PERSONAL NUCLEAR-WASTE-DISPOSAL (rock mechanics based) RESEARCH EXPERIENCES 1980-2010

(USA*, CANADA, SWEDEN*, UK, NORWAY)

Nick Barton, (with TerraTek, NGI, then as NB&A)

A WIDE RANGE OF EXPERIENCES AND SOME USEFUL LESSONS (in TEN locations)

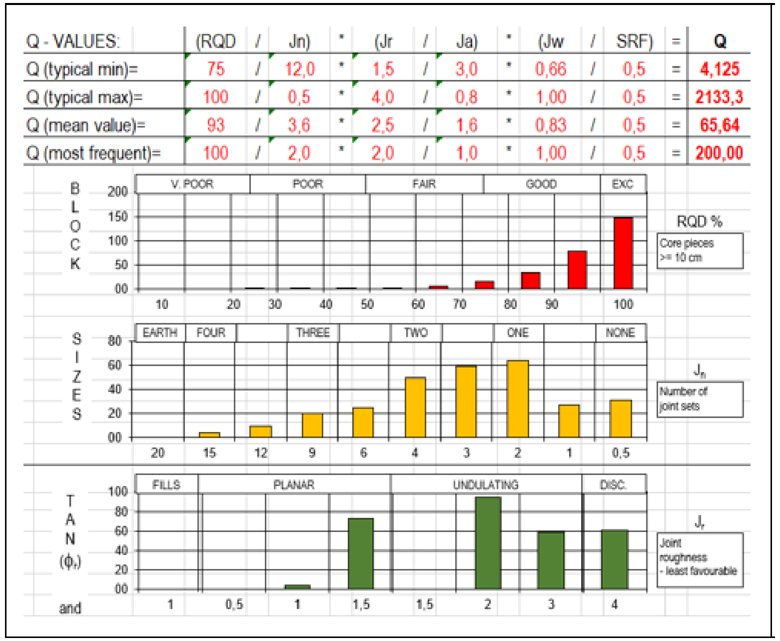
1. BWIP: Basalt waste isolation project, Hanford, Washington, USA 1981
2. ONWI: Office of nuclear waste isolation Heated Block Test, TerraTek, USA 1980-1981
3. AECL/CANMET: Atomic Energy of Canada, coupled modelling using B-B-B prior to UDEC-BB 1983

4a. DoE: Reviews of two consortia's rock mass characterization of Yucca Mountain, USA 1998, 2001

4b. AMBIENT and THERMAL OVER-CLOSURE consequences

5. SKB: Swedish Nuclear Fuels studies: Stripa SCV site characterization and validation 1986 -1990
6. Äspö ZEDEX velocity, modulus. APSE pillar study, tunnel characterization 1991 -1992, 2003
7. Simpevarp, surface and 2x 1000m deep borehole core Q-histogram 2003-4
8. Forsmark: surface and 2x 1000m deep borehole core Q-histogram 2007 – 2008

9. UK Nirex Geotechnical Consultant: Sellafield Repository and RCF studies. NGI/Atkins. 1990 -1996
10. Norwegian Himdalen ILW 'mini-repository' 1992-1994. (To be replaced).



Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	75	/	12,0	*	1,5	/	3,0	*	0,66	/	0,5	=	4,125
Q (typical max)=	100	/	0,5	*	4,0	/	0,8	*	1,00	/	0,5	=	2133,3
Q (mean value)=	93	/	3,6	*	2,5	/	1,6	*	0,83	/	0,5	=	65,64
Q (most frequent)=	100	/	2,0	*	2,0	/	1,0	*	1,00	/	0,5	=	200,00

EXAMPLES:

