

VINTERKONFERANSEN – BERGEN January 2009

**GEOPHYSICS INTERPRETATION OF  
FRACTURING MAY BE CONTRARY TO  
GEOMECHANICS AND HYDRO-  
GEOLOGICAL PRINCIPLES**

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# WARNING

## THIS IS A CROSS-DISCIPLINARY LECTURE

- **FIRST SOME SIMPLE GEOPHYSICS**
- (from a Rock Mechanic – therefore simple)
- **THEN SOME SIMPLE GEOMECHANICS**
- (from a Rock Mechanic – therefore simple)
- **THEN SOME HYDRAULICS**
- (from a Rock Mechanic – therefore simple)

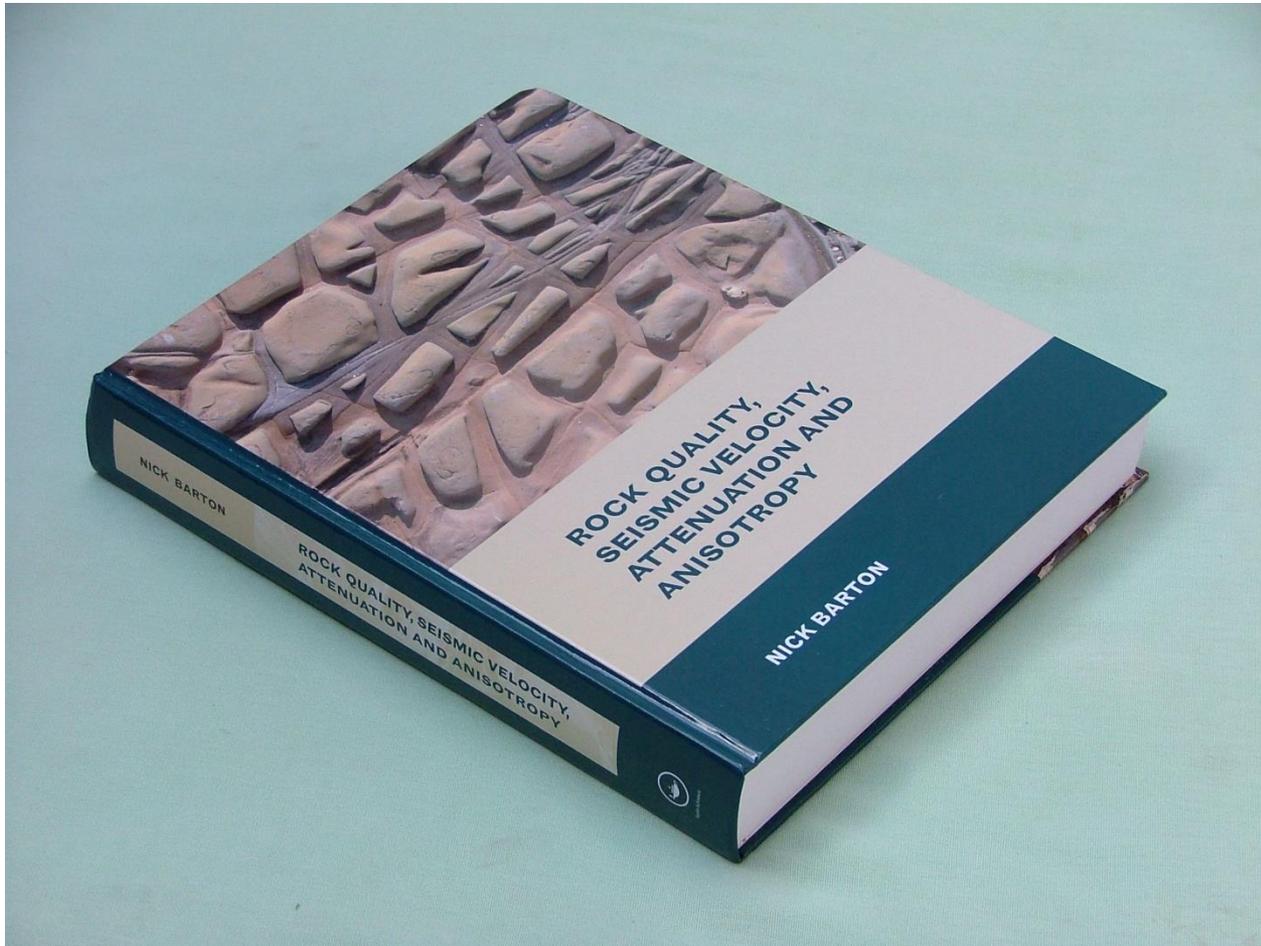
1. 'OPEN' *SINGLE* FRACTURE SET // TO  $\sigma_{H\ MAX}$ . The rule or an anomaly?
2. SHEAR WAVE *POLARIZATION* MAY BE CAUSED BY 2-SETS?
3. WATERFLOOD/PRODUCER 'PAIRS' NON-ALIGNED WITH  $\sigma_{H\ MAX}$ .
4. GOOD PERMEABILITY MAY IMPLY *PRE- or POST-PEAK* SHEARING
5. INEQUALITY OF FRACTURE APERTURES (hydraulic  $e \leq$  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)



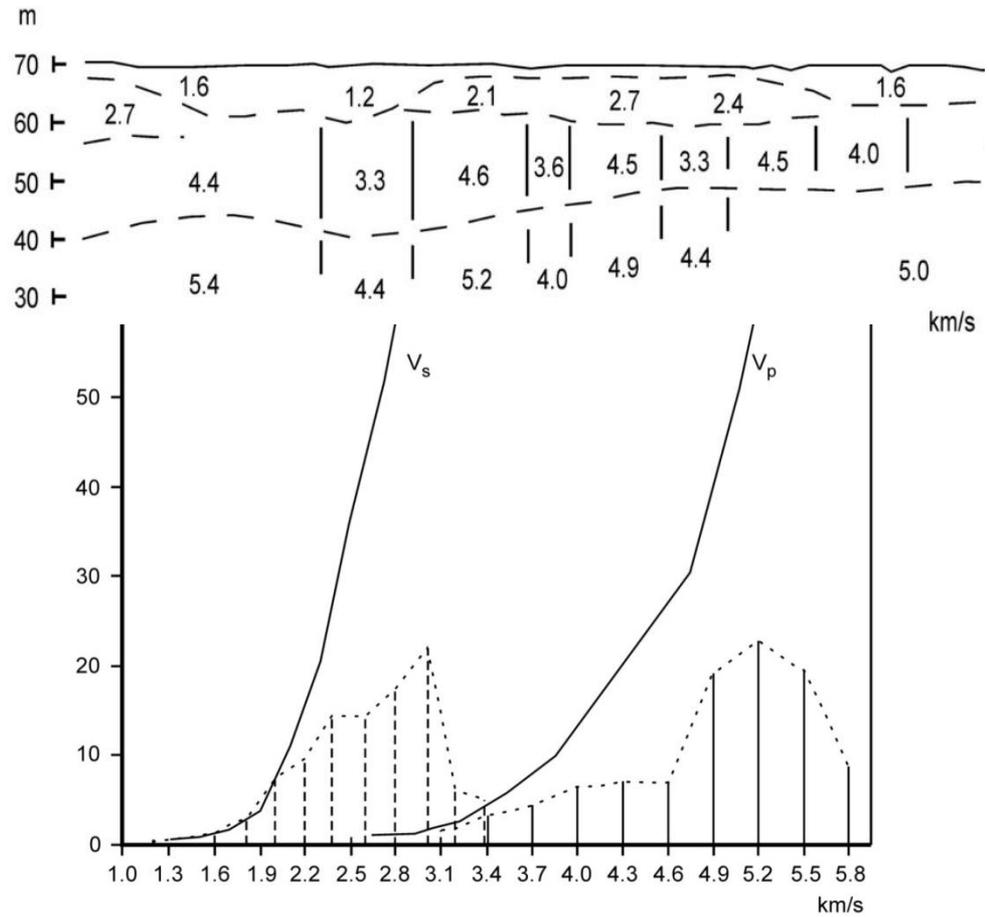
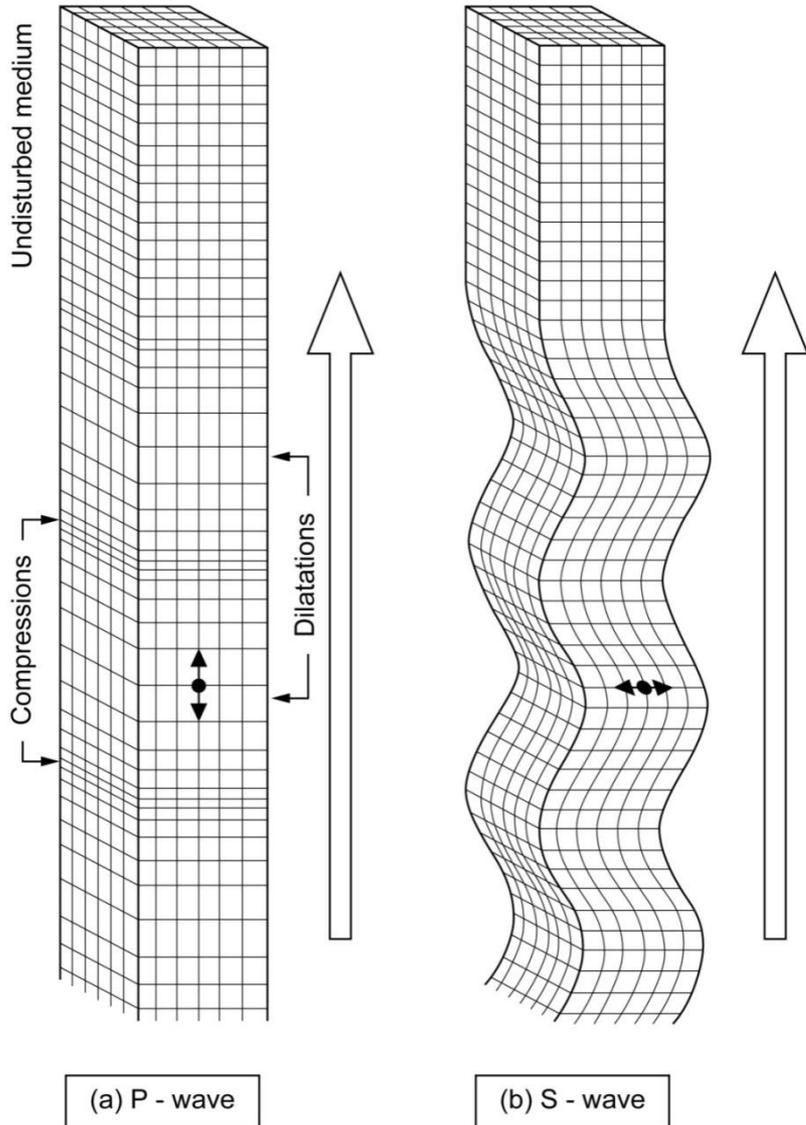
Obviously - a rock mass often has several joint sets which can be hindrances or *pathways* for flow.

# A MAJOR REVIEW OF GEOPHYSICS LITERATURE

.....suggested the 'problems' implied by the title of this lecture.....(830 references, >1000 figures).....see also for (joint deformation) 4D effects



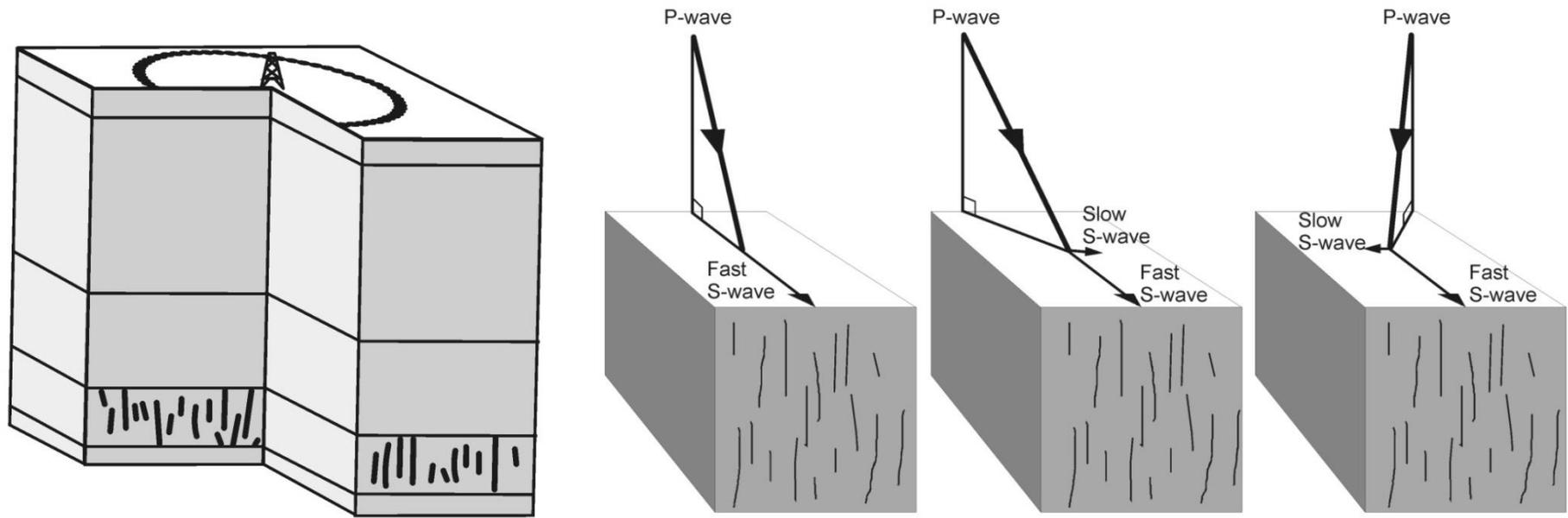
➤ P-waves *and* S-waves that cross jointed rock, get **SLOWER**

