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Shear-wave anisotropy may suggest the presence of a stress-aligned fast axis in a fractured reservoir, but what are the productivity characteristics of this fast axis?

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EXAMPLES OF LECTURE CONTENT:

1. **'OPEN' *SINGLE* FRACTURE SET // TO $\sigma_{H\ MAX.}$ The rule or an anomaly?**

2. **SHEAR WAVE *POLARIZATION* MAY BE CAUSED BY 2-SETS?**

3. **WATERFLOOD/PRODUCER 'PAIRS' NON-ALIGNED WITH $\sigma_{HMAX.}$**

4. **GOOD PERMEABILITY MAY IMPLY *PRE- or POST-PEAK* SHEARING**

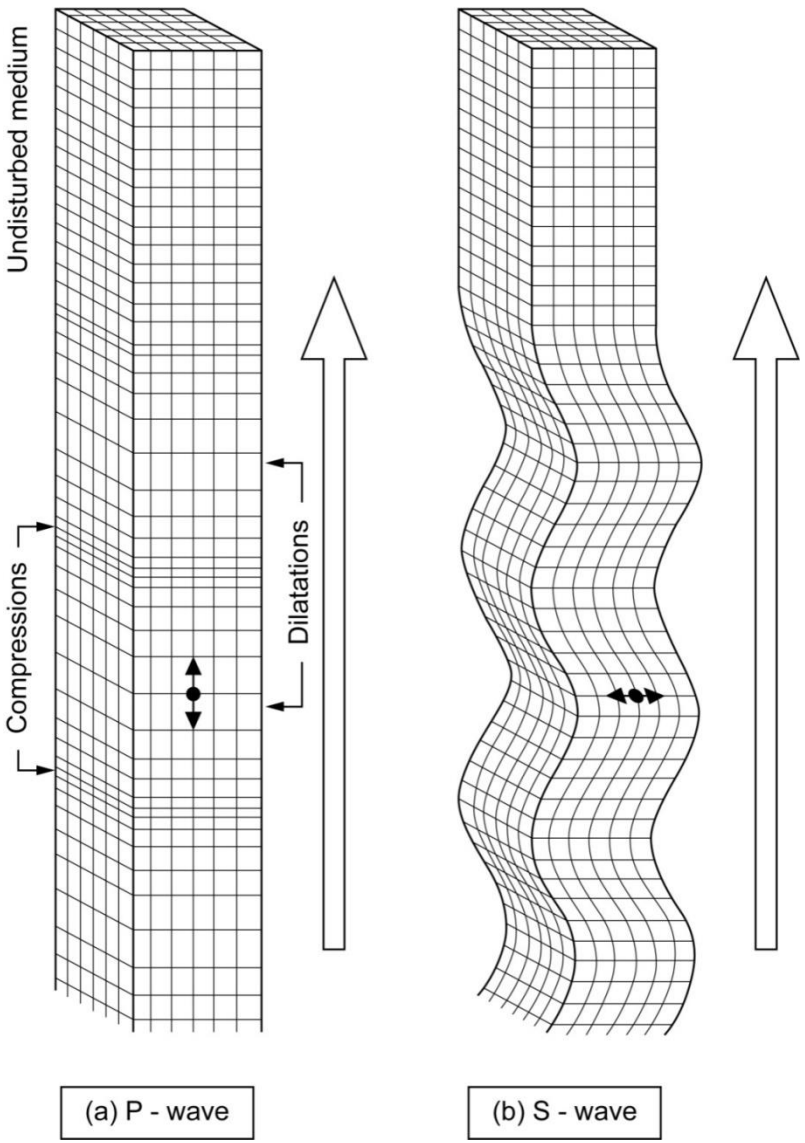
5. **INEQUALITY OF FRACTURE APERTURES (hydraulic e ≤ physical E)**

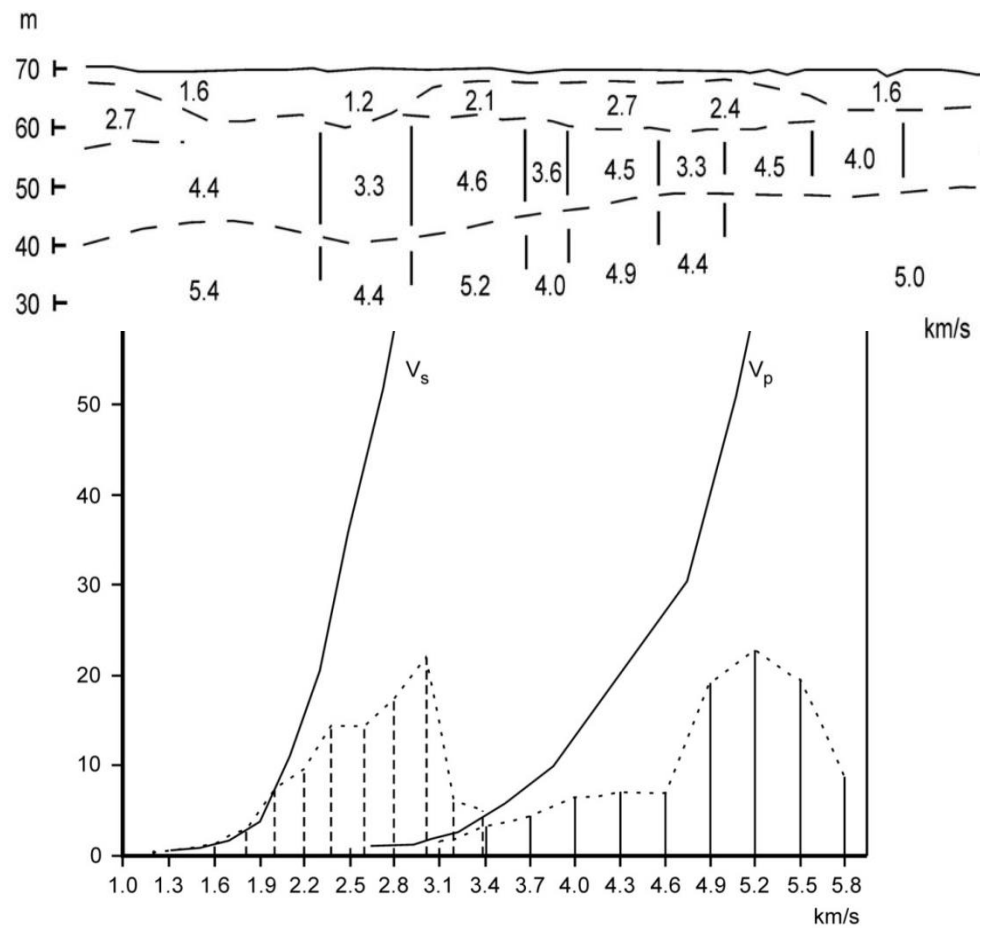
6. **JRC (roughness) AND JCS (strength) DESCRIPTION IN RESERVOIR MODELLING – NEEDED TO INTERPRET 4D (3D-seismic repeated in time)**

7. **SLICKENSIDED JOINTS or FRACTURES AT EKOFISK DUE TO PRODUCTION (=4D)**

Obviously - a rock mass often has several joint sets which can be hindrances or *pathways* for flow.

➢P-waves *and* S-waves that cross jointed rock, get *SLOWER*



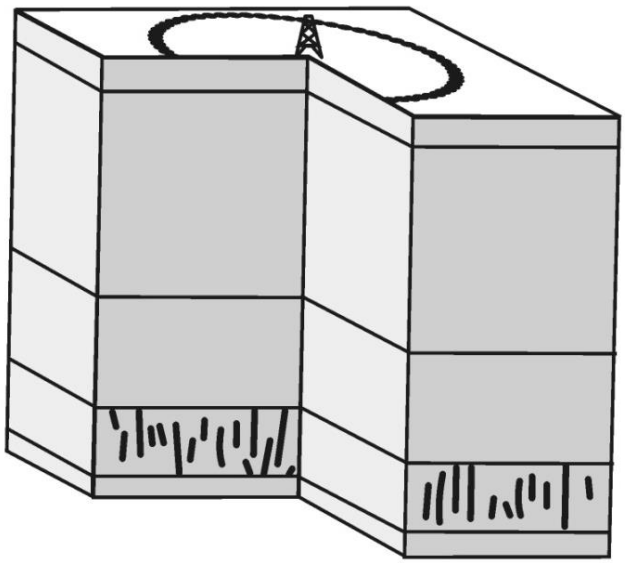


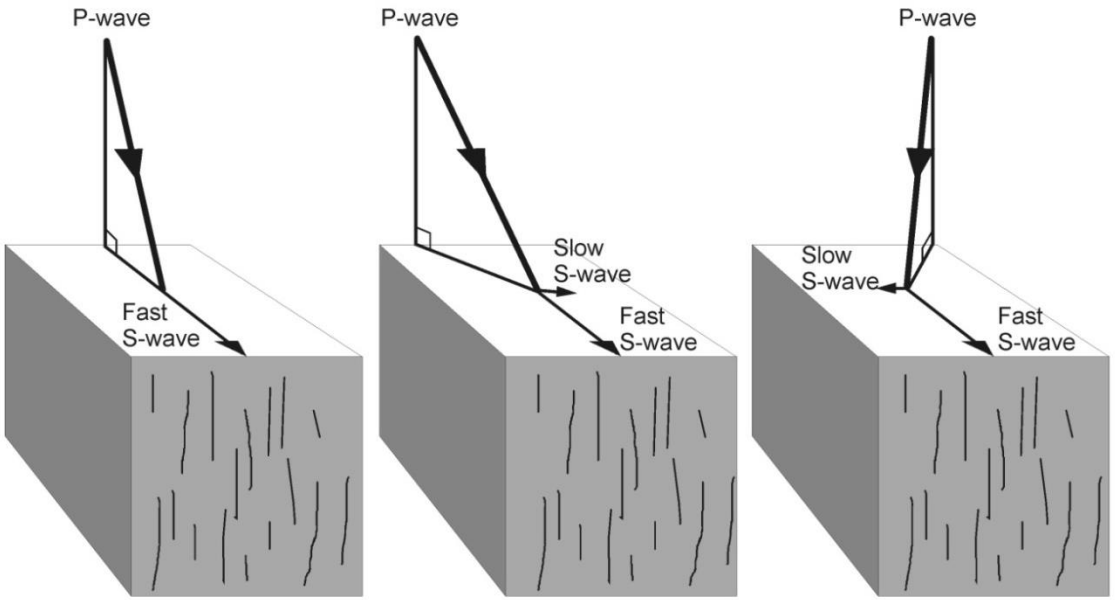
<u>S-waves may also be *polarised*</u>

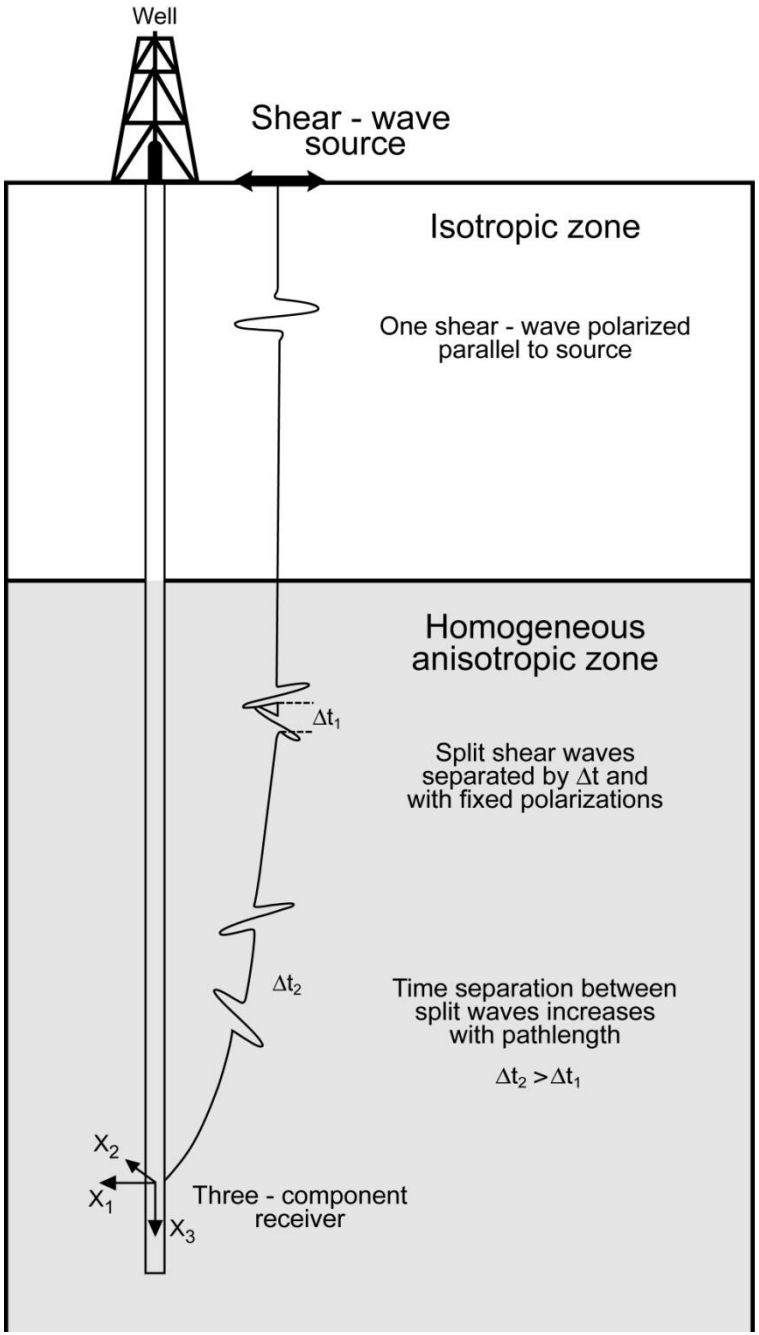
(into fast and slow components)

- **INCOMING P-WAVES from VSP (vertical seismic profiling)** GET CONVERTED TO **PS-WAVES** AT A GEOLOGICAL INTERFACE ……..

- THEY MAY THEN BE POLARIZED into ***FAST*** ***//*** and ***SLOW*** DIRECTIONS BY *ORIENTED 'STRUCTURE' (e.g. joint sets)* *(SUGGESTING* ***PRESENCE OF A POTENTIAL RESERVOIR ?)*** ***Horne, 2003***





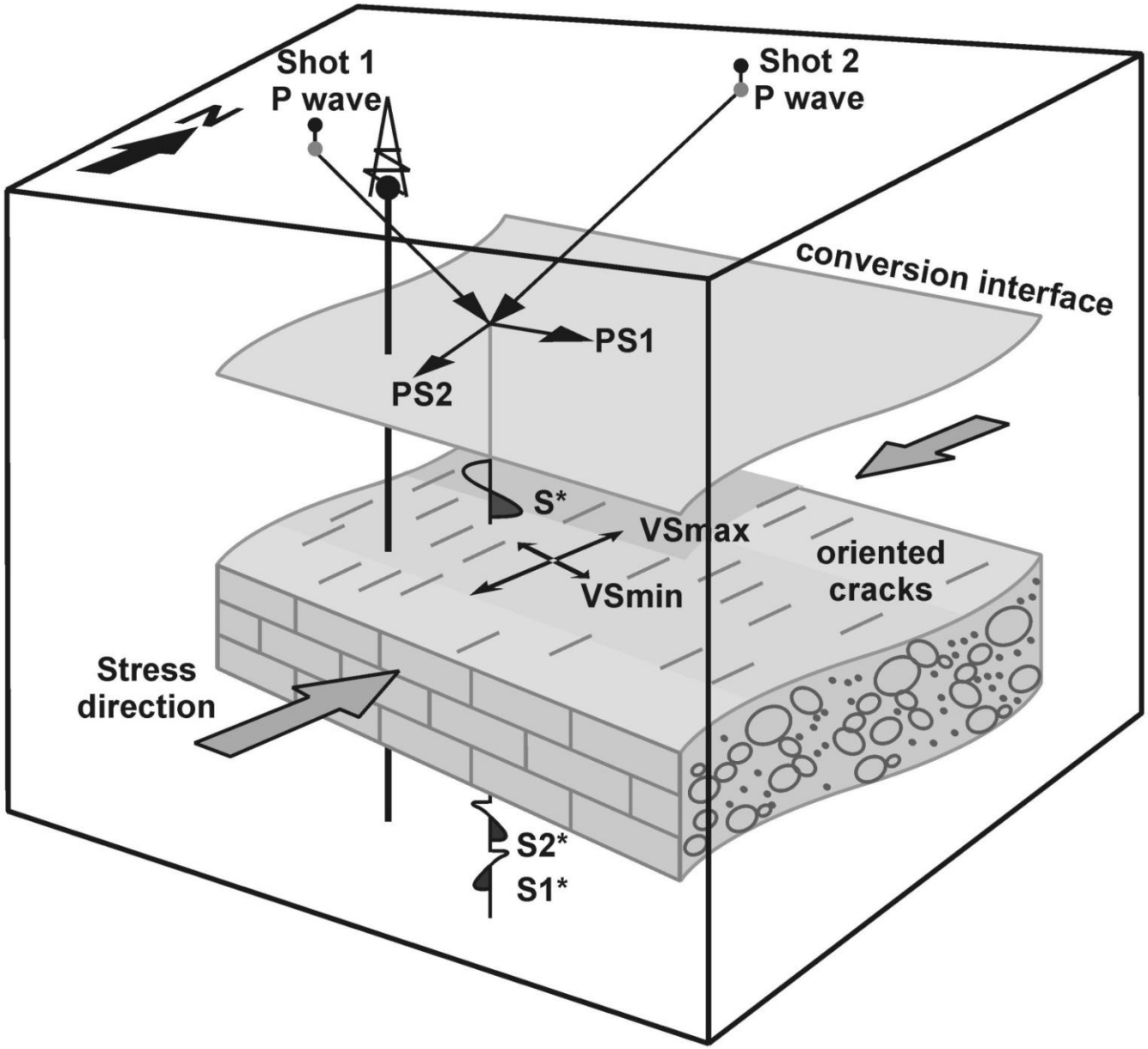


In this case: actual **shear-wave** source gives 'SS' waves

(pure S-waves, not PS waves)