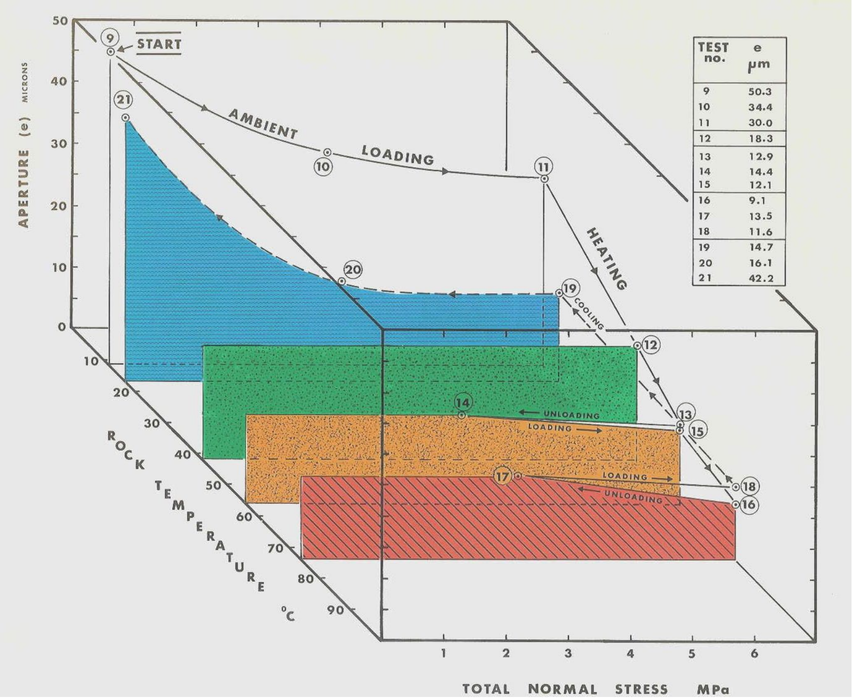
CHARACTERIZATION STUDIES FOR SKB IN SWEDEN (as NB&A)

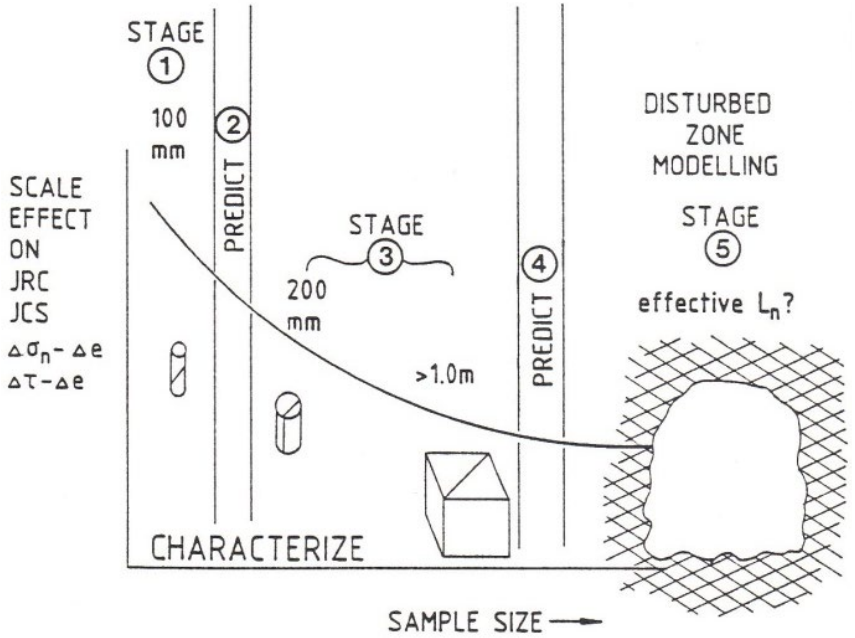
DEEP CORE, KFM-01A AT FORSMARK.