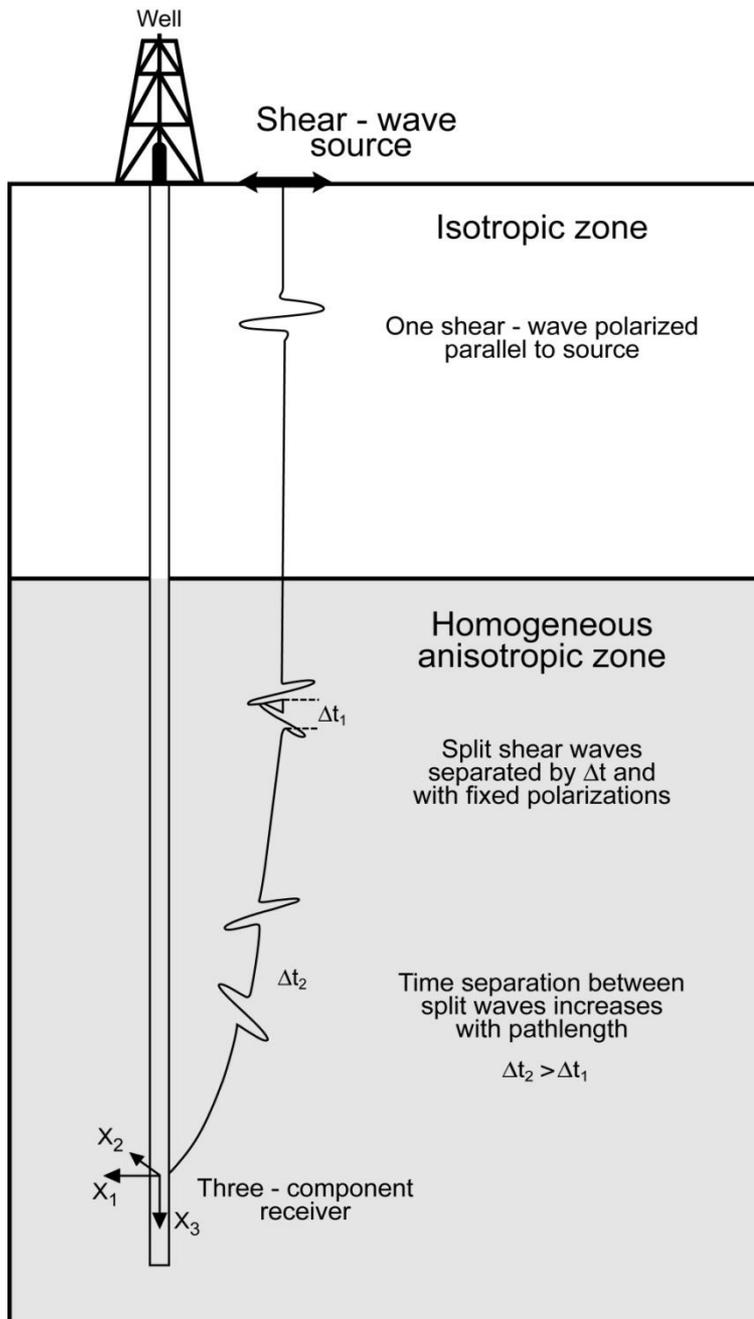


S-waves may also be *polarised* (into fast and slow components)

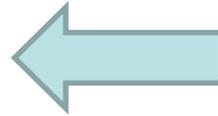
- **INCOMING P-WAVES** from VSP (vertical seismic profiling) GET CONVERTED TO **PS-WAVES** AT A GEOLOGICAL INTERFACE .....

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

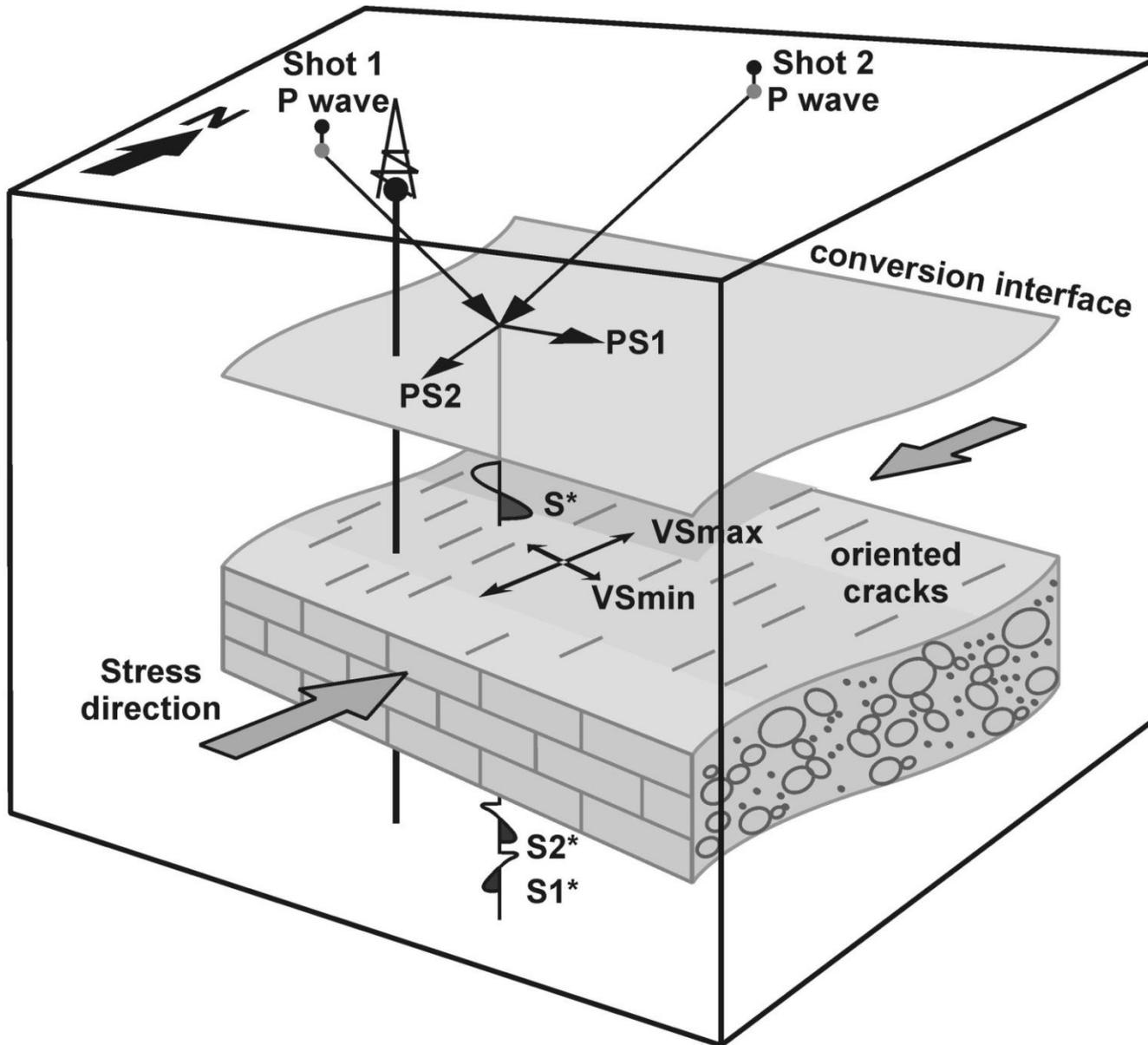




In this case: actual **shear-wave** source gives 'SS' waves (pure S-waves, not PS waves)



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

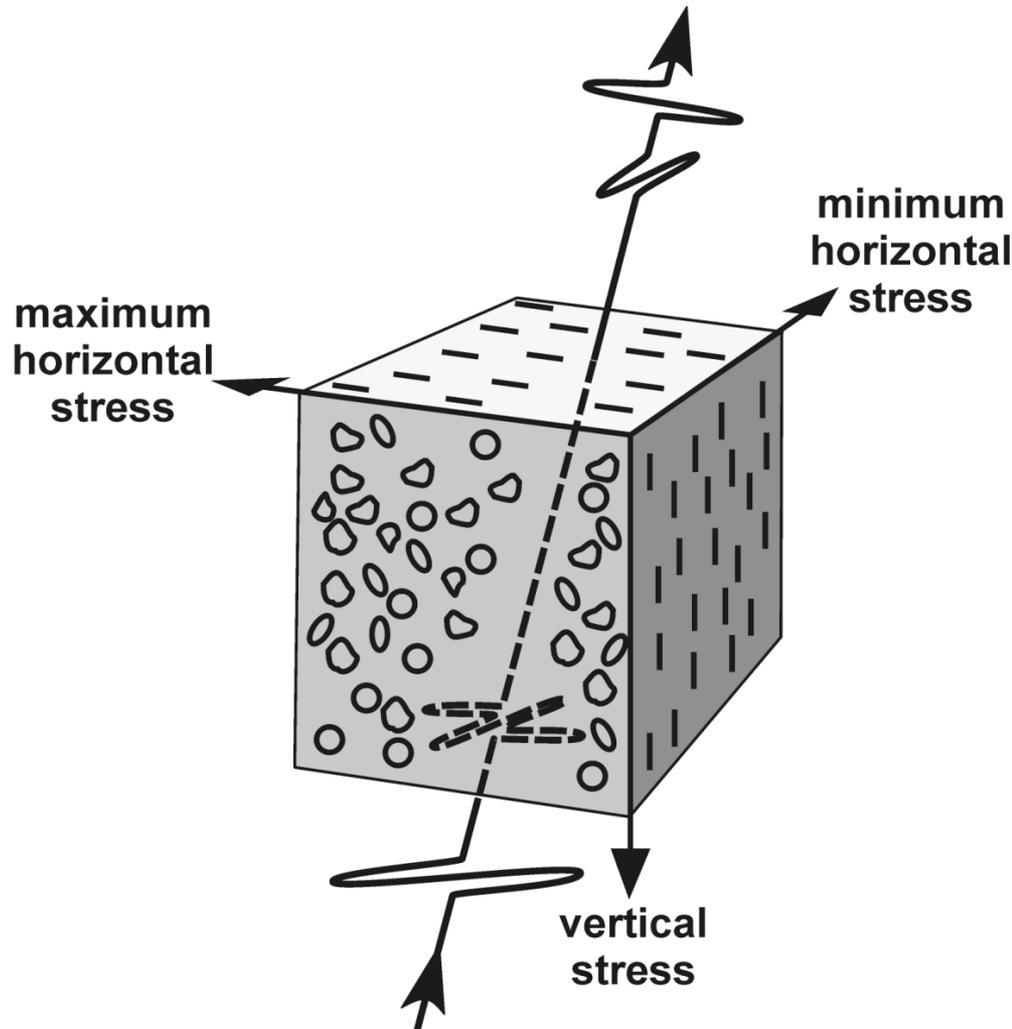


Principal question for geophysicists

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

(Stenin et al. 2002)

*In case of polarization components from two joint sets, the classic microcrack model of Crampin would need to be modified beyond the concept of a single set of stress-aligned cracks.*



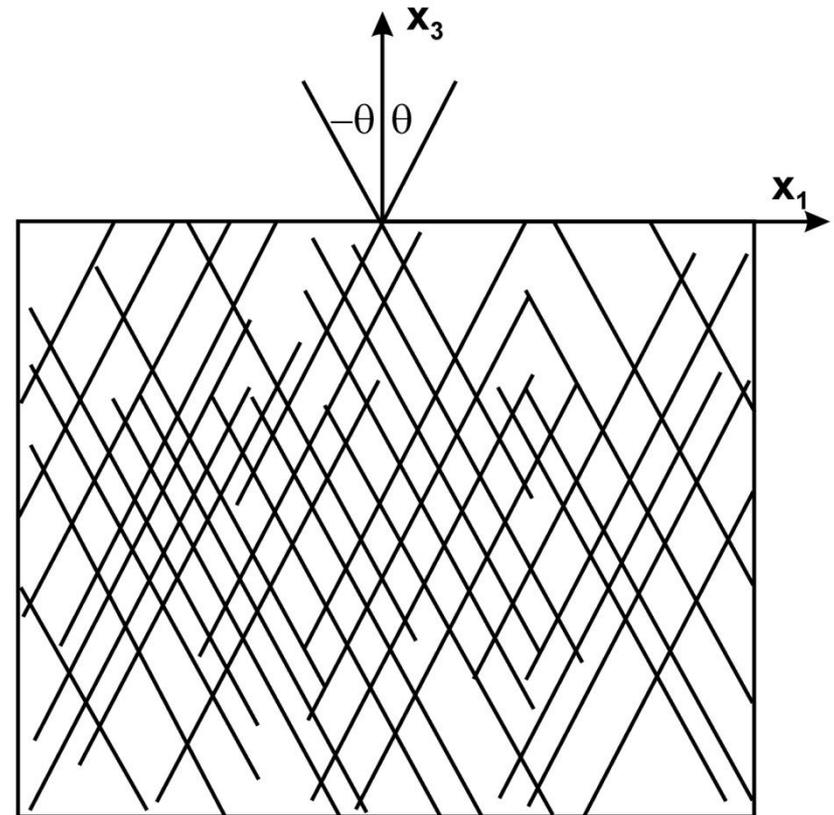
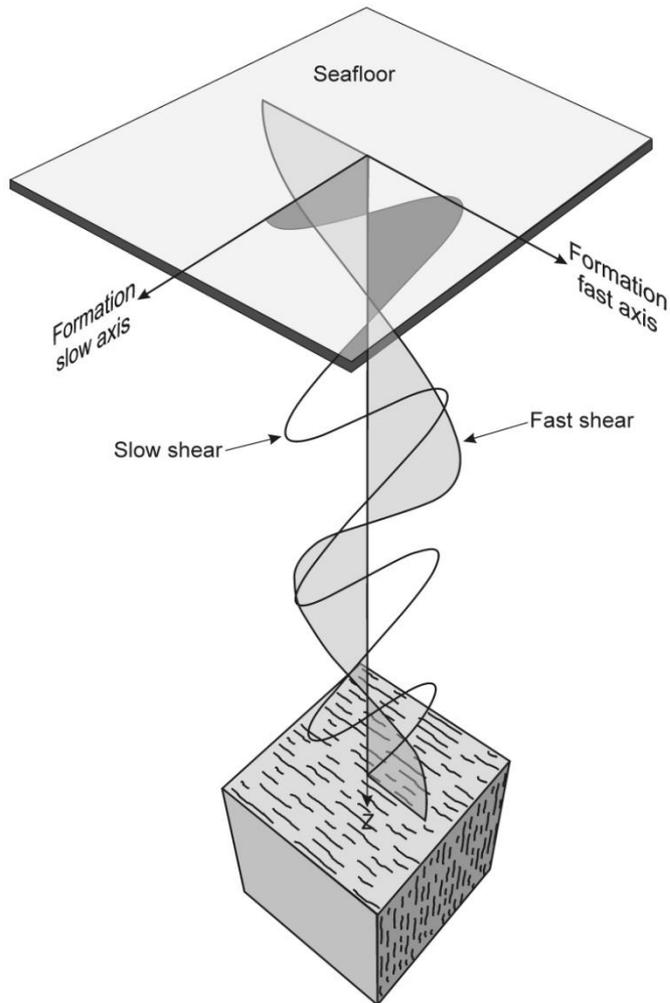
# **There are therefore two basic questions to be asked:**

- 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 20° to 40° rotation of polarization axes of maximum  $V_S$  relative to interpreted  $\sigma_H$  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). ?

