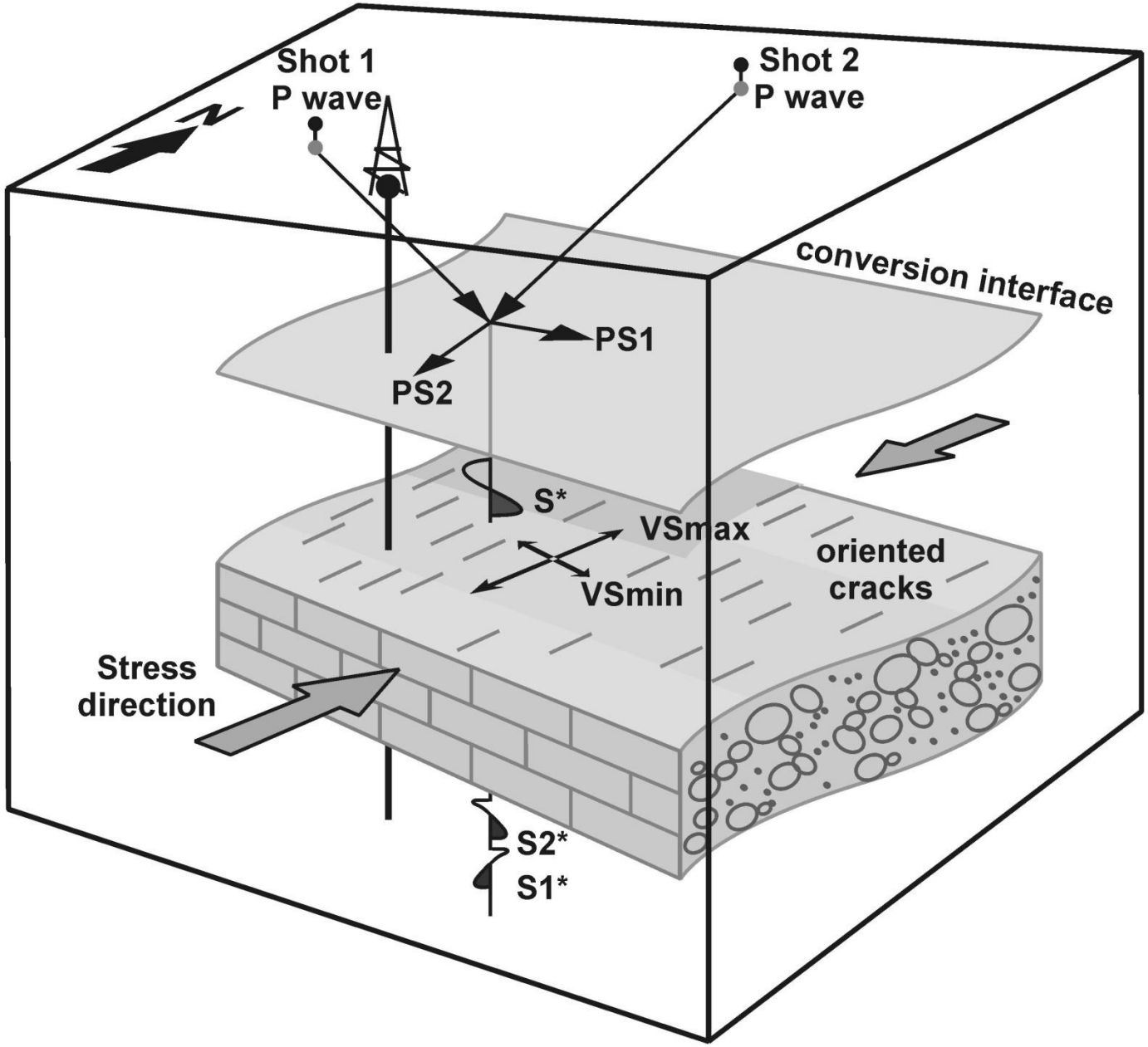
Two Fracture Sets, Four Apertures, Four Compliances, and Probable Shearing during Production from Fractured Reservoirs

Nick Barton, NB&A, Oslo, Norway



Principal question:

are there one or two sets of *'oriented cracks'?*

(Stenin et al. 2002)

CONVENTIONAL GEOPHYSICS ASSUMPTION

The conventional interpretation of shear-wave polarization is that the fast axis is caused by one set of stress-aligned fractures or microcracks.

A question arises as to whether there could actually be *two sets* causing the registered anisotropy from shear-wave polarization.

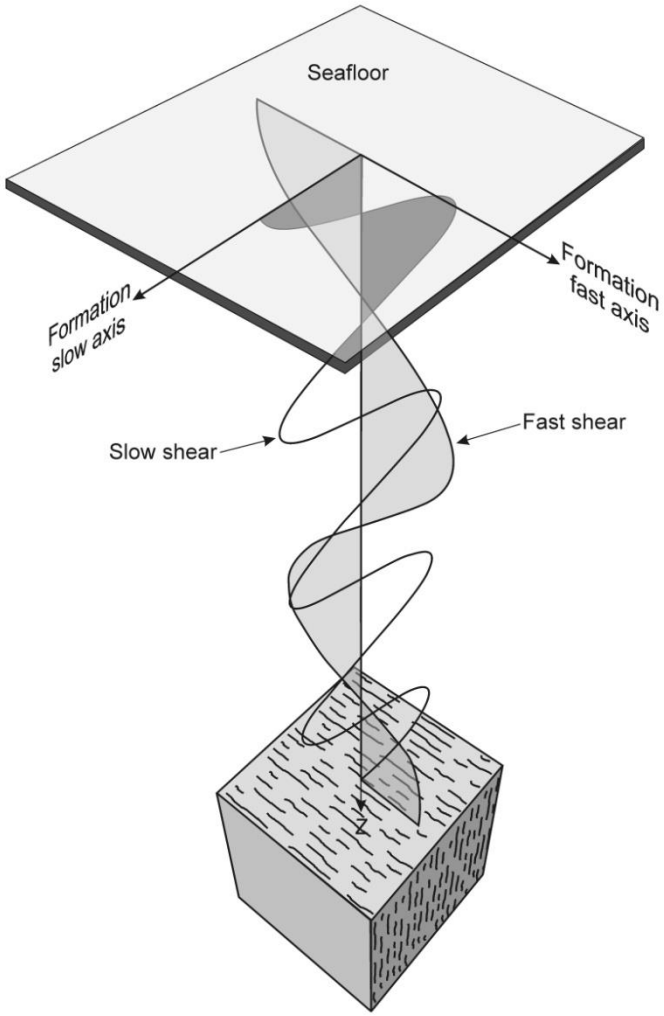
A significant number of fractured reservoir cases seem to be showing as much as 20º to 40º rotations of the polarization axes of qS_1 or maximum V_S relative to interpreted σ_H directions.

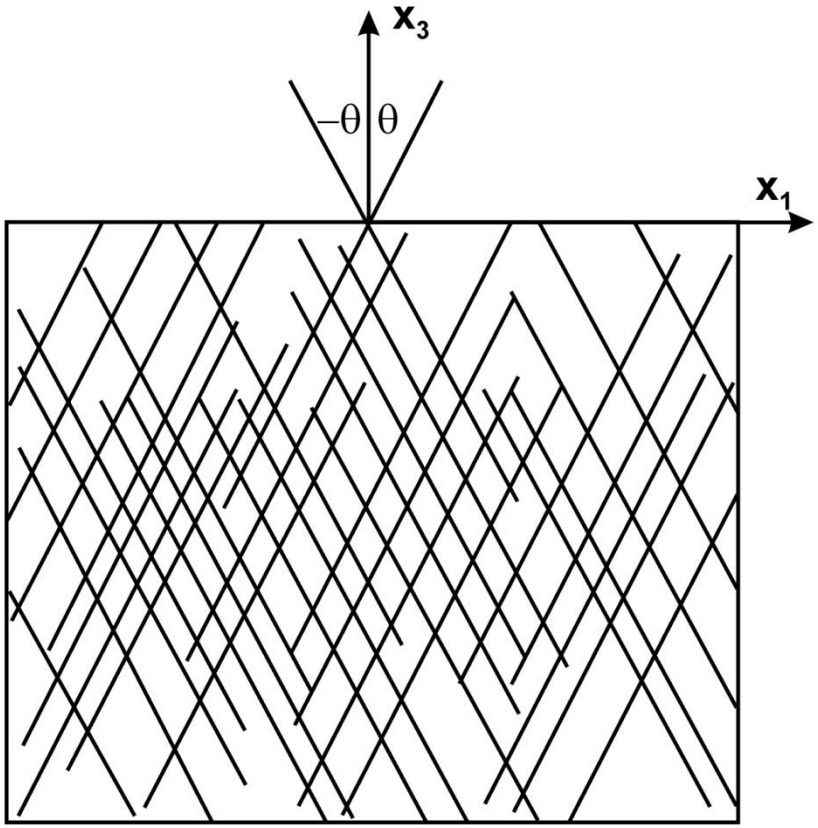
This is possibly because more than one set of fractures is present, as expected in most rock masses. Unequal components (compliances, apertures, fracture densities) from both sets?

It may also be due to the logic that fractures under shear stress are usually the best conductors, both from geomechanics principles, and from actual *deep well inflow measurements.*

Two fracture sets bisected by a principal stress direction may be a very logical model?

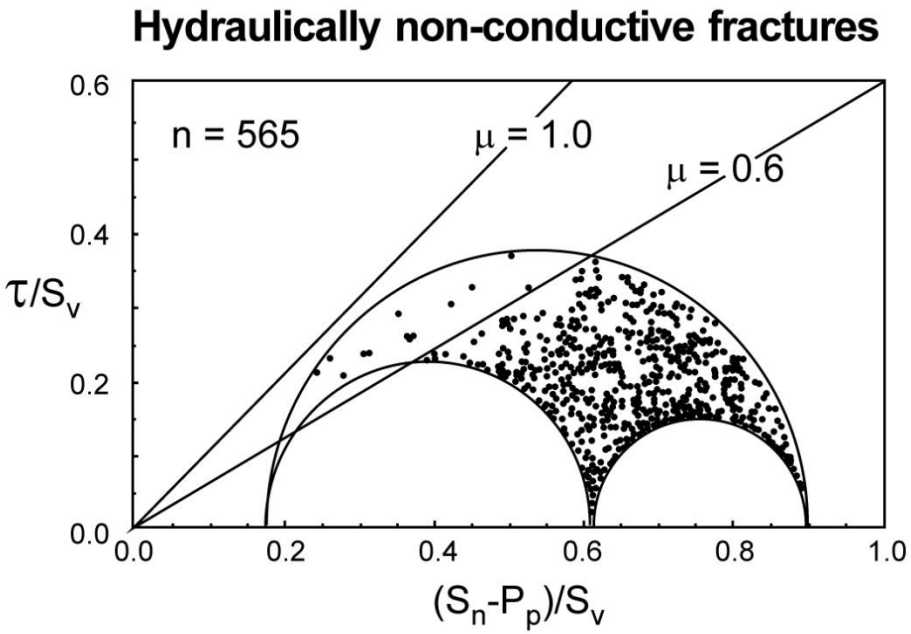
ONE SET OF FRACTURES, OR TWO SETS OF JOINTS ? (Barkved et al. 2004, Sayers, 2002)

