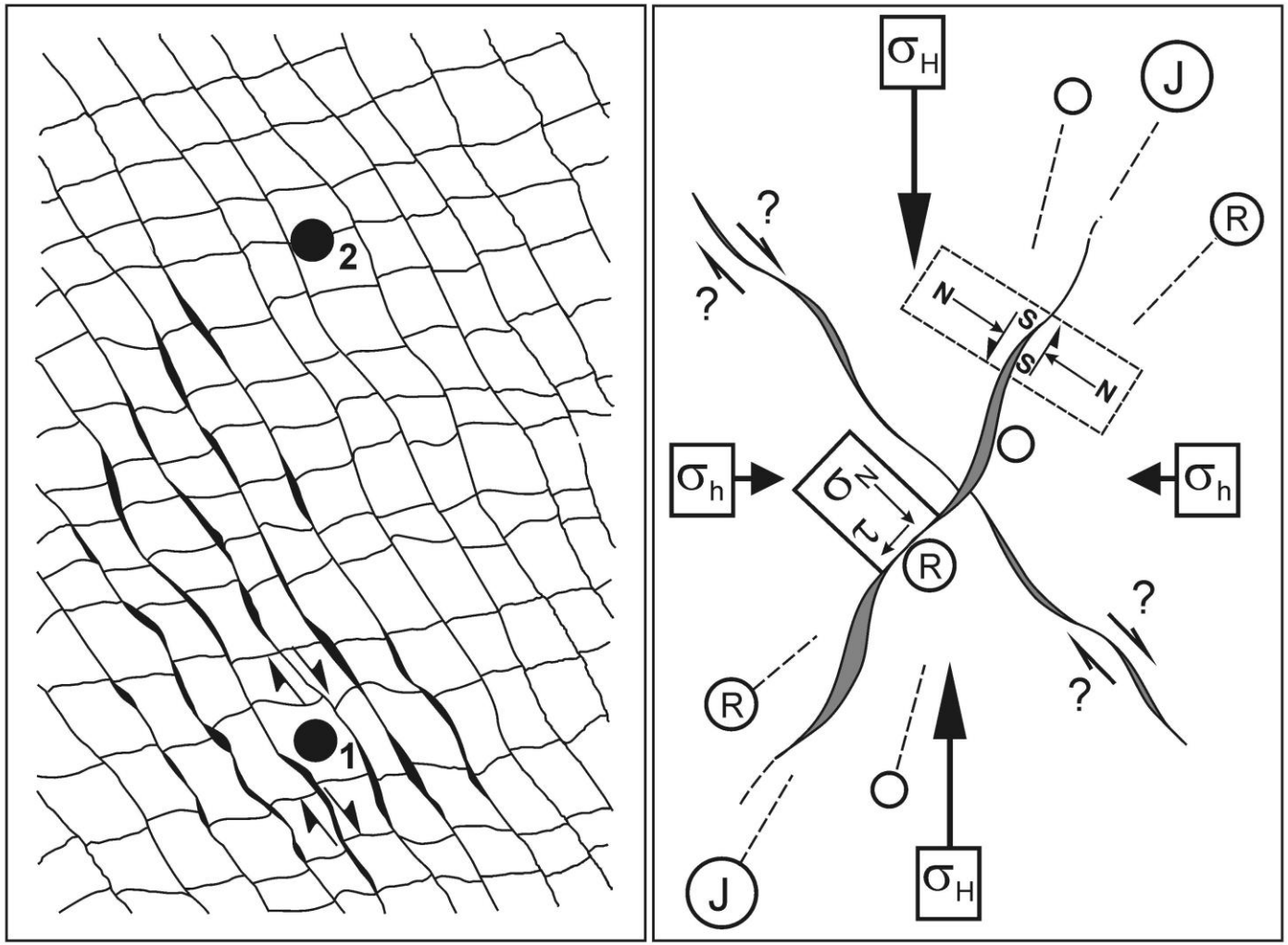


AS REVIEWED EARLIER - SHEAR WAVE POLARIZATION MAY DEVIATE 10º - 30º FROM THE 'UBIQUITOUS' $\sigma_{H\ MAX}$ DIRECTION ..... *PRE-PEAK SHEAR ??*

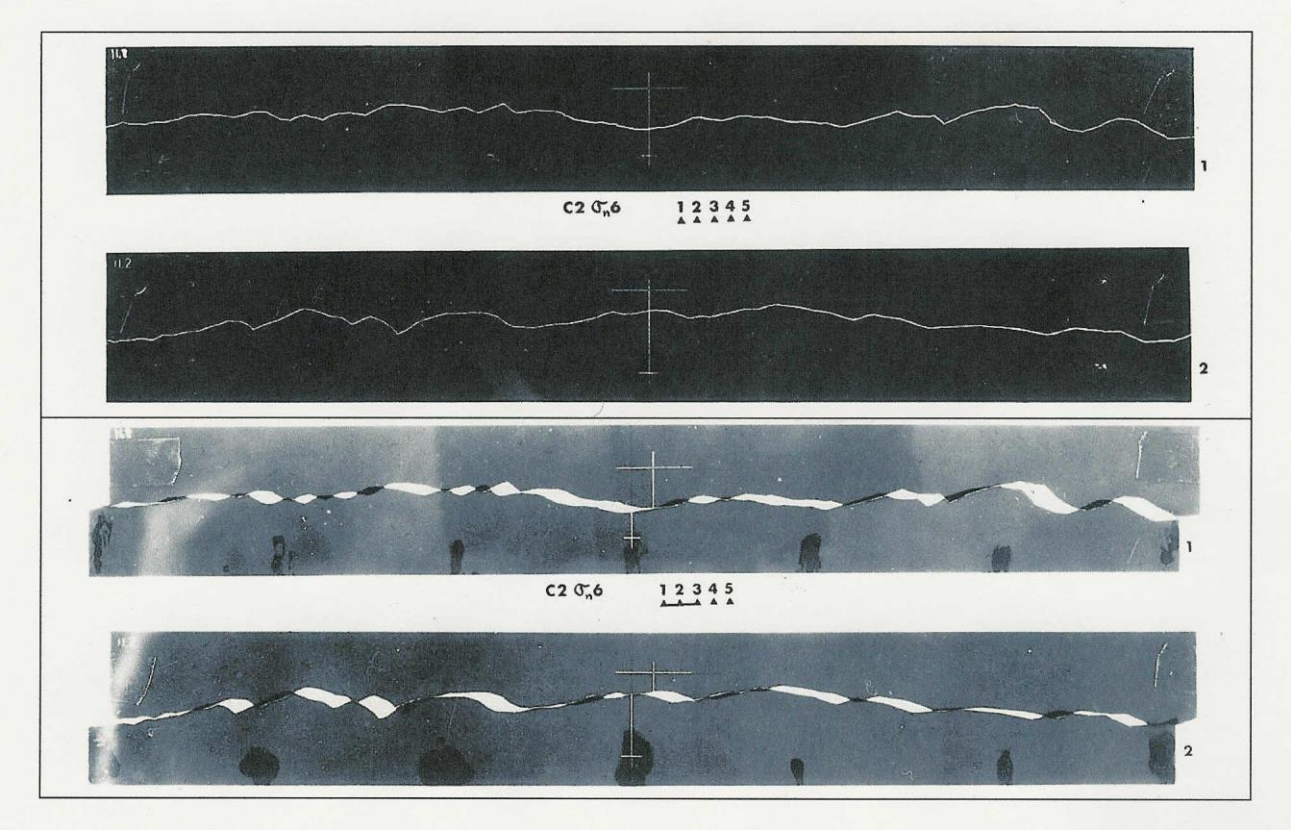
Left: HDR PROJECT: CORNWALL (schematic)

Barton, 1986.

Temporal rotation of anisotropy AND ATTENUATION axes would result (Barton, 2006)



Note the opposite rotation of rock-to-rock and fluid-filled parts of a pre-peak sheared, non-planar joint or fracture. (A possible *further* source of rotation for shear-wave polarization ?? (Barton, 1973)



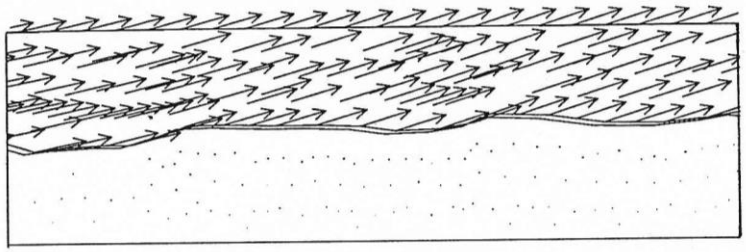
WHICH PARTS OF A STRESSED FRACTURE ARE MOST DOMINANT IN SHEAR WAVE SPLITTING?

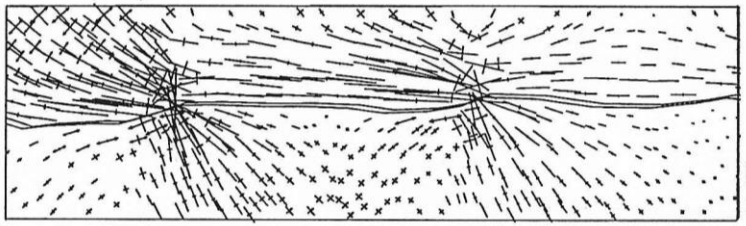
IS IT THE STIFFNESS/COMPLIANCE OF THE CONTACTING, STRESS-TRANSFERRING PARTS?