Below this horizon, polarization is due to anisotropic structure, with (INCREASING) delay between S1(fast) and S2(slow)

Slater, 1997

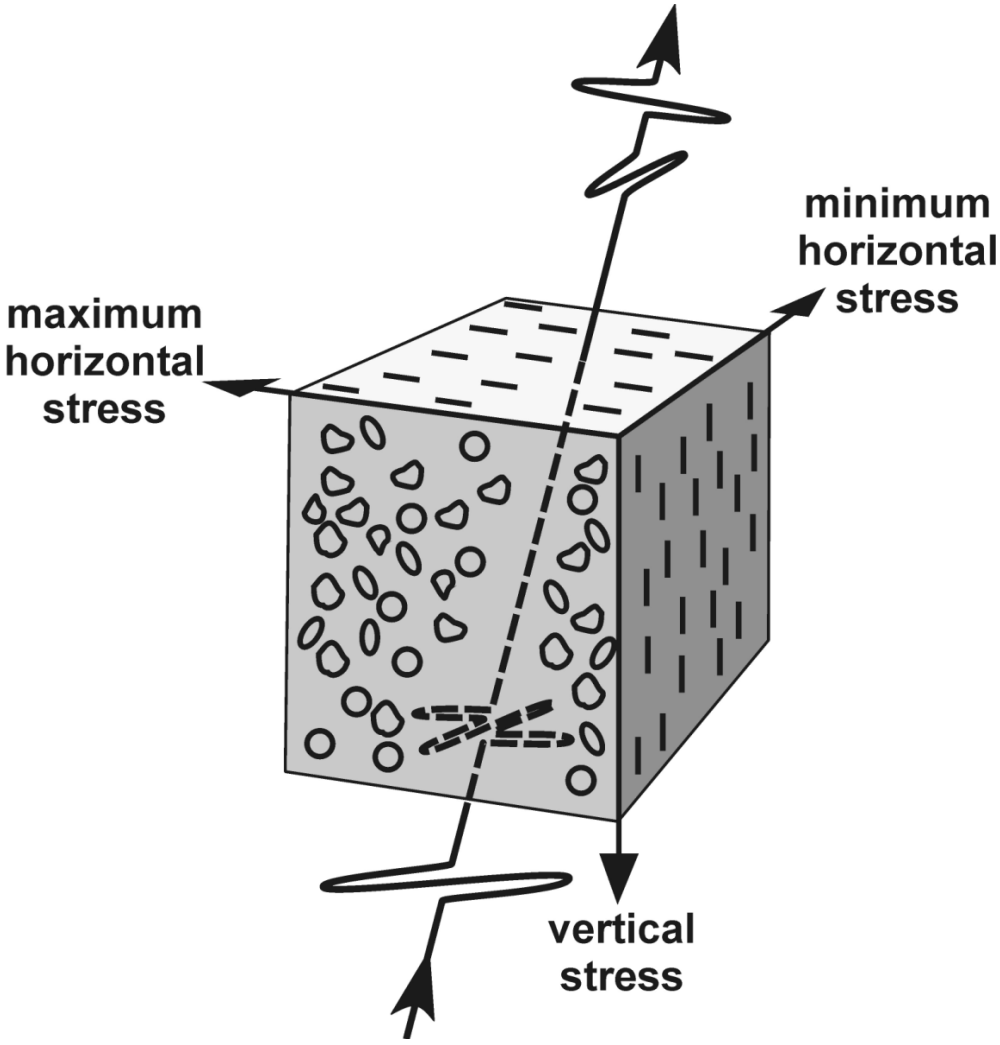


Principal question for geophysicists

Are there one or two sets of *'oriented cracks' in the reservoir?*

(Stenin et al. 2002)

In case of polarization components from <u>two joint sets</u>, the classic microcrack model of Crampin would need to be modified beyond the concept of a single set of stress-aligned cracks. (EAP - symbol).



There are actually two basic questions to be asked:

- Are *conducting* fractures parallel to, or *inclined-from*, the principal stress?

- What happens when reservoirs start to produce?

CONVENTIONAL GEOPHYSICS ASSUMPTION: is #1 only!

1. The classical interpretation: fast axis is caused by **one set** of principal stress-aligned fractures, joints or microcracks.

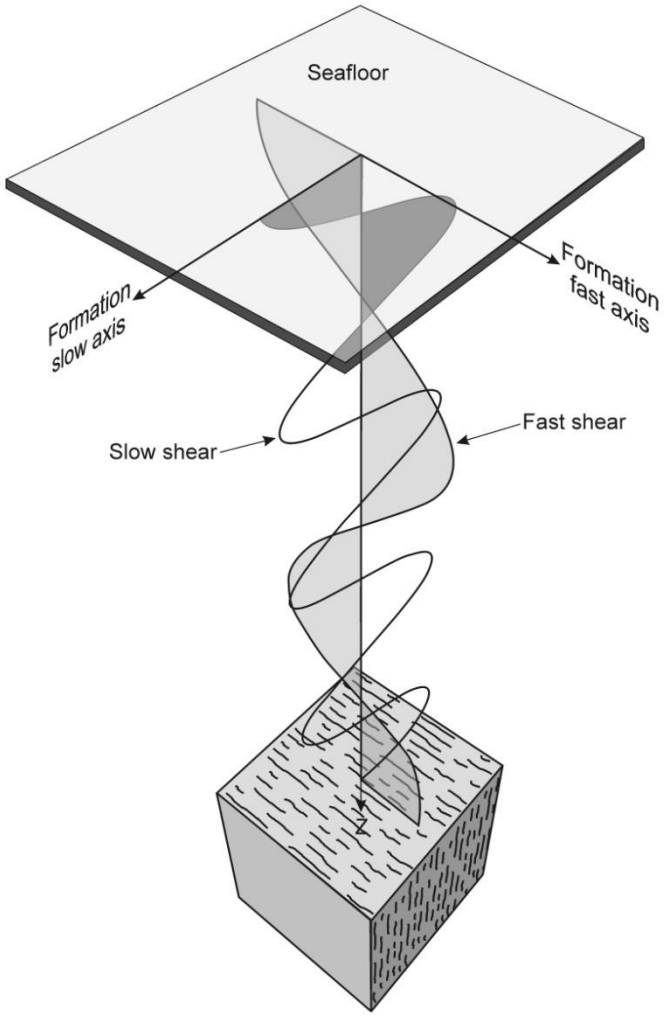
2. **Problem: fractured reservoirs may show 20º to 40º rotation of *polarization axes* of maximum V_S relative to interpreted σ_H max. (Barton, 2006)**

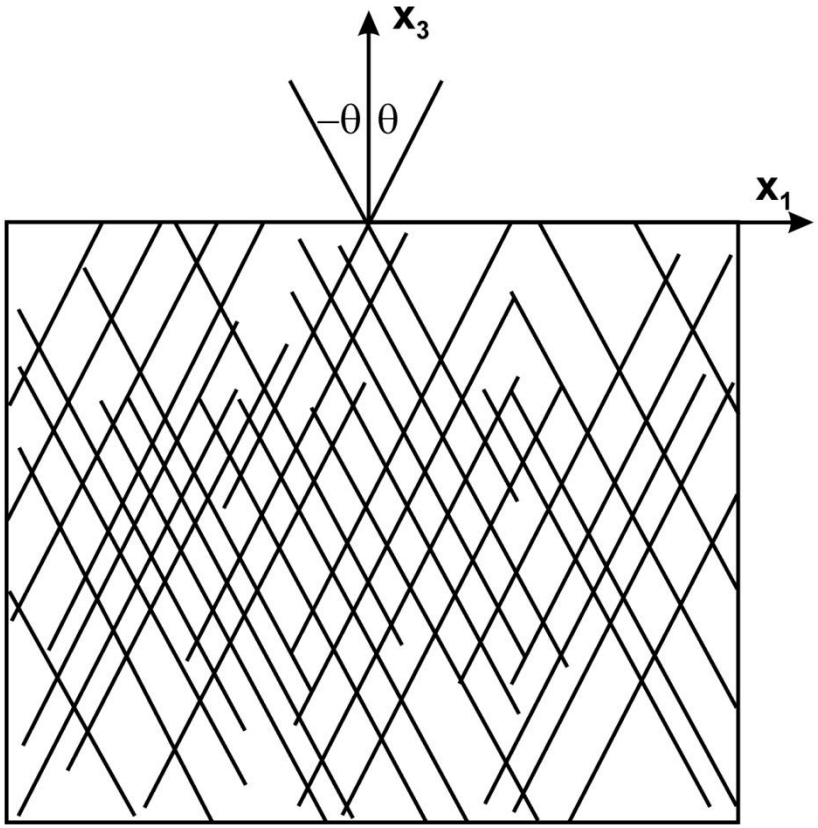
3. **More than one set of joints or fractures present**? Each has unequal components of stiffness (=1/compliance), aperture, frequency?

4. **This is a logical conclusion** since fractures or joints under shear stress are the best conductors, from geomechanics principles, and from actual *deep well inflow measurements.*

5. **CONCLUSION: Two joint or fracture sets bisected by a principal stress direction may be a very logical model.**

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





TWO SETS….FOUR COMPLIANCES…FOUR APERTURES…..(Barton, 2007, TLE)

- Two sets of (conjugate) fractures:

- Shear wave components qS_1 and qS_2 depend on *shear <u>and</u> normal compliances* *(= 1/dynamic stiffness)*

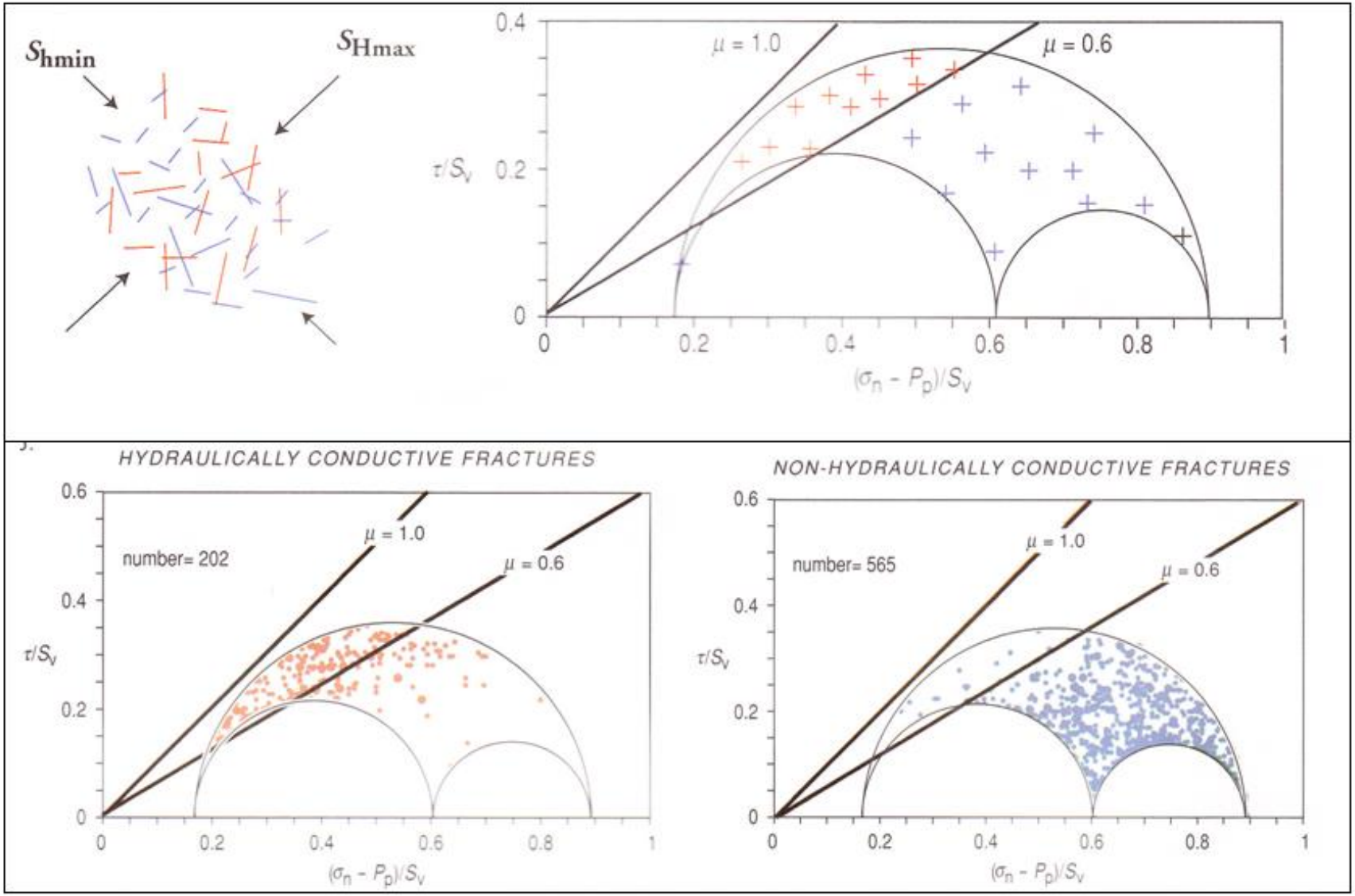
- Incident angles no longer parallel to the fractures.

- Conjugate pair of dipping fracture sets is typical of domal / anticlinal reservoirs (e.g. Ekofisk, Valhall).

- **The joints (fractures) under *significant shear stress* are the best conductors in the case of *hard* crystalline rocks (to many kilometers depth)**

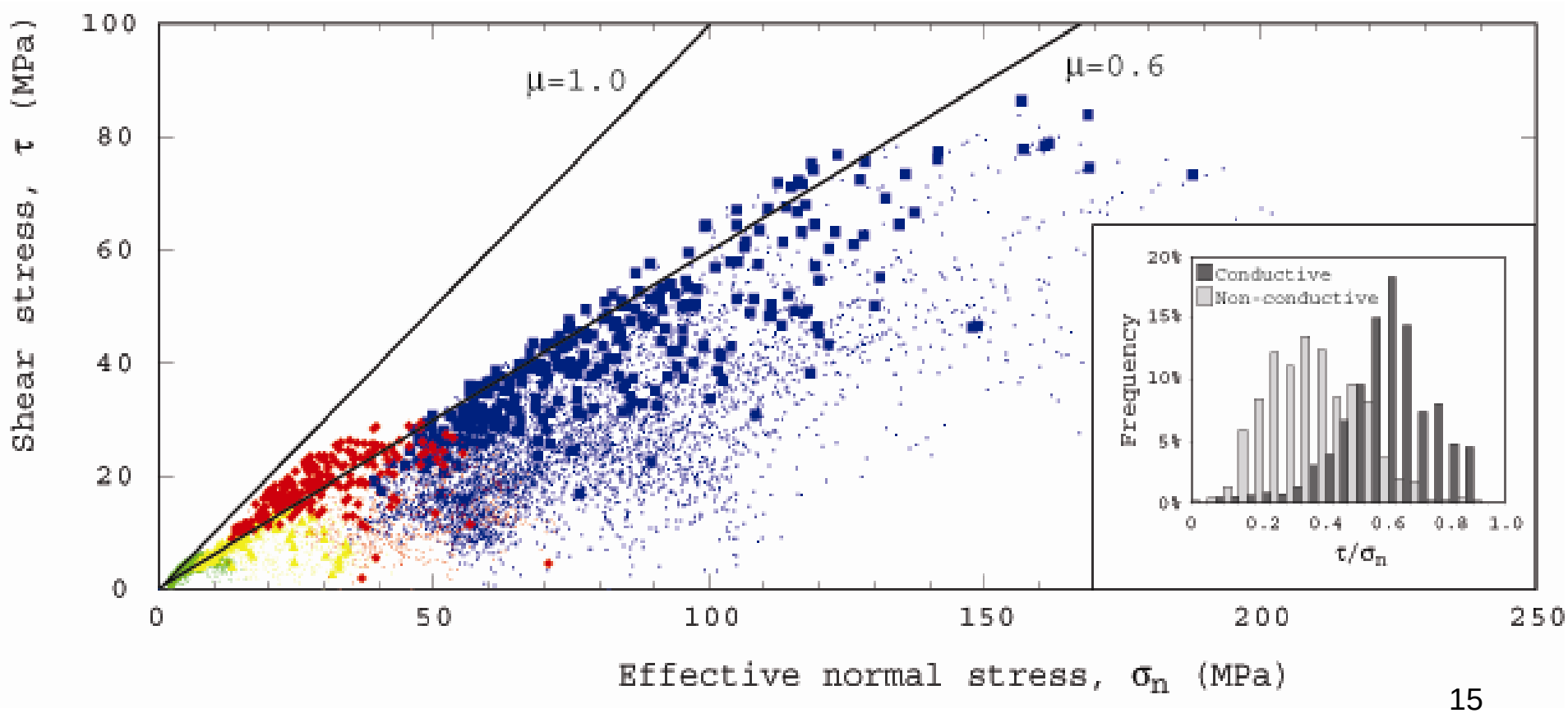
- **Seems even more likely in the case of softer reservoir rocks**

Orientation-dependent permeability – in an *anisotropic* stress field (after C.Barton et al., 1995, M. Zoback, 2007)