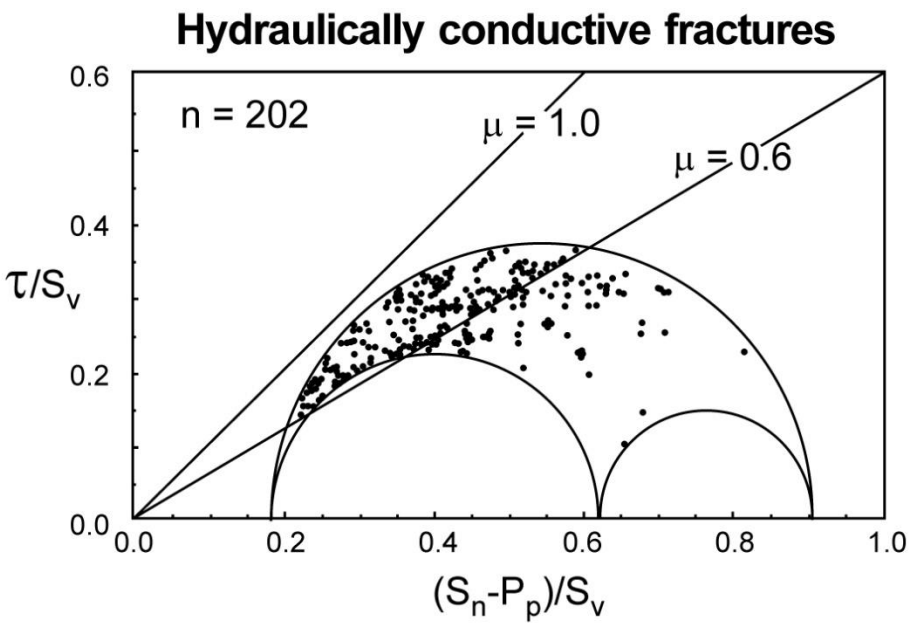




TWO SETS….FOUR COMPLIANCES…ETC

In the case of two sets of (conjugate) fractures, the shear wave components qS_1 and qS_2 depend on both the *shear and normal compliances*, since the incident angles are no longer parallel to the fractures. The conjugate pair of dipping fracture sets are typical of domal / anticlinal reservoirs (e.g. Ekofisk, Valhall).





The joints under *significant shear stress* are the best conductors in the case of hard crystalline rocks.

(Should surely apply to reservoir rocks too??)

Colleen Barton et al. 1995

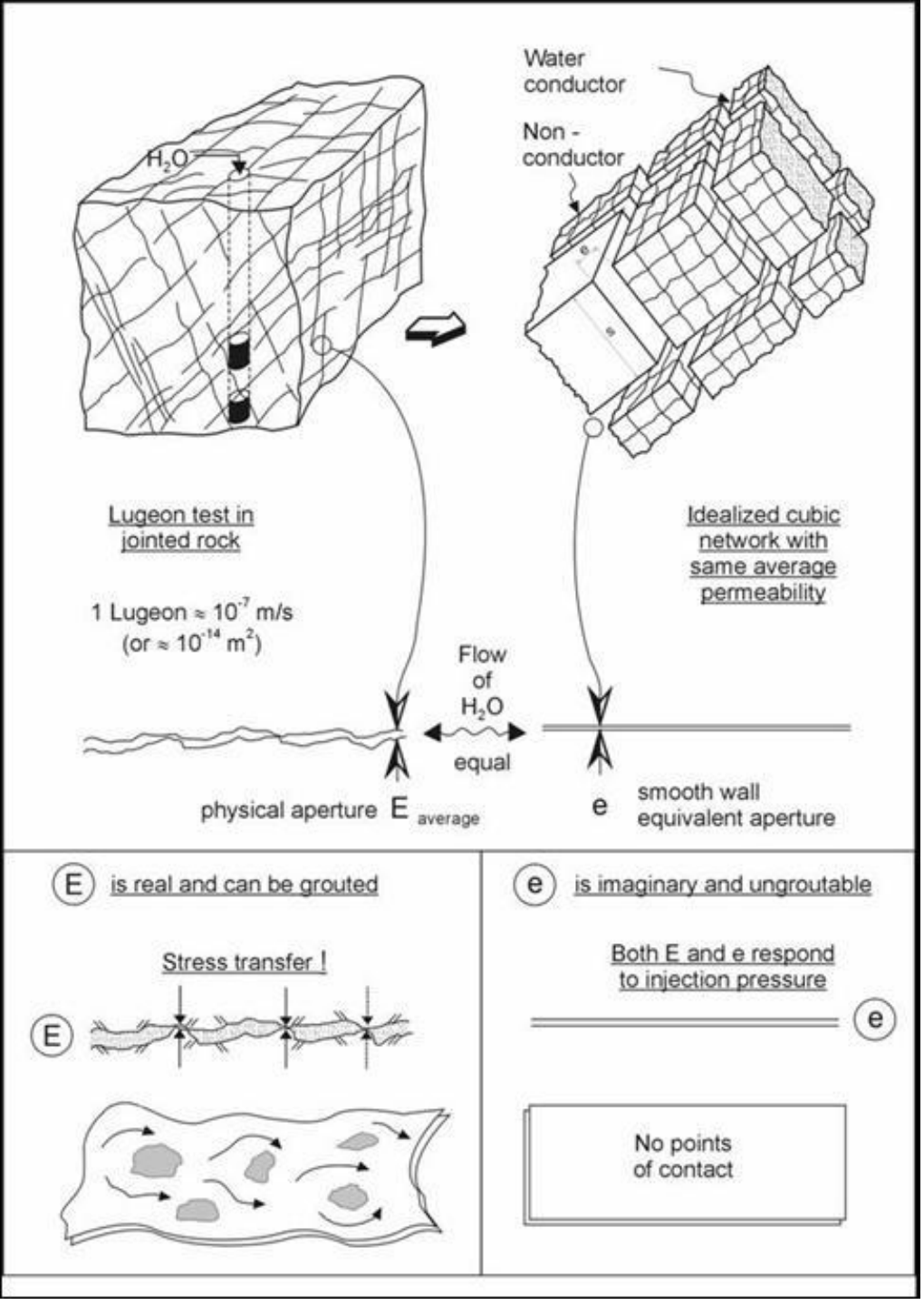
FRACTURES ARE 'CLOSED' OR 'OPEN' DEPENDING ON ORIENTATION, STRESS LEVEL AND ROUGHNESS

- The *non-conducting* fractures in deep wells are presumably held 'closed' by the resultant normal stress, which would be consistent with geomechanics modelling.

- But with sufficient fracture roughness and wall strength, apertures could be large enough to be 'open' // σ_H.

- Minerally 'bridged' partly open fractures can also be // σ_H.

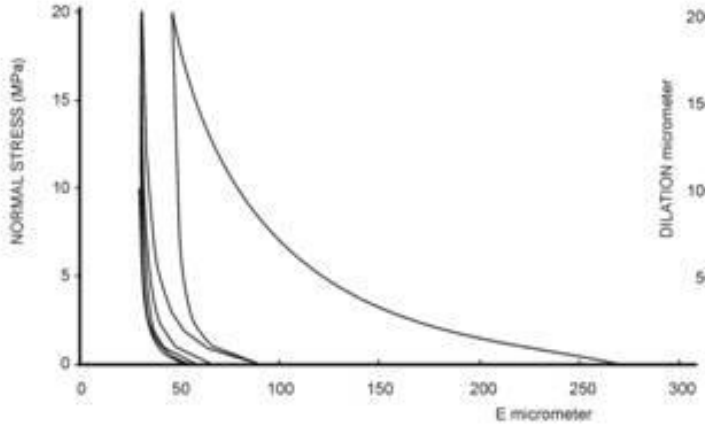
- Mobilized friction coefficients μ of mostly 0.5 to 0.9 have been interpreted in the case of numerous deep wells with *shear-stressed conducting fractures*, e.g. Zoback and Townend, 2001.

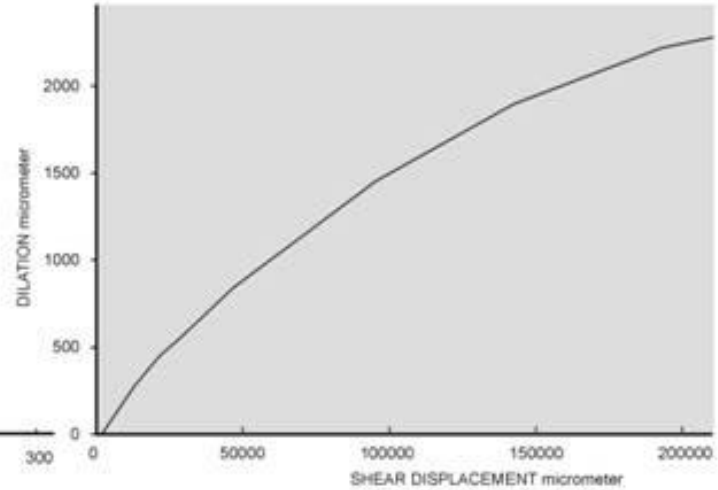


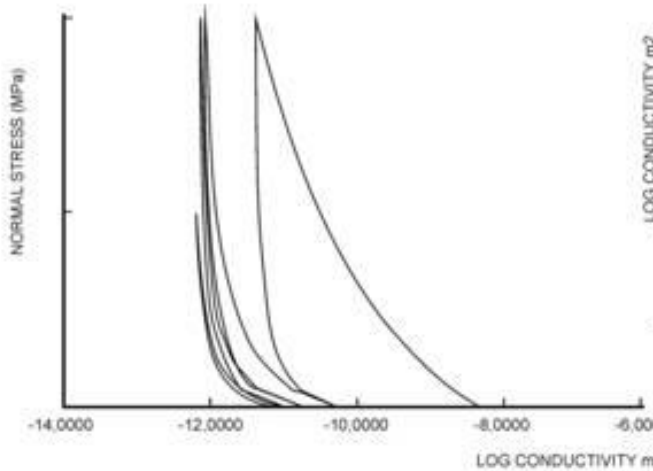
PHYSICAL (= rough) APERTURES, AND IDEALIZED (= smooth) HYDRAULIC APERTURES

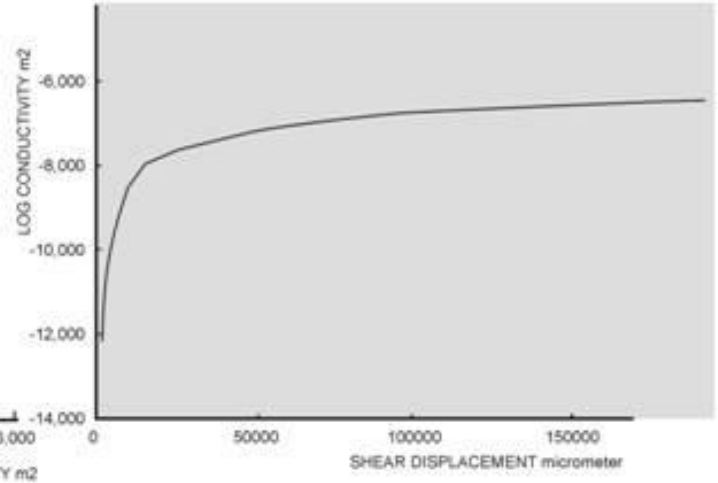
Barton Bandis Joint Model			NORMAL CLOSURE CALCULATION					
INPUT PARAMETERS		SNORM	CYCLE 1	CYCLE 2	CYCLE 3	CYCLE 4	CYCLE 5	
JRC	10	LOAD	20	20	20	10	0	MPa
JCS	50	UNLOAD	0	0	0	0	0	MPa
SIGMAC	60	APERTURE	0,280	0,090	0,068	0,059	0,056	mm
CALCULATED PARAMETERS								
LOAD		KNI	13,5	20,17	23,4	25,41	26,33	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









Rougher joint (JRC = 10) in harder rock (JCS = 50 MPa.