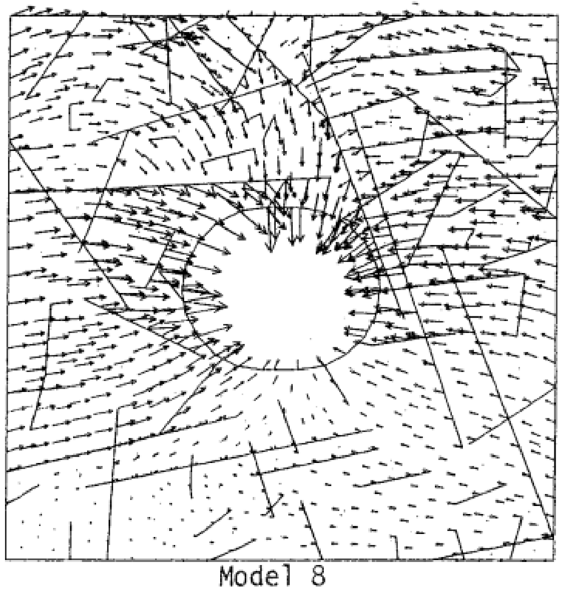
EXPERIMENTAL TUNNEL (APSE / Äspö)

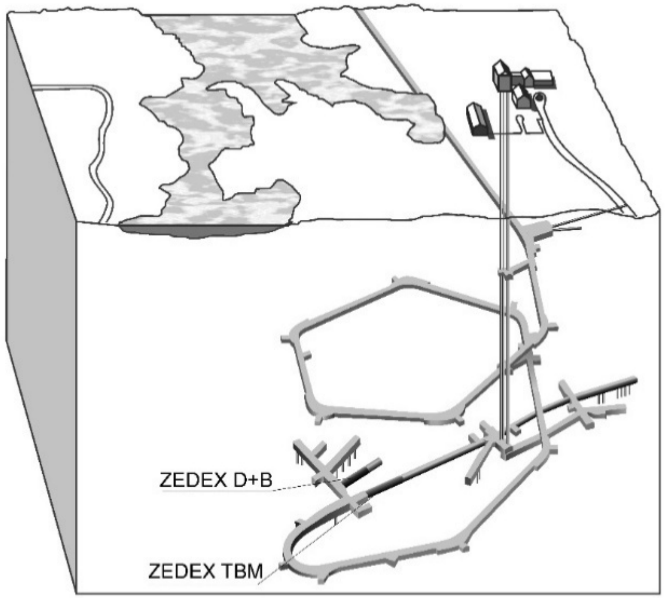
'FRACTURE ZONES' AT SURFACE AND IN DEEP CORE KSH-01A AT SIMPEVARP.

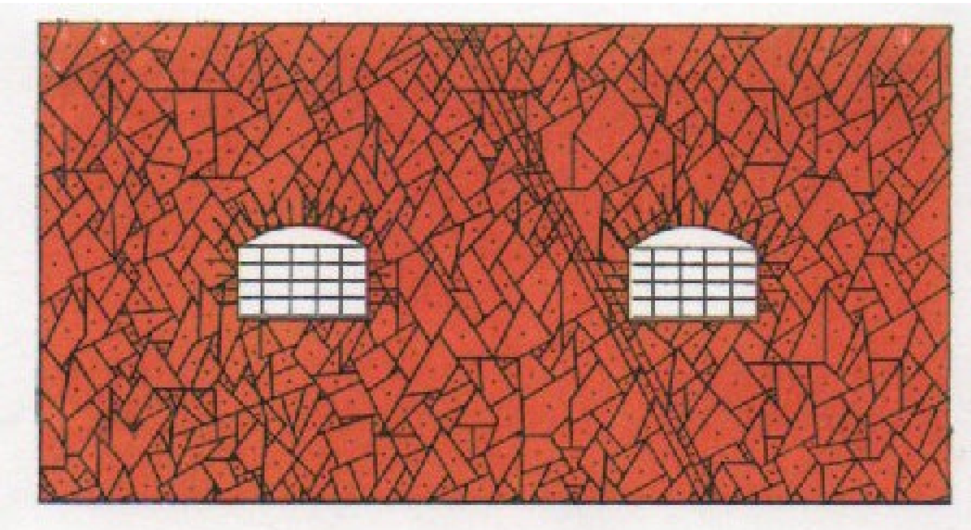
FIRST 3 Q-PARAMETERS STATISTICS IN APSE PILLAR TUNNEL.