IS IT THE FLUID 'LENSES' WHICH MAY STIFFEN THE 'overall' NORMAL COMPLIANCE..... WHEN BEARING OIL RATHER THAN GAS?

(c.f. Natih Field, Oman)

(UDEC- BB model from Gutierrez and Barton, 1994)





VERTICAL EXPLORATION – BIAS AGAINST VERTICAL STRUCTURE – SAVED BY SEISMIC INVERSION

- Shear-wave qS_1 and qS_2 splitting and polarization, due to vertical or aligned structure, (and P-wave anisotropy), are miraculous means for rectifying poor fracture-sampling strategies, in view of the long seismic wave lengths.

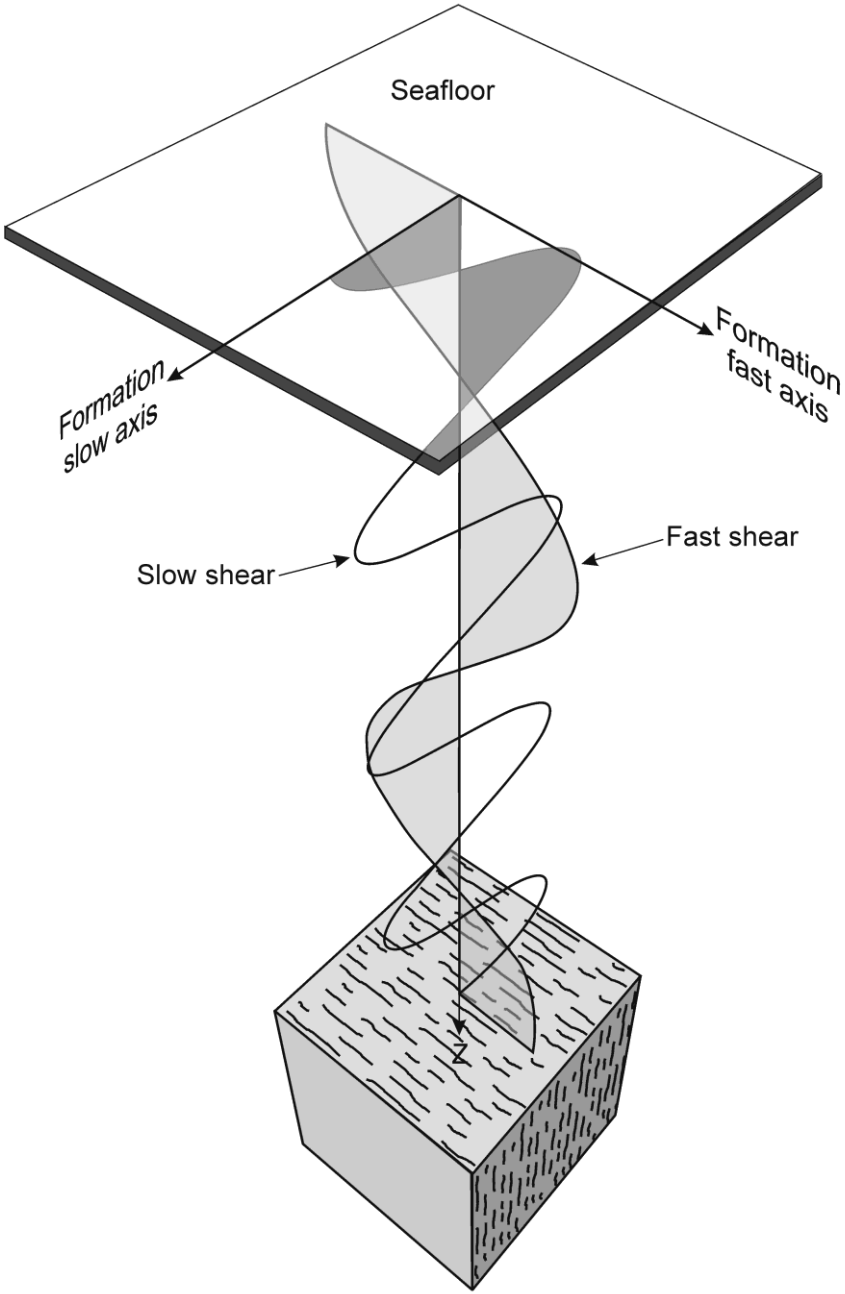
- Direct observation is ‘always’ prejudiced by the vertical wells.

- An early deviation of 10º or more would greatly improve understanding of both the overburden jointing and the reservoir jointing !!

- The former also has important influence on the inversion results of the latter due to velocity-depth modelling.

THE MIRACULOUS MEANS OF RESCUING POOR FRACTURE-SAMPLING STRATEGY CAUSED BY VERTICAL WELLS.....

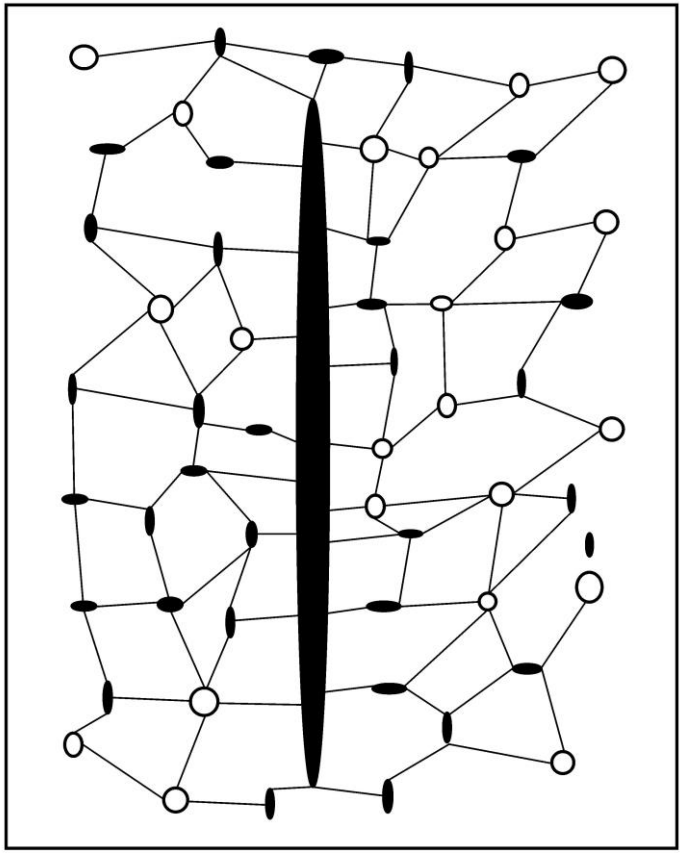
....BY INTERPRETING THE ANISOTROPIC AND DISPERSIVE NATURE OF SPLIT SHEAR WAVES (e.g Chapman model)