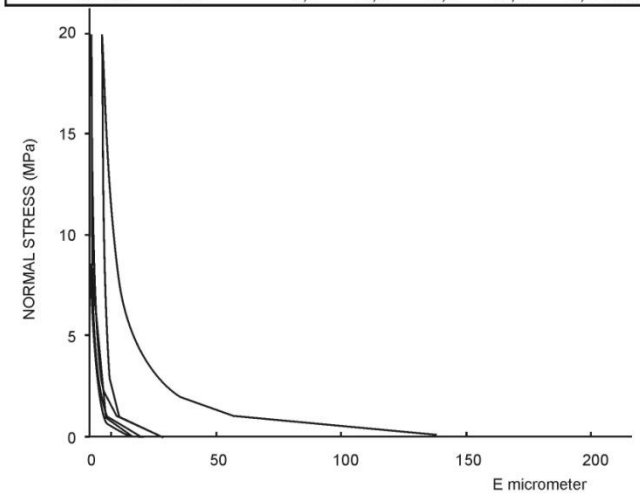
Left: physical aperture (E) and permeability ($e^2/12$) versus <u>normal</u> stress.

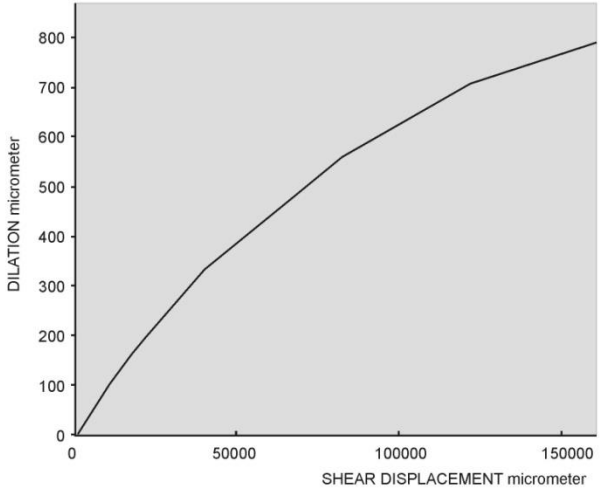
Right: dilation and permeability caused by <u>shear</u> displacement.

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

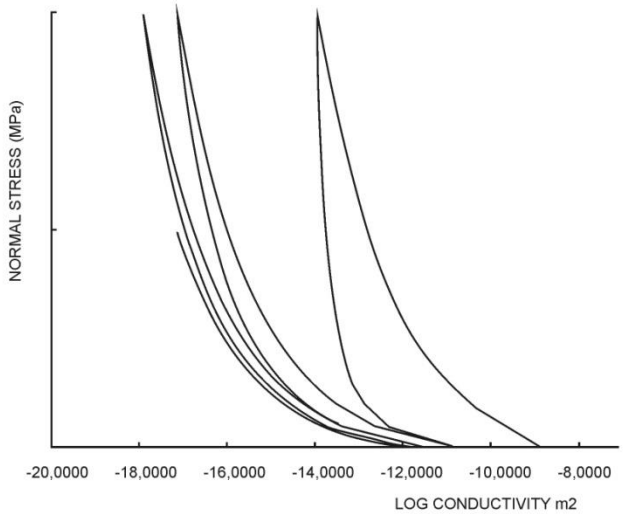
INPUT PARAMETRS			FULL SCALE PARAMETERS		
JRCo	5,00		JRCn	4,26	
JCSo	25,00	MPa	JCSn	19,64	MPa
Lo	0,10	M	DPEAK	2,03	mm
Ln	0,50	M	ROUGH	1,25	
PHIr	27,00	DEG	LFACT	0,01	
SIGMA n	10,00	MPa	PHIr RAD	0,47	Rad
SIGMAC	30,00	MPa	PPEAK	28,25	Degrees
APERTURE	0,000	mm	KS	2,650	MPa/mm

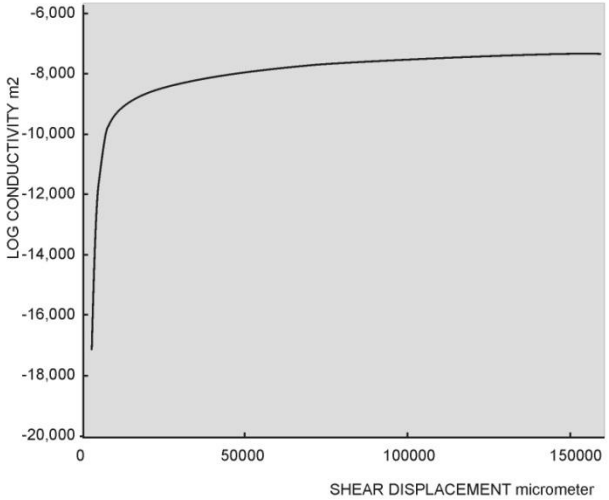
Smoother joint (JRC = 5) in weaker rock (JCS = 25 MPa.



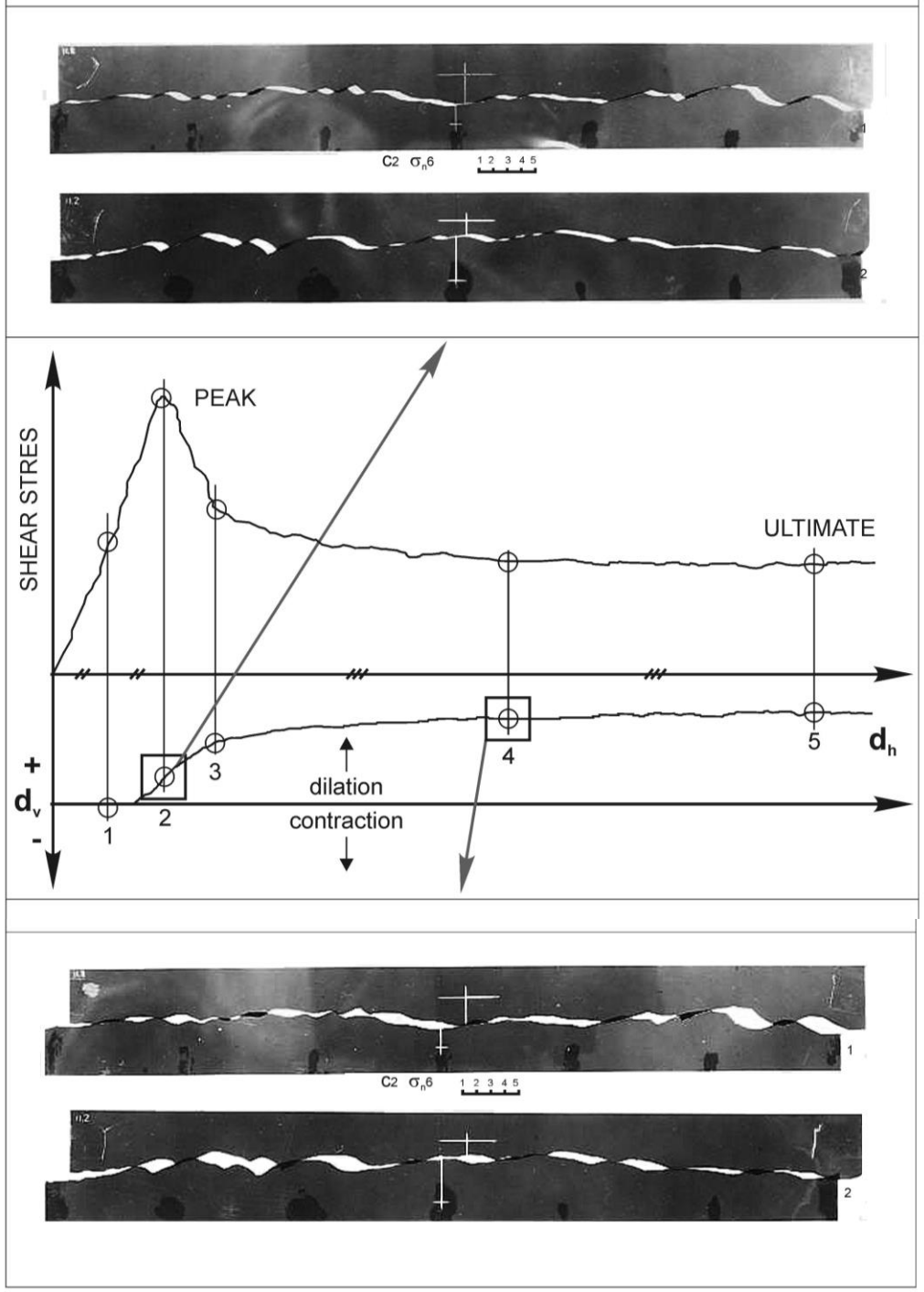


Left: physical aperture (E) and permeability ($e^2/12$) versus <u>normal</u> stress.