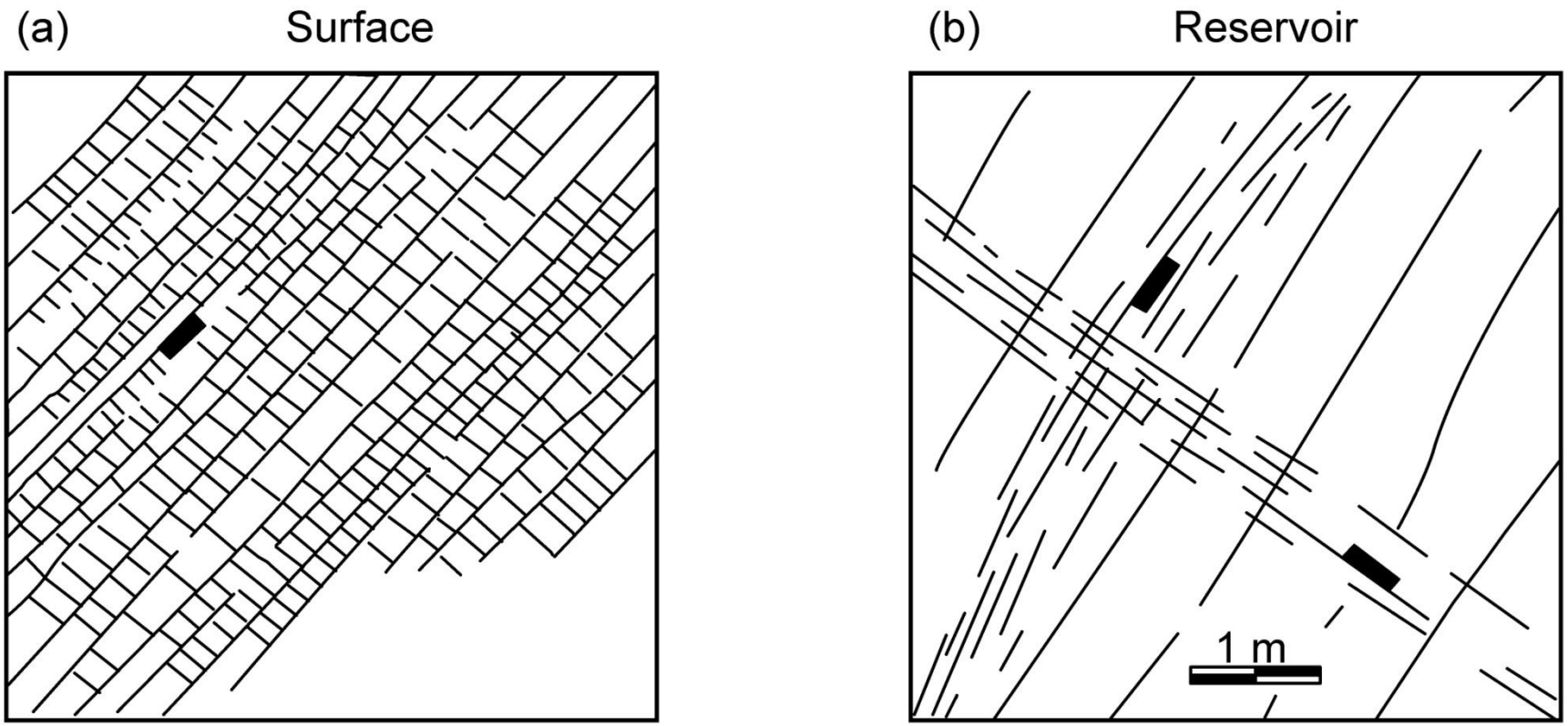
Conducting features are under greater shear stress

Townend and Zoback, 2000,
Zoback and Townend, 2001



Both sets of joints in this limestone reservoir (Oman) are steeply-dipping……may be (must be?) under shear stress.

Van der Kolk et al., 2001.



JOINT or FRACTURE CONDUCTIVITY

- Which apertures apply?

- For permeability $k = e^2/12$ (laminar flow)

- But during closure and shear (i.e. when a reservoir is producing)….it is the physical aperture (E) that is changing (too).

DEFORMATION → *(Δ)* FLOW

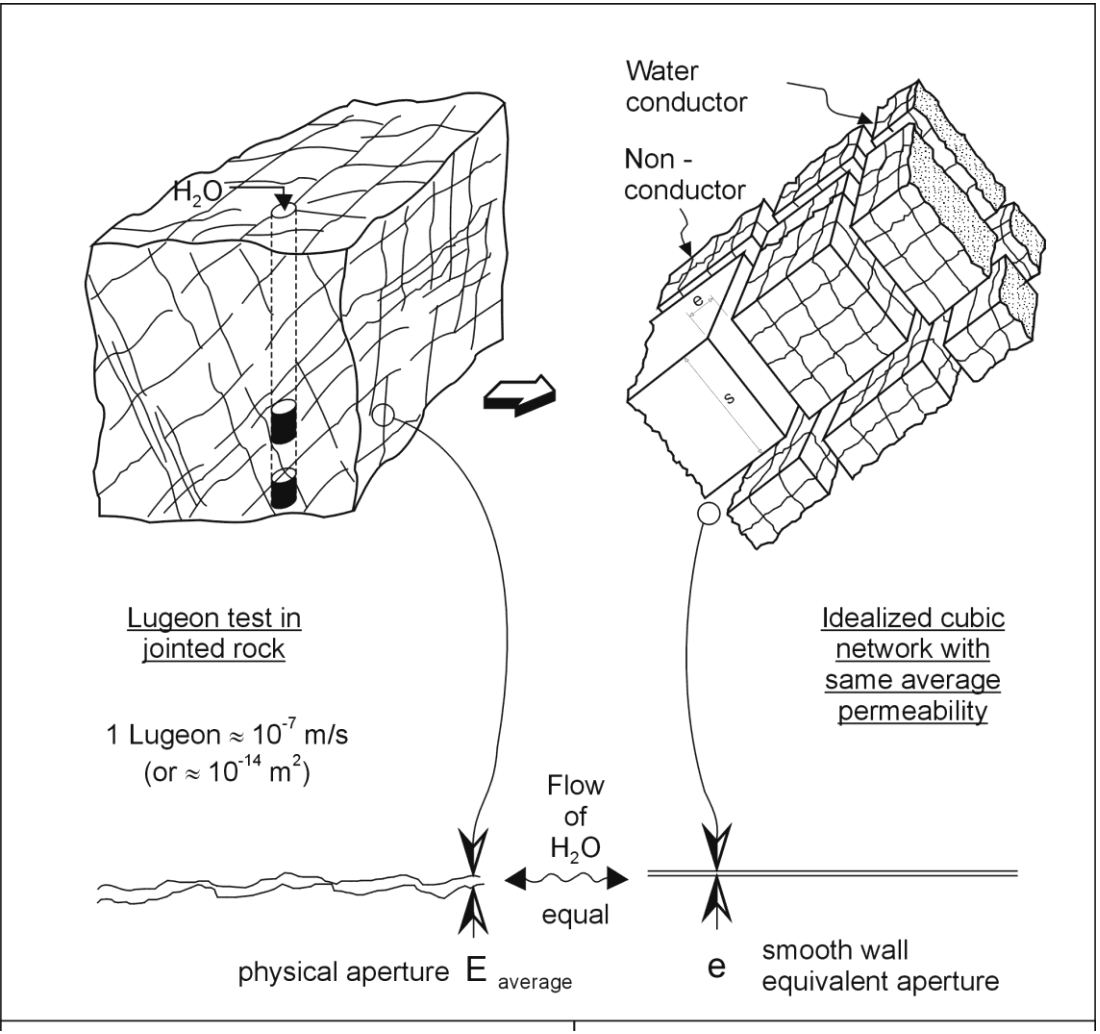
- Aperture changes caused by (effective) stress changes, by shear, by dilation, are *'physical'* aspects of aperture change (*ΔE*)

- Flow modelling requires *theoretical* hydraulic apertures (K ≈ $e^2/12$……for laminar flow)

- *Δe* effects production strongly…see in 4D

- *Hydraulic aperture* **e** ≤ *physical aperture* **E**

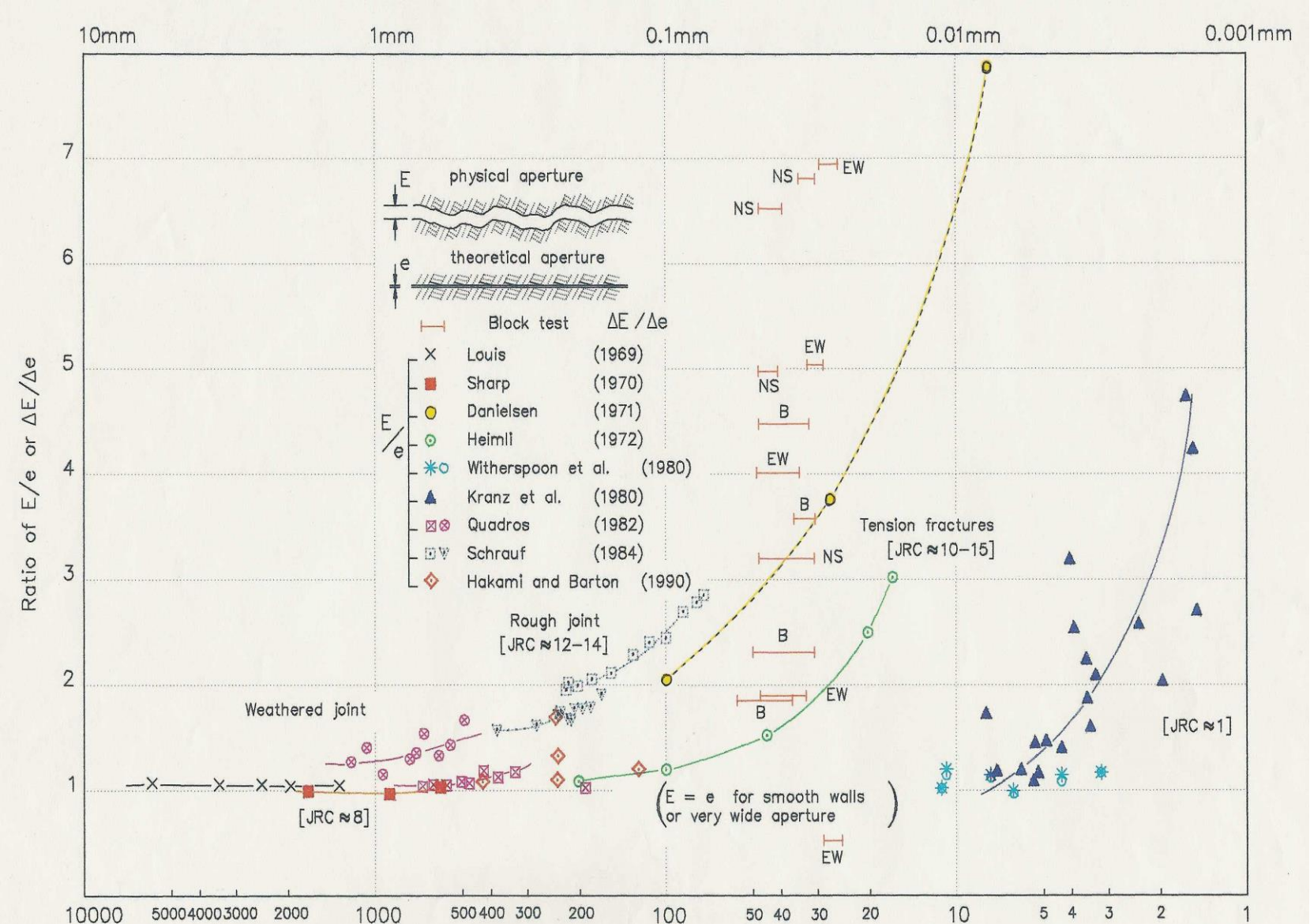
PHYSICAL (= rough) APERTURES (E), AND IDEALIZED (= smooth) HYDRAULIC APERTURES **(e)**



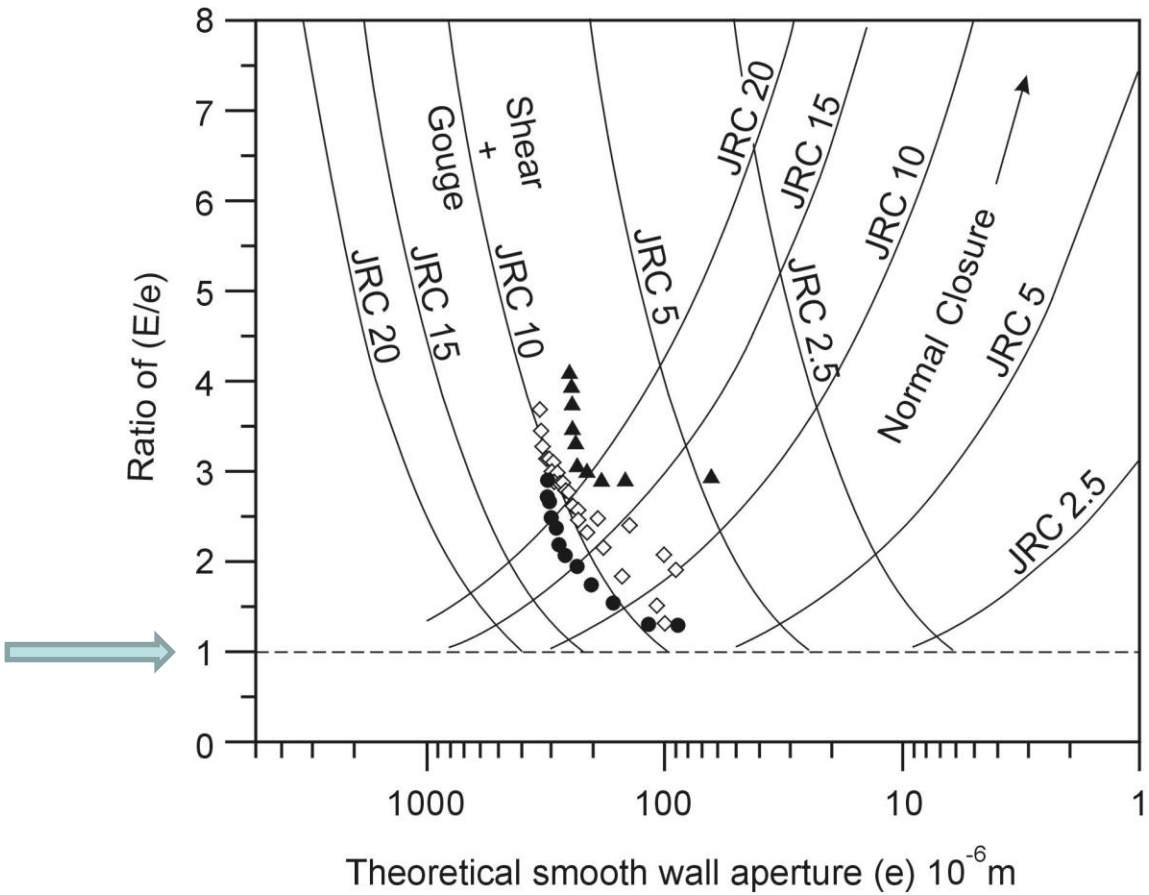
E ≥ e data for joints under ***normal closure.***

Barton, 1972, Barton et al. 1985, Barton and Quadros, 1997

(lower axis is e = hydraulic aperture in μm)



NORMAL CLOSURE *AND* SHEAR-DILATION-GOUGE MODELLING



Olsson, R. & Barton, N. 2001.
An improved model for hydro-mechanical coupling during shearing of rock joints. Int. J. Rock Mech. Min. Sci. & Geomech. Abstracts, 38: 317-329. Pergamon.

Normal Closure

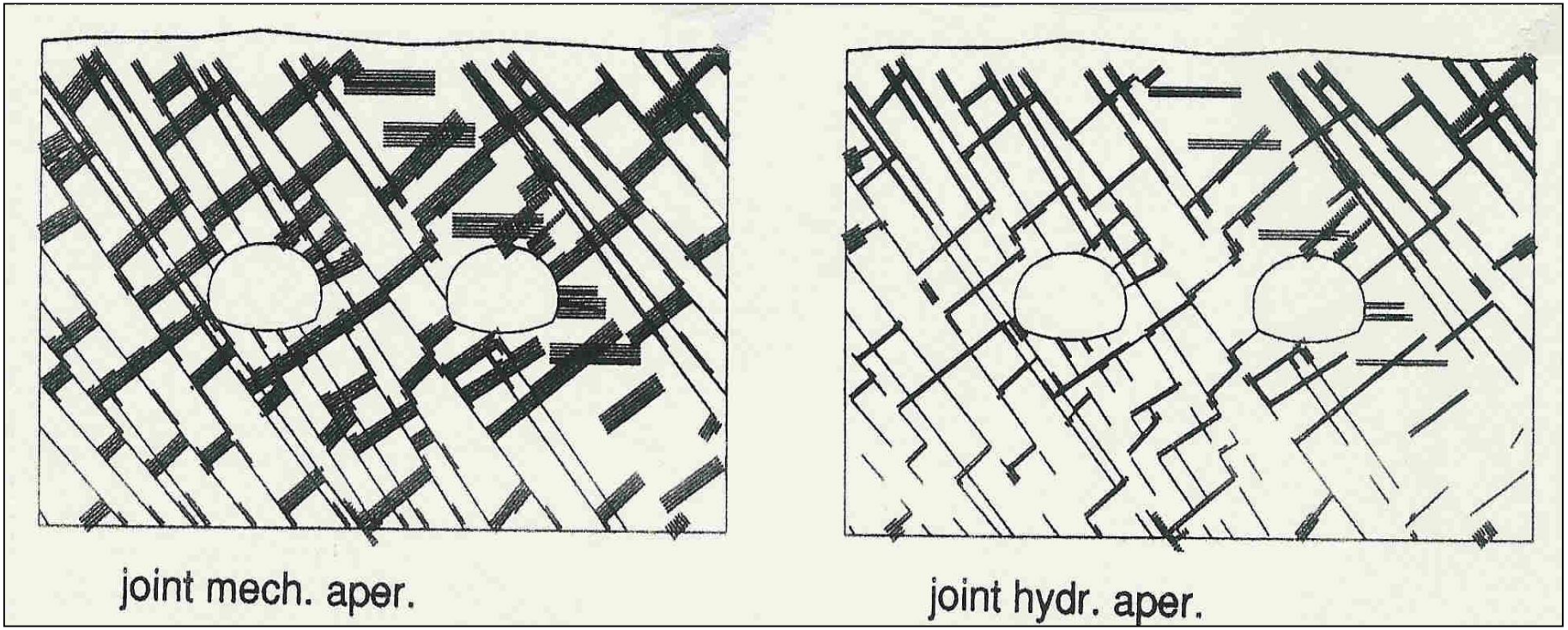
$$e = \frac{JRC_0^{2.5}}{(E/e)^2} \quad \Big\} \quad e = E^2/JRC_0^{2.5}$$