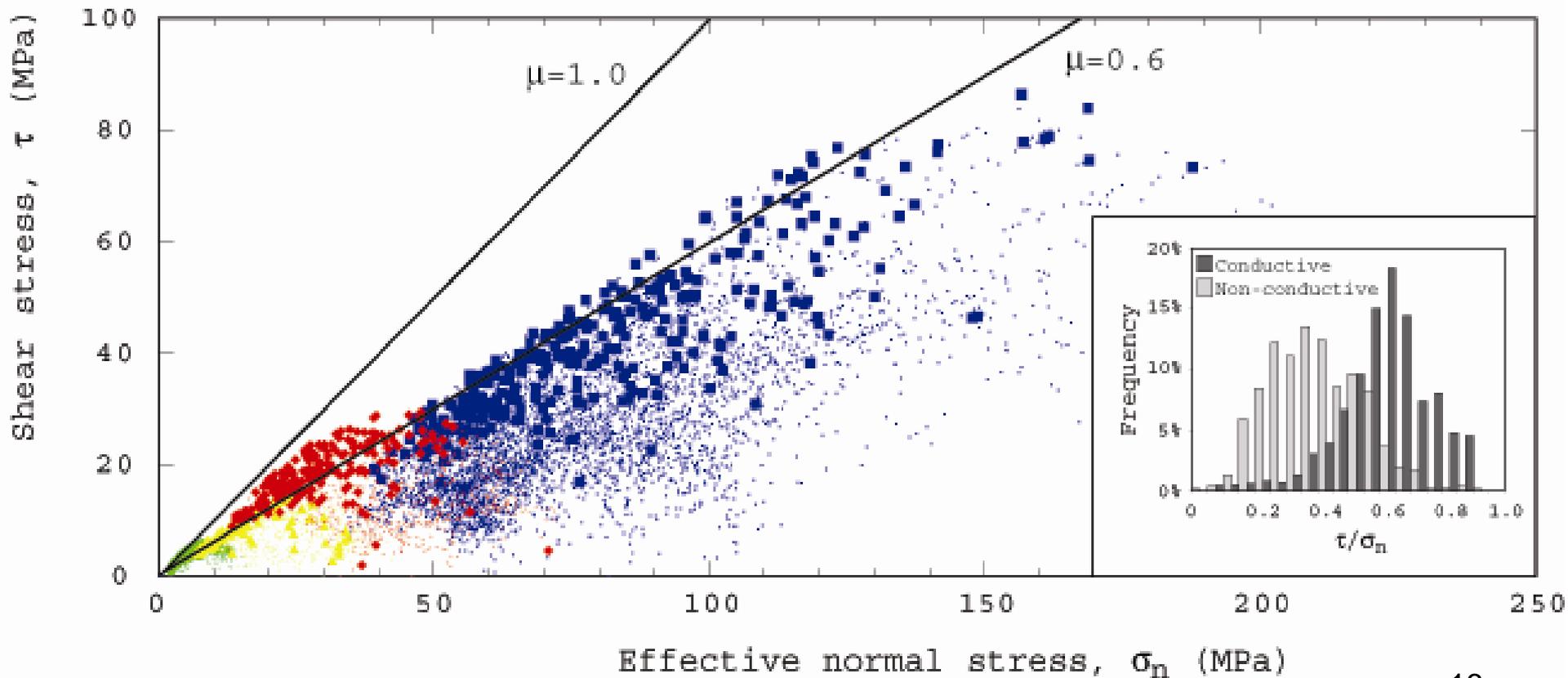


## TWO SETS....FOUR COMPLIANCES...FOUR APERTURES.....(Barton, 2007, Leading Edge)

- Two sets of (conjugate) fractures:
- Shear wave components  $qS_1$  and  $qS_2$  depend on *shear and 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).

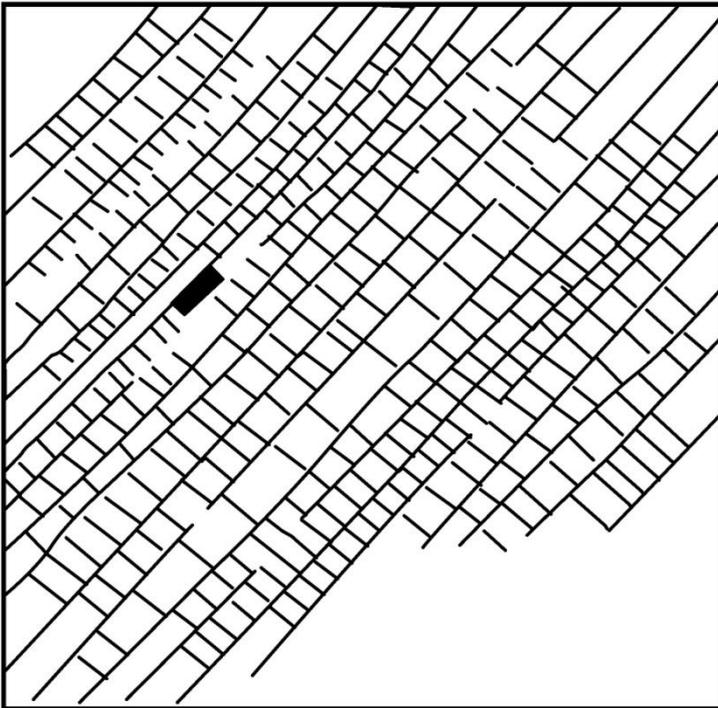
- The joints (fractures) under *significant shear stress* are the best conductors in the case of *hard* crystalline rocks (to many kilometers depth)
- Seems even more likely in the case of softer reservoir rocks

(e.g. Townend and Zoback, 2000,  
Zoback and Townend, 2001)

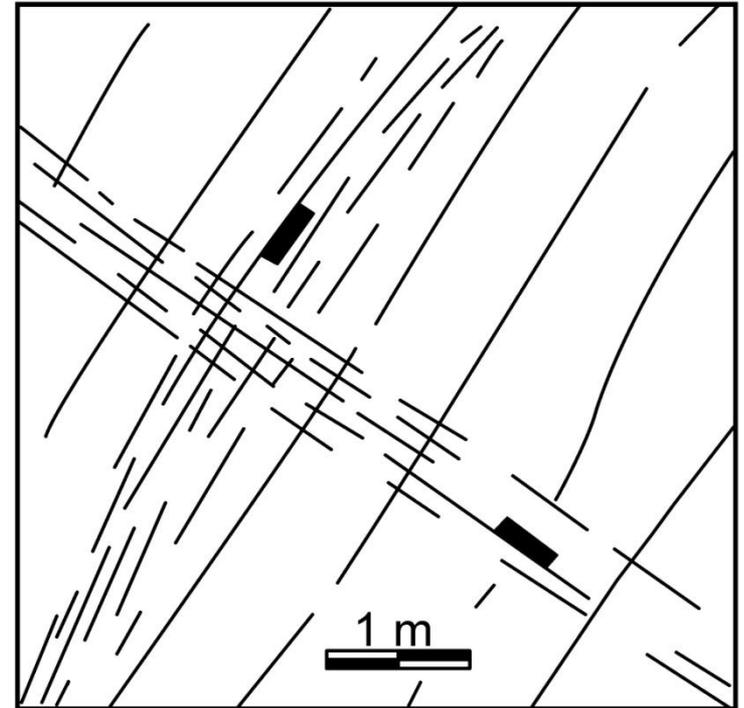


Both sets of joints in this reservoir (Middle East) are steeply-dipping.....may be (must be?) under shear stress

(a) Surface



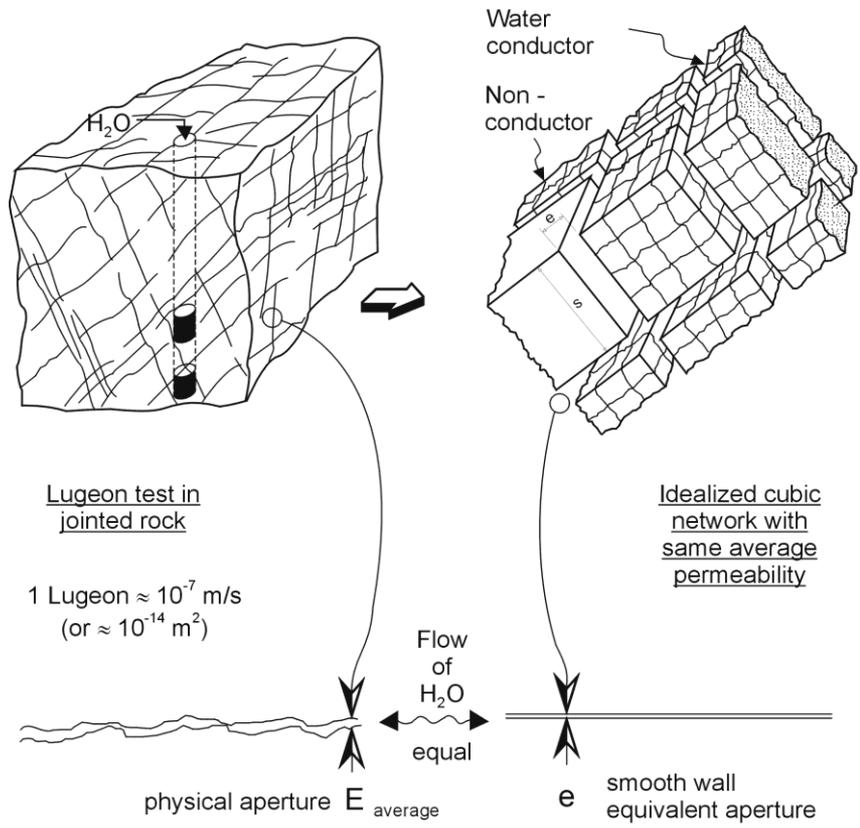
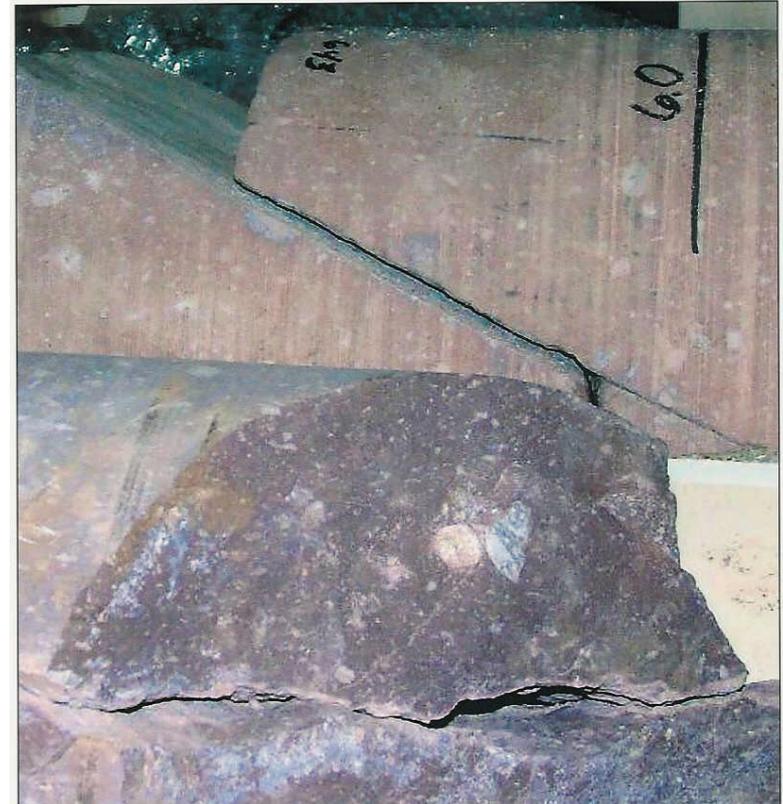
(b) Reservoir



# A LOOK AT CONDUCTIVITY

- ❑ Which apertures apply?
- ❑ For permeability  $k = e^2/12$
- ❑ But during closure and shear (i.e. when a reservoir is producing)....it is the physical aperture (E) that is changing (too).

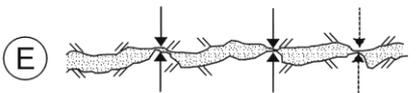
# PHYSICAL (= rough) APERTURES (**E**), AND IDEALIZED (= smooth) HYDRAULIC APERTURES (**e**)



**E** is real and can be grouted

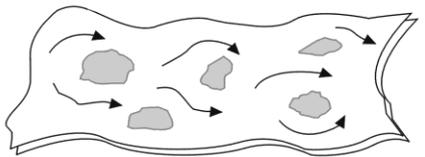
**e** is imaginary and ungroutable

Stress transfer !