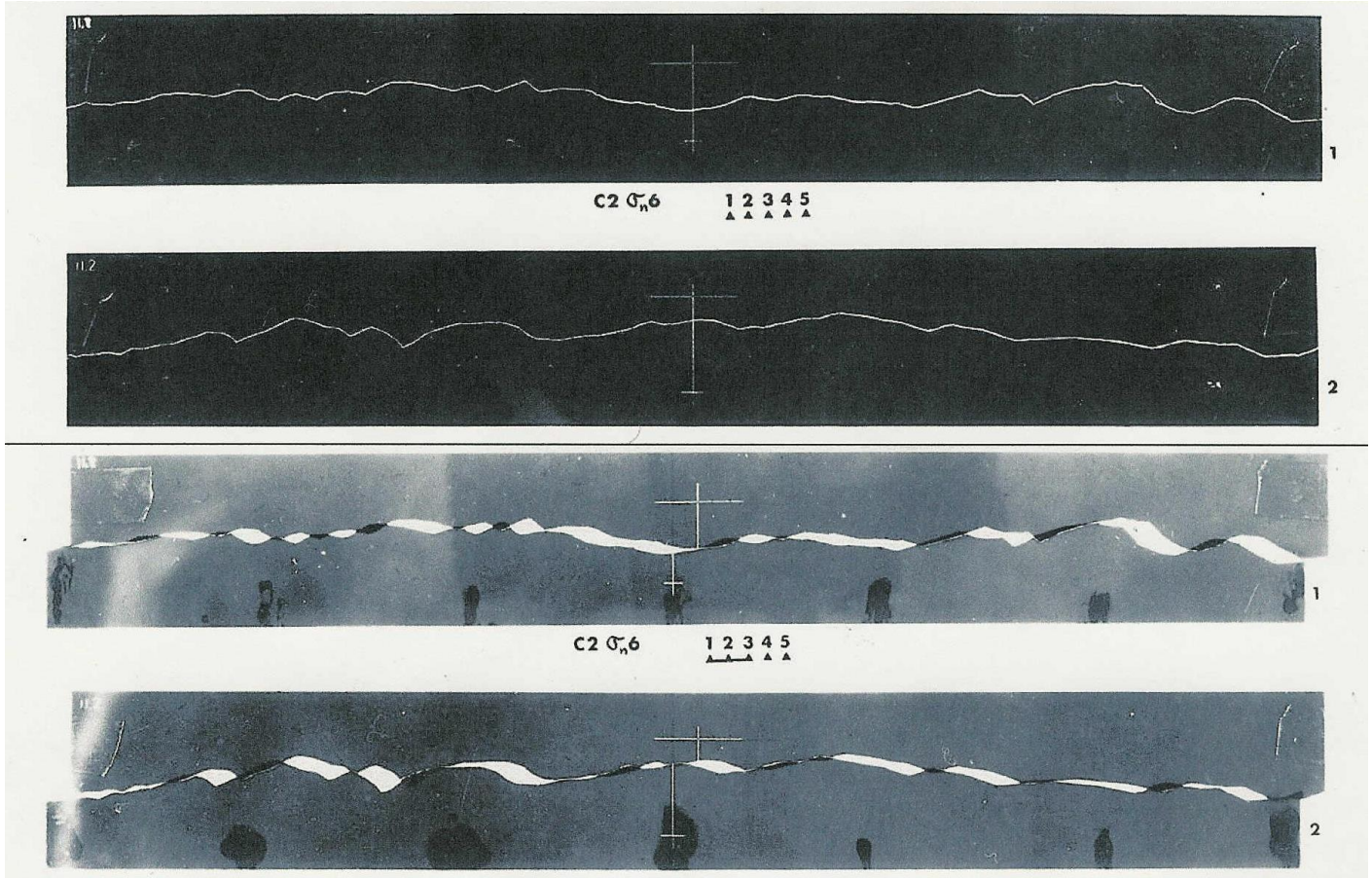


Right: dilation and permeability caused by <u>shear</u> displacement.

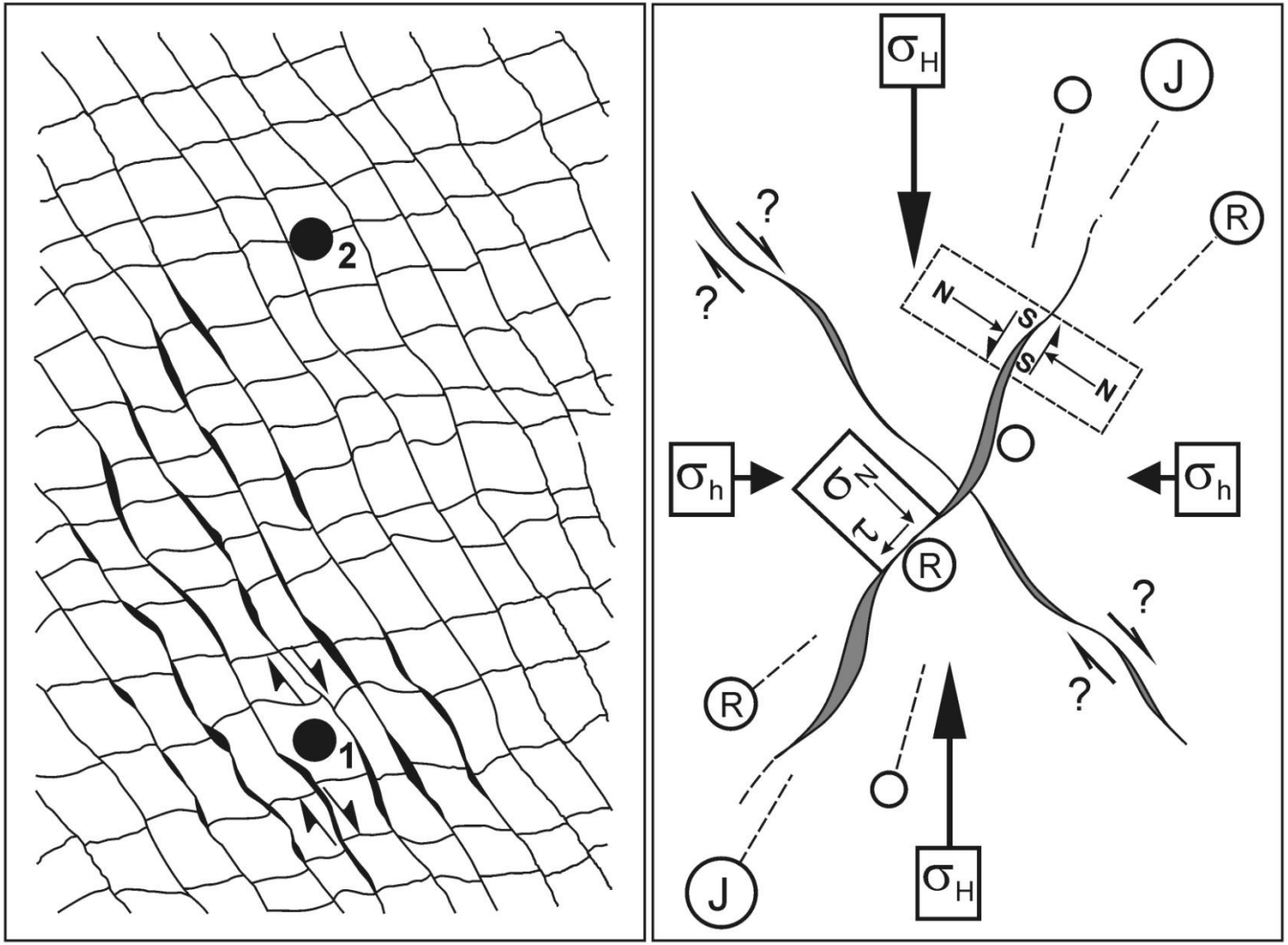


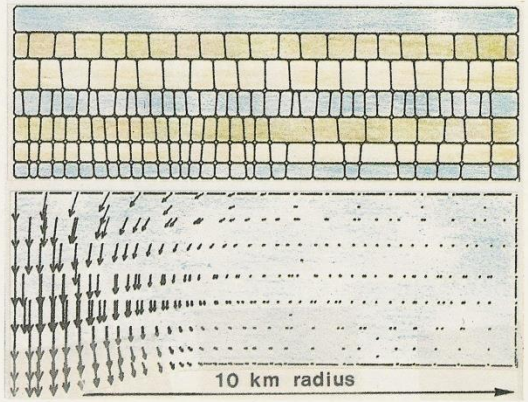
PRE-PEAK, OR POST-PEAK SHEARING IS DESIRABLE……
IF ONE IS INTERESTED IN PERMEABILITY !!

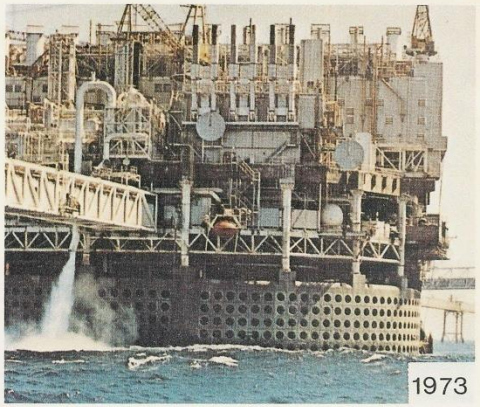
Note (also) the opposite 'rotations' of open lenses ('O') and contacting rock ('R') seen in physical models of shearing. Barton (2006).



FRACTURE SETS THAT ARE UNDER SHEAR STRESS ARE VERY COMMON, *AND THEY MAY BE AMONG THE BEST CONDUCTORS* – BOTH FROM OBSERVATION AND FROM ROCK MECHANICS THEORY (Barton et al. 1985, C.Barton et al. 1995, Barton, 2006)







Subsidence of the North Sea Ekofisk reservoir. Compare 1973 and 1986 photographs of tank depths.

NUMEROUS ROCK MECHANICS PROCESSES AT MANY SCALES WERE SET IN MOTION BY PRODUCTION FROM THE FRACTURED CHALK AT EKOFISK

The principal mechanisms were *effective stress increase, compaction and shearing* (at many scales)