HEATED BLOCK TEST: ONWI

SCV, STRIPA, UDEC-BB: SKB

ZEDEZ Vp – Qc at Äspö: SKB

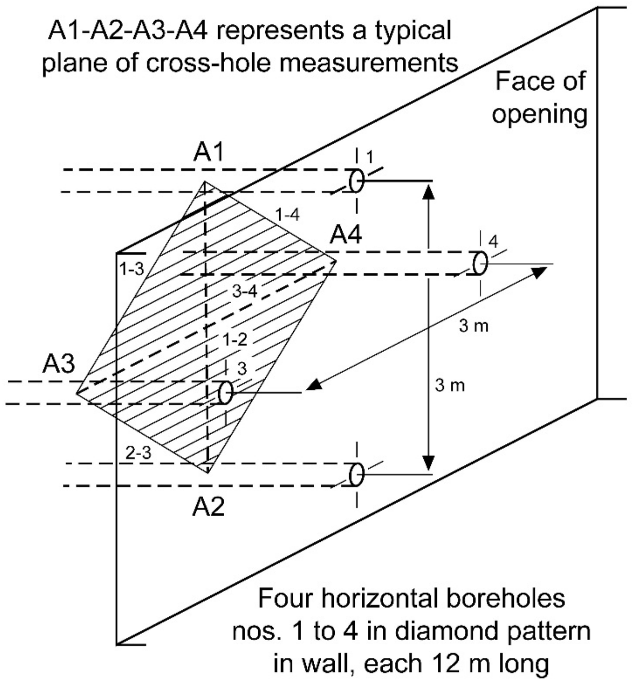
ILW CAVERNS, UK NIREX

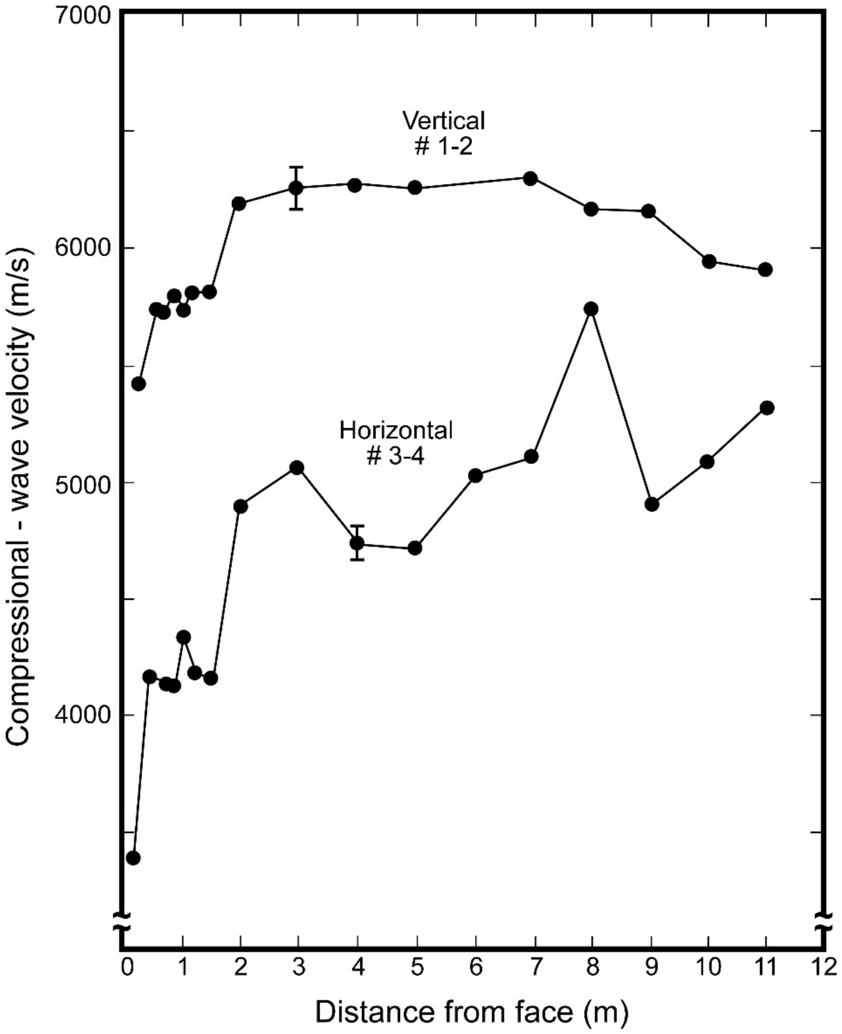
1). BWIP – HANFORD, WASHINGTON STATE (1981)