Shear+ Gouge

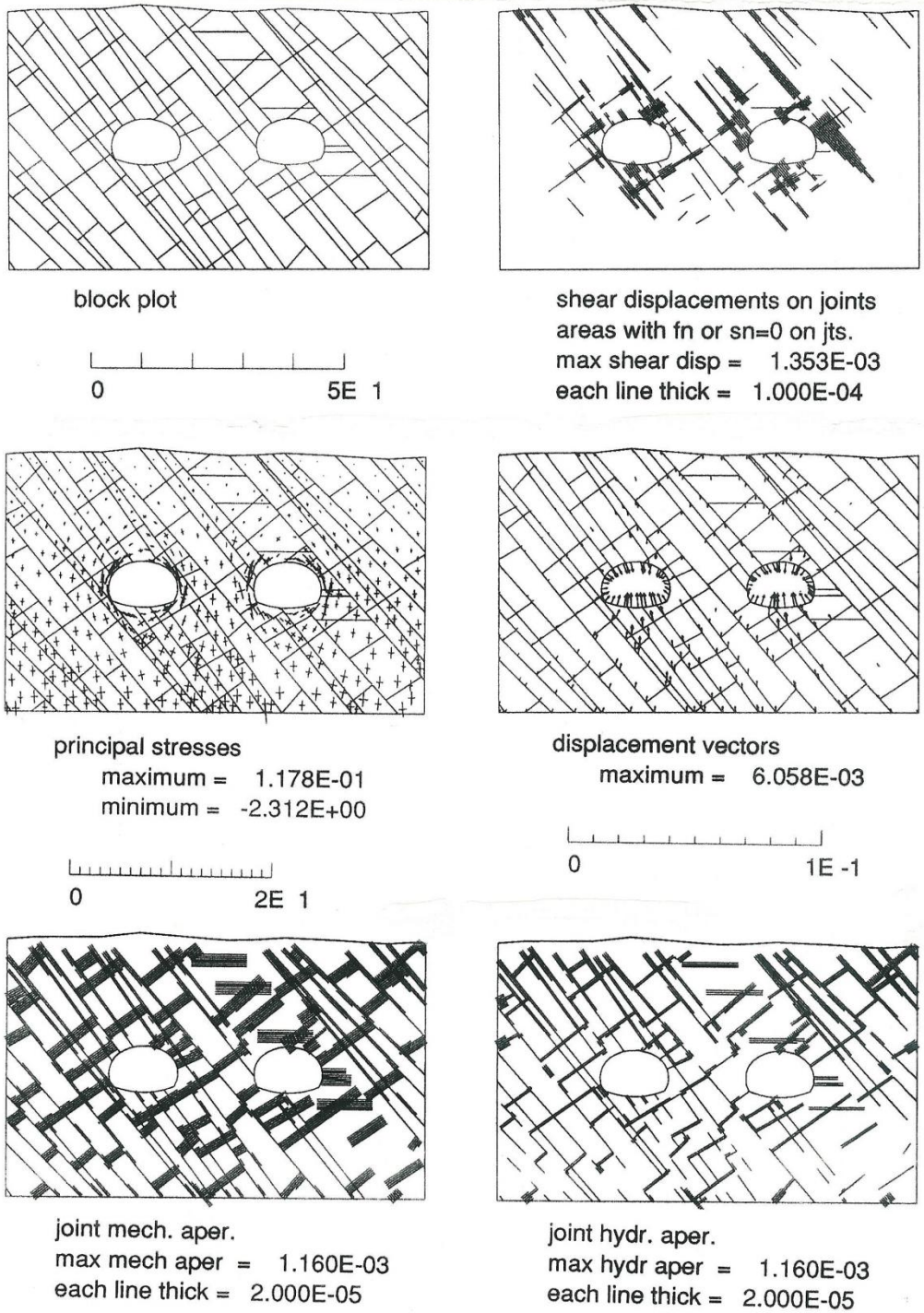
$$e = \left(\frac{E}{e}\right) JRC^2 \quad \Big\} \quad e = \sqrt{E} \cdot JRC_{mob}$$

WHAT DOES THIS MEAN?
……we have more oil than assumed……but need water flooding to flush it out!

MODELLING (E) and (e) with UDEC (-BB)……..
BOTH (E) and (e) ARE AFFECTED BY ROCK STRESS…AND therefore DEPTH (Oslo Tunnel, Makurat and Barton 1988)



Apertures are tighter at depth…..also in hydrocarbon reservoirs….
…so where do the 'open' joints come from….in a 'fractured reservoir' ?
(mineral bridging, channelling……..and <u>shear</u>)

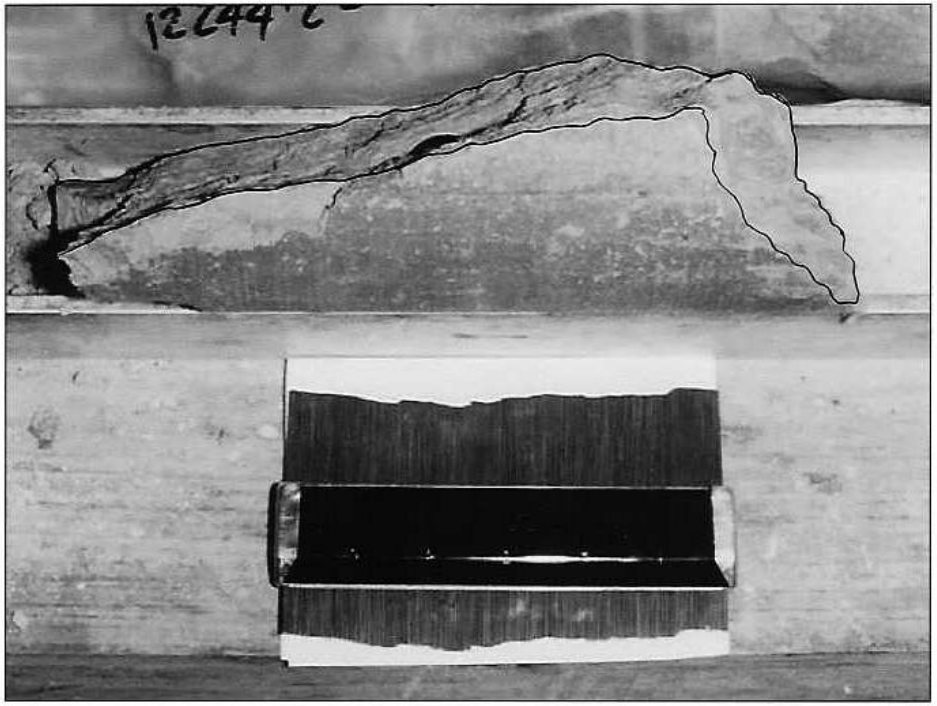


Why not similar conceptual models to demonstrate ‘actual’ 4D effects?

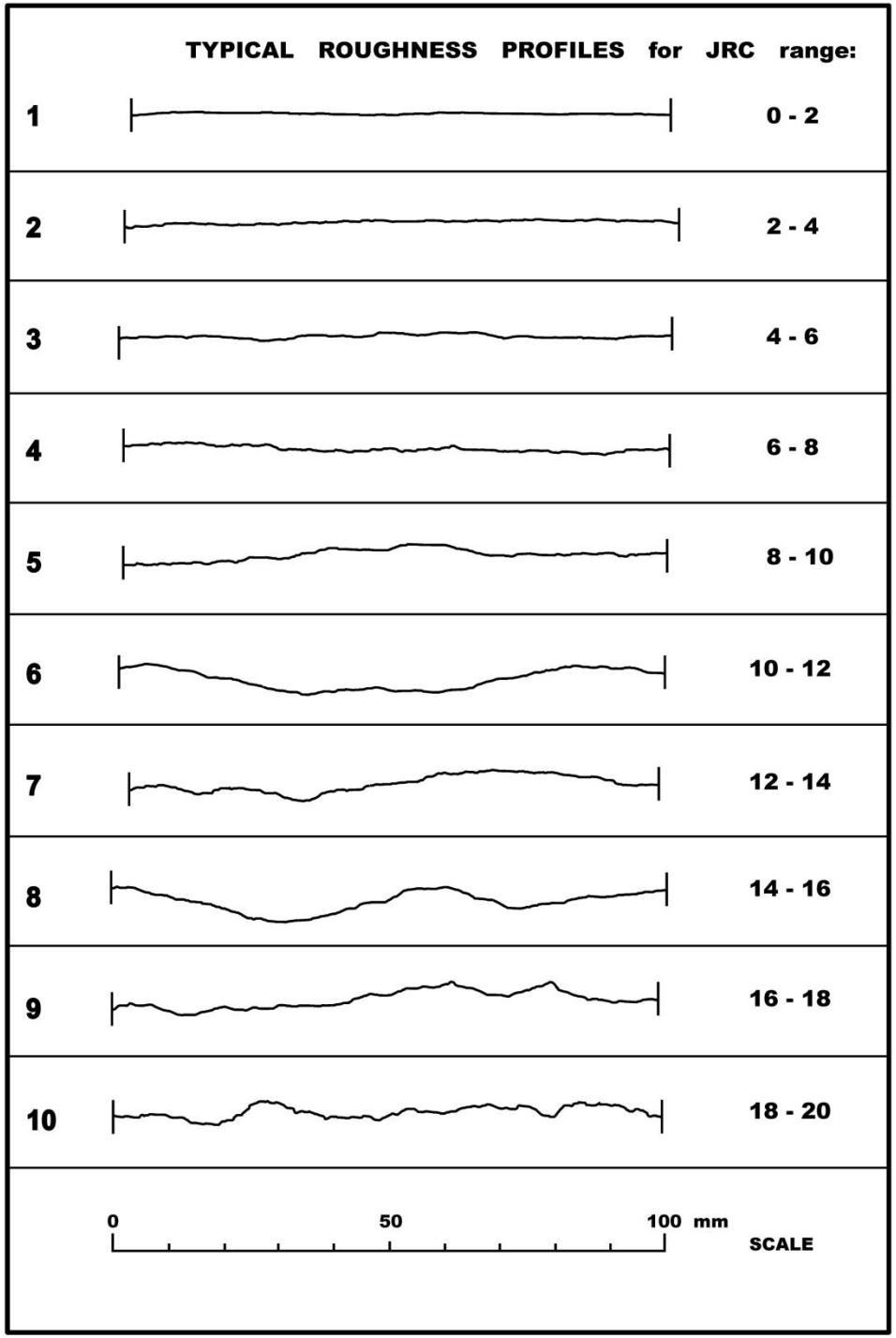
JOINT ROUGHNESS (JRC) and STRENGTH (JCS) CHARACTERIZATION can help in 4D INTERPRETATION (these are joints from Ekofisk)

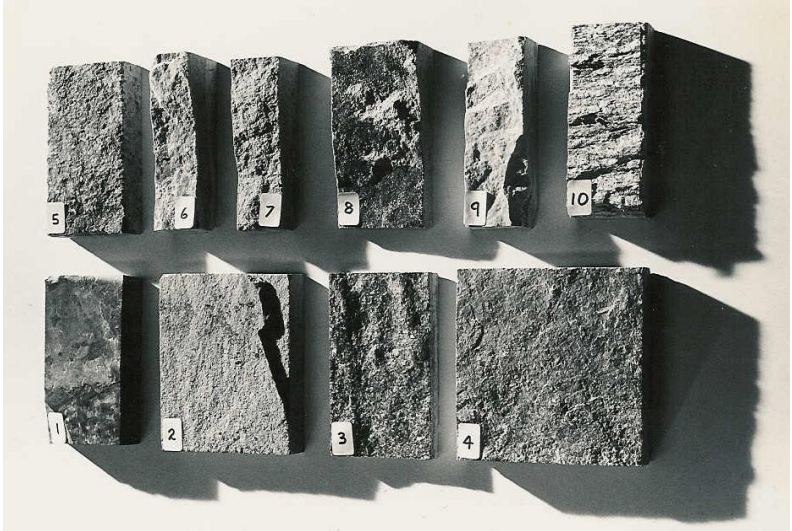
JRC = joint roughness coefficient used to estimate shear strength, dilation, *physical-to-hydraulic-aperture* conversion, shear and normal stiffness.

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



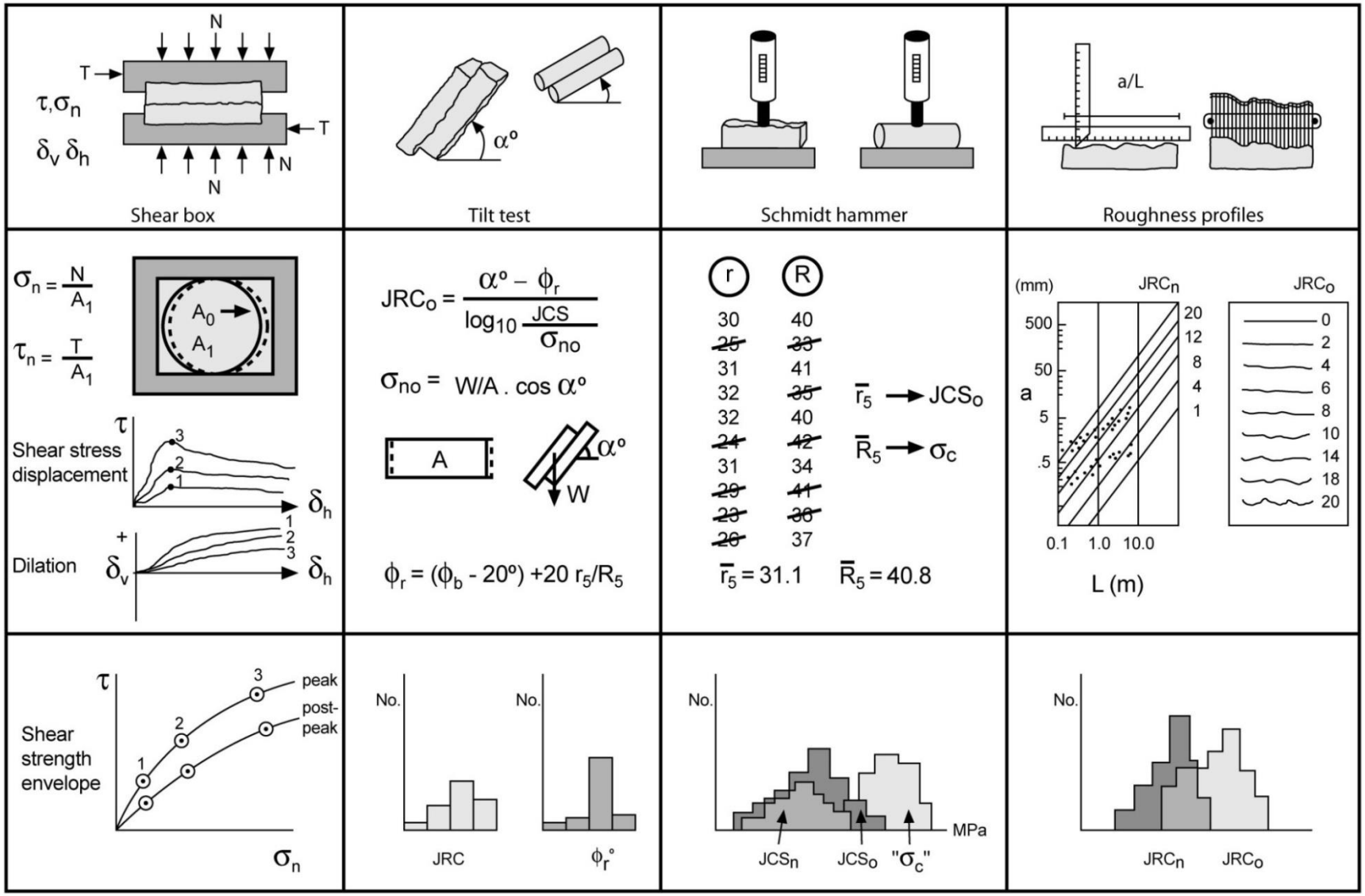
A simple quantitative approach to roughness description – and a basis for constitutive modelling (Barton and Choubey, 1977)