Both E and e respond to injection pressure

**e**

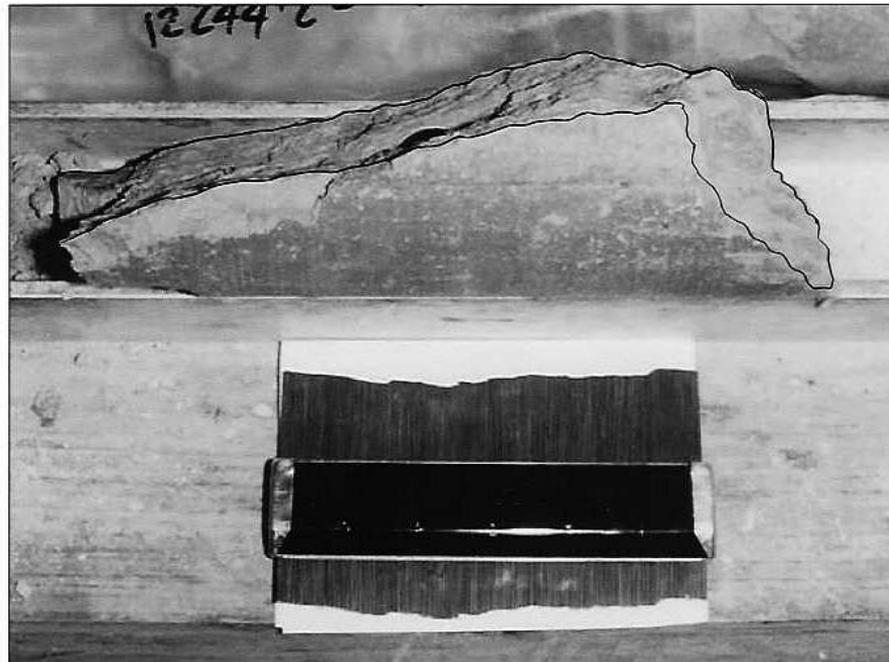


No points of contact

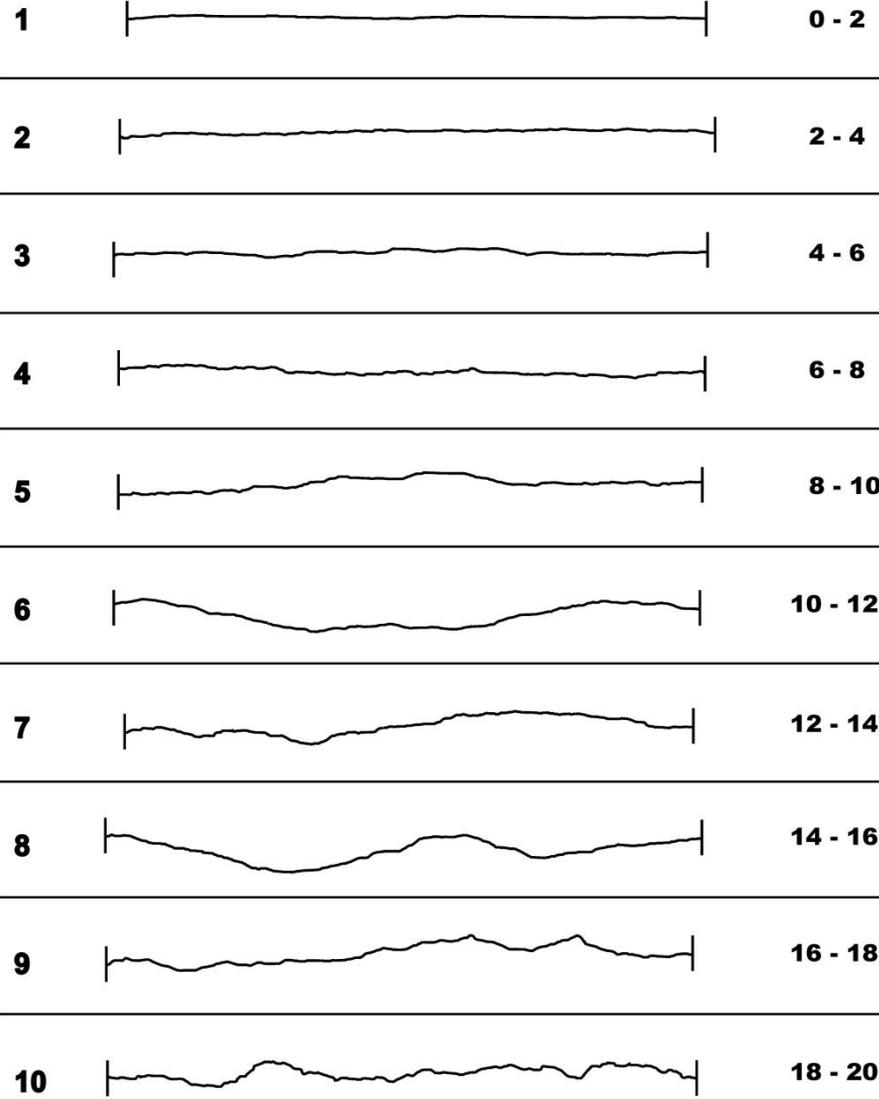
# JOINT ROUGHNESS and STRENGTH CHARACTERIZATION NEEDED in 4D INTERPRETATION!

*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  $\leq$  UCS, due to alteration/weathering) also needed for stiffness, strength, dilation.



**TYPICAL ROUGHNESS PROFILES for JRC range:**

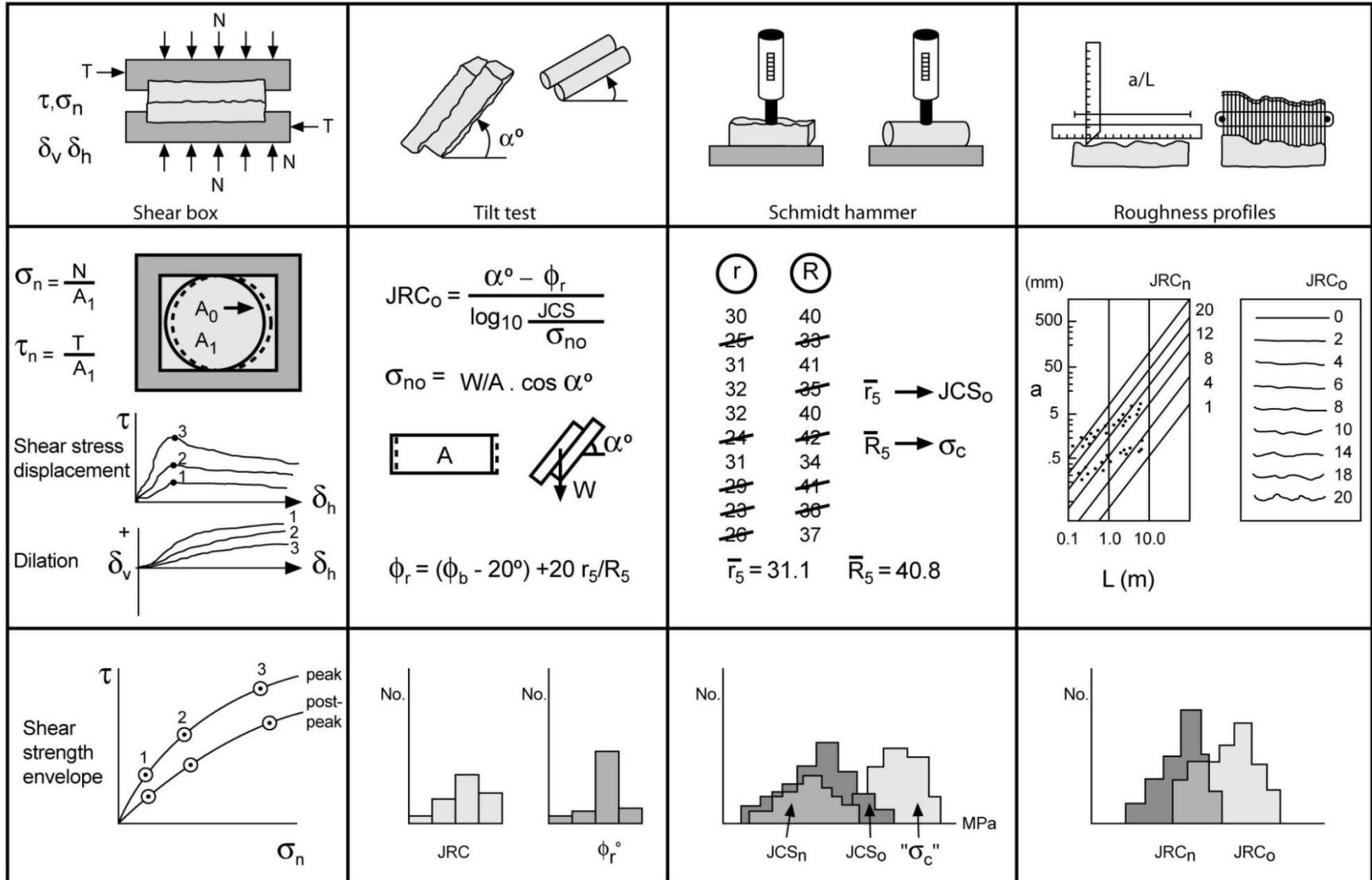


A simple quantitative approach to roughness description – and a basis for constitutive modelling (Barton and Choubey, 1977)

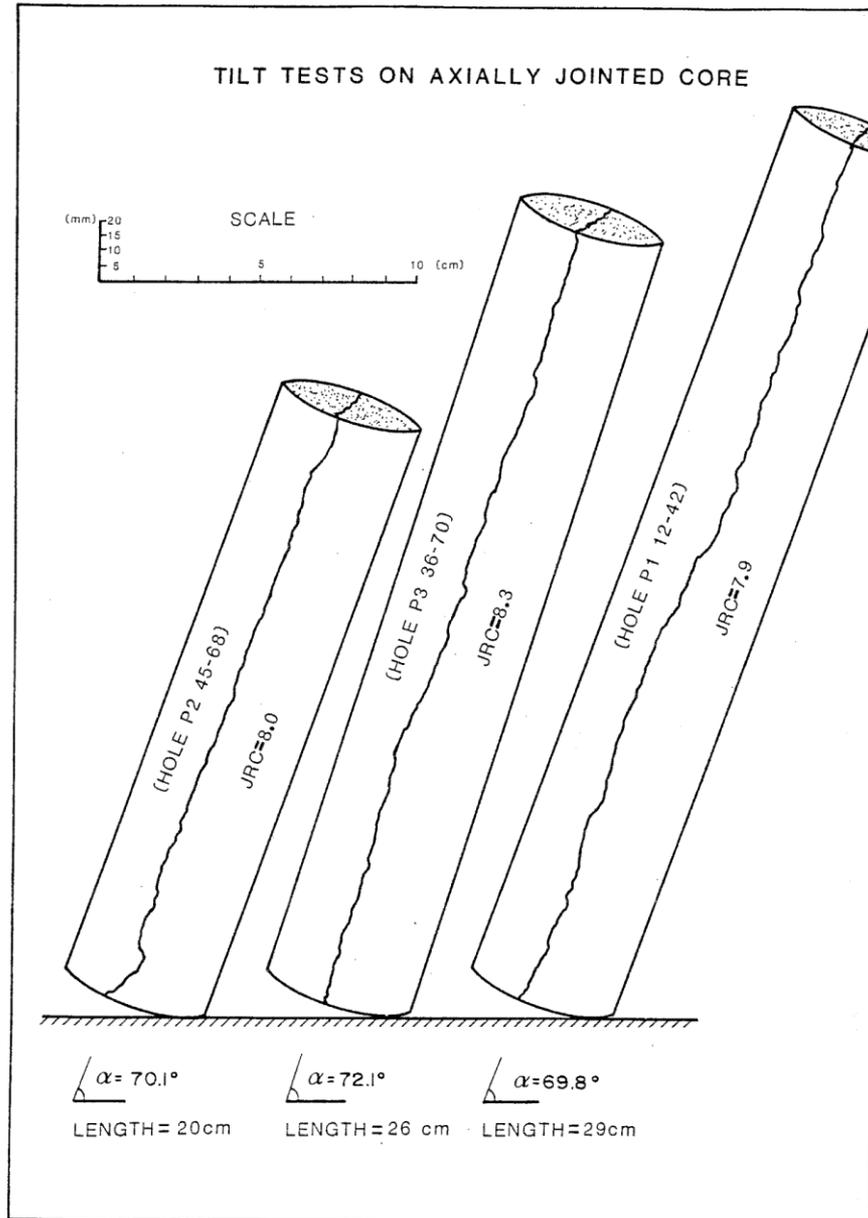


# How to obtain JRC and JCS and $\phi_r$ - the basis for modelling (among other things) *closure, shear and permeability coupling* in 4D interpretation