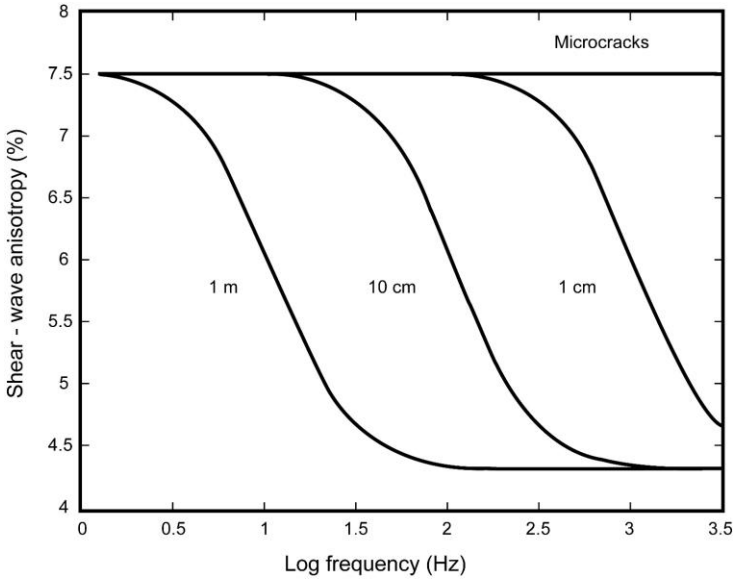


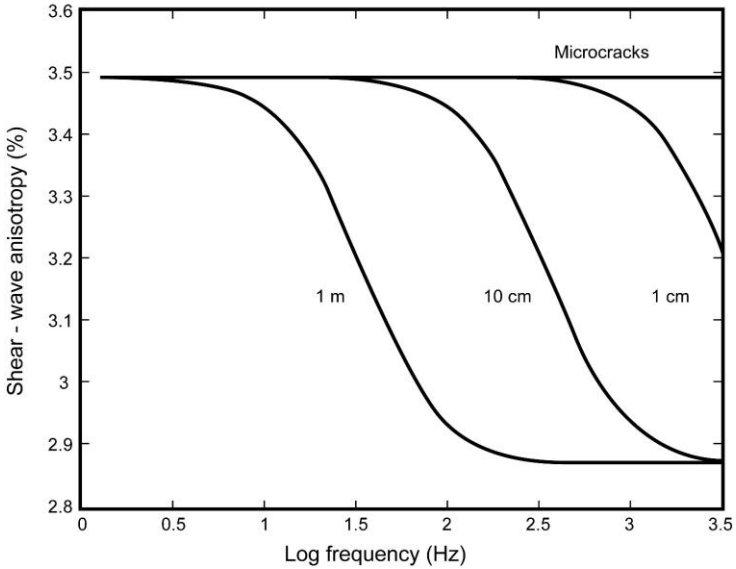
CHAPMAN, 2003

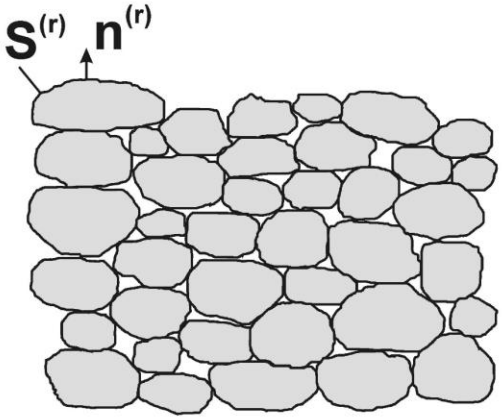
Top: 10% porosity, crack density 0.1
Bottom: 0% porosity, crack density 0.02

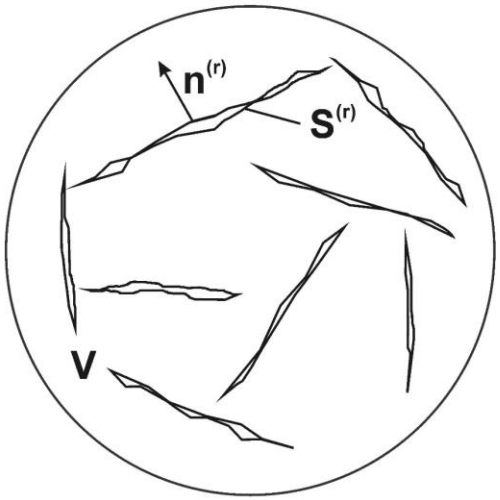
?? Is a 2-set model possible ??

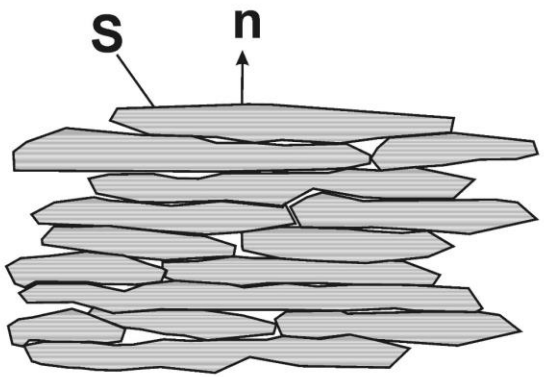












WHAT ABOUT: (dynamic) n and S for grains?

(psuedo-static) Kn and Ks for fractures ?

(dynamic) Z_N and Z_T *for fractures ?*

Is $Kn \approx 1/Z_N$ *?*

Sayers, 2002, Liu et al. 2000

Near-equality of the fracture compliances ??

(as implied in some literature)

- An *inequality* of the joint or fracture compliances Z_N and Z_T would actually be *more consistent* with the experience of Ks < Kn, the *pseudo-static* shear and normal *stiffnesses* of joints and fractures.

- Stiffness is the inverse of compliance. The magnitude of K_n (static) proves to be less than, but quite close to $1/Z_N$ in good quality unweathered hard rock.

- In the shearing direction, Ks (static) < $1/Z_T$, sometimes << $1/Z_T$ *(??)* However Z_T data is extremely limited compared to the large body of Ks (pseudo-static) data.

The ‘excess’ compliance matrix for a single set of vertical fractures

$$S(f) = \begin{bmatrix} Z_N & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & Z_T & 0 \\ 0 & 0 & 0 & 0 & 0 & Z_T \end{bmatrix}$$

INVOLVEMENT OF Z_N OR Z_T ??

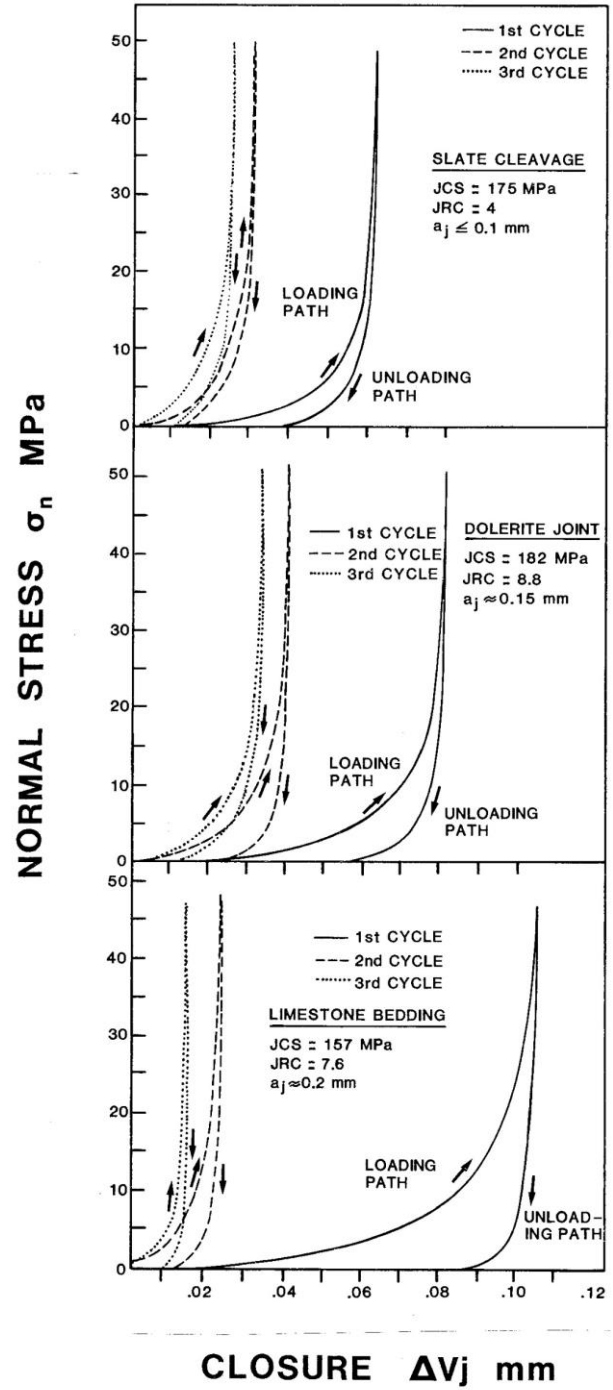
- Involvement of Z_N in the slow shear wave velocity requires dipping fractures, or non-vertical wave propagation.

- When polarized shear-waves sense the different viscosity of oil or gas in the fractures, Z_N is more likely to be involved than Z_T.

- Z_T would have a less obvious dependence on fluid viscosity differences.

NOTE EXTREME STIFFNESS OF JOINTS IN HARD ROCK, WHEN NORMAL STRESS LEVELS ARE HIGH (Bandis et al., 1983)

(Kn (static) ≈ 1/Z_N dynamic)



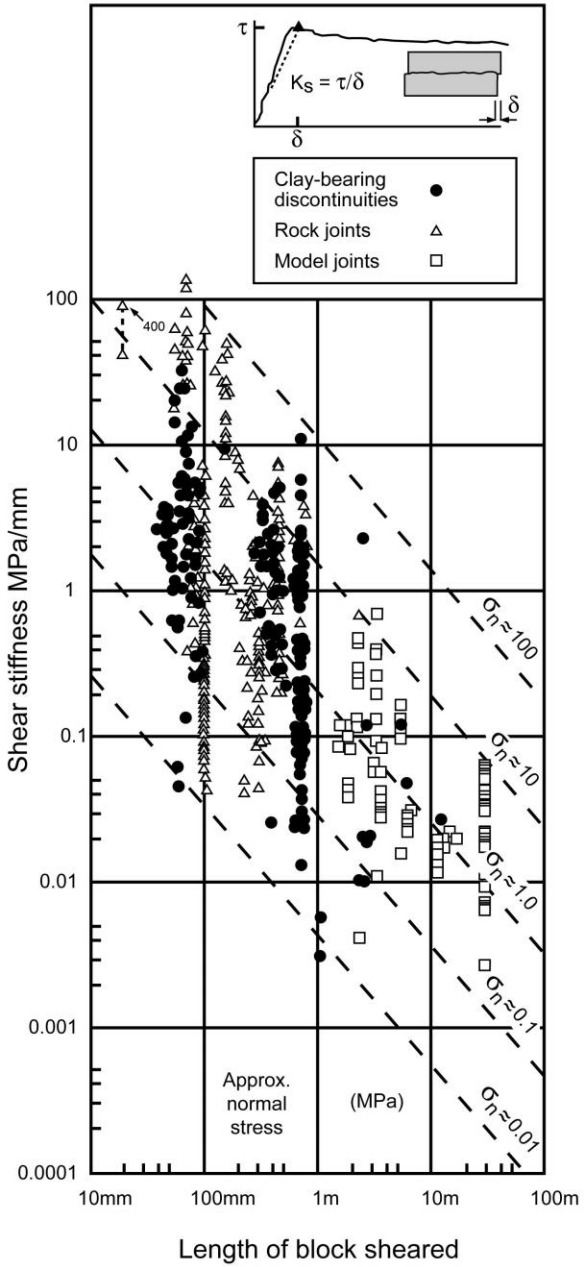
COMPARING DYNAMIC AND STATIC STIFFNESSES