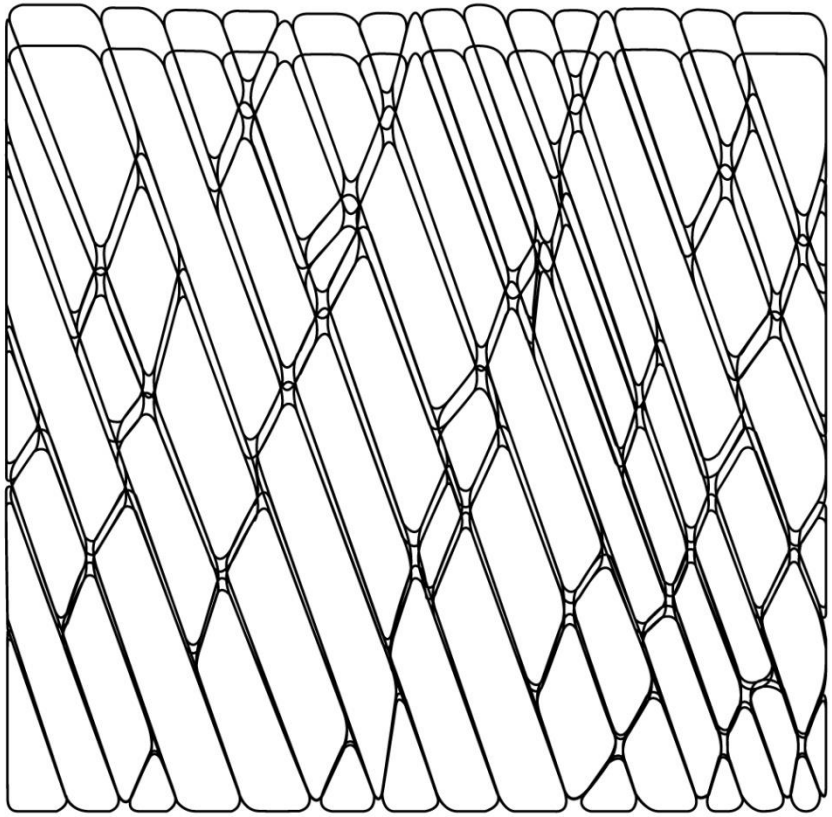
Slickensided fractures

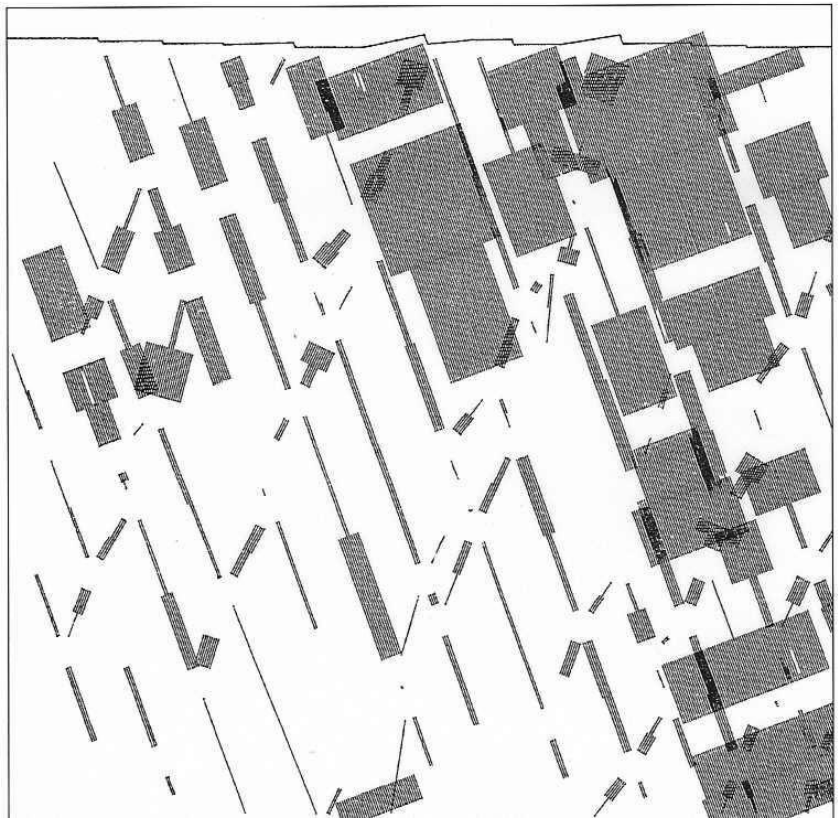
- Newly developed slickensides identified many years after exploration are evidence of *shear-with-production* mechanisms at e.g. Ekofisk.
- These were discretely modelled in 1986/87 yet hardly believed, *prior to* subsequent recognition as production-related slickensiding.
- Slickensides were apparently not detected during exploration of the Ekofisk field in the late 1960's.
- Later, Albright et al. (1994) mention Ekofisk exhibiting: *'Shear fracture micro-seismicity, possibly indicating that subsidence is caused by a combination of pore collapse and shear sliding'.*

Distinct element UDEC-BB modelling of compaction-induced shearing of natural conjugate fracture sets in Ekofisk chalk, from Barton et al. 1986,1988.

Fracture shear *(max 4 to 10mm)* and dilation causes changes to fracture permeabilities, which can be sequentially tracked by following physical aperture (E) and conducting aperture (e) developments *(see later discussion of apertures E and e)*

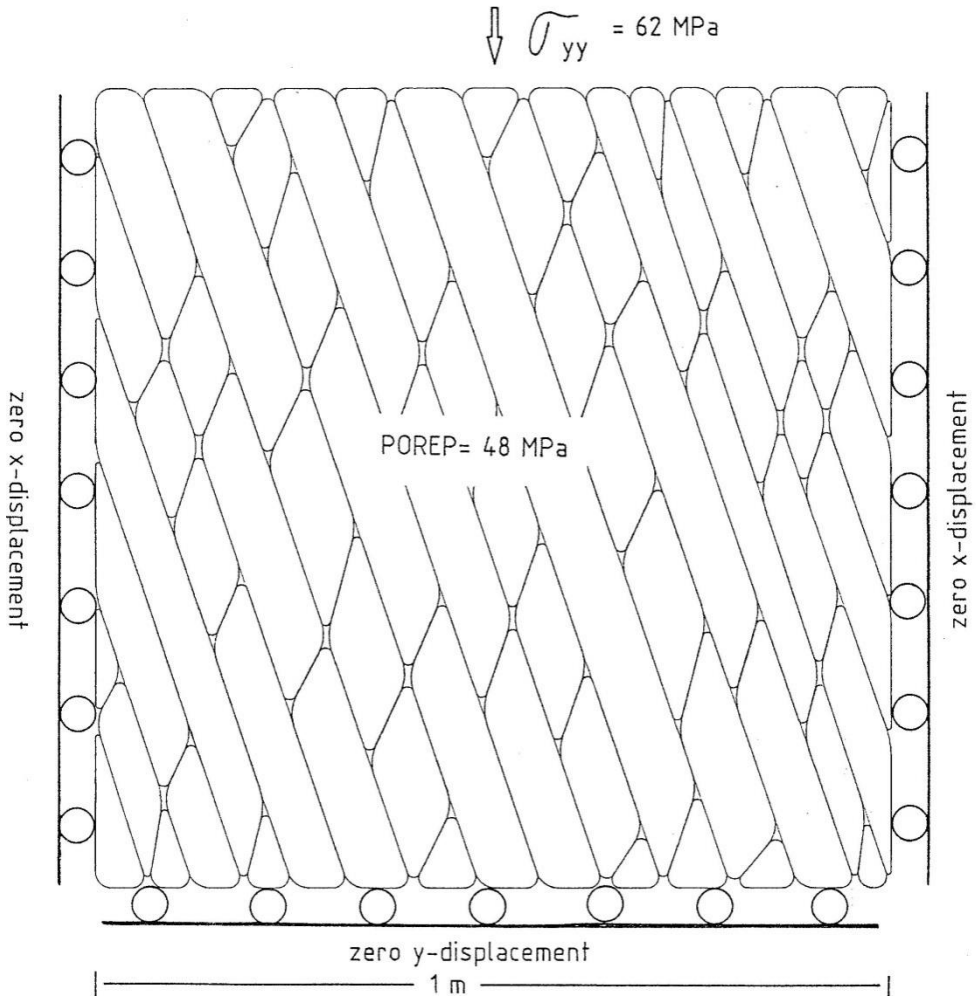
Fracture density, as conventionally defined (and ambiguously used) in geophysics *($e=N.a^3/V$)* is as high as 1.4 for portions of this reservoir.





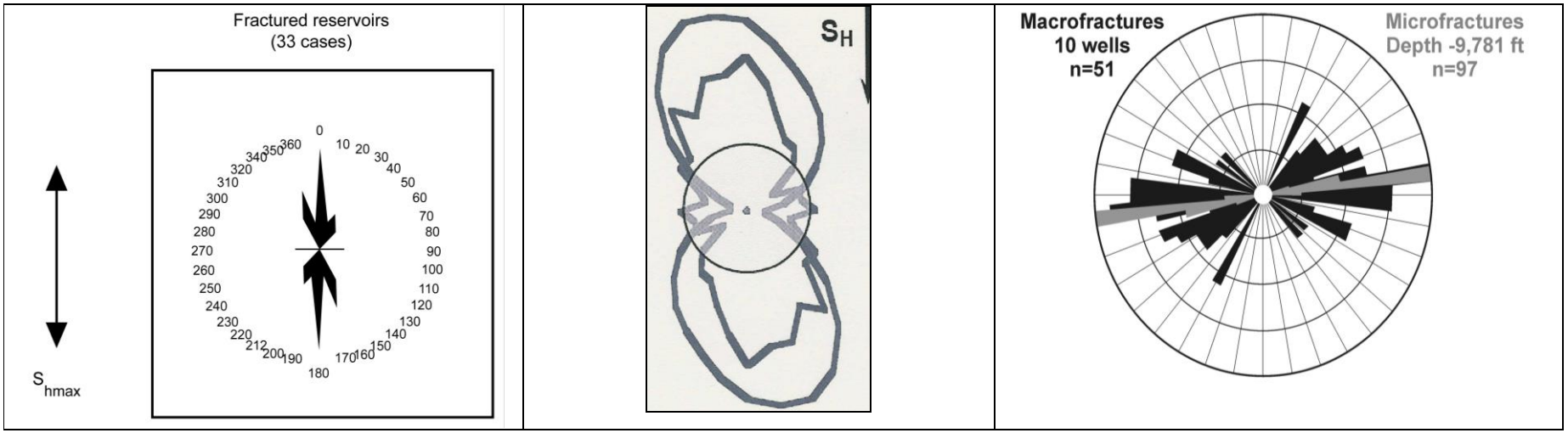
These were the initial boundary conditions for the discrete-fracture modelling of an idealized ‘1m block’ of Ekofisk chalk

(2D - UDEC-BB model)



Conjugate sets of fractures

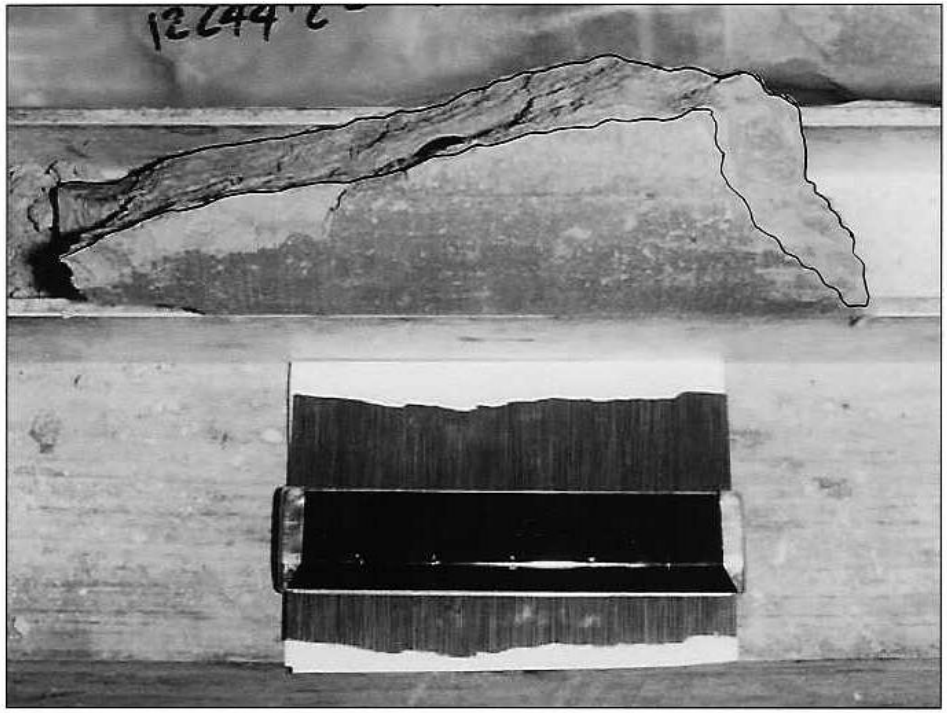
- Two figures showing very extensive evidence of flow directions from pairs of wells (injector/producer) from Heffer, 2002 and Heffer et al. 2007(*= half a million pairs of injector-producer wells, aggregated from eight field areas).*
- Measurements in individual producer wells from Laubach et al. 2000, suggesting conjugate macro-fractures.
- All are suggesting the strong probability of anisotropy-axis deviation from $\sigma_{H\ max}$……..due to flow (and polarization) contributions from unequal conjugate sets??