## Shear box and index testing of rock joints

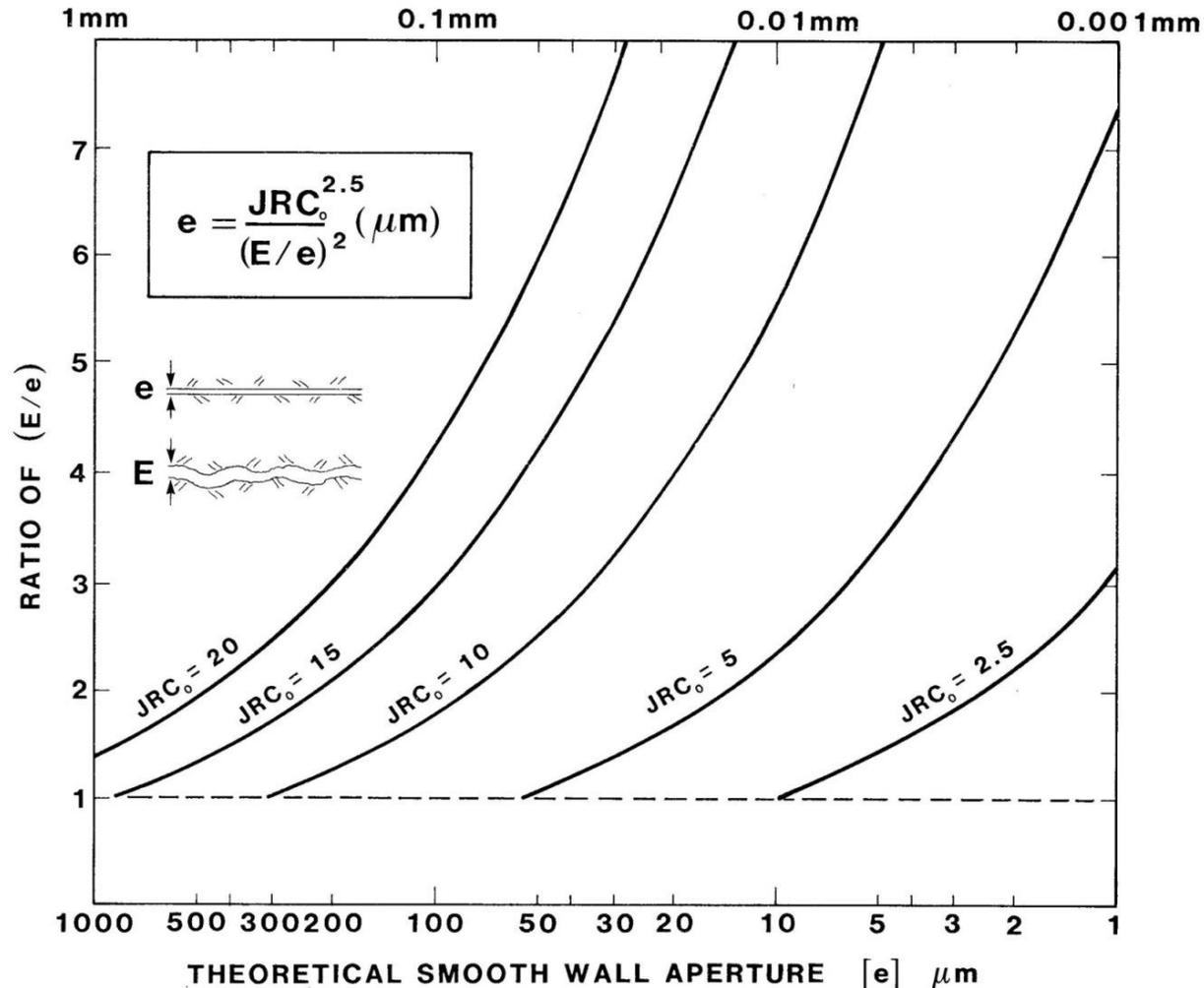


# These are tilt tests !

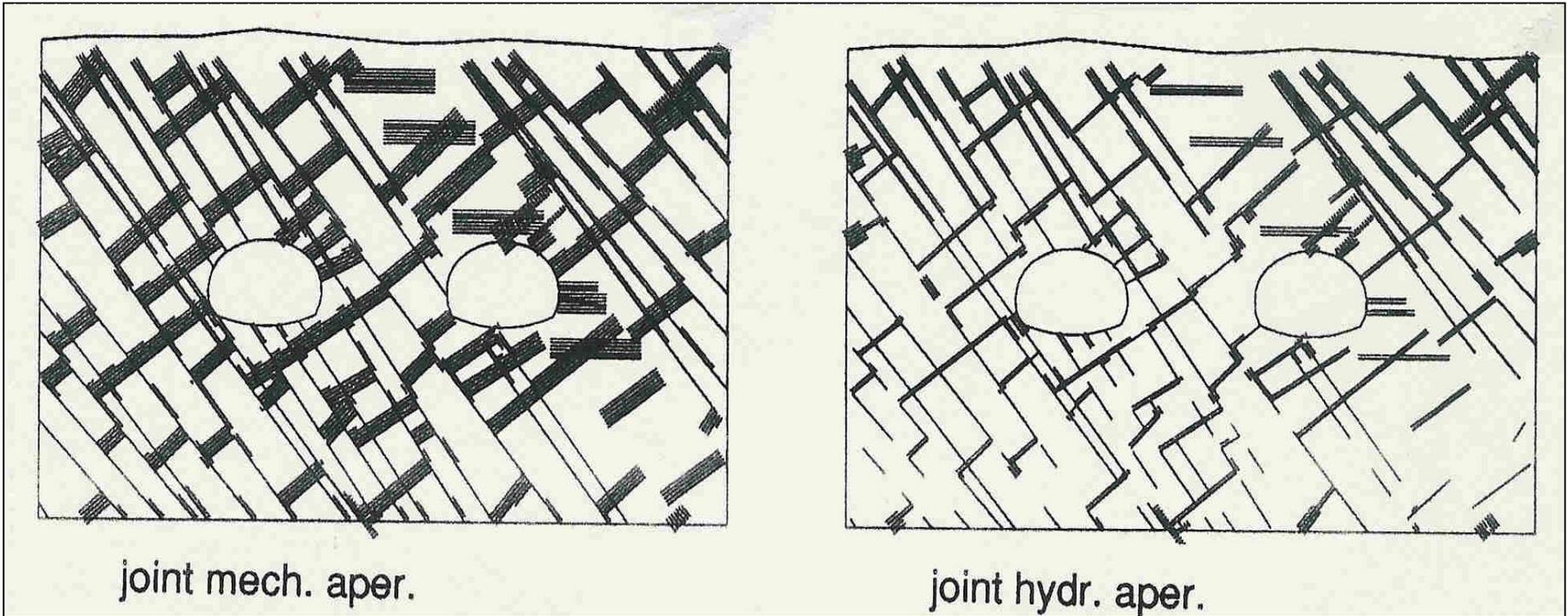


# Empirical model linking E and e via (small-scale) $JRC_0$ value - strictly for joint or fracture closure modelling. (Another model for shear).

Barton, N., Bandis, S. & Bakhtar, K. 1985. Strength, deformation and conductivity coupling of rock joints. Int. J. Rock Mech. & Min. Sci. & Geomech. Abstr. 22: 3: 121-140.



**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 )**



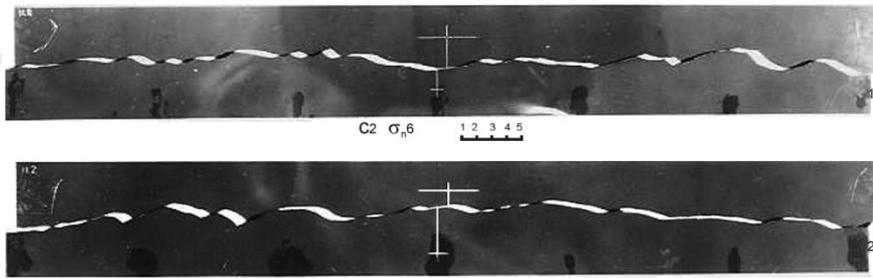
**Apertures are tighter at depth.....also in hydrocarbon reservoirs....**  
**...so where do the 'open' joints come from....in a 'fractured reservoir' ?**  
**(mineral bridging, channelling.....and shear)**



# SHEARING

to compensate for CLOSURE

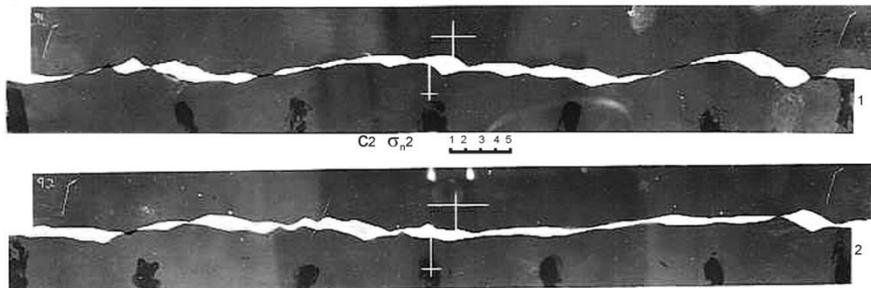
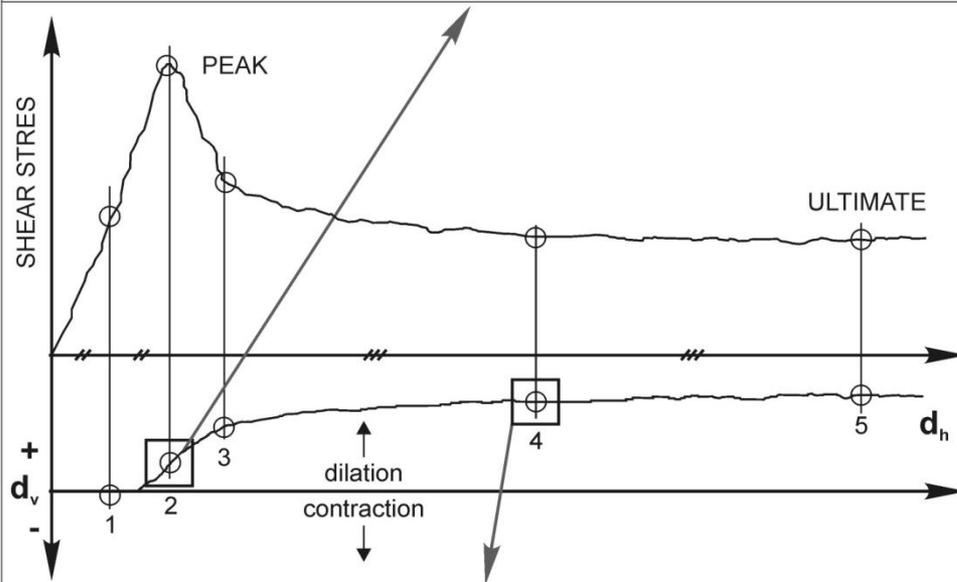
- **GIVES PERMEABILITY AT RESERVOIR DEPTHS AND EVEN CRUSTAL DEPTHS**
- **NOTE FOLLOWING EXAGGERATION of SHEAR AND DILATION and therefore *PERMEABILITY***



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

IF ONE IS INTERESTED  
IN PERMEABILITY

Barton, 1971

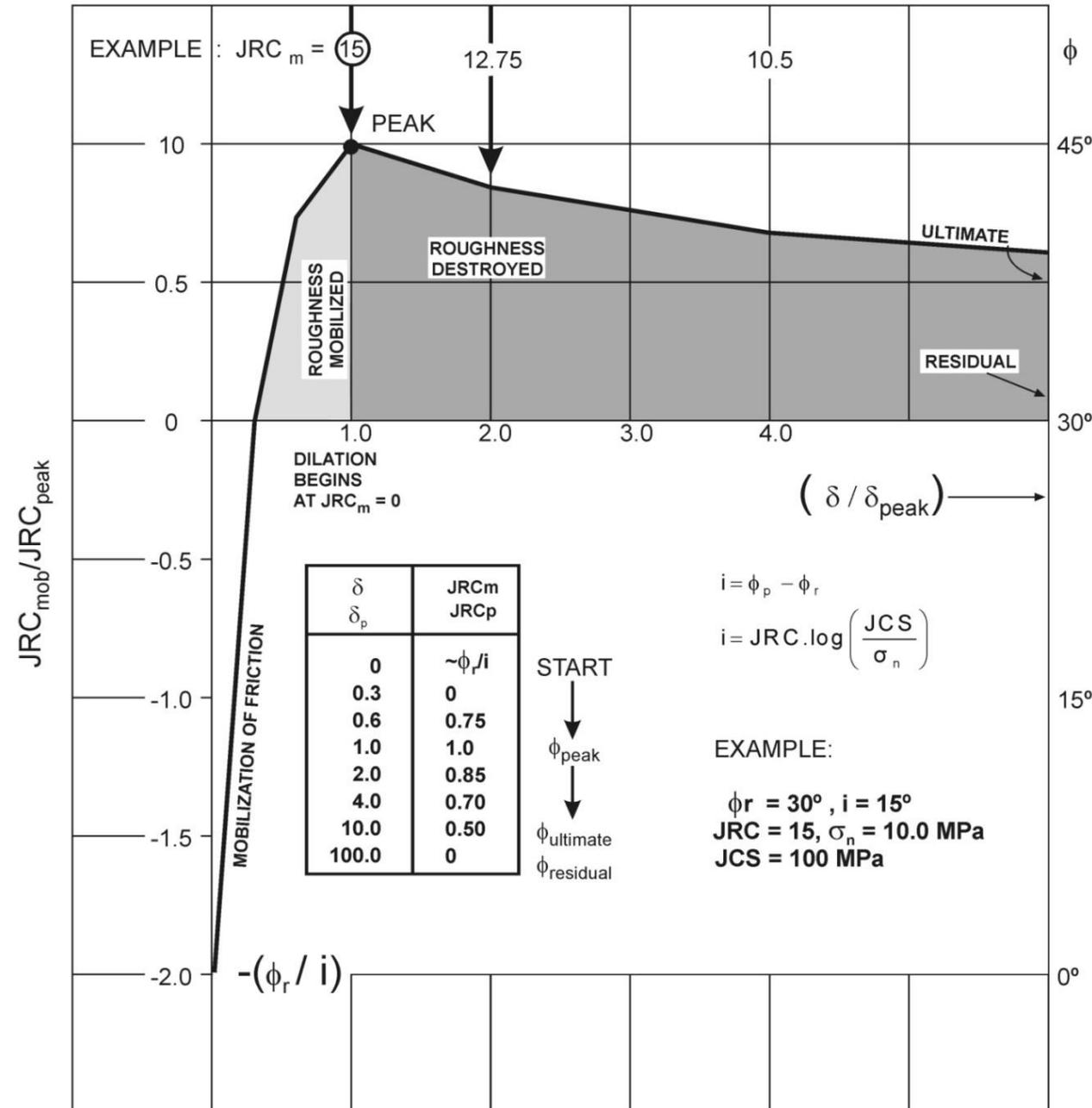


(Note: gouge production not  
shown)