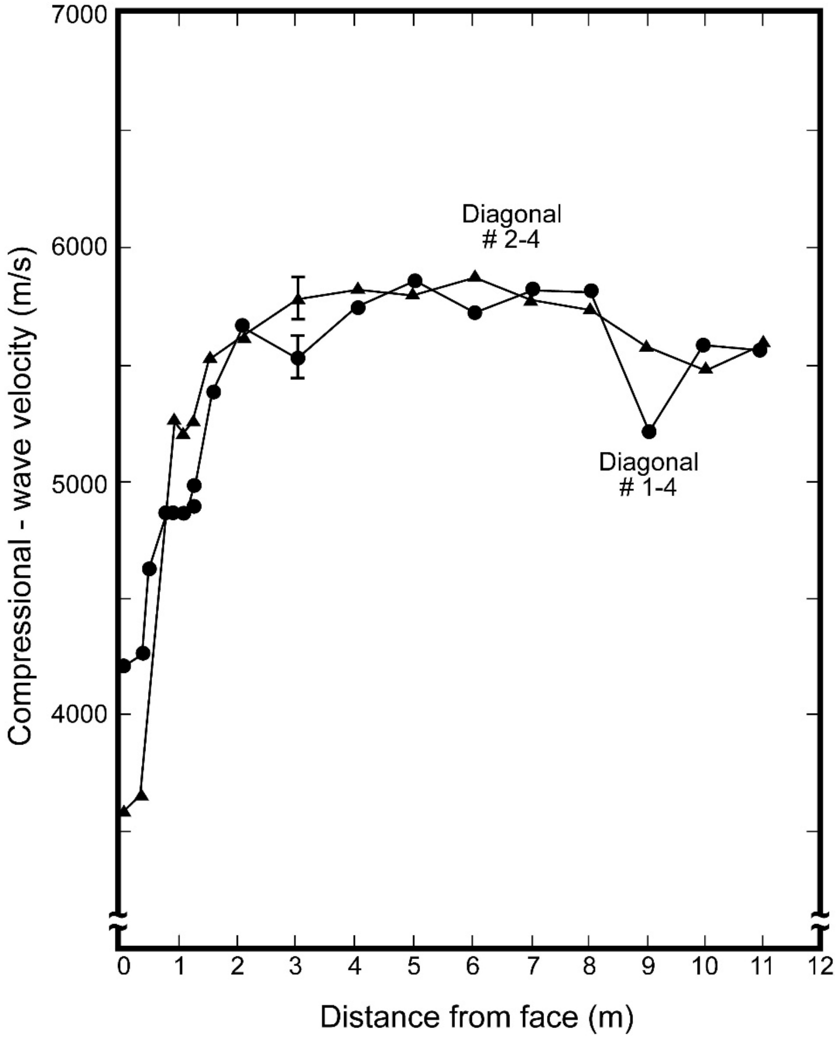
THICK EXPOSURE OF THE 'PLANNED' COHASSET FLOW ALONG THE COLOMBIA RIVER FAR WEST OF HANFORD SITE, WASHINGTON STATE

(OF COURSE) BASALT HAS TOO MUCH PERMEABLE JOINTING – AND SERIOUS EDZ BEHAVIOUR IS LIKELY: A HOPELESS USA 'CHOICE'.