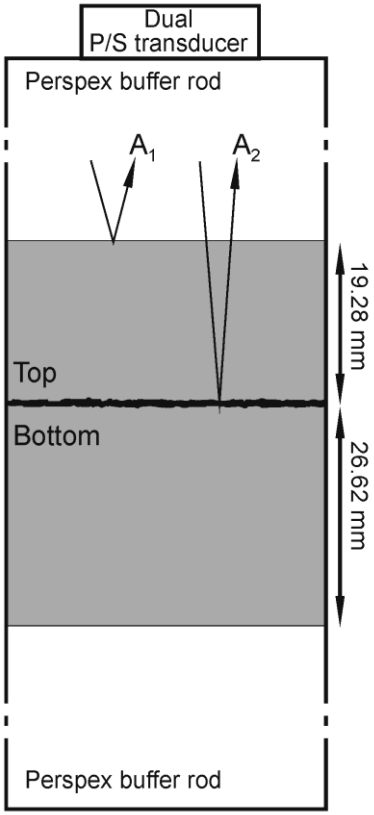
- Depending on stress levels, and on rock strength (described by JCS), and joint roughness (described by JRC), the dynamic normal stiffness *Kn(dyn)* may apparently range from 10^{12} to 10^{14} Pa/m, or 1,000 to 100,000 MPa/mm (also 1 to 100 MPa/μm). But there is very limited data.

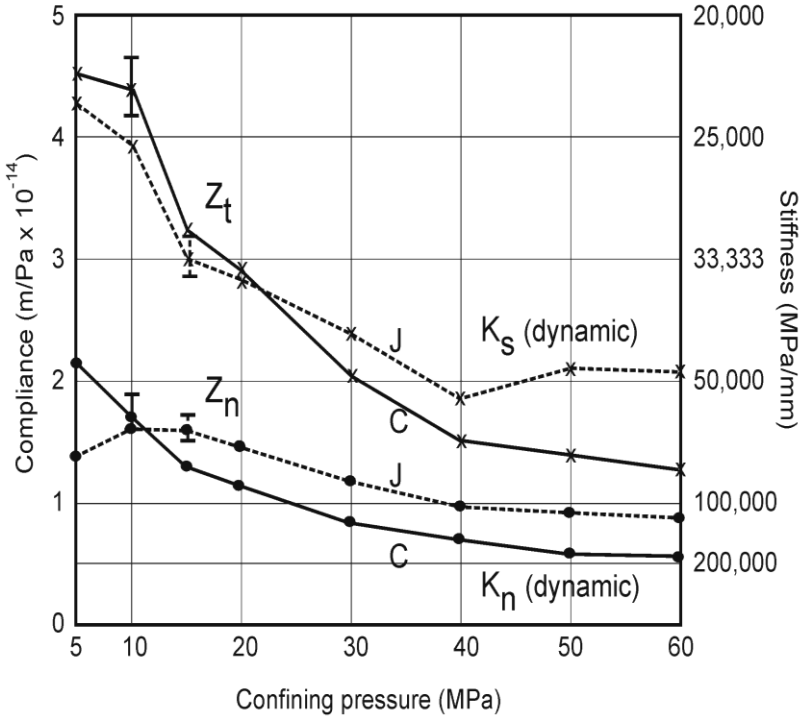
- By comparison, *Kn(psuedo-static)* values from a much wider range of rock and joint types, may vary from as low as 100 MPa/mm to almost 50,000 MPa/mm.

- There is therefore a large degree of overlap between the static and dynamic stiffnesses in this *stiffest* perpendicular loading direction.

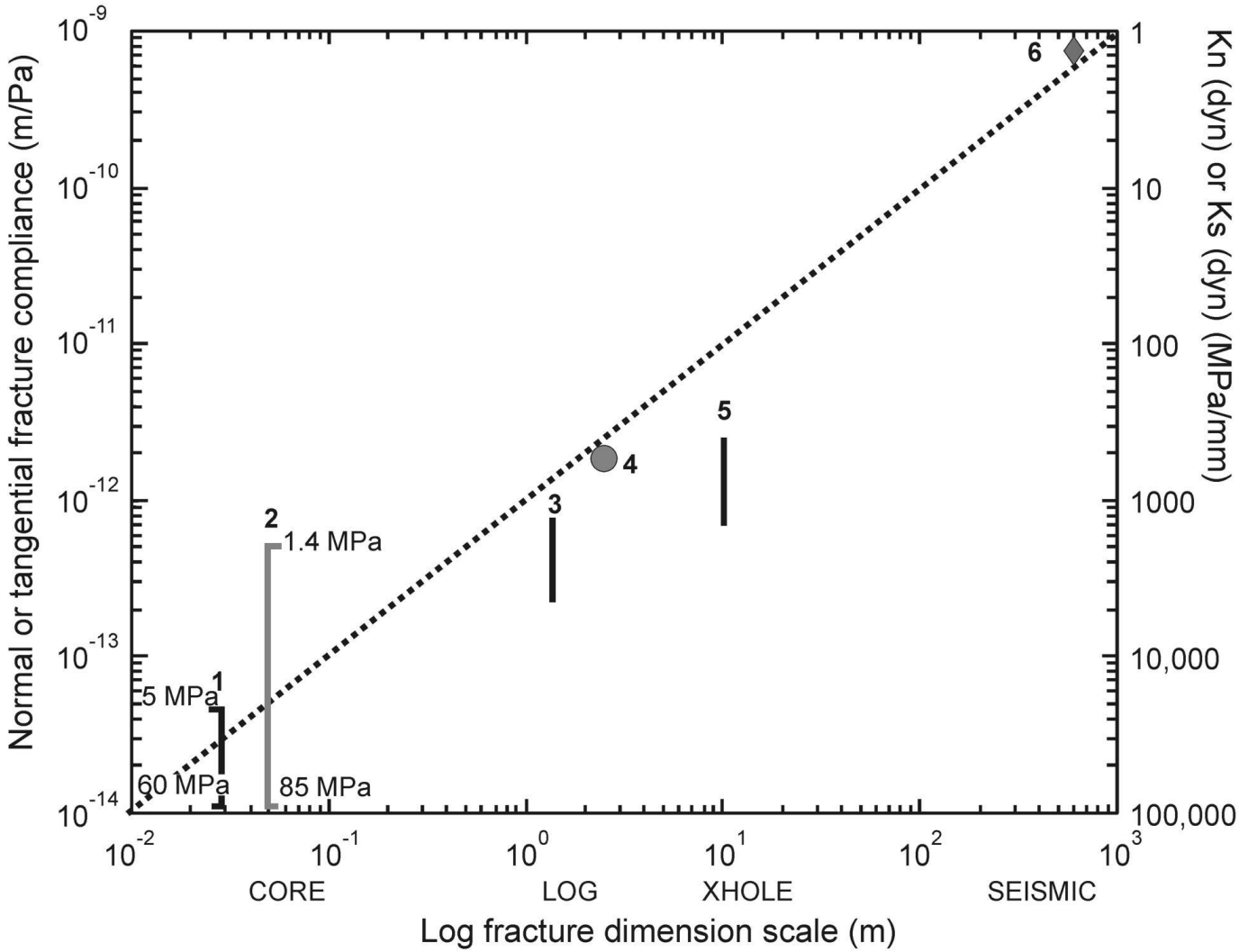
COMPARING PSUEDO-STATIC (Barton, 1982) AND DYNAMIC *SHEAR STIFFNESSES (Lubbe, 2005)* (THE DYNAMIC TESTS on the right, ARE ON AN ARTIFICIAL SURFACE IN LIMESTONE)