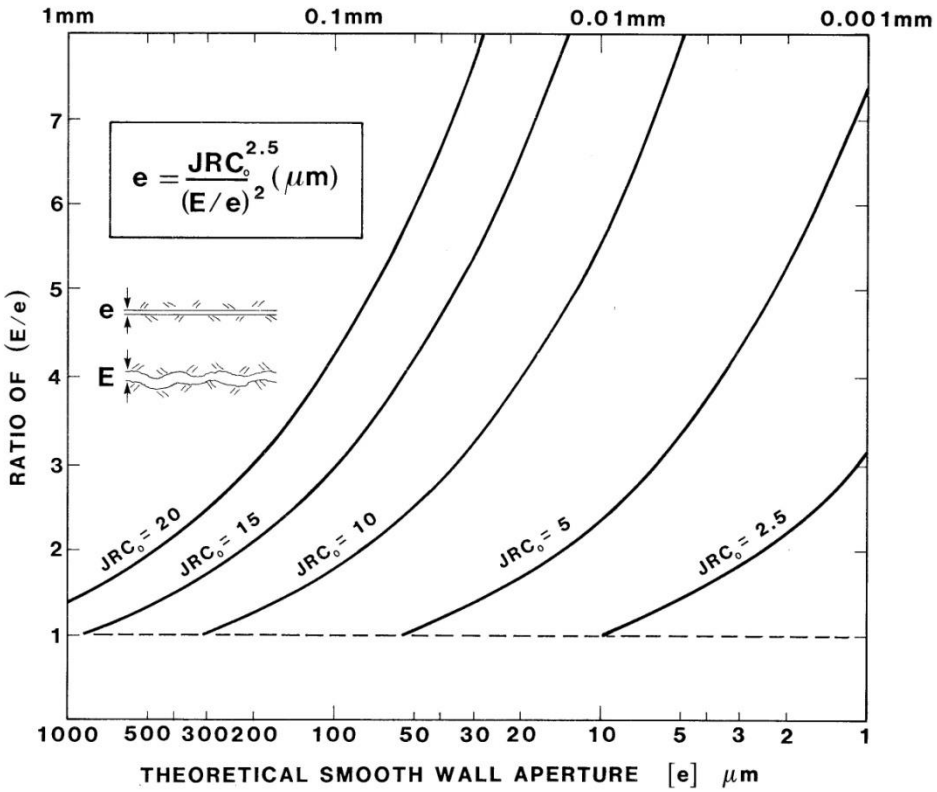
IMPORTANCE OF JOINT (or fracture) ROUGHNESS and STRENGTH CHARACTERIZATION (for understanding contributions from different fracture sets)

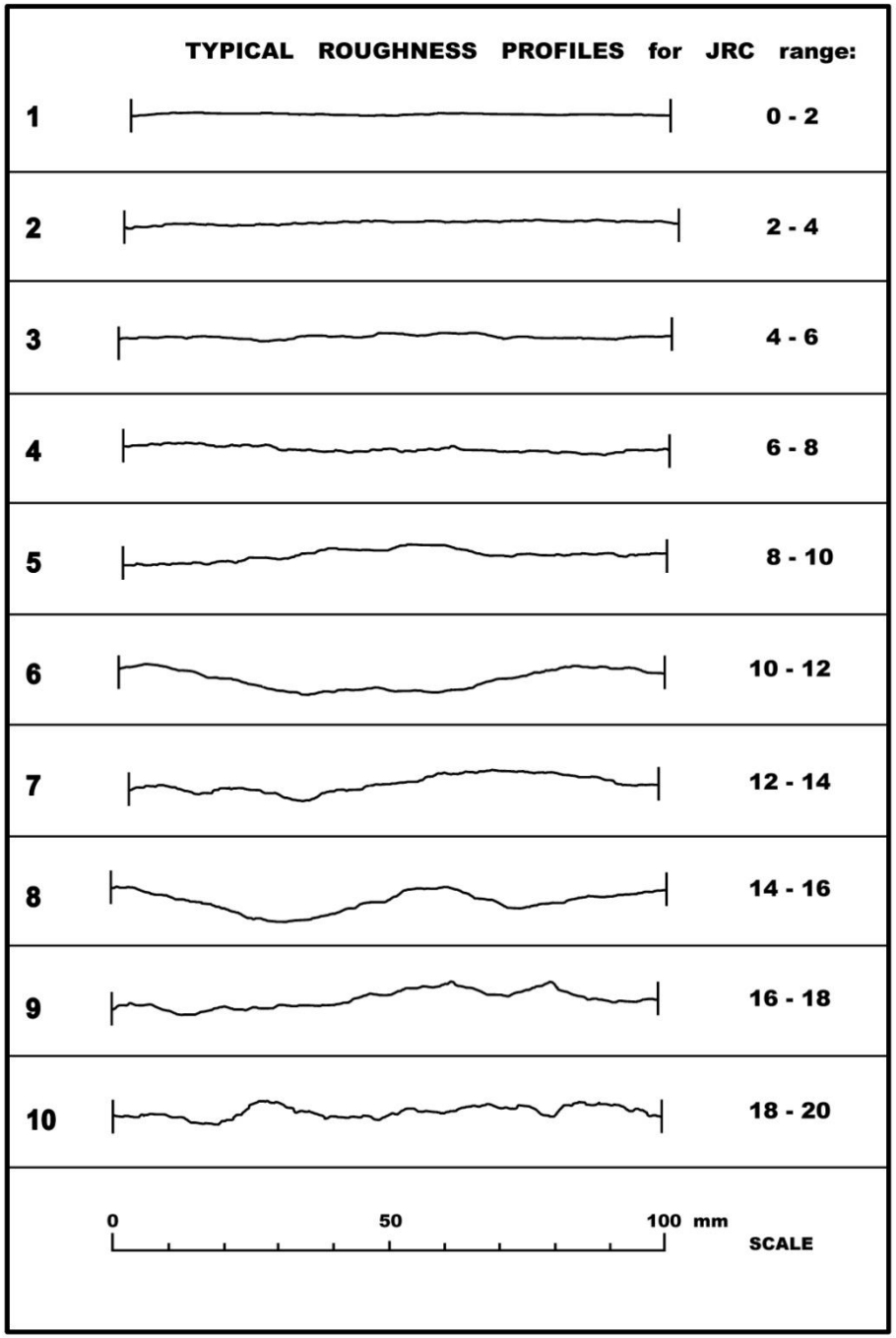
JRC = joint roughness coefficient (see next screen) is used to estimate shear strength, dilation, *physical-to-hydraulic-aperture* conversion, shear and normal stiffness.

JCS = joint wall compression strength (usually ≤ UCS, due to alteration/weathering) is also needed.

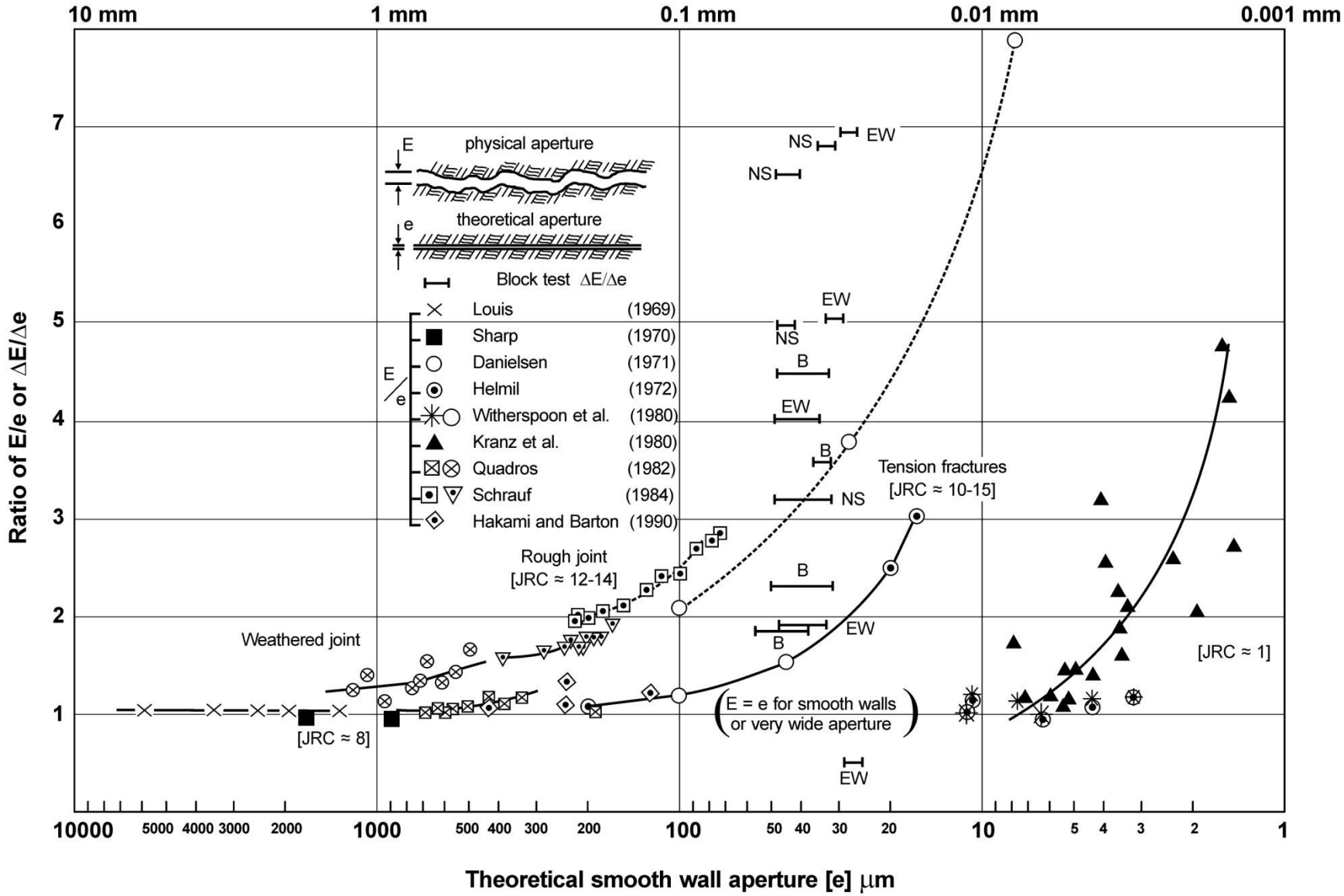


JRC – and illustration of one of its uses

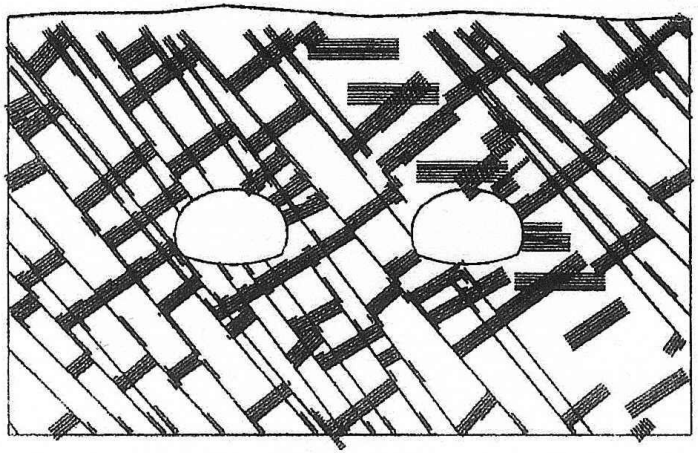




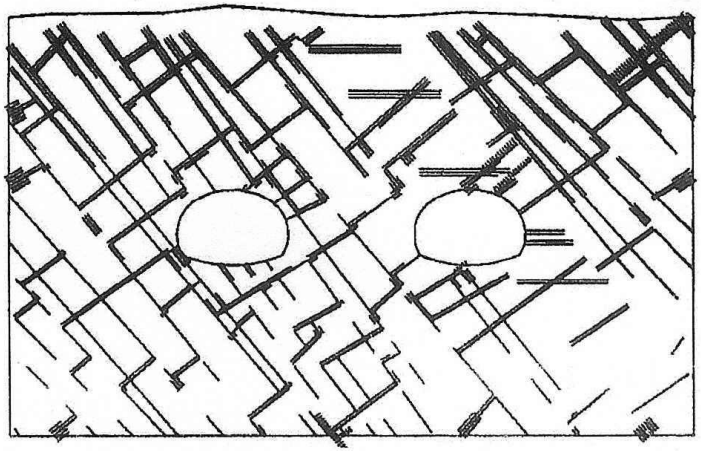
Apertures E (≥ e) will actually affect several assumptions in geophysical modelling (e.g. fracture aspect ratio - squirt losses – volume of fluid)