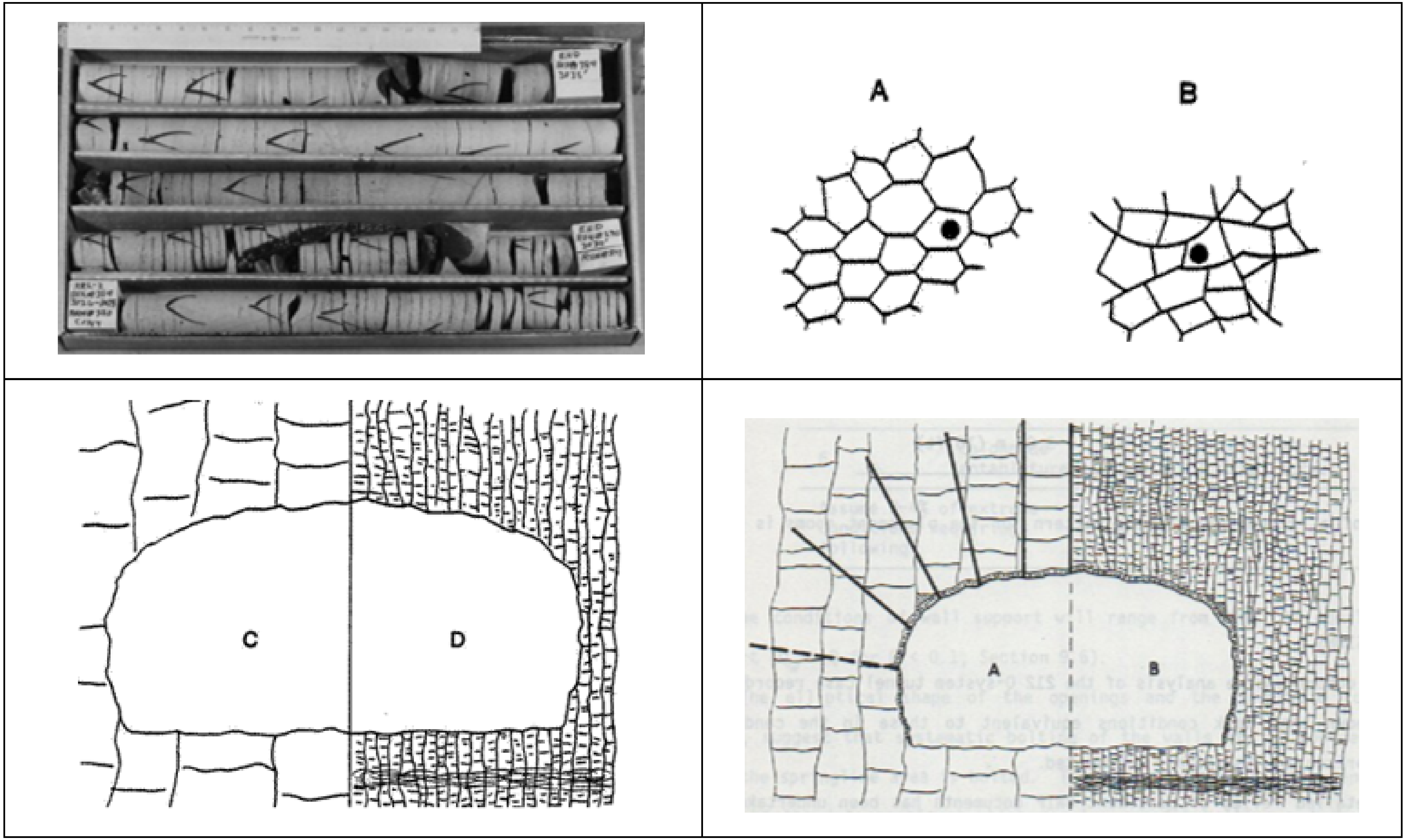
EDZ INVESTIGATIONS IN SHALLOW COLUMNAR BASALT IN THE BWIP PROJECT. King et al. 1980







Cross-hole velocity: vertical, diagonal, horizontal EDZ. (Crack density, saturation).