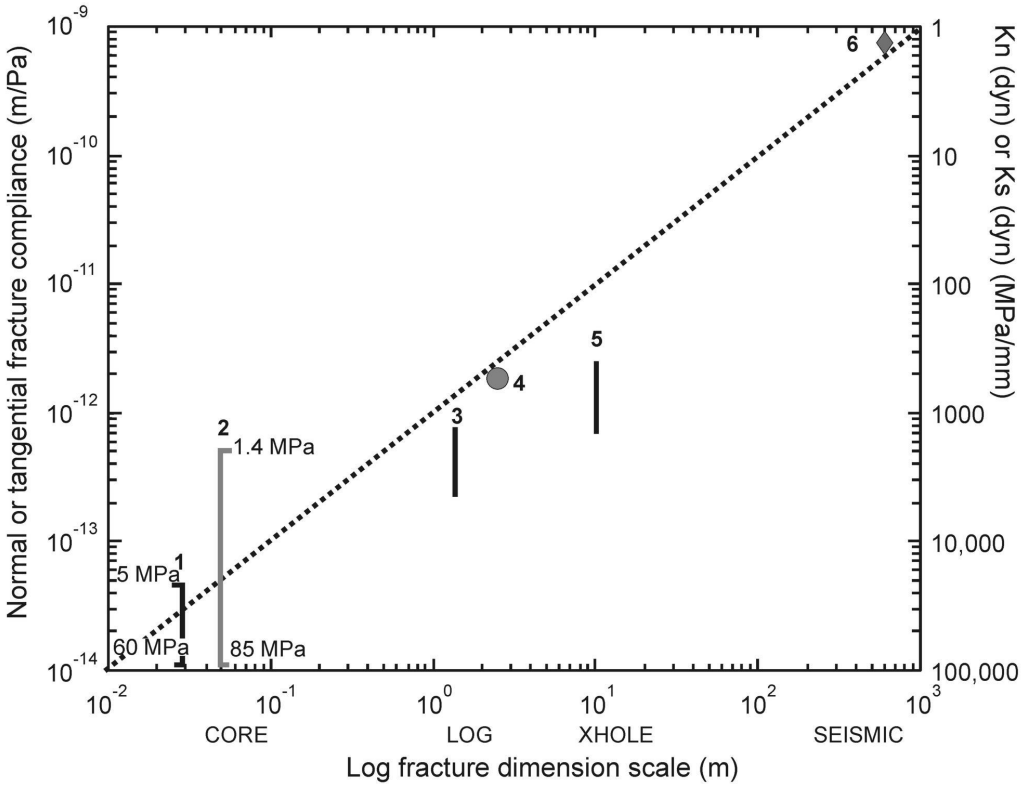


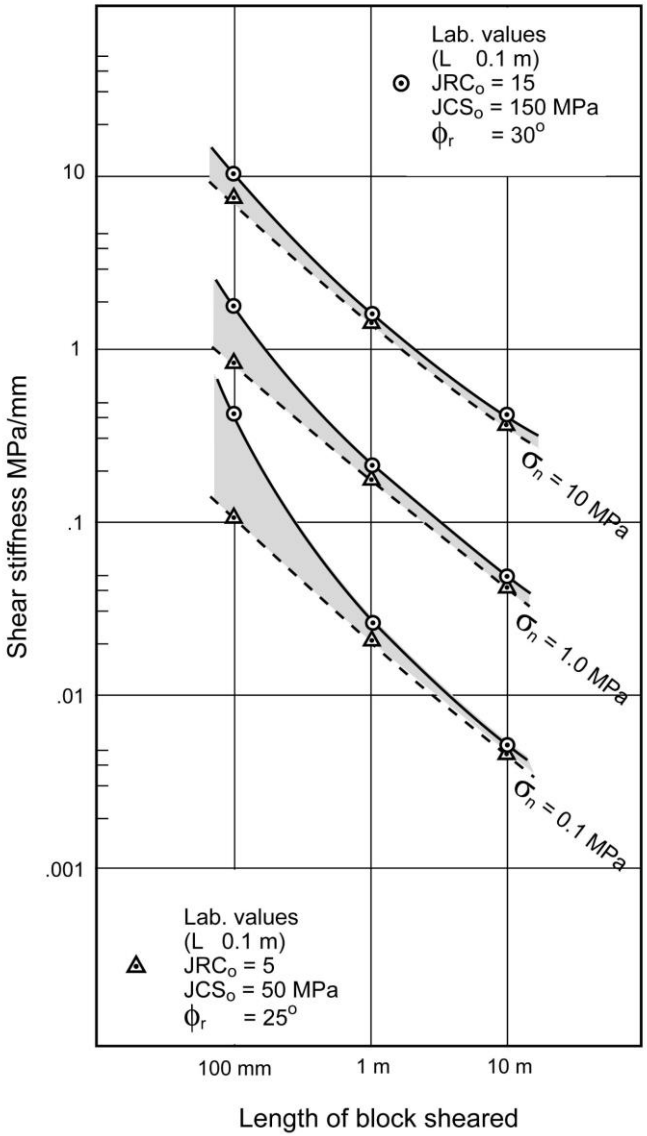
From Lubbe, Worthington and Hudson (Lubbe, 2005). For the extremely low $K_{S\ DYN}$, see Hudson et al. 1997 equations, with Worthington and Lubbe, 2004 correction on next screen.

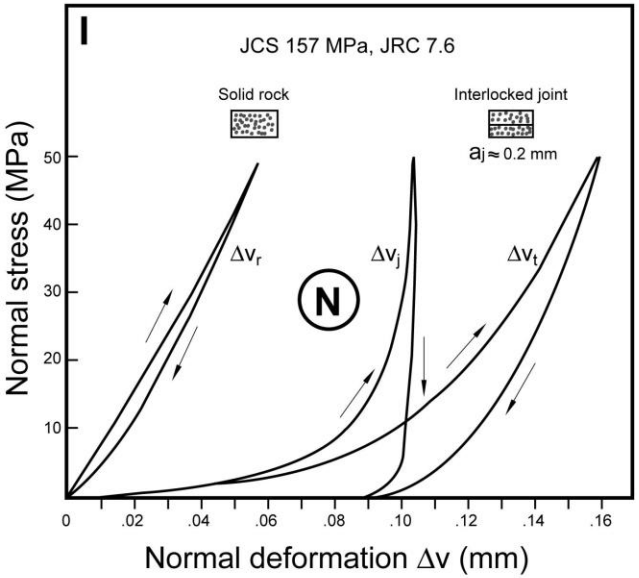


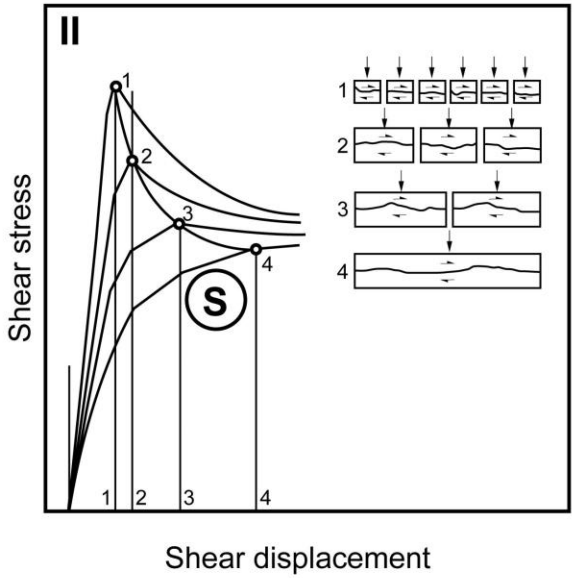
$$B_n = r^w \left(\frac{4\mu}{\pi a}\right)\left(1-\frac{\beta^2}{\alpha^2}\right)\left\{1+\frac{2\left(r^w\right)^{1/2}}{\sqrt{\pi}}\right\}+\frac{\kappa'+(4/3)\mu'}{\Delta}$$

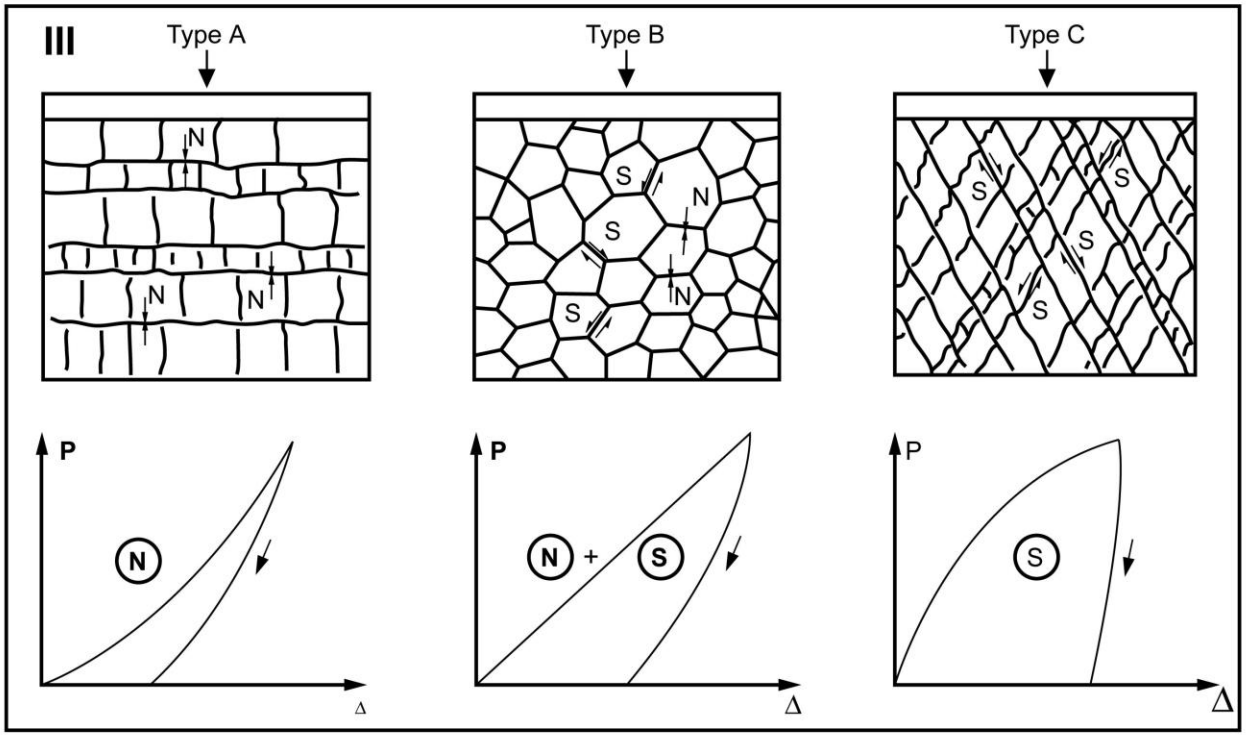
$$B_t = r^w \left(\frac{8\mu}{\pi a}\right)\frac{\left(1-\frac{\beta^2}{\alpha^2}\right)}{\left(3-\frac{2\beta^2}{\alpha^2}\right)}\left\{1+\frac{2\left(r^w\right)^{1/2}}{\sqrt{\pi}}\right\}+\frac{(\mu')}{\Delta}$$