Civil engineering applications of apertures (E) and (e)



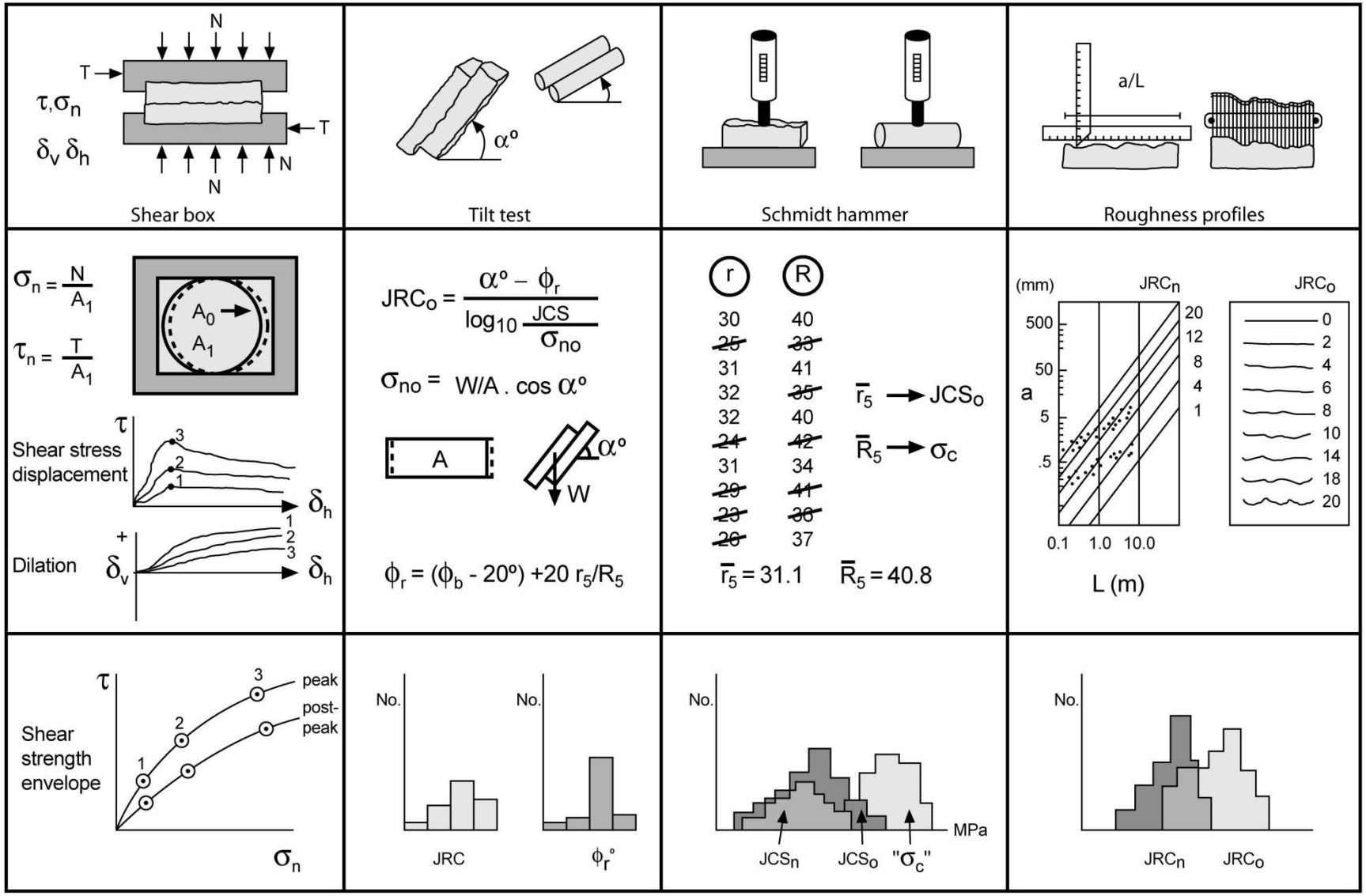
joint mech. aper.
max mech aper = 1.160E-03
each line thick = 2.000E-05



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

CHARACTERIZATION OF JOINTS OR FRACTURES (Barton, 1999)

Shear box and index testing of rock joints

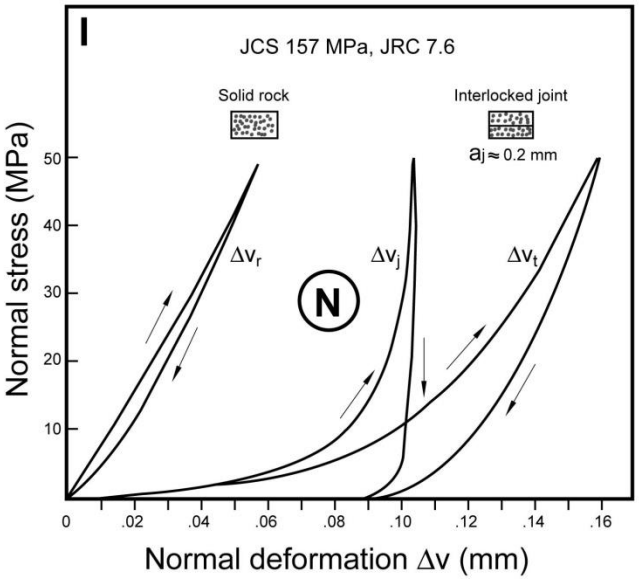


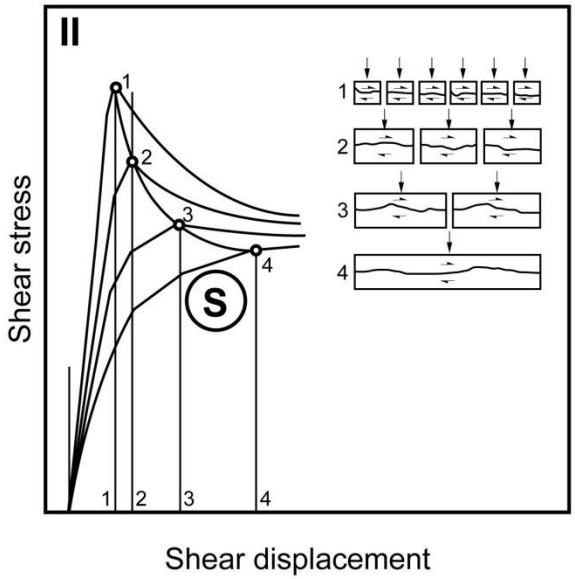
COMPLIANCES and STIFFNESSES

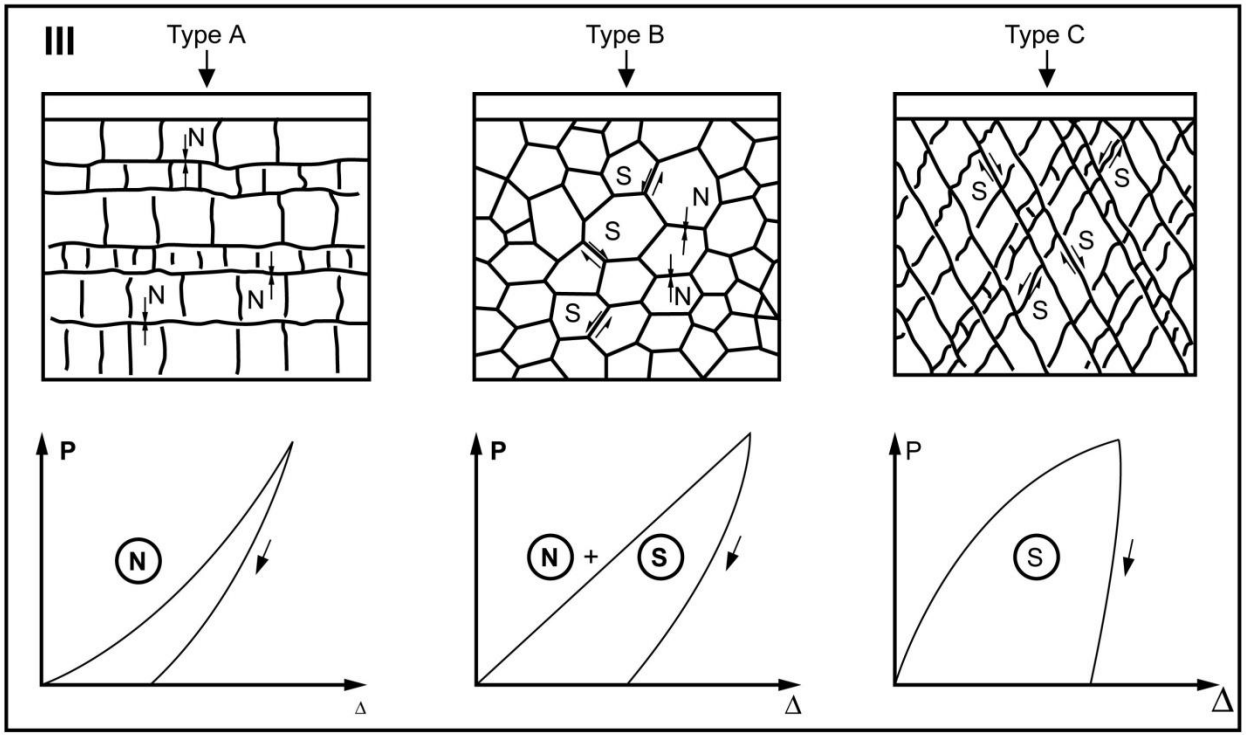
- The potential magnitudes of the shear and normal fracture compliances, the inverse of (dynamic) stiffnesses, dictate the strength of shear wave anisotropy, the degree of attenuation, and the interpretation of fluid type in the case of shear waves that are not propagated in perpendicular or parallel directions relative to fracturing.

- Barton (2006) found from experimental studies such as Pyrak-Nolte et al. (1990), and Bandis et al. (1983), that the overall range of reported data for pseudo-static stiffness Kn and normal compliance B_N suggested Kn(static) ≈ 1/ B_N (dynamic) in this stiffest of loading directions. (i.e.10^{-12} to 10^{-14} m.Pa^{-1} ≈ 1/*1000* to 1/*100,000* MPa/mm).