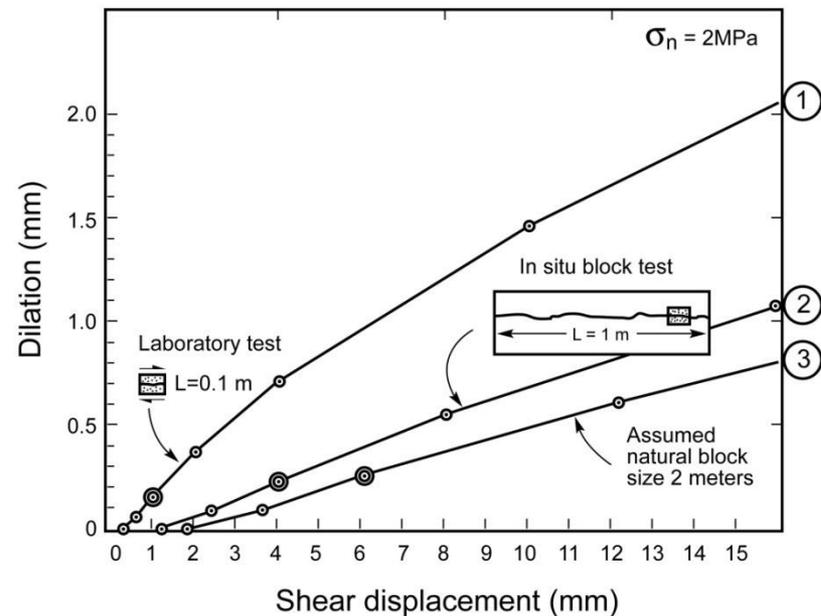
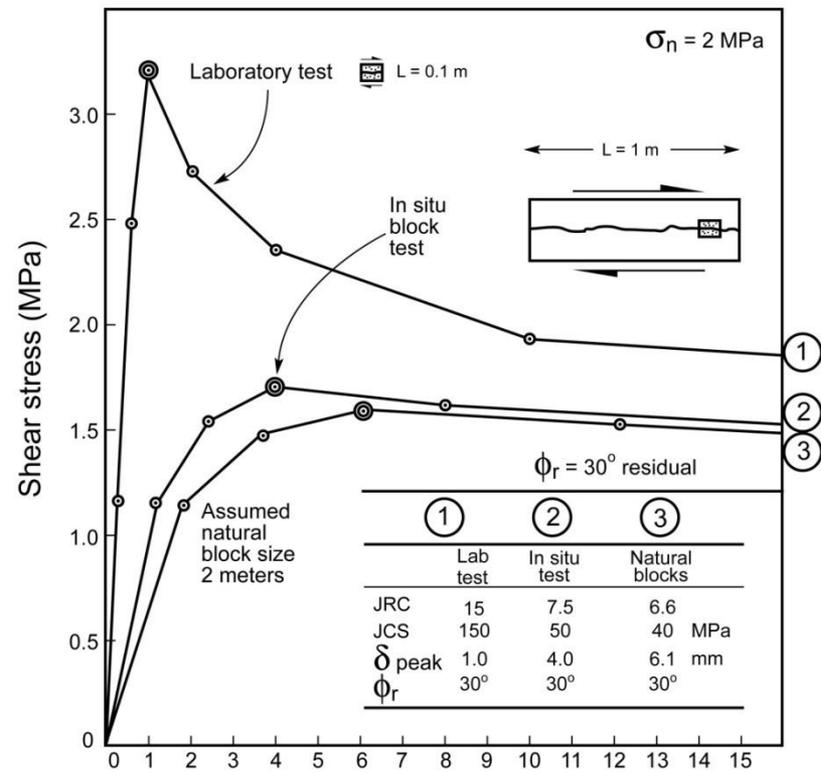
# The JRC<sub>mobilized</sub> concept

(Barton, 1982)

**ENABLES  
STRENGTH-  
DISPLACEMENT-  
DILATION  
MODELLING**



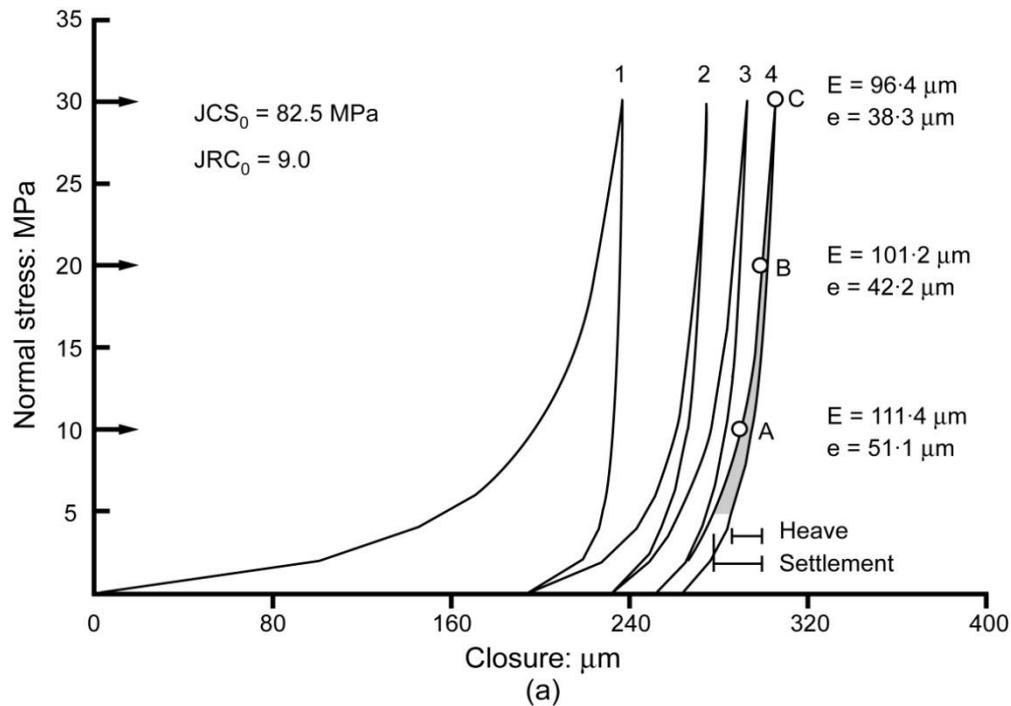
# Shear stress-displacement and dilation-displacement modelling (Barton, 1982).



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

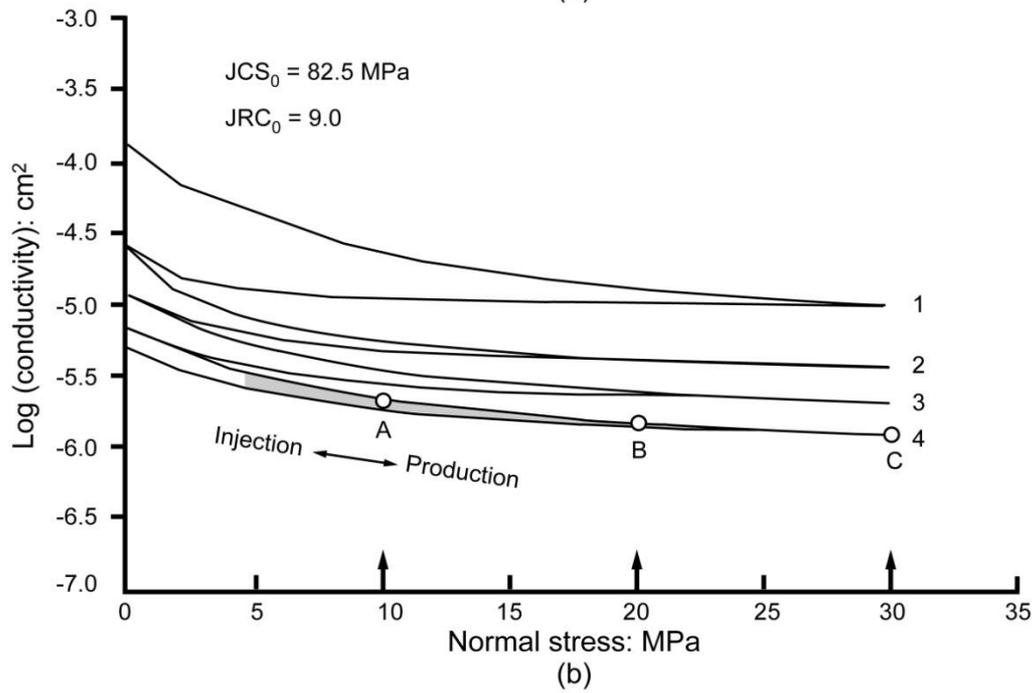
# FRACTURES ARE 'CLOSED' OR 'OPEN' DEPENDING ON ORIENTATION, STRESS LEVEL AND ROUGHNESS

- *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' //  $\sigma_H$ .
- Minerally 'bridged' partly open fractures can also be //  $\sigma_H$ .
- Mobilized friction coefficients  $\mu$  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.



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

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



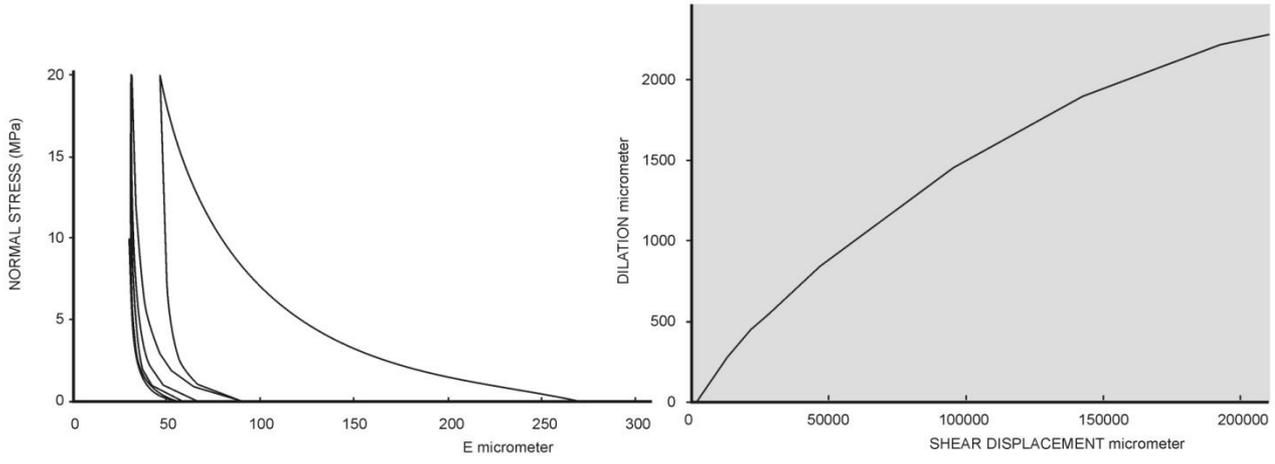
(from Schmidt hammer, tilt  
testing and profiling)

(Barton et al. 1985)

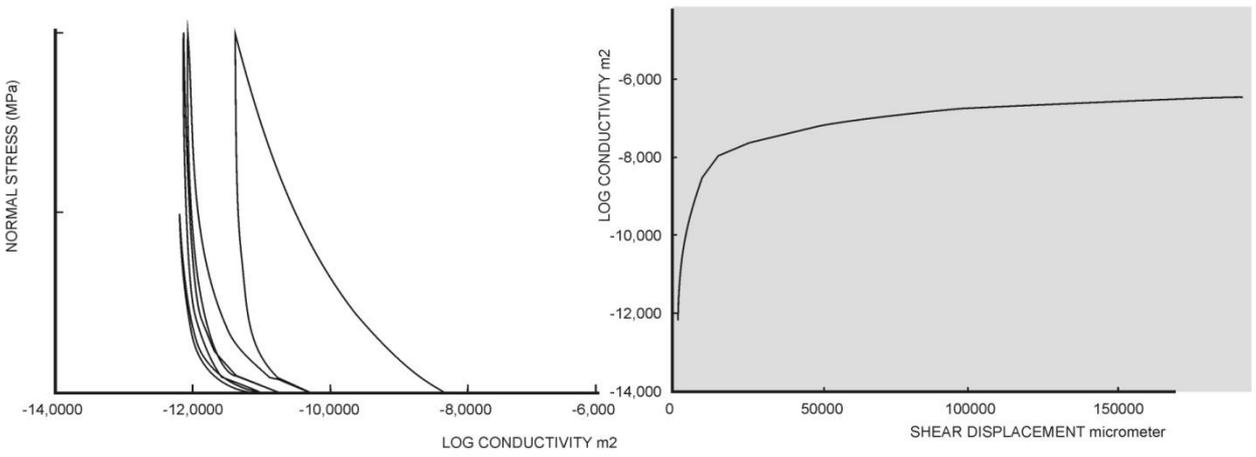
Barton Bandis Joint Model		NORMAL CLOSURE CALCULATION					
INPUT PARAMETERS		SNORM	CYCLE 1	CYCLE 2	CYCLE 3	CYCLE 4	CYCLE 5
JRC	10	LOAD	20	20	20	10	0 MPa
JCS	50	UNLOAD	0	0	0	0	0 MPa
SIGMAC	60	APERTURE	0,280	0,090	0,068	0,059	0,056 mm
CALCULATED PARAMETERS							
LOAD	KNI		13,5	20,17	23,4	25,41	26,33 MPa/mm
	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 PARAMETERS			FULL SCALE PARAMETERS		
JRC <sub>o</sub>	10,00		JRC <sub>n</sub>	7,25	
JCS <sub>o</sub>	50,00	MPa	JCS <sub>n</sub>	30,85	MPa
L <sub>o</sub>	0,10	M	DPEAK	2,42	mm
L <sub>n</sub>	0,50	M			
PHI <sub>r</sub>	33,00	DEG			
SIGMA <sub>n</sub>	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 normal stress.*

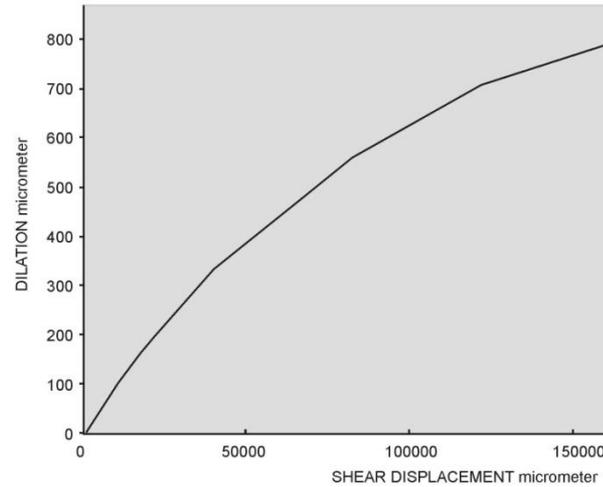
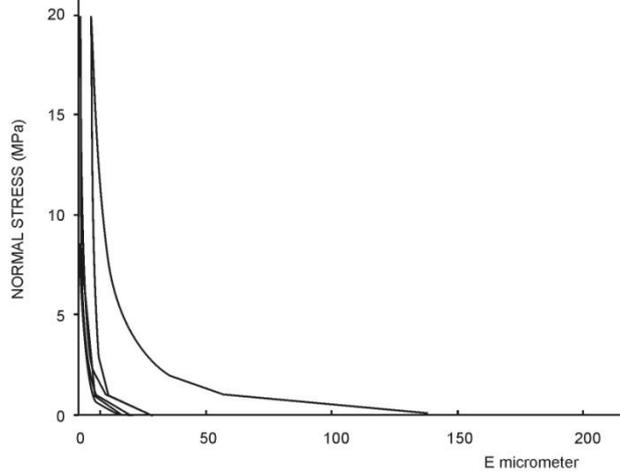