The (psuedo-static) deformation mode (N) has the same (inverted) stiffness units (and similar magnitudes) as Z_N .

Perhaps Z_T is also scale-dependent like (S) ??

Units for Z_N and Z_T are the inverse of those used for rock mechanics (psuedo-static) stiffnesses Kn and Ks

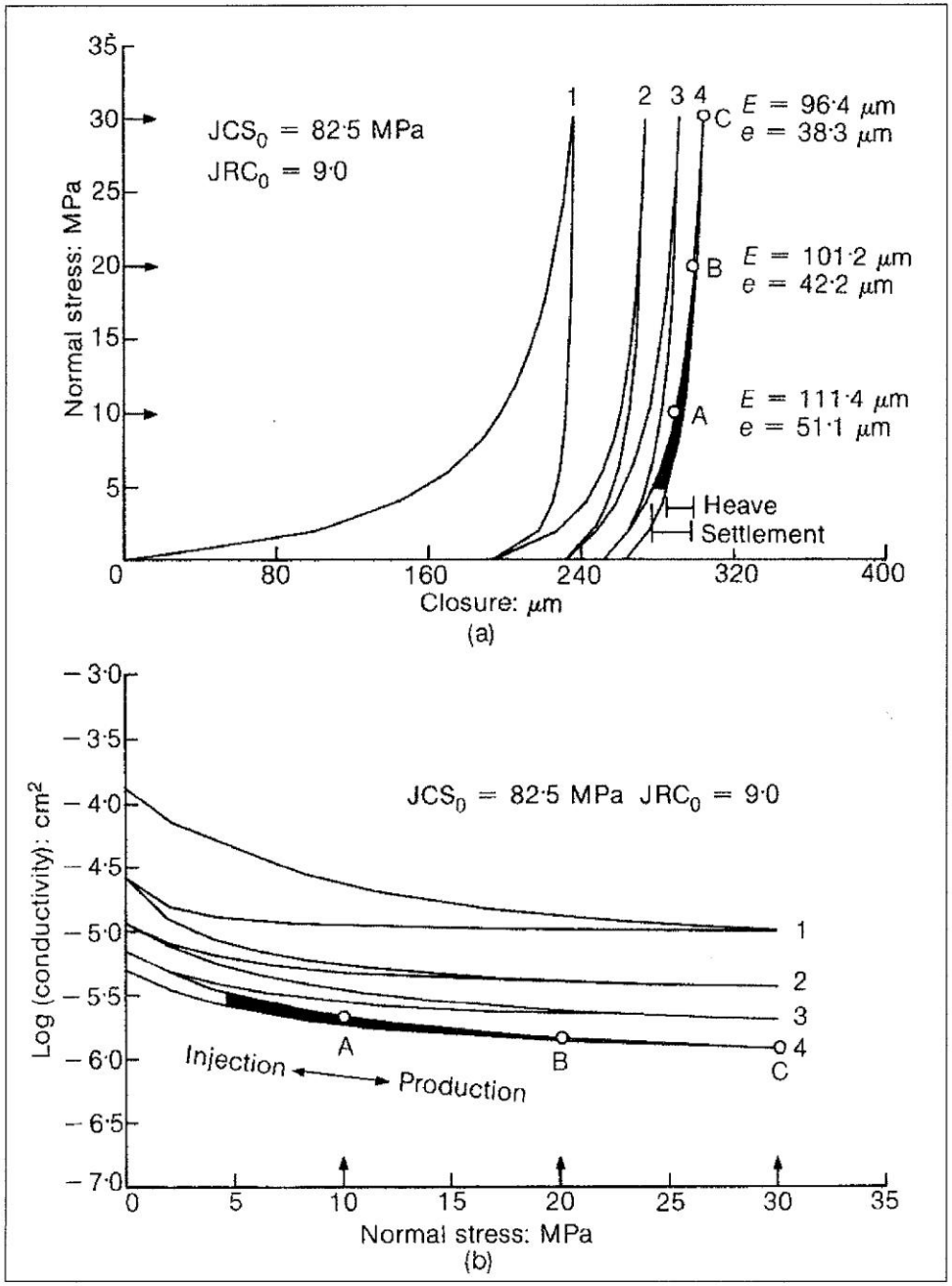
10^{-12}m.Pa^{-1} = 1μm/MPa !

ASPECT RATIO REPRESENTATION OF FRACTURES OR JOINTS

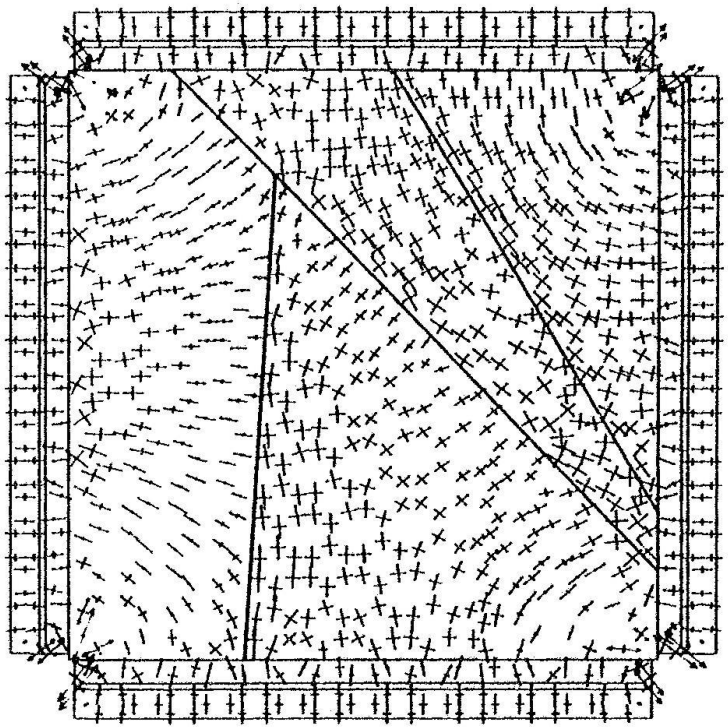
BB- modelling of normal stiffness and permeability for a medium rough joint. (Barton et al., 1985)

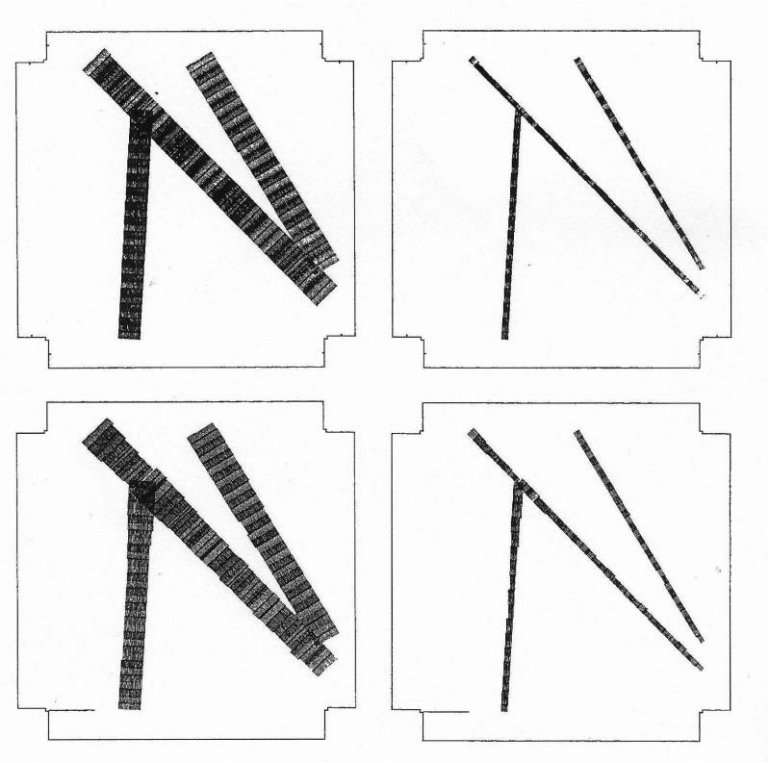
Hydraulic aperture(e), and mean physical aperture (E) need to be distinguished.