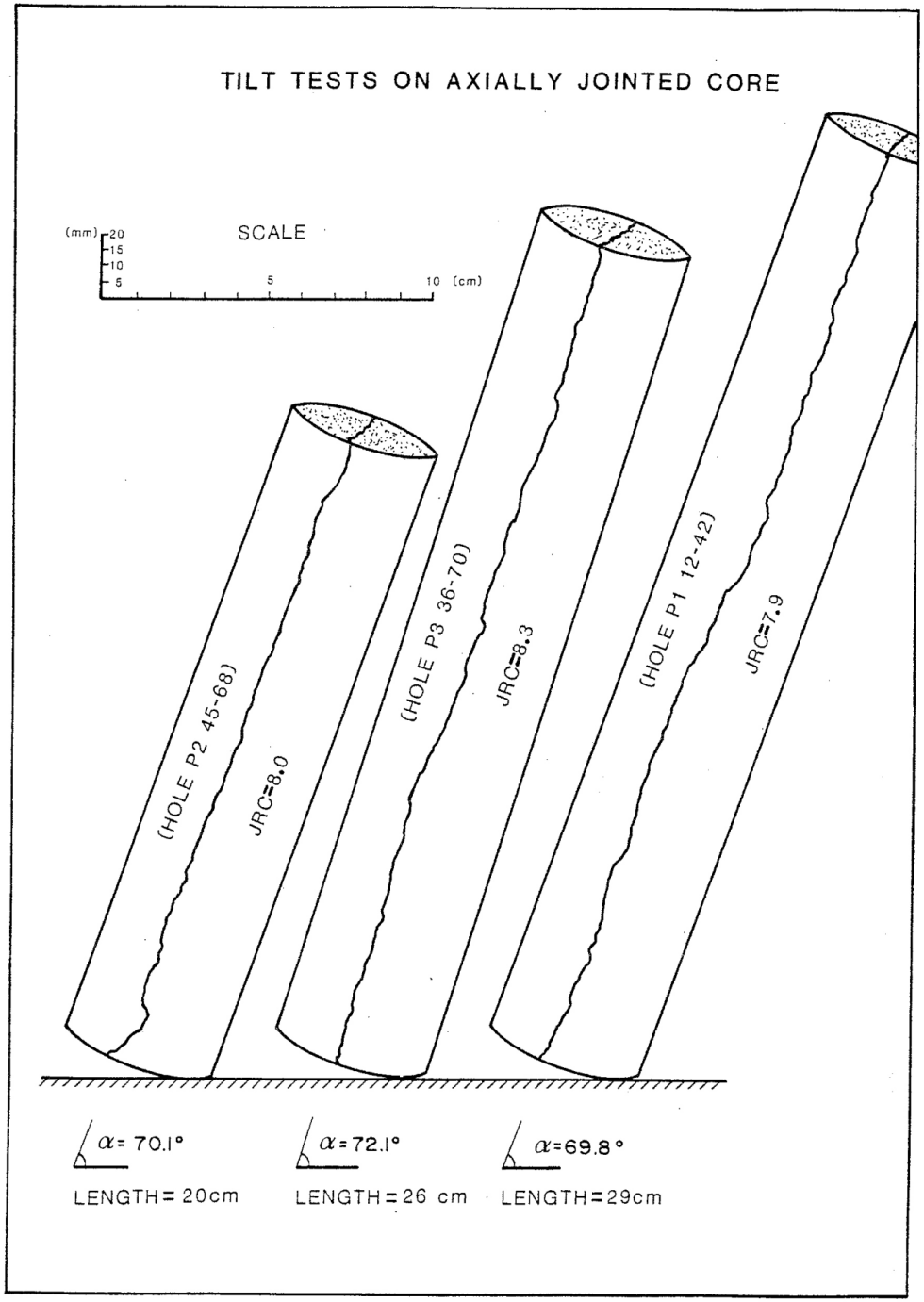




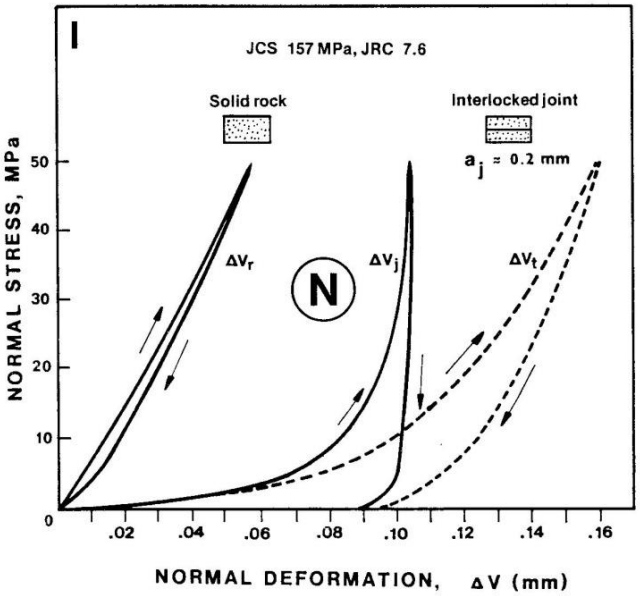
How to obtain JRC and JCS and φ_r - the basis for modelling (among other things) *closure, shear and permeability coupling* in 4D interpretation

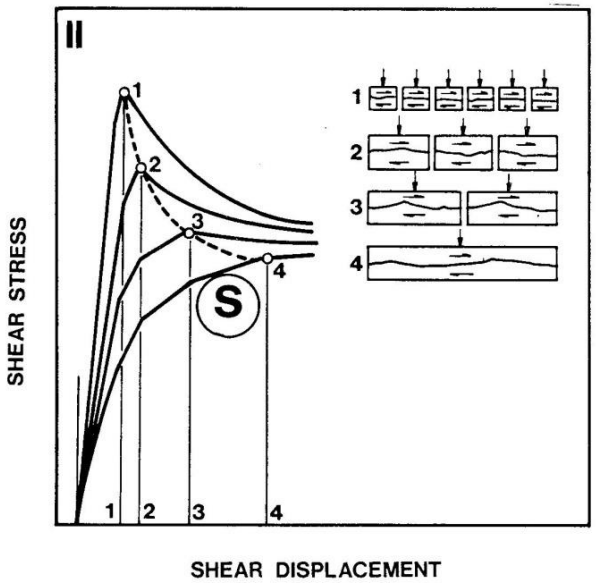
Shear box and index testing of rock joints

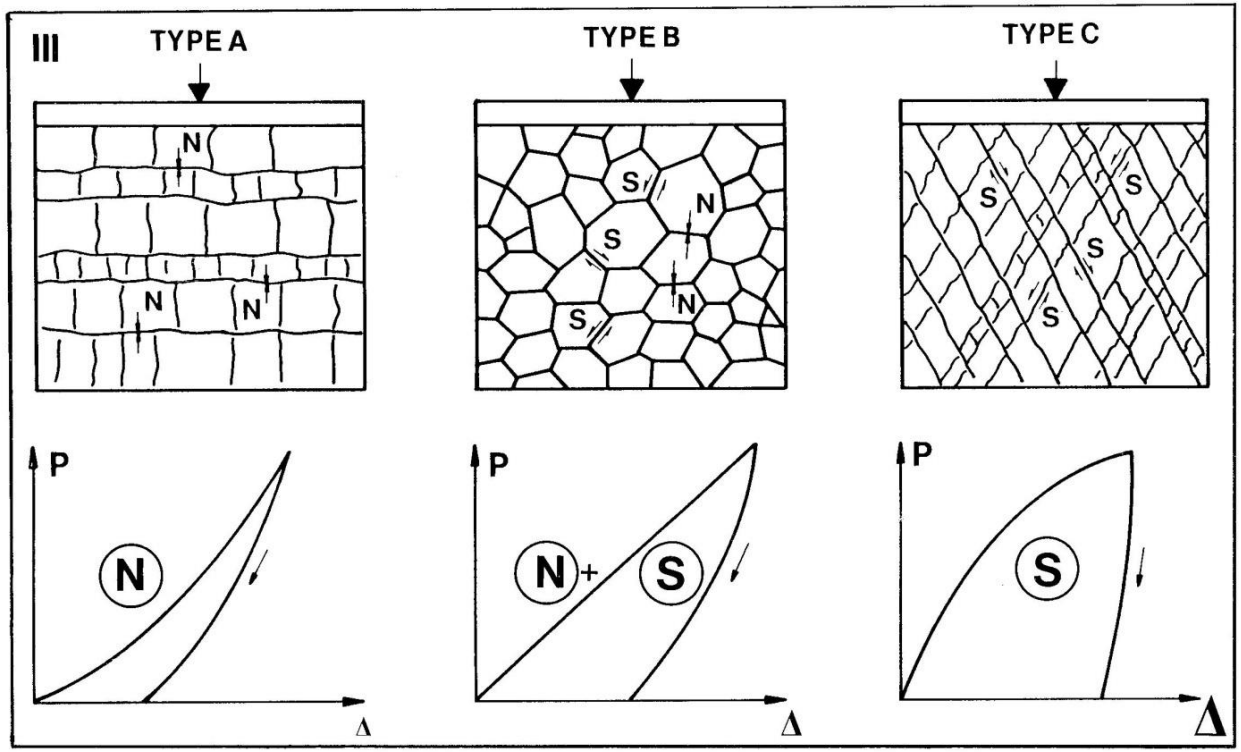




These are tilt tests, performed on joints recovered in core !







Rock Mass Deformation Modes:

Type C

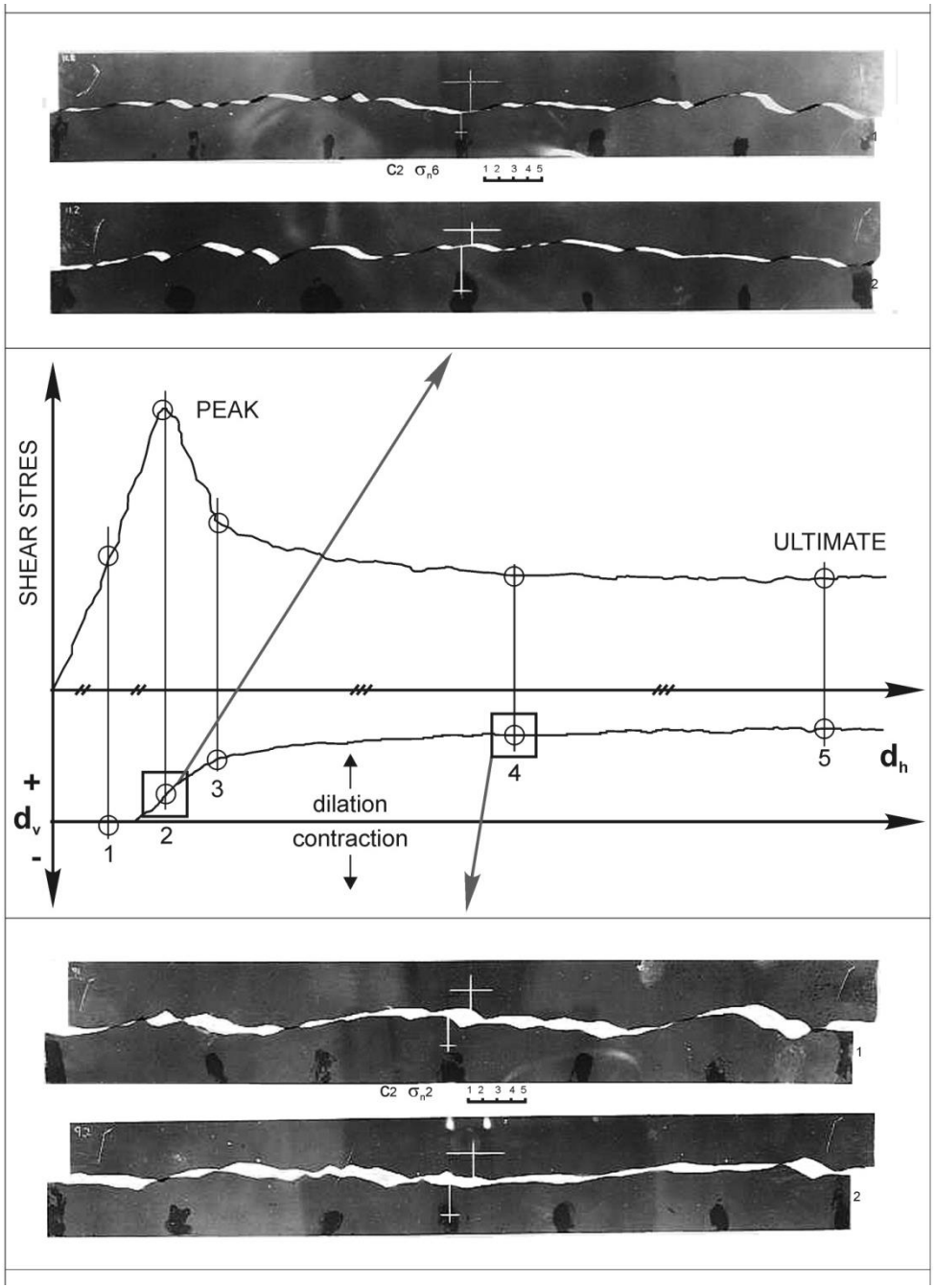
(deformation dominated by *shearing*)

(Bandis et al. 1981, 1983. Barton 1986, 2006)

SHEARING compensates for CLOSURE !

- **GIVES PERMEABILITY AT RESERVOIR DEPTHS AND EVEN CRUSTAL DEPTHS**

- **NOTE FOLLOWING EXAGGERATION of SHEAR AND DILATION and therefore *PERMEABILITY***

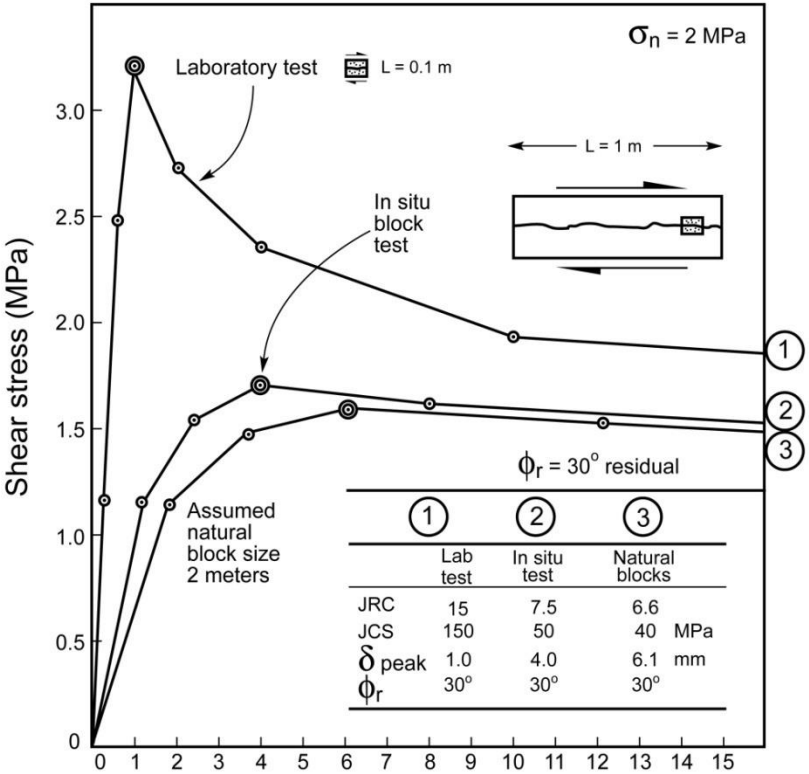


PRE-PEAK, OR POST-PEAK SHEARING IS DESIRABLE……

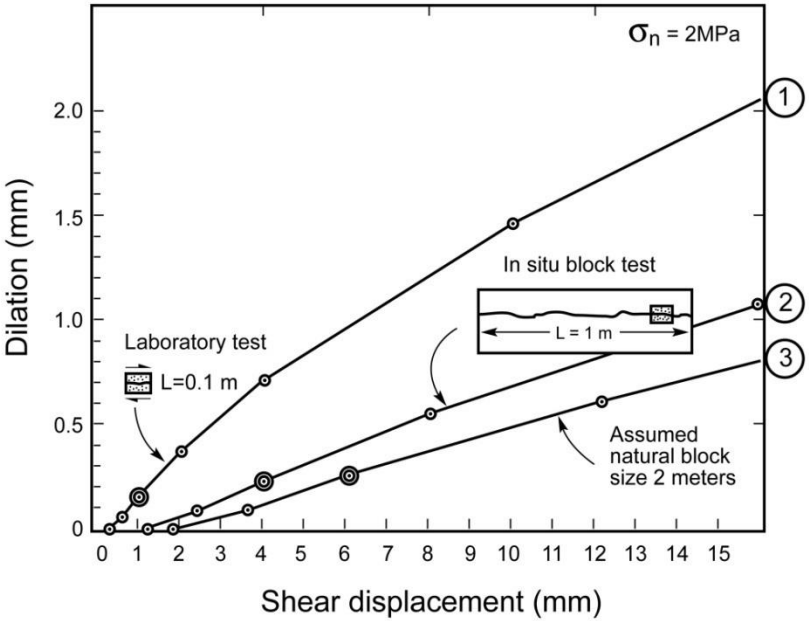
IF ONE IS INTERESTED IN PERMEABILITY

Barton, 1971

(Note: gouge production not shown)



	1 Lab test	2 In situ test	3 Natural blocks	
JRC	15	7.5	6.6	
JCS	150	50	40	MPa
δ peak	1.0	4.0	6.1	mm
ϕ_r	30°	30°	30°	

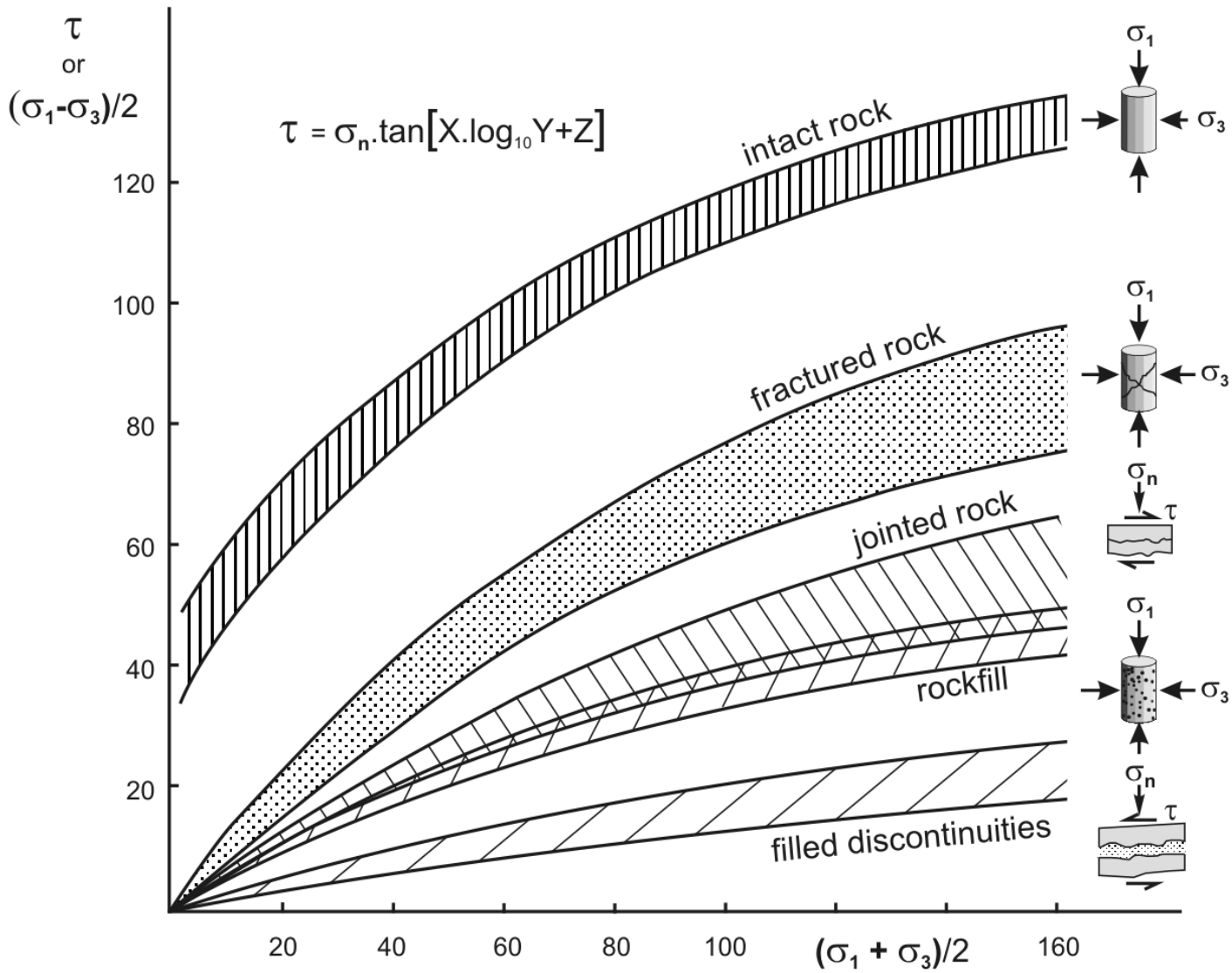


Shear stress-displacement and dilation-displacement modelling (Barton, 1982).