- This is despite the huge differences in displacement between the dynamic and static case. This may be due to ‘traversing’ the same stress-displacement curves, but over widely differing increments.





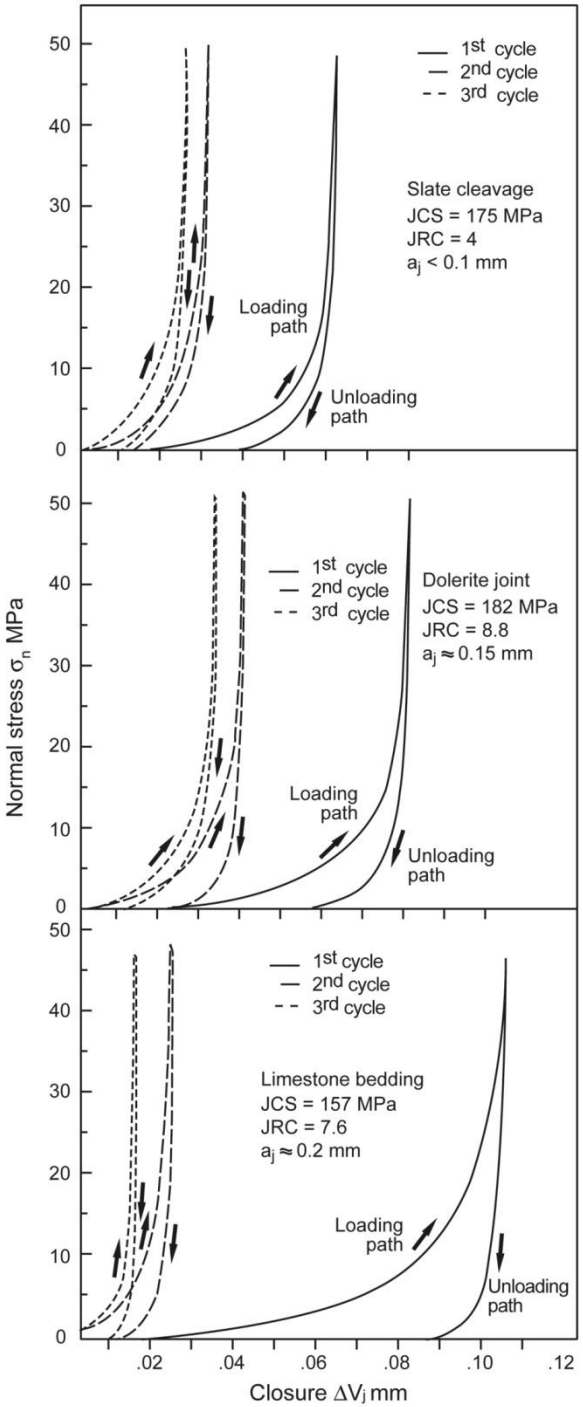


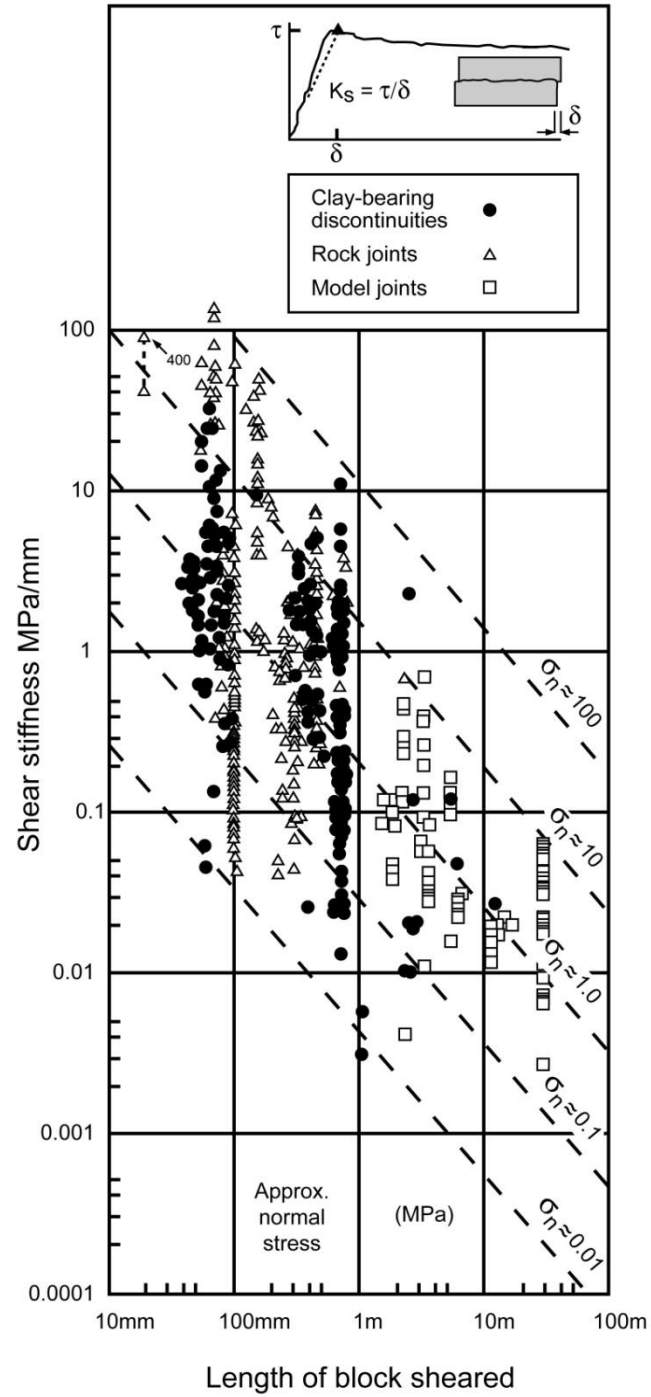
Psuedo-static stress-displacement behaviours in diverse rock masses….will occur during production too!

Elements of the Barton-Bandis joint modelling concepts.

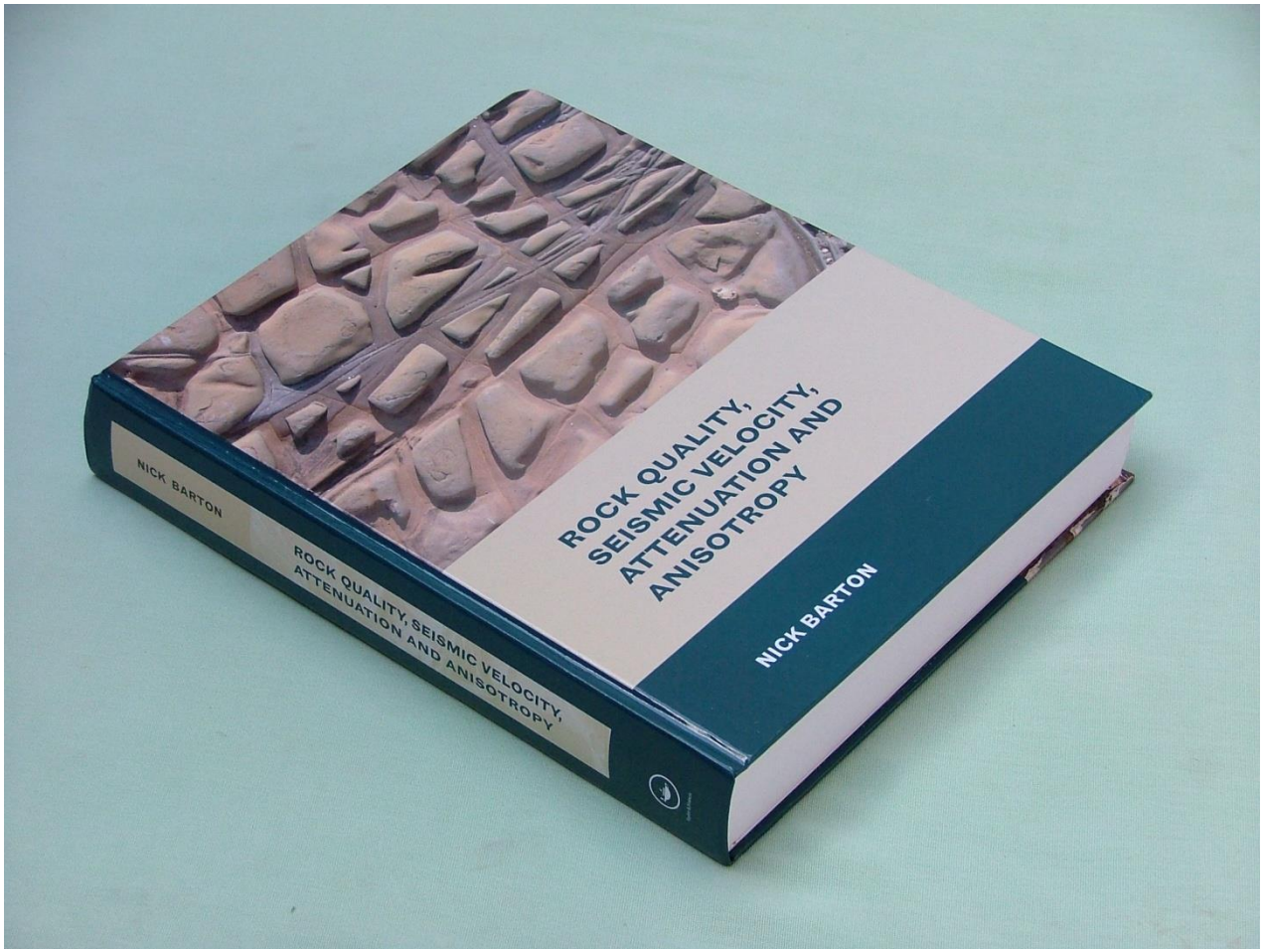
(Note scale effects for Ks…..perhaps also *for* B_S?)

Psuedo-static experiences with Kn and Ks





CROSS-DISCIPLINE REFERENCES (≈ 830 refs)



CONCLUSIONS

1. Shear-wave splitting is conventionally thought to be caused by stress-aligned open micro-cracks, and/or by a set of stress aligned vertical fractures in an NFR (naturally fractured reservoir) context.
2. There are other possibilities if two conjugate sets are present and each are under shear stress, for which there can be several scenarios.
3. This 'fractures-under-shear-stress model, certainly true in the case of domal or anticlinal NFR, is more consistent with geomechanics principles (and deep-well measurements) that indicate clearly that fractures under shear stress are better conductors of fluids.
4. Newly developed slickensides identified many years after exploration are evidence for such a *shear-with-production* mechanism at Ekofisk, and were discretely modelled, yet hardly believed, *prior to* recognition as production-related slickensiding.
5. If one of the shearing fracture sets is dominant, and with different strike, it would probably give detectable 4D effects, such as rotation of both anisotropy and attenuation axes, and rotation of the principal permeability axis as well.
6. Dynamic normal compliance B_N is of similar magnitude, when inverted, to the pseudo-static normal stiffness Kn that is much researched in rock mechanics. The dynamic shear compliance B_T may be scale-dependent, perhaps following, but with reduced intensity, the better known scale-effect trends for the pseudo-static shear stiffness Ks.