(The assumption of a single aspect ratio for a 'crack' is too simplified. *Squirt and stiffness losses are unlikely to be governed by the same aperture*).

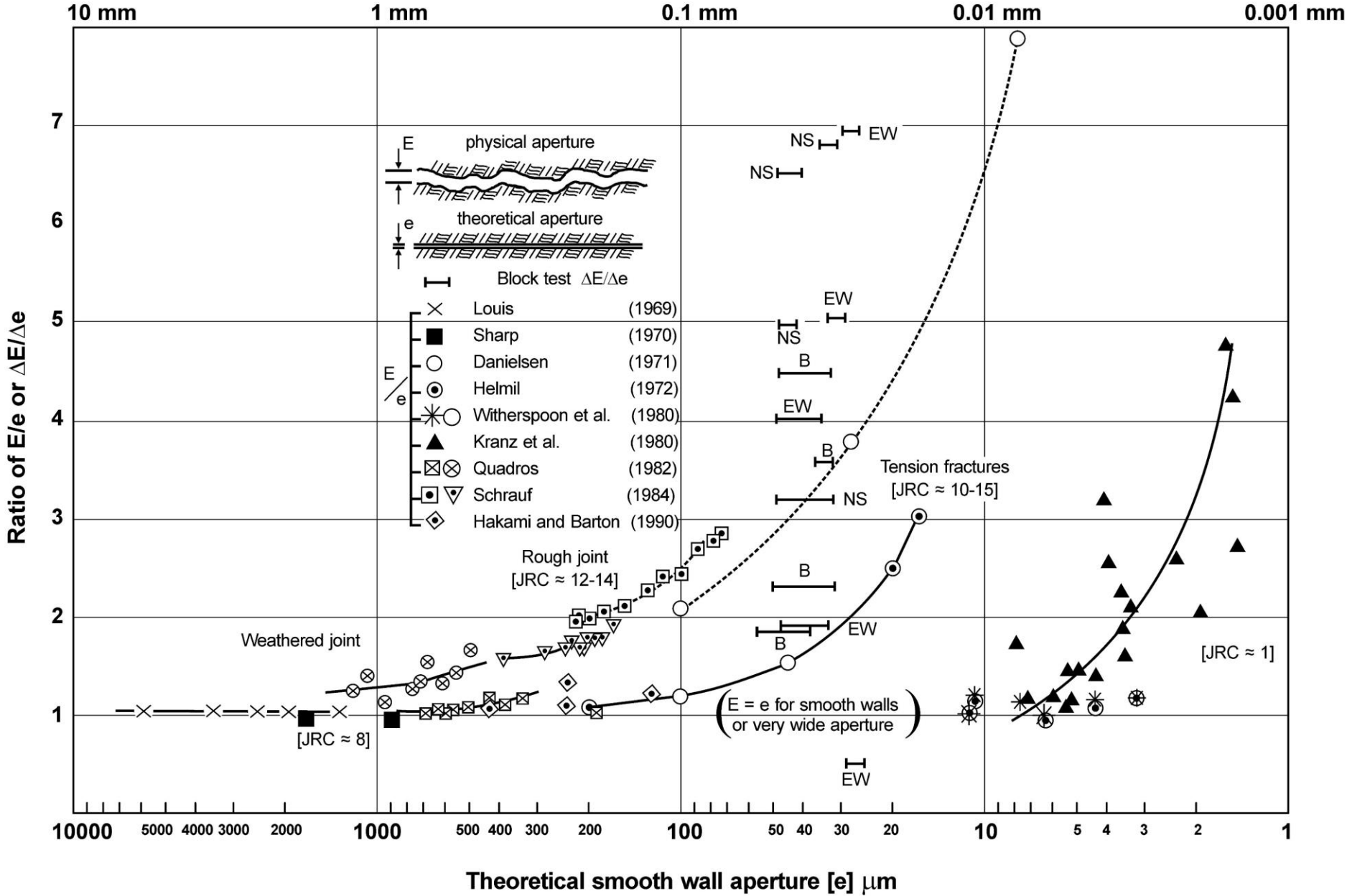


Examples of E and e due to *normal* and *pre-peak shear* loading
(UDEC-BB model of heated-block test, NGI 1991)