The space created by dilation (minus gouge blockage) is the source of permeability increase with shear.

Shear strength envelopes for rock/fractured rock/joints…….

hence μ = 0.6, 1.0 etc. (Barton, 2006).



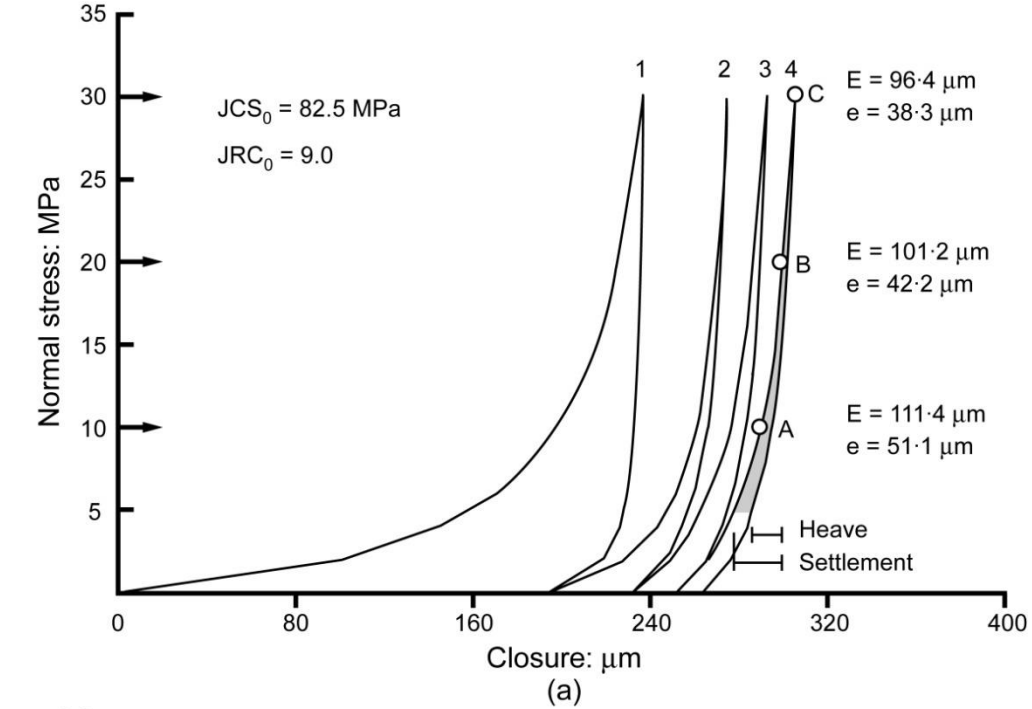
x	y	z
50	$\left(\frac{\sigma_1 - \sigma_3}{\sigma_n}\right)$	ϕ_c
20	$\left(\frac{\sigma_1 - \sigma_3}{\sigma_n}\right)$	ϕ_b
JRC or	$\left(\frac{\sigma_1 - \sigma_3}{\sigma_n}\right)$ or $\left(\frac{JCS}{\sigma_n}\right)$	ϕ_b or ϕ_r
R	$\left(\frac{S}{\sigma_n}\right)$	ϕ_b
$[J_r / J_a]$ (from Q-system)		

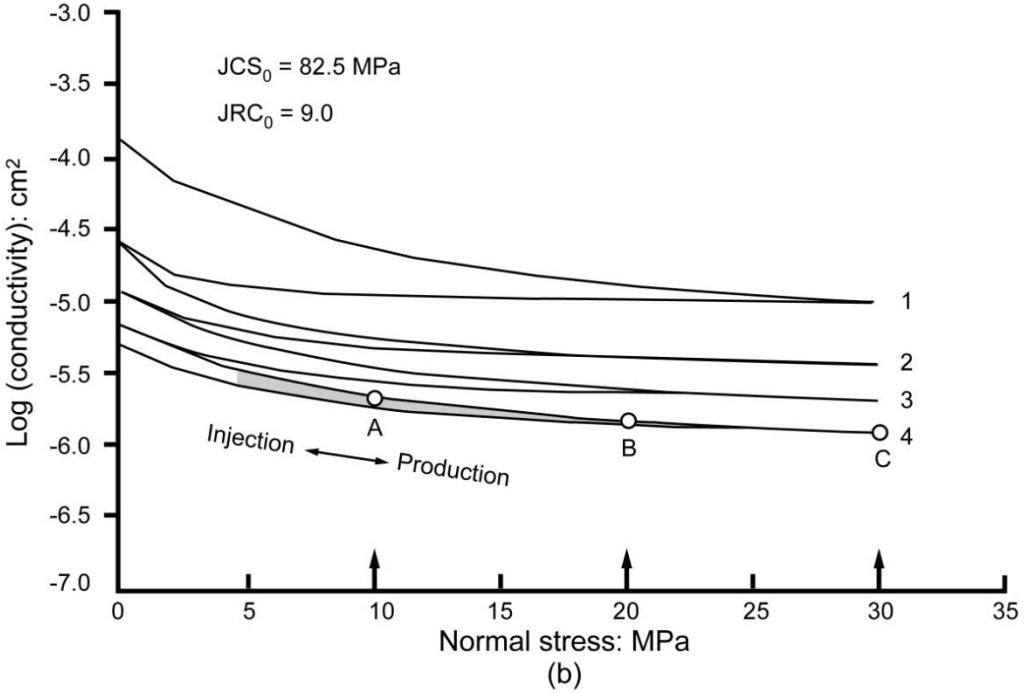
FRACTURES ARE ‘CLOSED’ OR ‘OPEN’ DEPENDING ON ORIENTATION, STRESS LEVEL AND ROUGHNESS

- *Non-conducting* fractures in deep wells are held ‘closed’ by resultant normal stress: would be consistent with geomechanics modelling.

- But with sufficient fracture roughness and wall strength, apertures could be large enough to be ‘open’ // σH.

- Minerally ‘bridged’ partly open fractures can also be // σH.





Barton-Bandis modelling of **normal stress-closure-permeability**

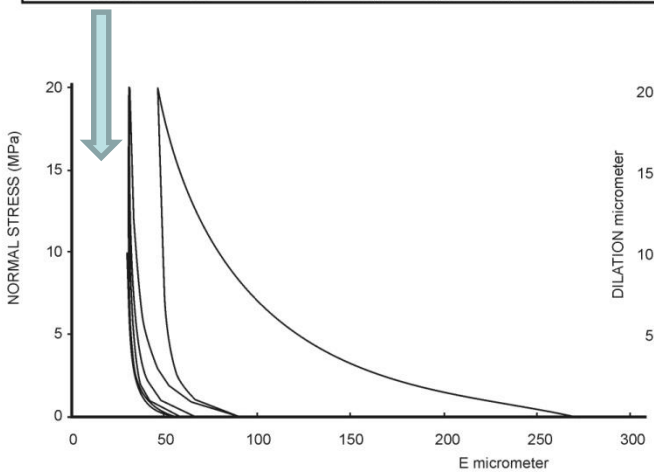
Note JRC, JCS input data from joints in welded tuff, Nevada Test Site

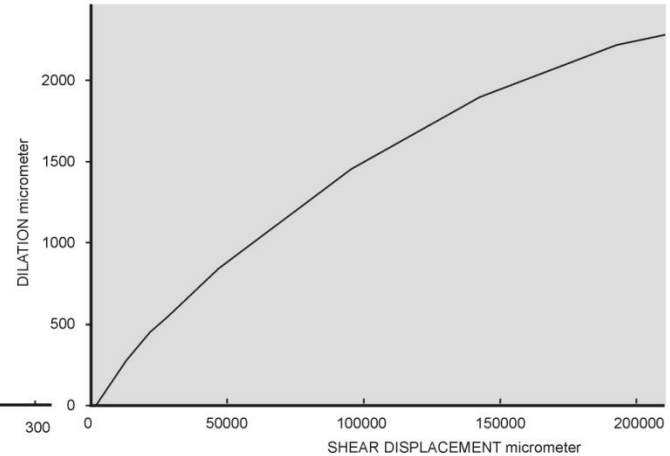
(from Schmidt hammer, tilt testing and profiling)

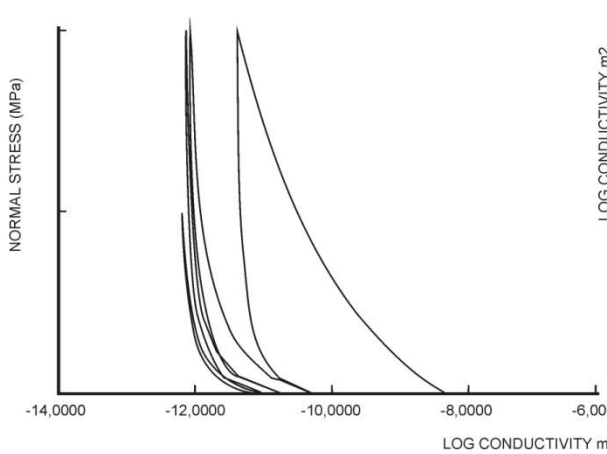
(Barton et al. 1985)

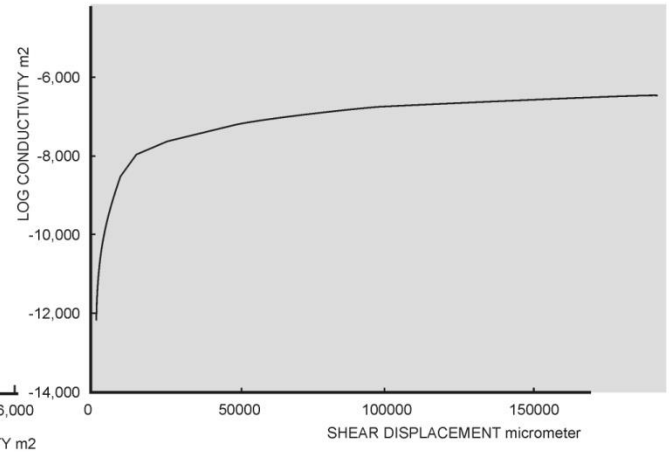
Barton Bandis Joint Model		NORMAL CLOSURE CALCULATION						
INPUT PARAMETERS		SNORM	CYCLE 1	CYCLE 2	CYCLE 3	CYCLE 4	CYCLE 5	
JRC	10	LOAD	20	20	20	10	0	MPa
JCS	50	UNLOAD	0	0	0	0	0	MPa
SIGMAC	60	APERTURE	0,280	0,090	0,068	0,059	0,056	mm
CALCULATED PARAMETERS								
LOAD		KNI	13,5	20,17	23,4	25,41	26,33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









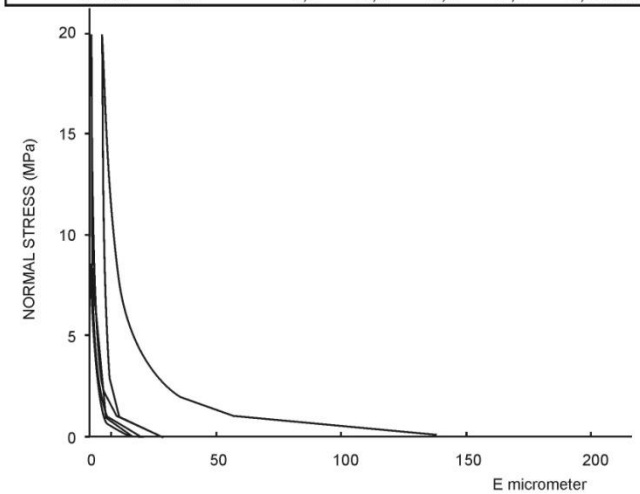
Rough joint (JRC = 10) in harder rock (JCS = 50 MPa)

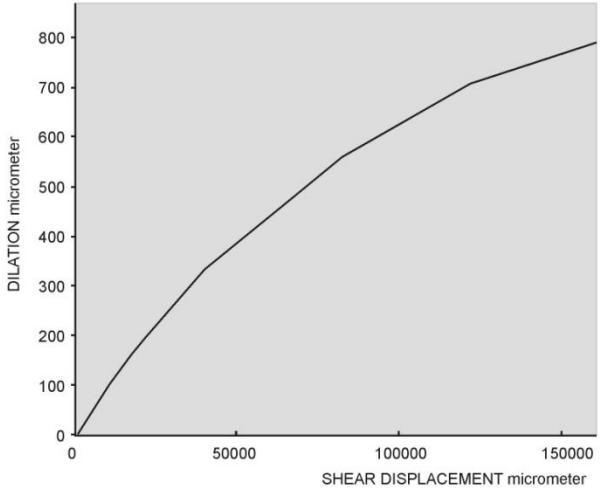
Left: physical aperture (E) and permeability ($e^2/12$) versus <u>normal</u> stress.

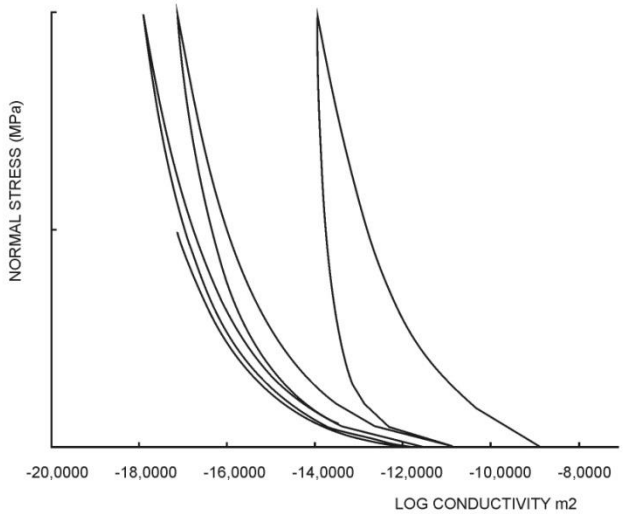
Right: dilation and permeability caused by <u>shear</u> displacement.

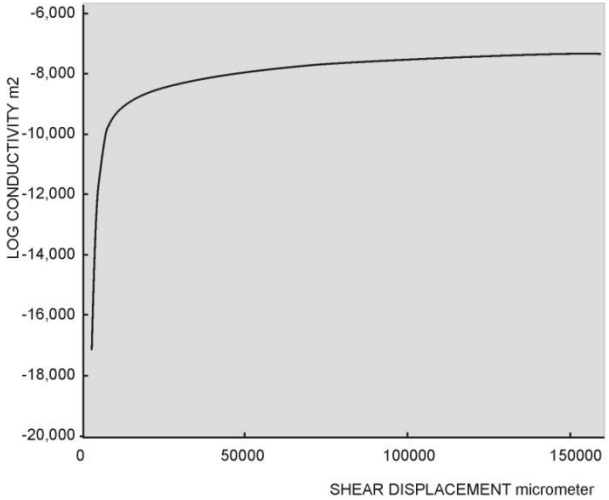
Barton Bandis Joint Model			NORMAL CLOSURE CALCULATION					
INPUT PARAMETERS		SNORM	CYCLE 1	CYCLE 2	CYCLE 3	CYCLE 4	CYCLE 5	
JRC	5	LOAD	20	20	20	10	0	MPa
JCS	25	UNLOAD	0	0	0	0	0	MPa
SIGMAC	30	APERTURE	0,140	0,030	0,020	0,016	0,015	mm
		KNP	4,60E+03	2,80E+04	4,50E+04	1,40E+04	3,00E+01	
CALCULATED PARAMETERS								
		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