*Right: dilation and permeability caused by shear displacement.*

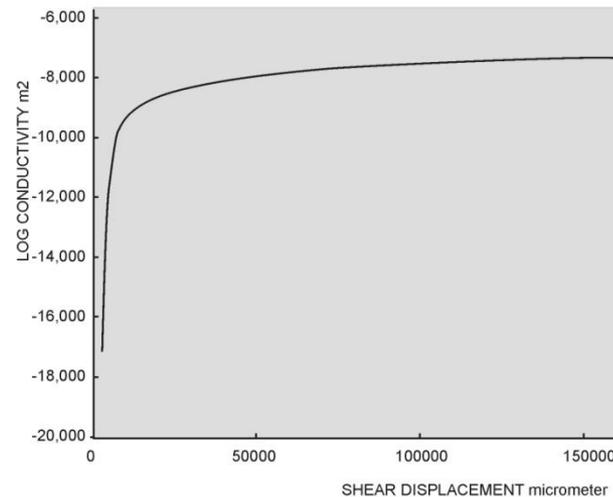
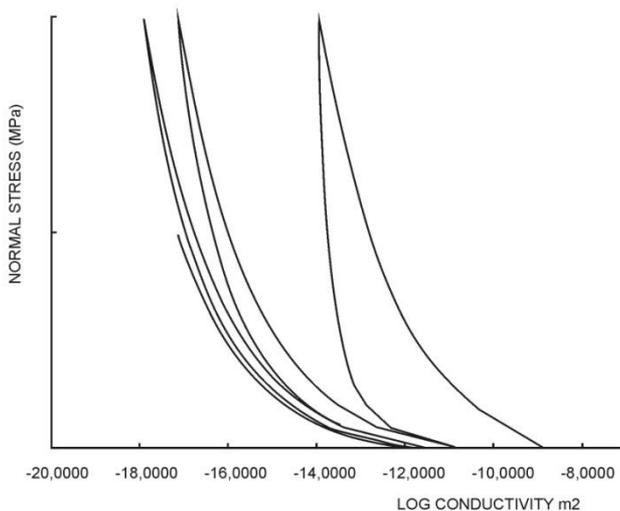
Barton Bandis Joint Model		NORMAL CLOSURE CALCULATION					
INPUT PARAMETERS		SNORM	CYCLE 1	CYCLE 2	CYCLE 3	CYCLE 4	CYCLE 5
JRC	5	LOAD	20	20	20	10	0 MPa
JCS	25	UNLOAD	0	0	0	0	0 MPa
SIGMAC	30	APERTURE	0,140	0,030	0,020	0,016	0,015 mm
		KNP	4,60E+03	2,80E+04	4,60E+04	1,40E+04	3,00E+01
CALCULATED PARAMETERS							
		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
PHlr	27,00 DEG	LFACT	0,01
SIGMA n	10,00 MPa	PHlr 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.*



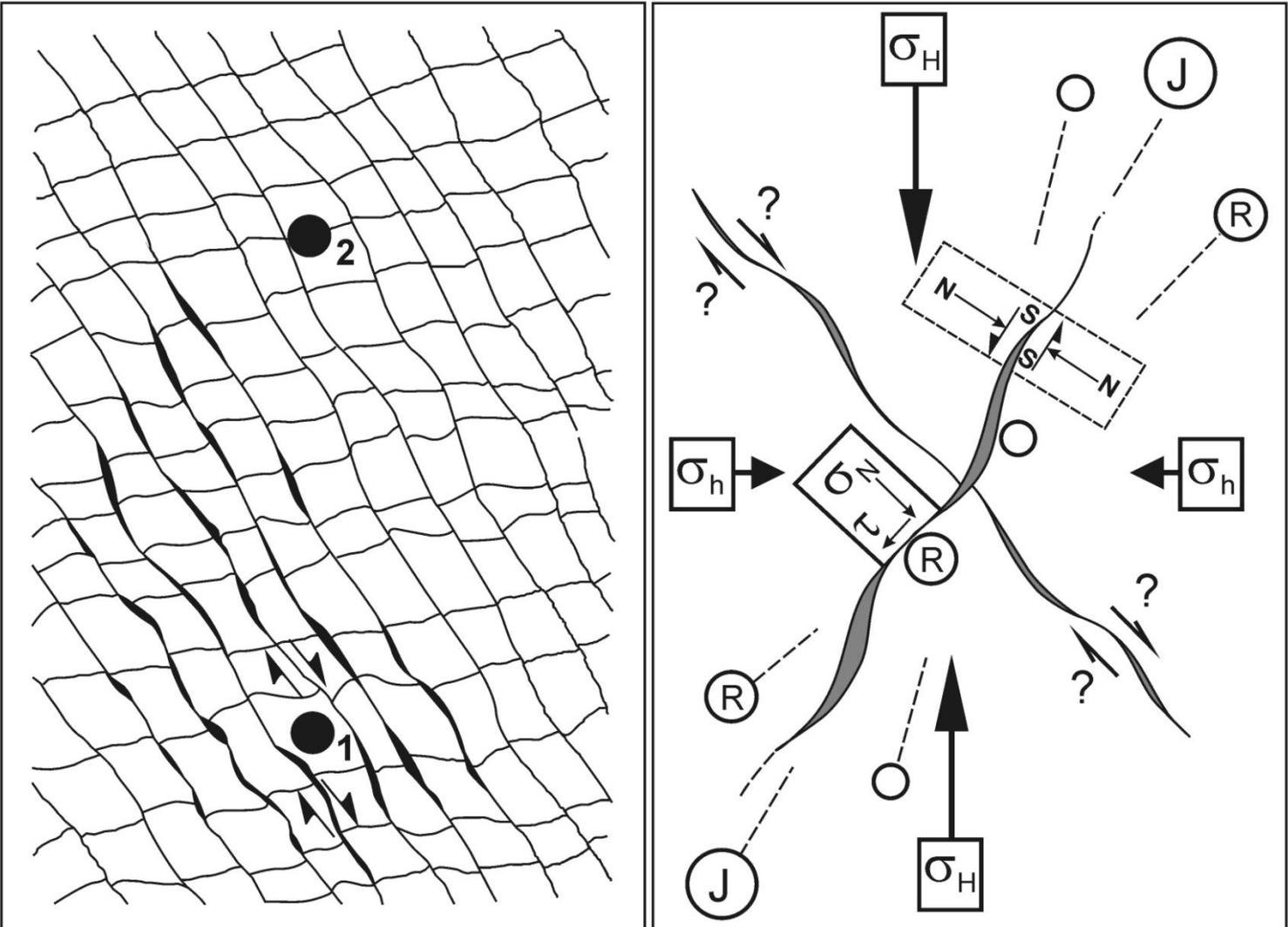
*Right: dilation and permeability caused by shear displacement.*

# An exaggeration of conducting and 'non-conducting'



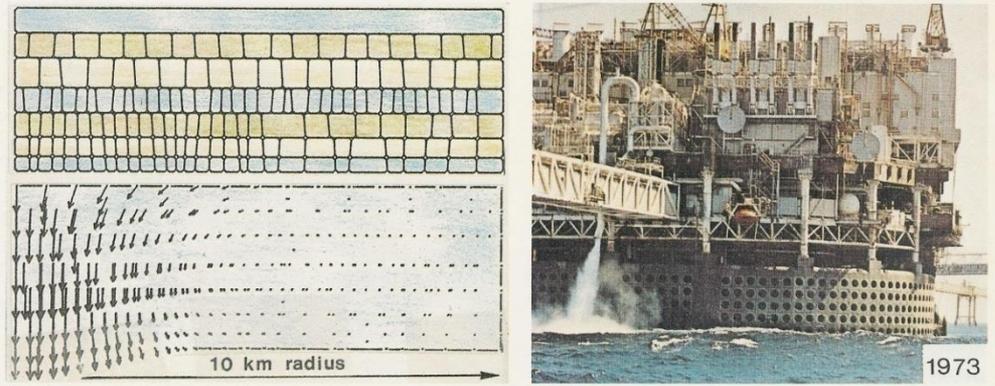
JOINT SETS THAT ARE UNDER SHEAR STRESS VERY COMMON, MAY BE AMONG BEST CONDUCTORS – FROM OBSERVATION IN WELLS, AND FROM ROCK MECHANICS THEORY

(Barton et al. 1985, Barton, 2006)



# **A GLIMSE OF EKOFISK compaction (from 1986 modelling)**

NUMEROUS ROCK MECHANICS PROCESSES AT MANY SCALES were SET IN MOTION BY (for example) PRODUCTION FROM FRACTURED CHALK AT THE EKOFISK FIELD, NORTH SEA, NORWAY



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

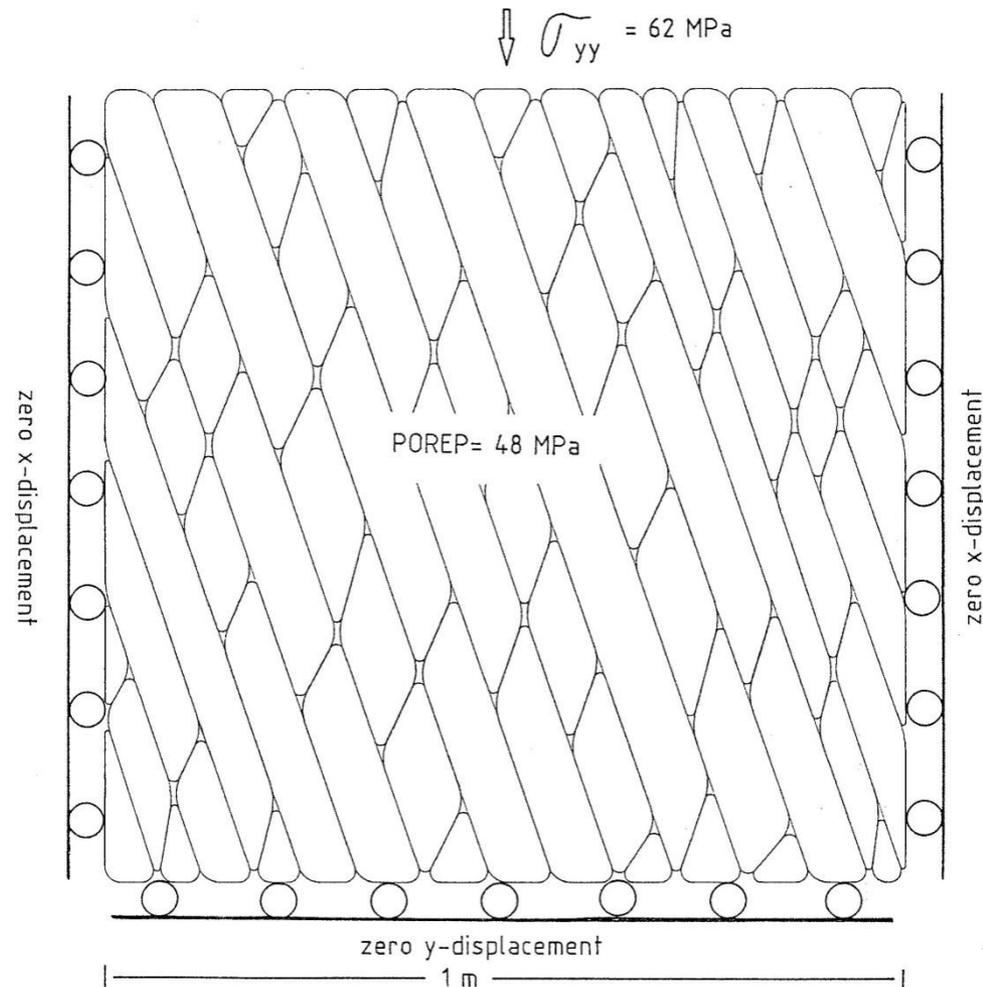
- Principal mechanisms:
- ❑ *Effective stress increase*
  - ❑ *Shearing of fractures*
  - ❑ *Compaction, subsidence*