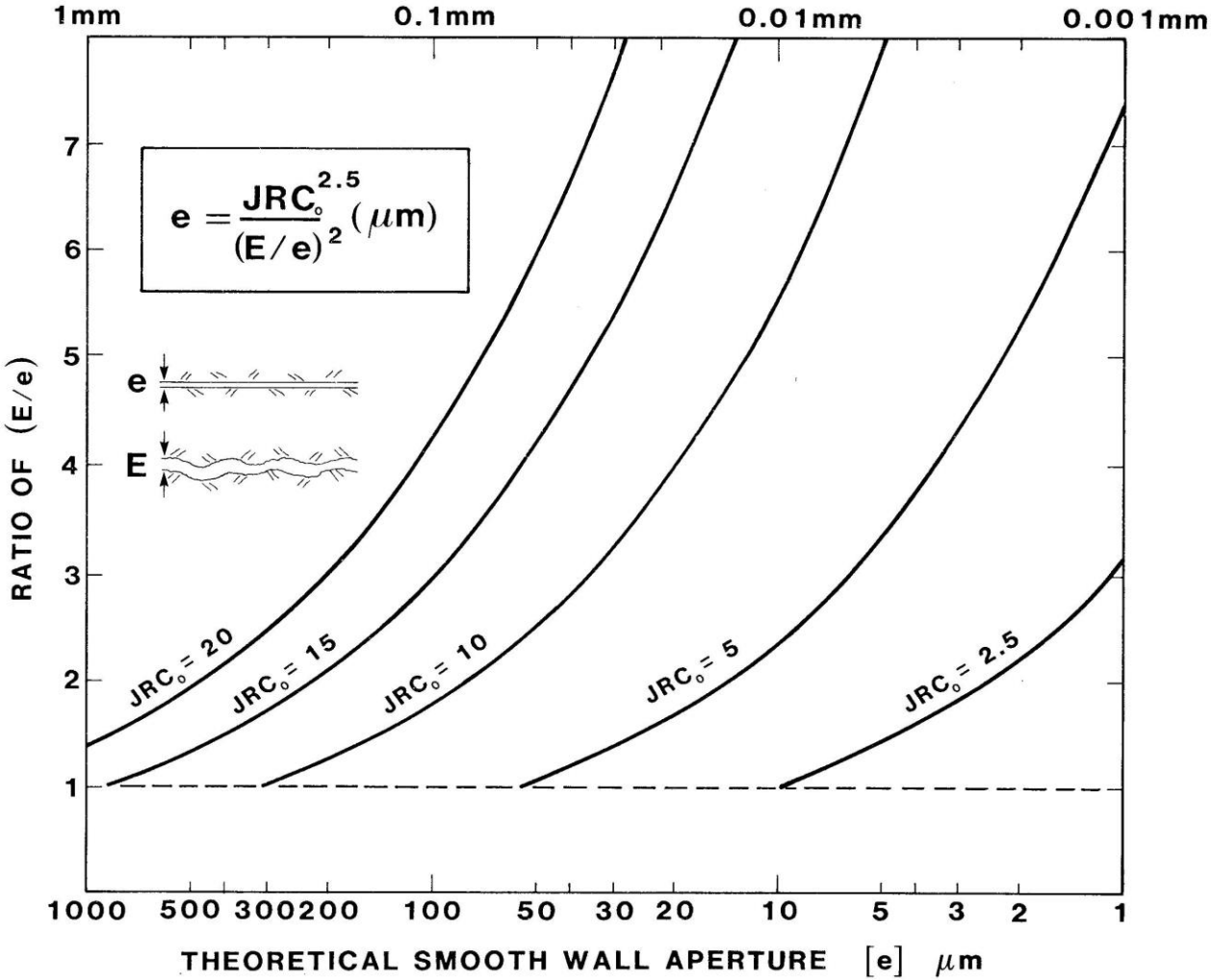




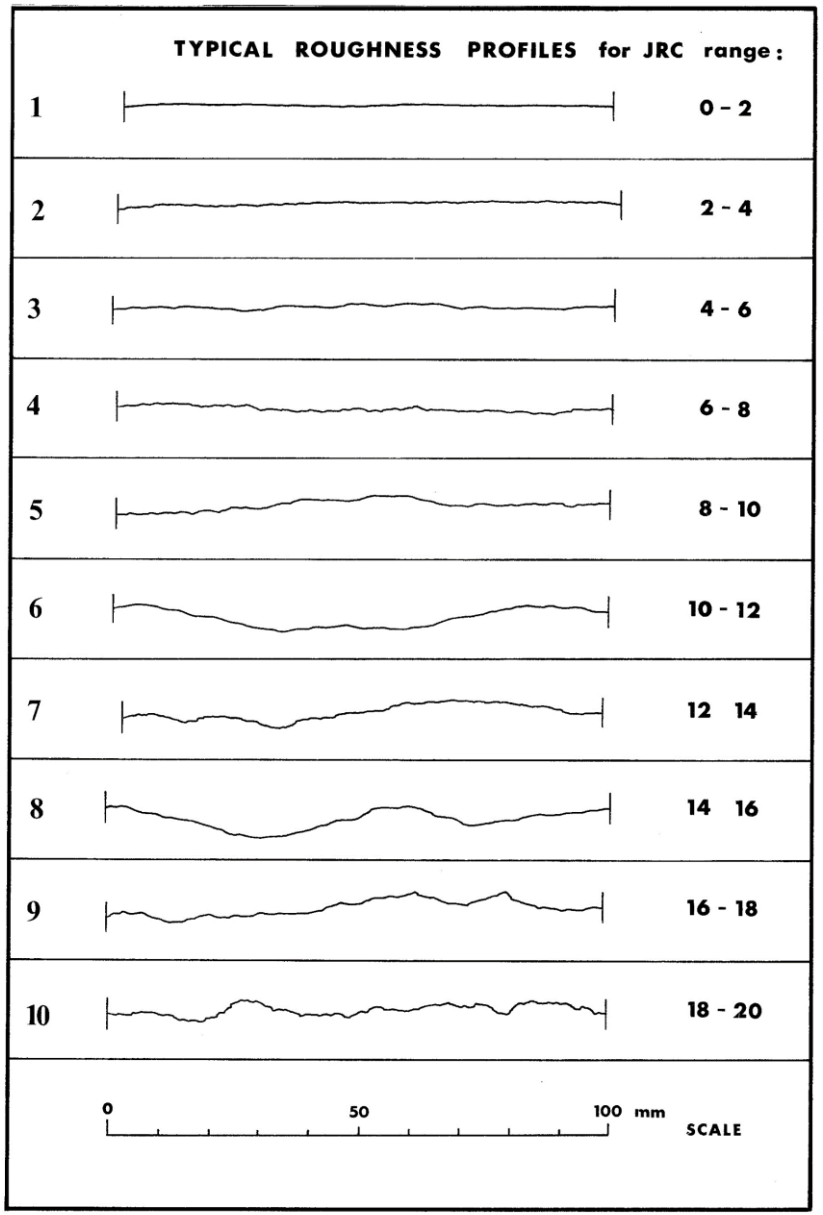
E/e and ΔE/ Δe data (Barton et al. 1985, Barton and Quadros, 1997)

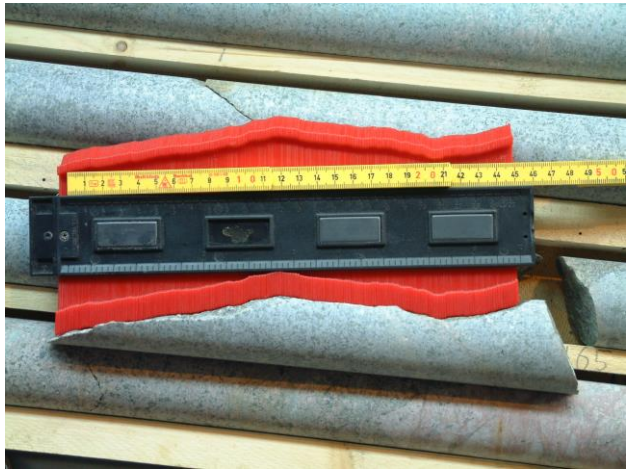


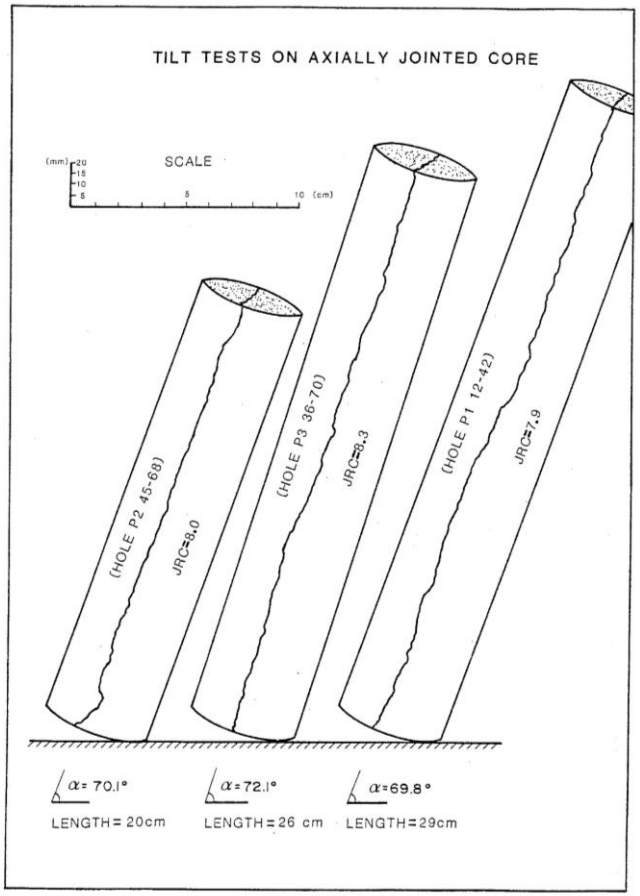
The inequality E ≥ e is dependent on roughness JRC (Barton, 1982)



Roughness JRC explained

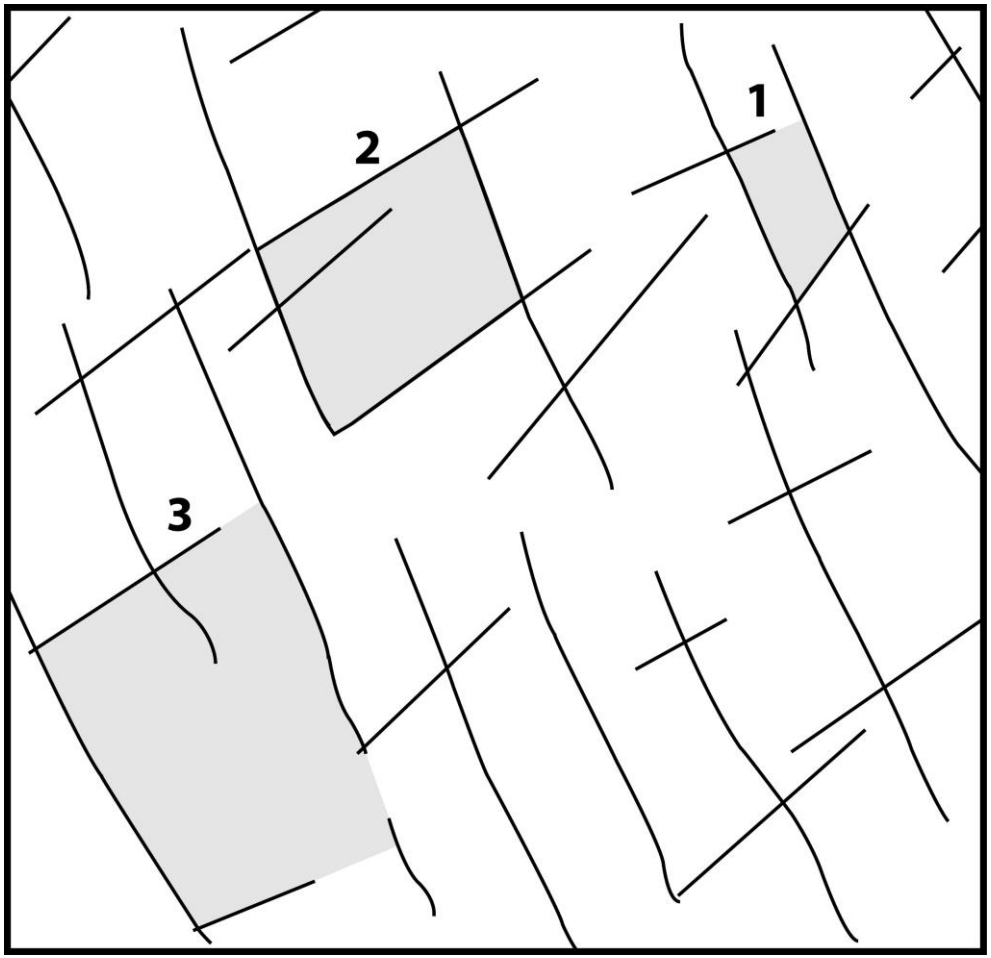






THE ROCK MASS OFTEN HAS MULTIPLE SETS OF JOINTS or FRACTURES

ONE DOMINANT SET ?....OR TWO (making blocks)?



CLOSING OBSERVATIONS

Several sets of joints or fractures
do not cause a rock mass
to ’disintegrate’
or ’lose fluid’!!

Crack density $\varepsilon = N a^3/V$ ... surely too ambiguous !
(10^7 @ 100 μm/10cm cube.....?=?.....10@ 1m/10m cube)