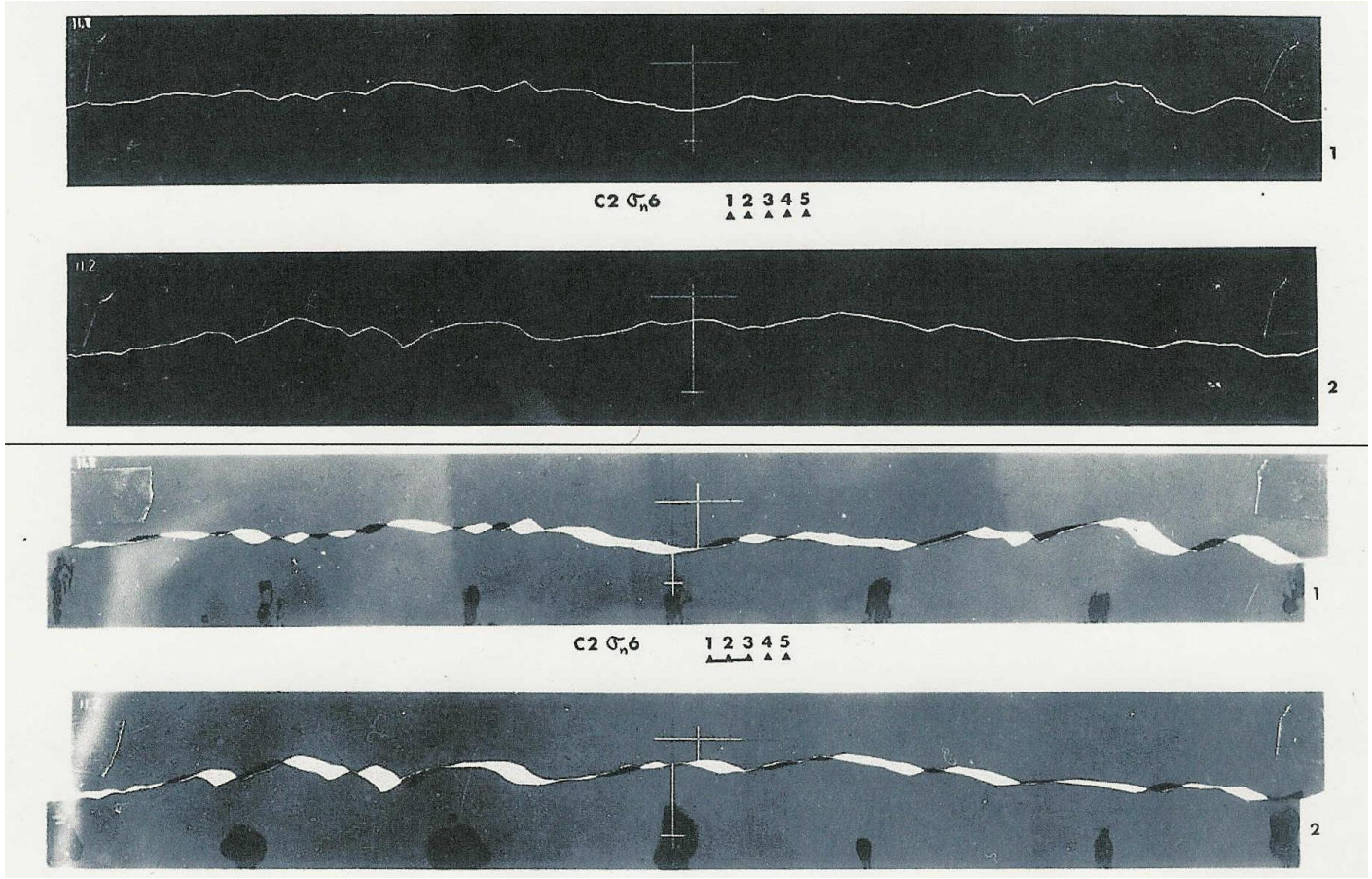


Smoother joint (JRC = 5) in weaker rock (JCS = 25 MPa)

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

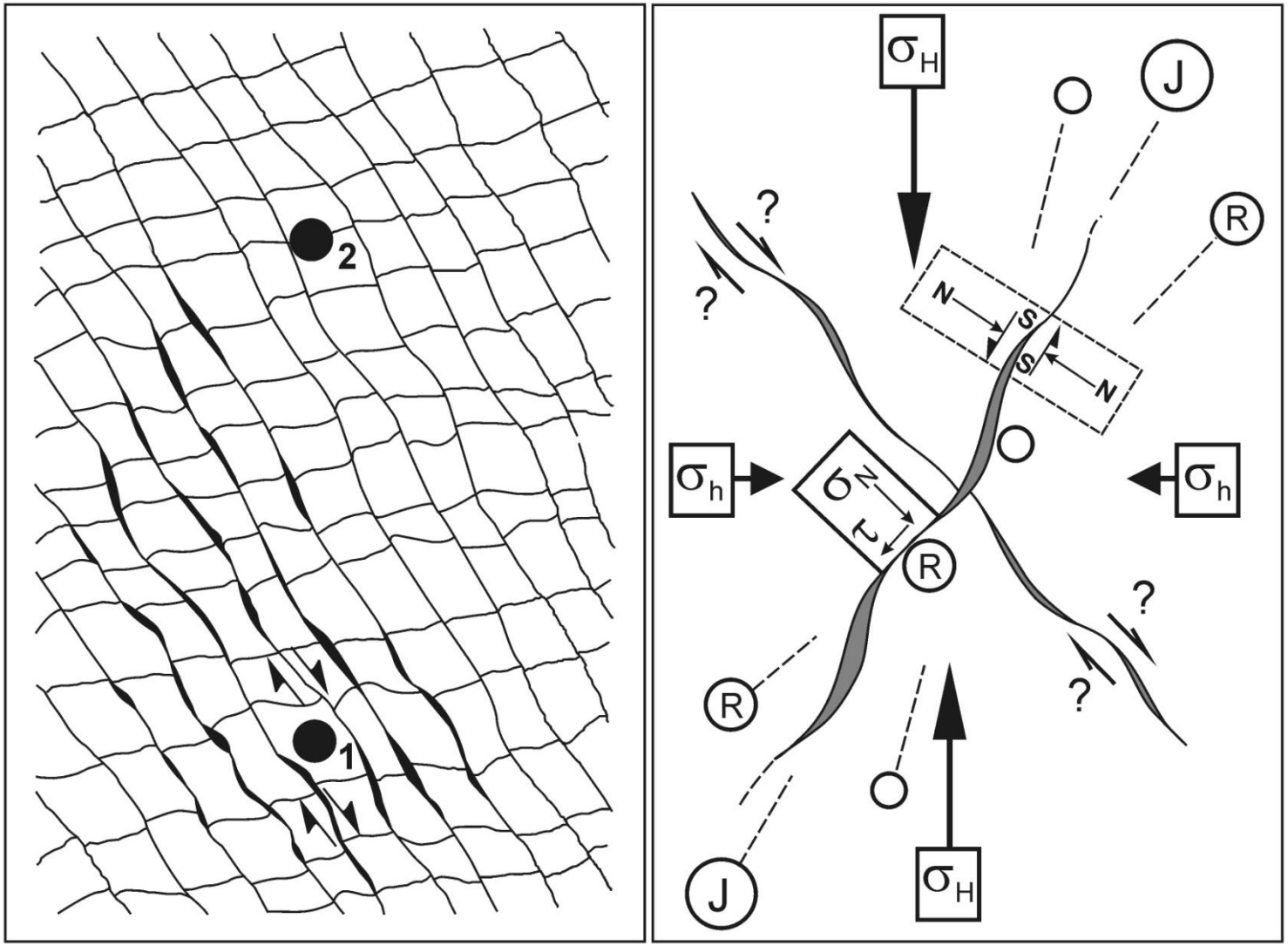
Right: dilation and permeability caused by shear displacement

Note the opposite 'rotations' of open lenses ('O') and contacting rock ('R') seen in physical models of shearing. Barton (1968/2006)…..any influence on fast axis???



JOINT SETS THAT ARE UNDER SHEAR STRESS ARE VERY COMMON, *MAY BE AMONG BEST CONDUCTORS – FROM OBSERVATION IN WELLS, AND FROM ROCK MECHANICS THEORY*

(Barton et al. 1985, Barton, 2006)

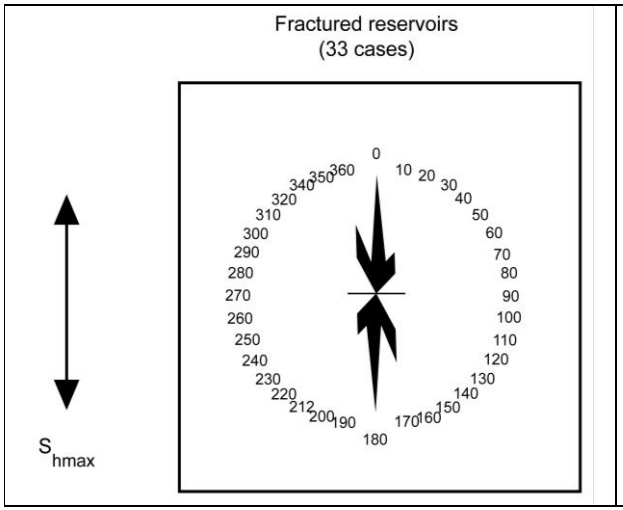


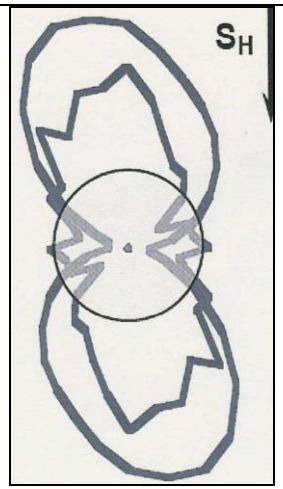
Conjugate sets of fractures

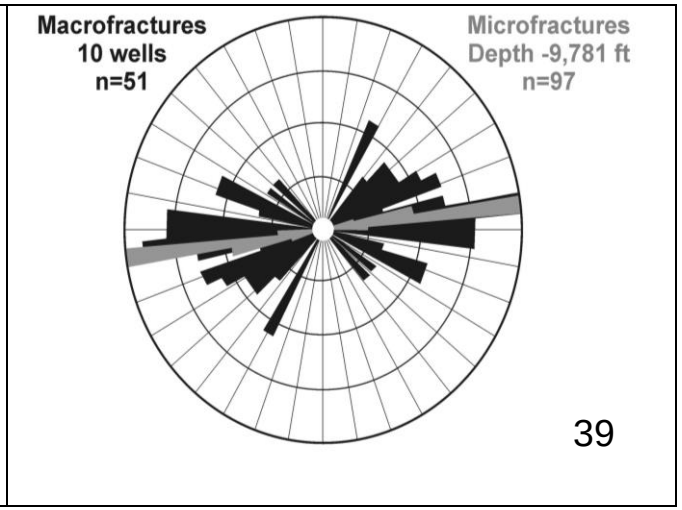
- Evidence of flow directions from pairs of wells (injector/producer) Heffer, 2002 and (Heffer) et al. 2007*(400,000 pairs of injector-producer wells, aggregated from eight field areas).*

- Measurements in individual producer wells from Laubach et al. 2000, *conjugate macro-fractures,* conventional micro-cracks?

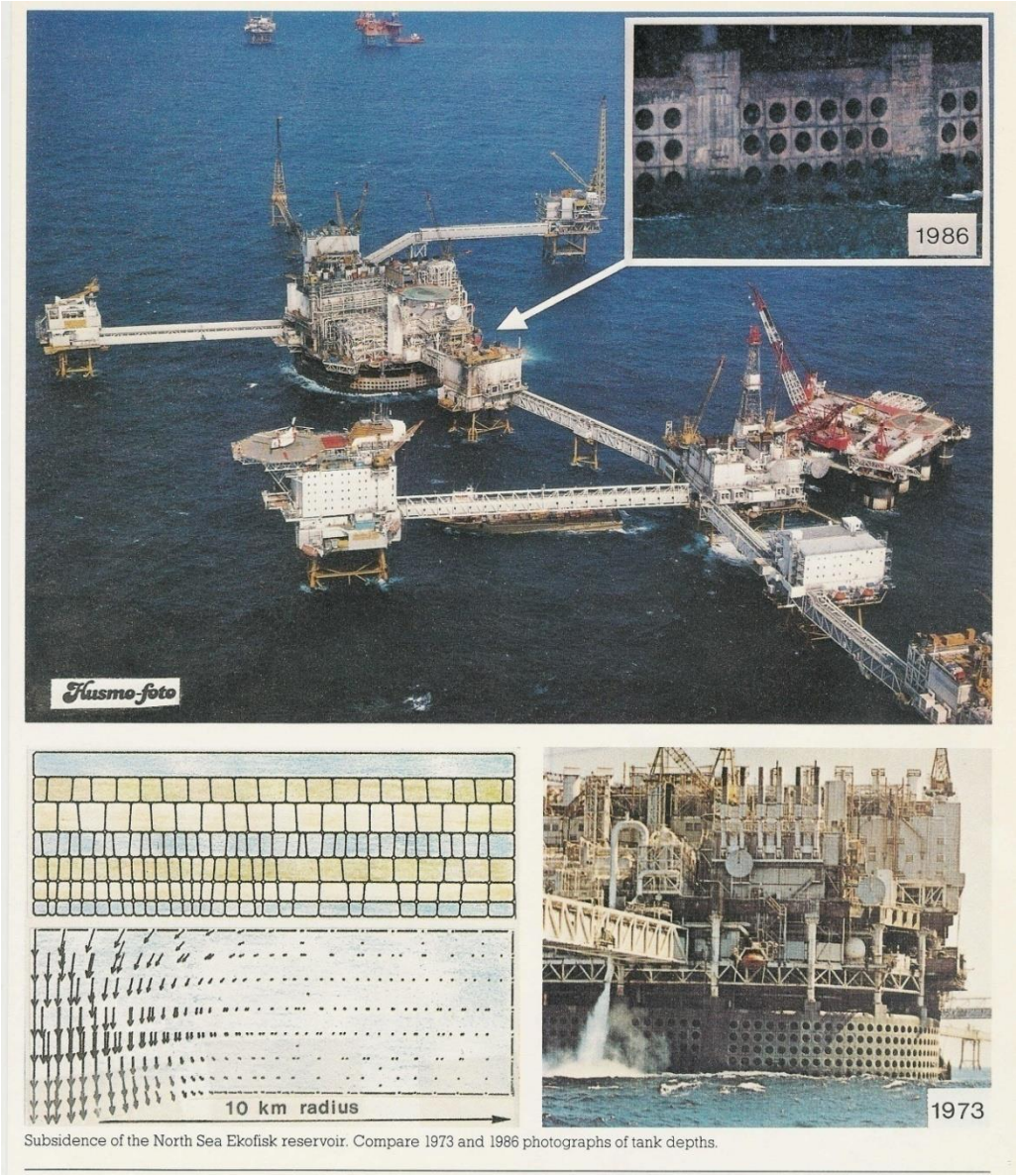
- All suggesting strong probability of anisotropy-axis deviation from $\sigma_{H\,max}$……..due to flow (and polarization) contributions from unequal conjugate sets??







A GLIMSE OF EKOFISK compaction (from 1986 modelling at NGI)



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 THE PRODUCTION FROM FRACTURED CHALK AT THE EKOFISK FIELD, NORTH SEA, NORWAY (since 1970 ca.)

Principal mechanisms:

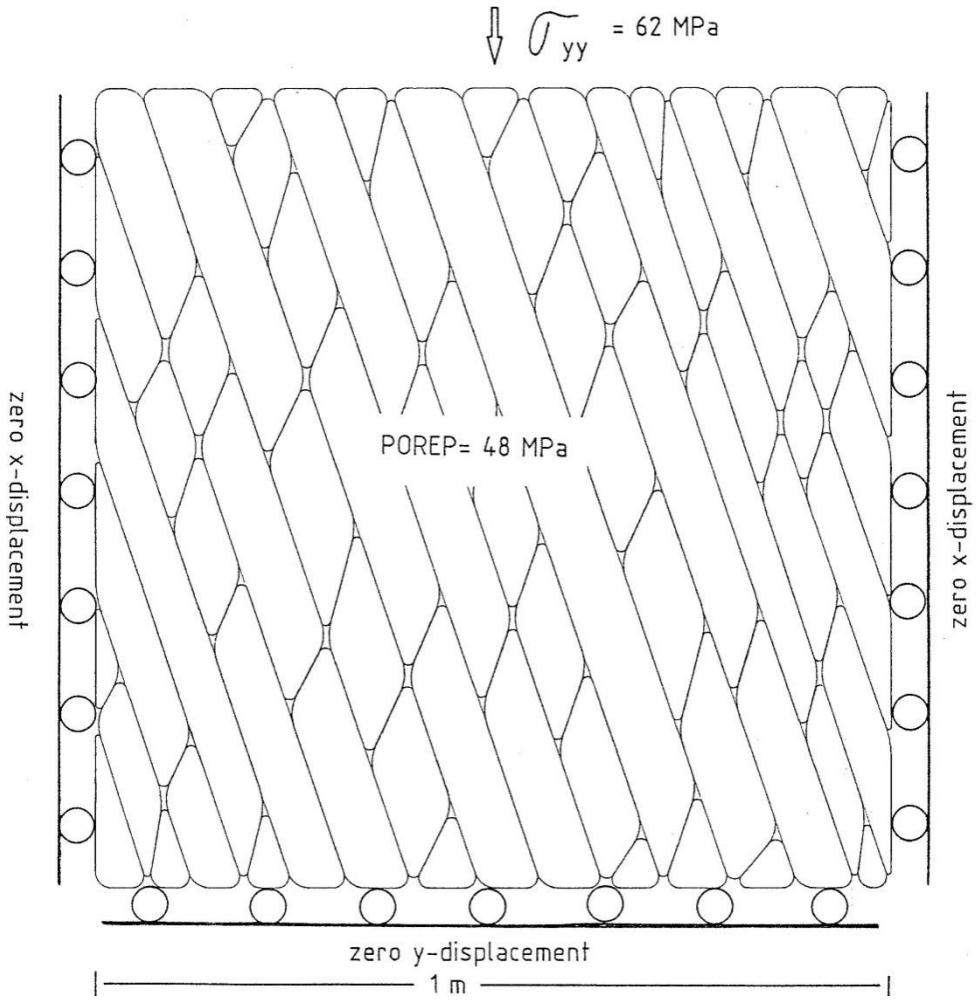
- *Effective stress increase*
- *Shearing of fractures*
- *Compaction, subsidence*

Slickensided fractures at Ekofisk

- Newly developed slickensides identified many years after exploration.
- Evidence of *shear-with-production* mechanisms.
- Discrete-element *modelled* (UDEC-BB) in 1986/87 (Barton et al. NGI team) yet hardly believed, *prior to* subsequent recognition as production-related *slickensiding.*
- *Slickensides* apparently not detected during exploration of Ekofisk field in late 1960's (Farrell, pers. comm.)
- 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'.*