# Slickensided fractures at Ekofisk

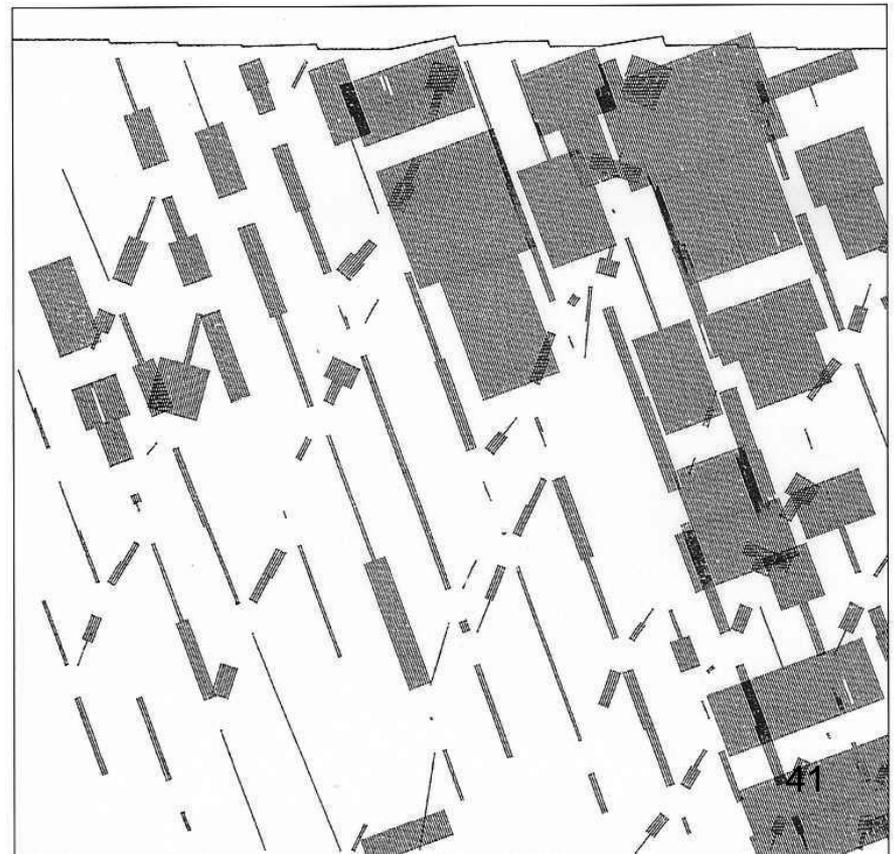
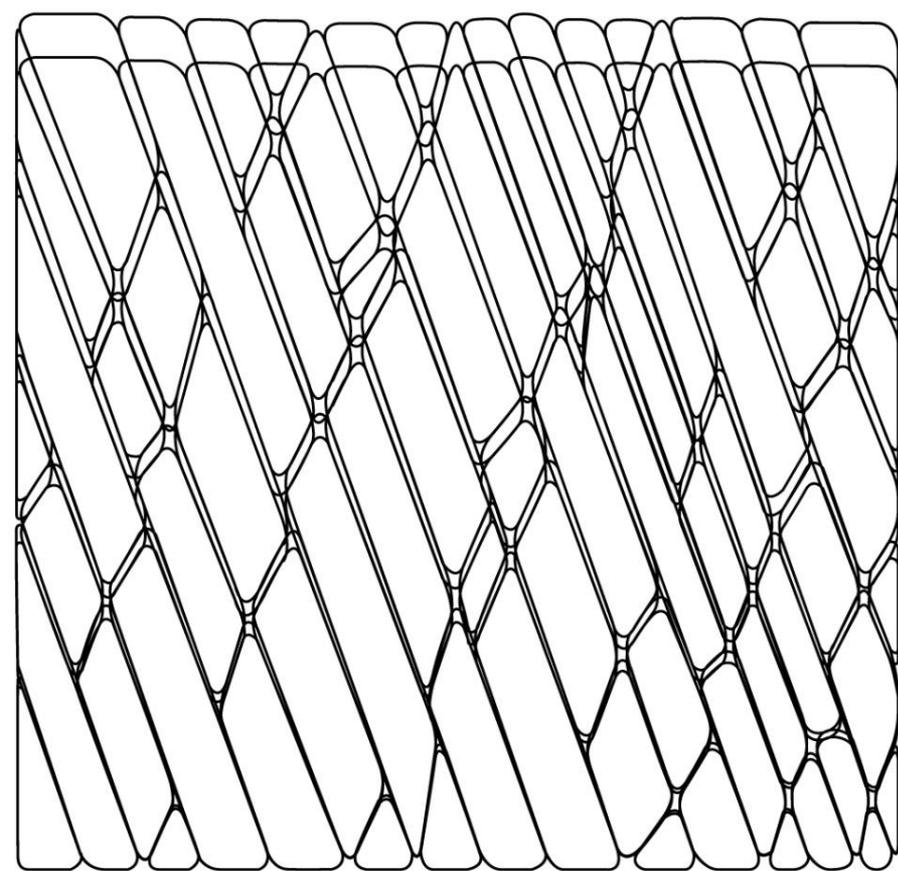
- ❑ Newly developed slickensides identified many years after exploration.
- ❑ Evidence of *shear-with-production* mechanisms.
- ❑ Discrete-element modelled (UDEEC-BB) in 1986/87 (Barton et al. NGL team) yet hardly believed, *prior to* subsequent recognition as production-related *slickensiding*.
- ❑ *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*'.

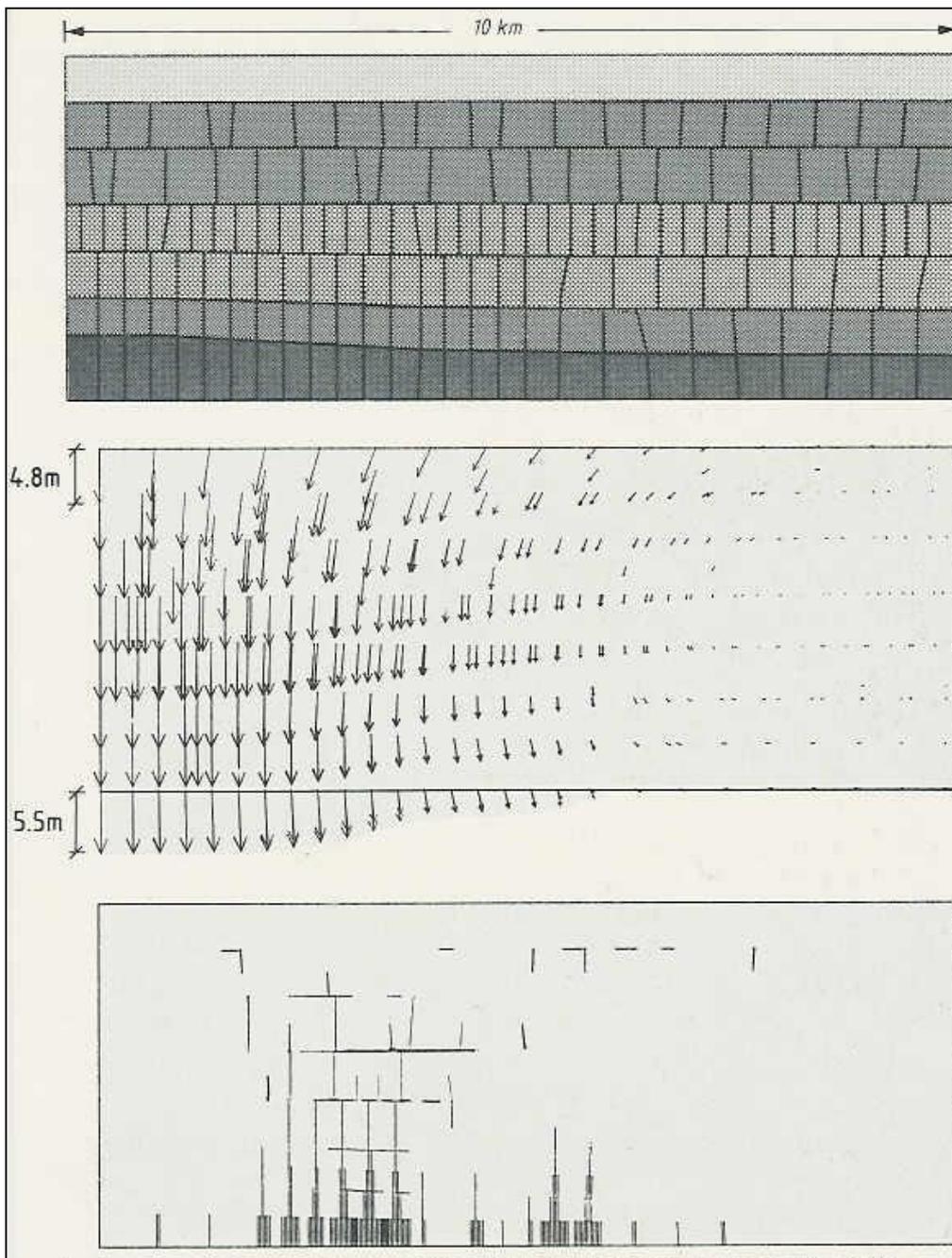
# Initial boundary conditions for discrete-fracture modelling of 2D/3D idealized '1m block' of Ekofisk chalk

(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 .





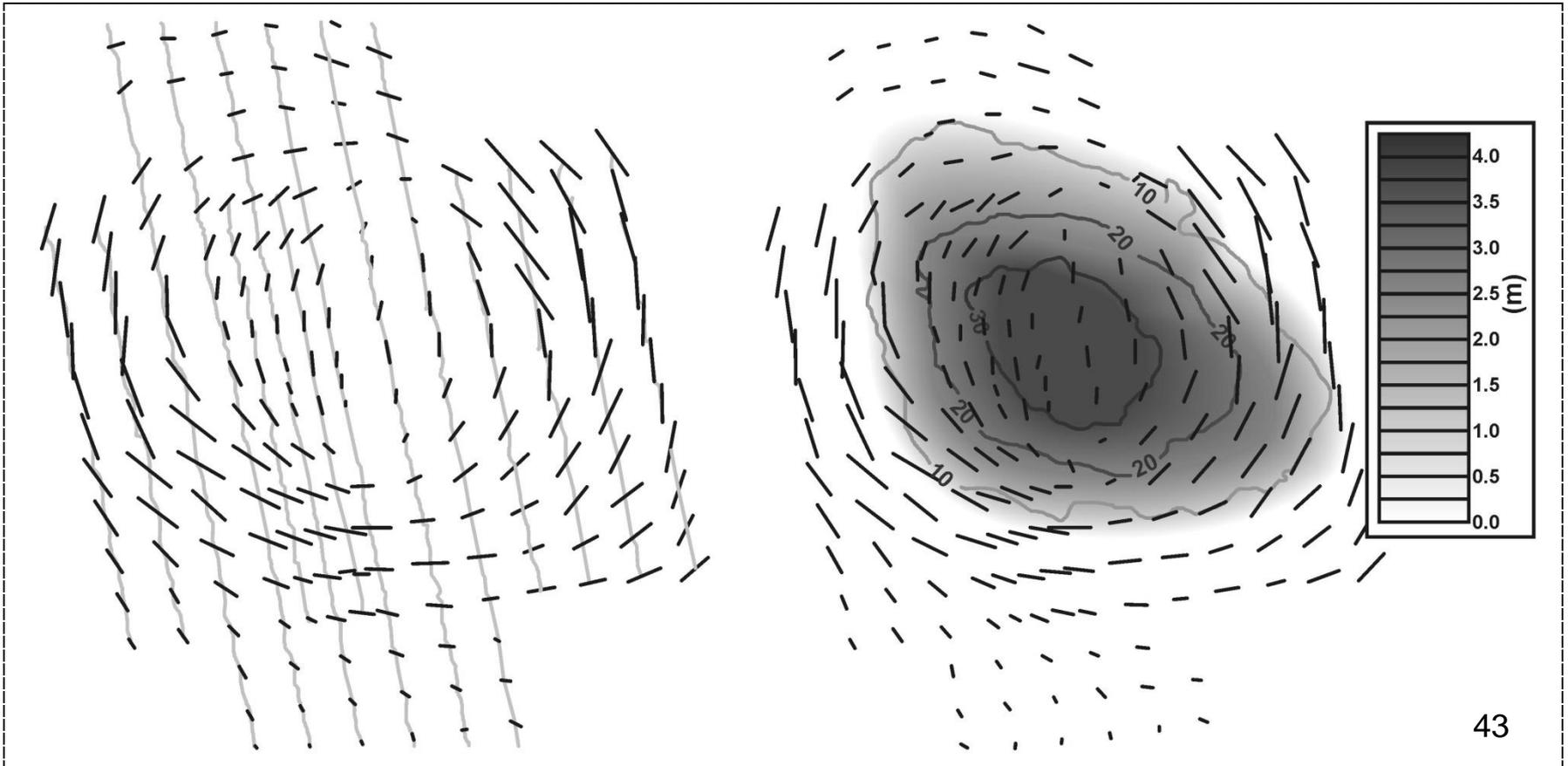
Large-scale (axisymmetric, 10 km radius) distinct element (UDEEC) modelling of the *Ekofisk* overburden response to modelled compaction, using numerous *coarsely* 'bedded-jointed-and-faulted' (2D) models (Barton et al., 1986, 1988). Note 'block' opening and shear.

**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??

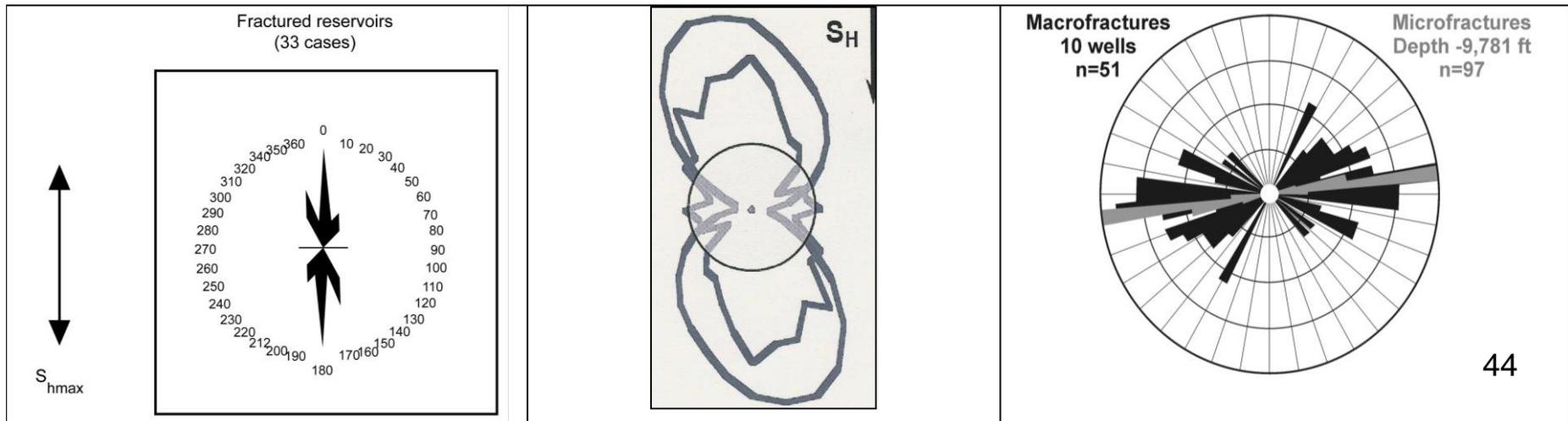
Olofsson and Kommedal, 2002.

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



# 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??



# 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. 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