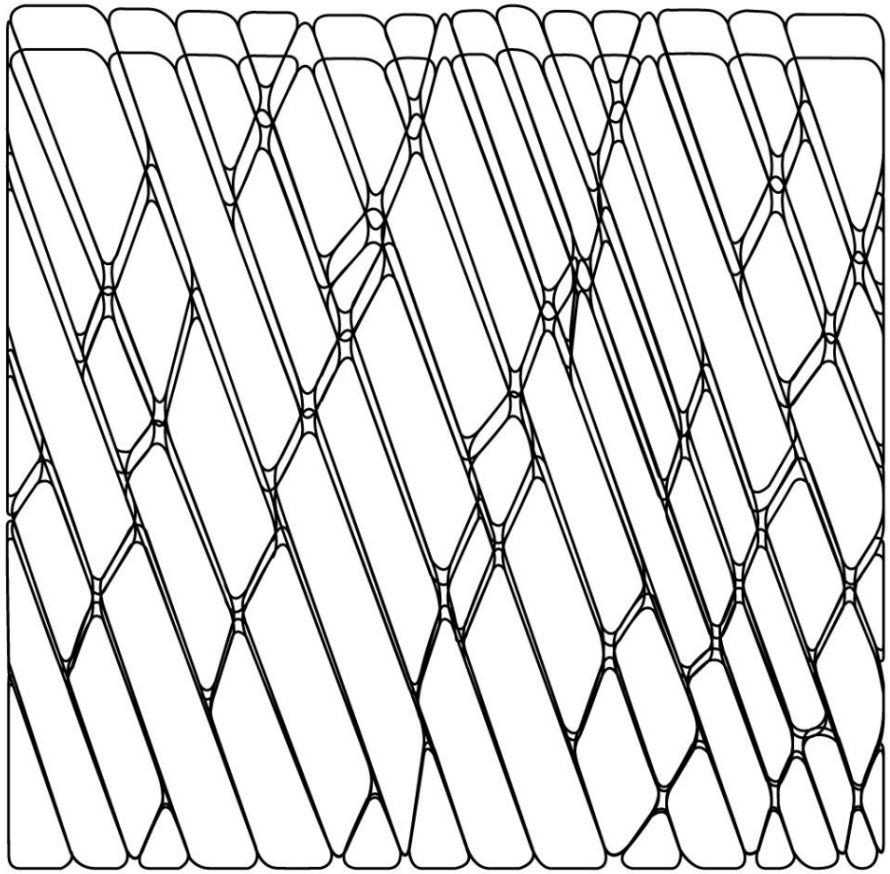
Initial boundary conditions for discrete-fracture modelling of 2D/3D idealized ‘1m block’ of Ekofisk chalk

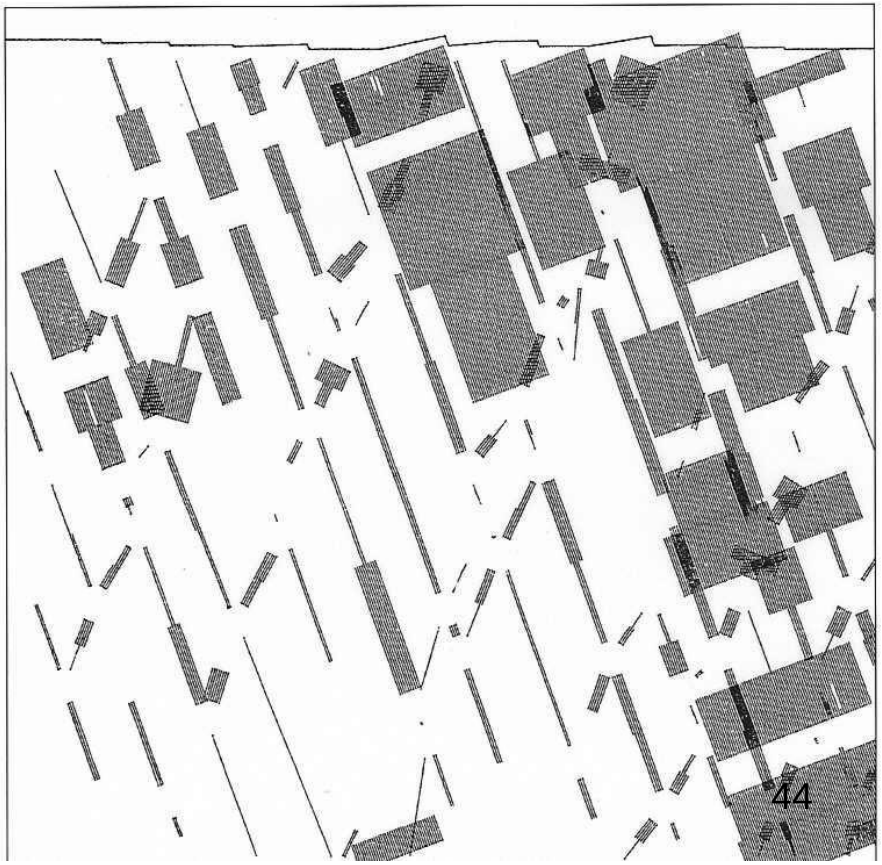
(2D - UDEC-BB model)

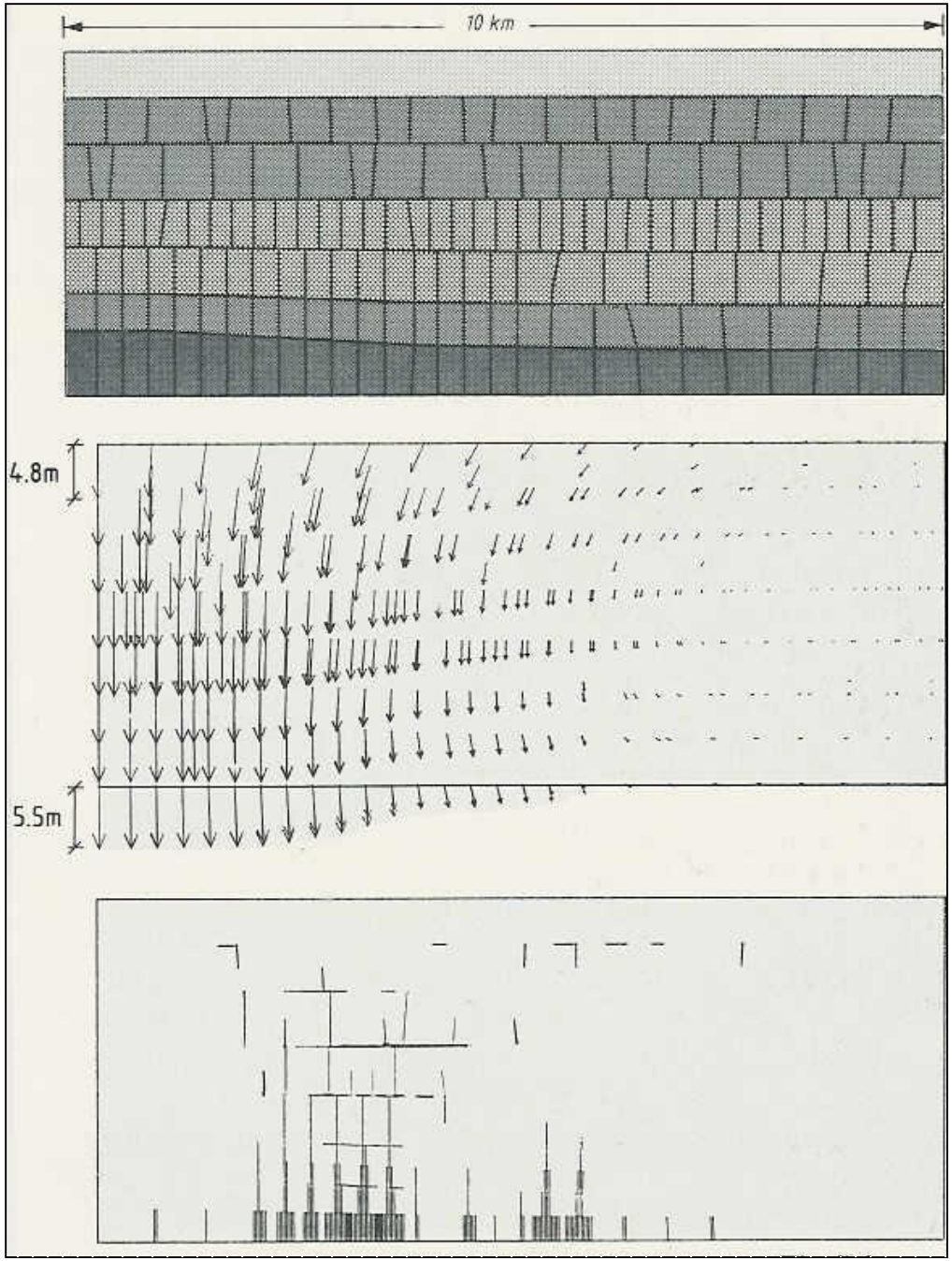


Distinct element UDEC-BB modelling of compaction-induced shearing of natural conjugate fracture sets in Ekofisk chalk, from Barton et al. 1986,1988.

Fracture shear *(max 4 to 10mm)* and dilation caused changes to fracture permeabilities, which can be sequentially tracked by following physical aperture (E) and conducting aperture (e) developments .







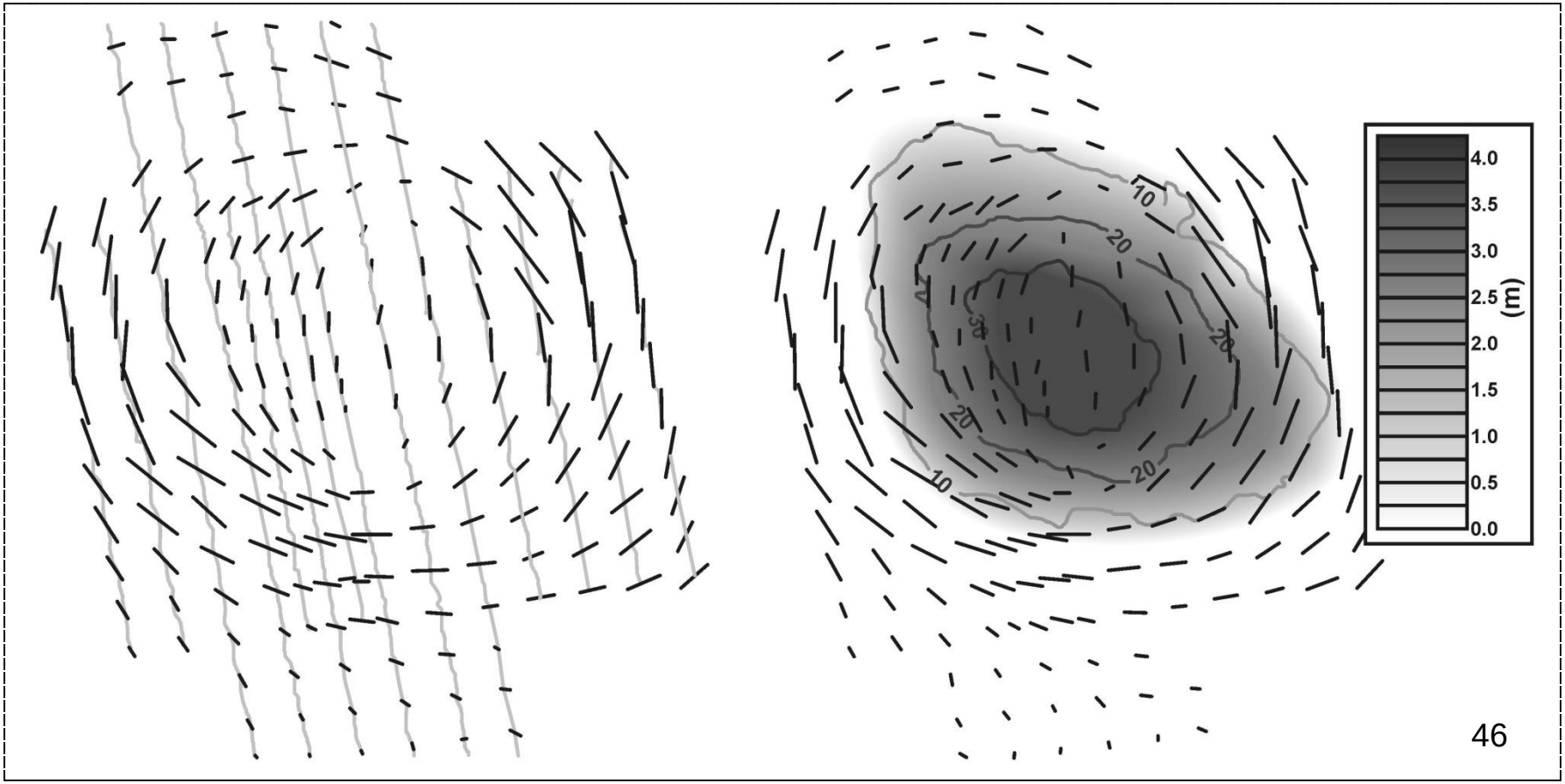
Large-scale (axisymmetric, 10 km radius) distinct element (UDEC) modelling of the *Ekofisk* overburden response to modelled compaction, using numerous *coarsely* 'bedded-jointed-and-faulted (2D) models (Barton et al., 1986, 1988). Note 'block' opening and shear.

At finer scale, *intra-bed* fractures could be a source of shear wave splitting and 4D effects?

Shear-wave splitting in shallow subsiding overburden above Valhall chalk reservoir. ……'square pattern'?? …..joints??

Olofsson and Kommedal, 2002.

(Lines show the qS_1 direction, with their *length* corresponding to the time delay or 'lag'.



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.

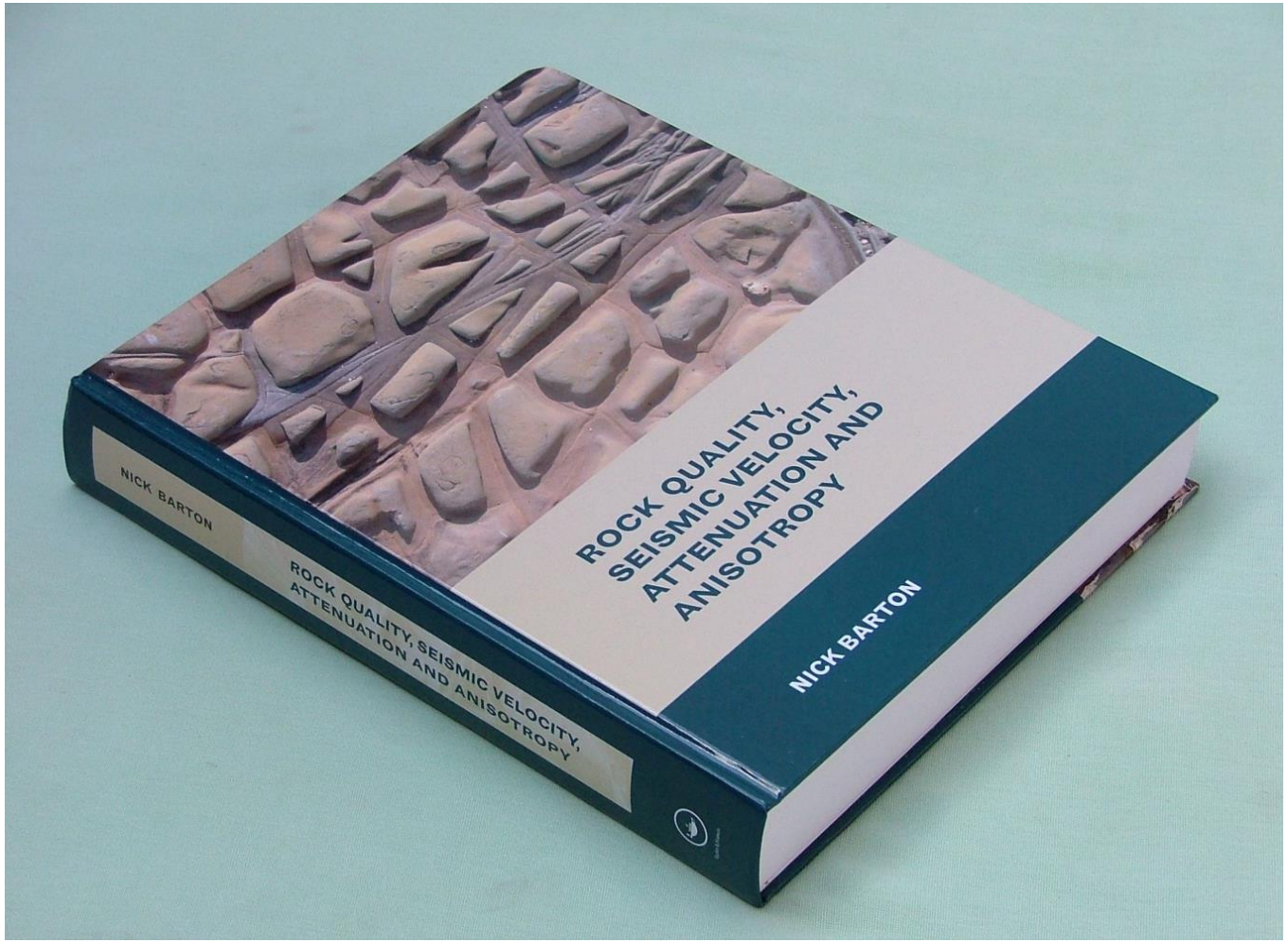
2. There are other possibilities if two conjugate sets are present and each are under shear stress, for which there can be several scenarios.

3. This ‘fractures-under-shear-stress’ model, certainly true in the case of domal or anticlinal NFR, is more consistent with rock mechanics theory and geomechanics-interpreted 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. The shear mechanism guarantees long life.

5. There is possibly (several times) greater volume of oil in-place in the fractures/joints of a fractured reservoir than assumed from well testing, *if the latter depends mostly on permeability for this estimate*…… because of the joint-aperture inequality $e \leq E$.

A MAJOR REVIEW OF CROSS-DISCIPLINE-INTERPRETED GEOPHYSICS LITERATURE suggested the ‘question’ in the title of this lecture.

…….(830 references, >1000 figures)…..

see also for (joint deformation) 4D effects