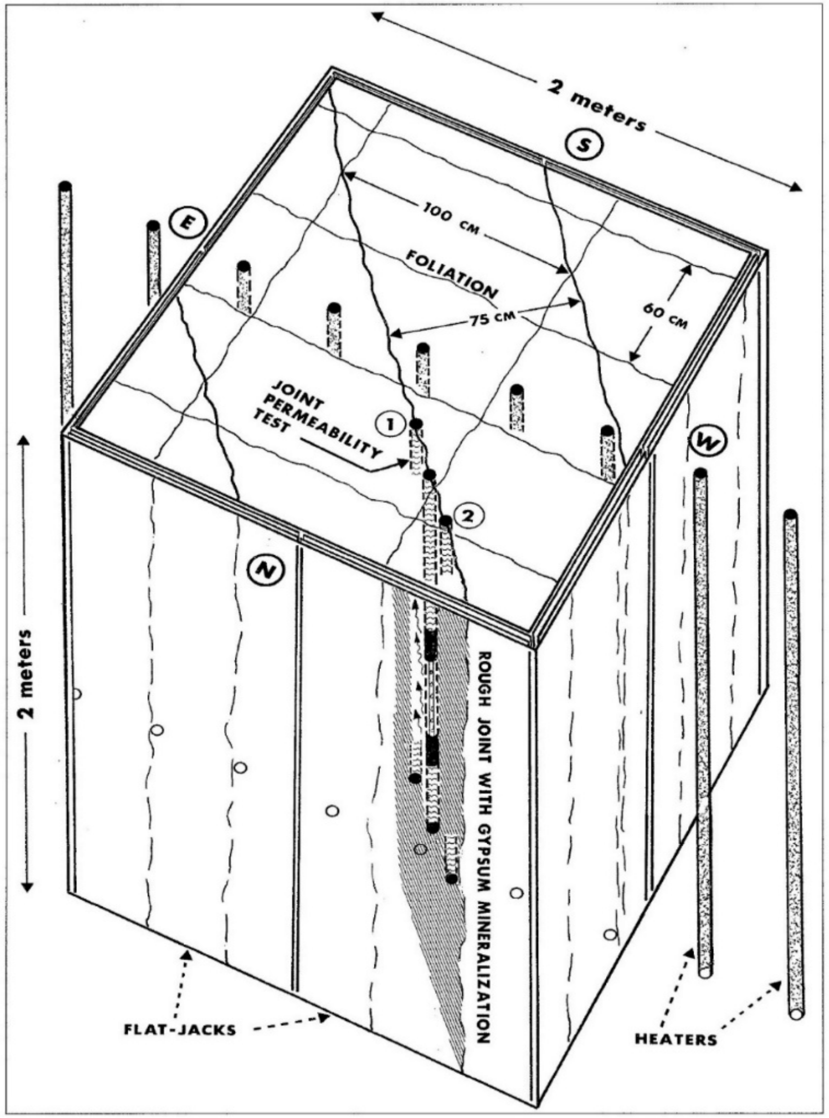
COLUMNAR BASALT AND THE MORE RANDOM ‘ENTABLATURE’.

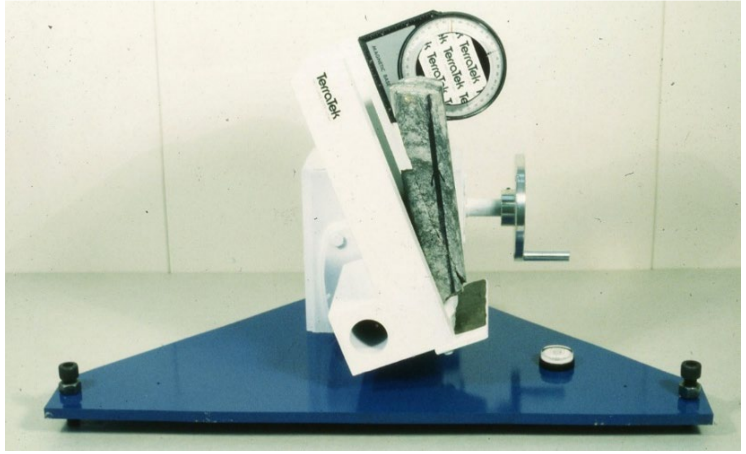
CORE DISCING: 900m DEEP, ANISOTROPIC STRESSES: 60, 40, 20MPa.

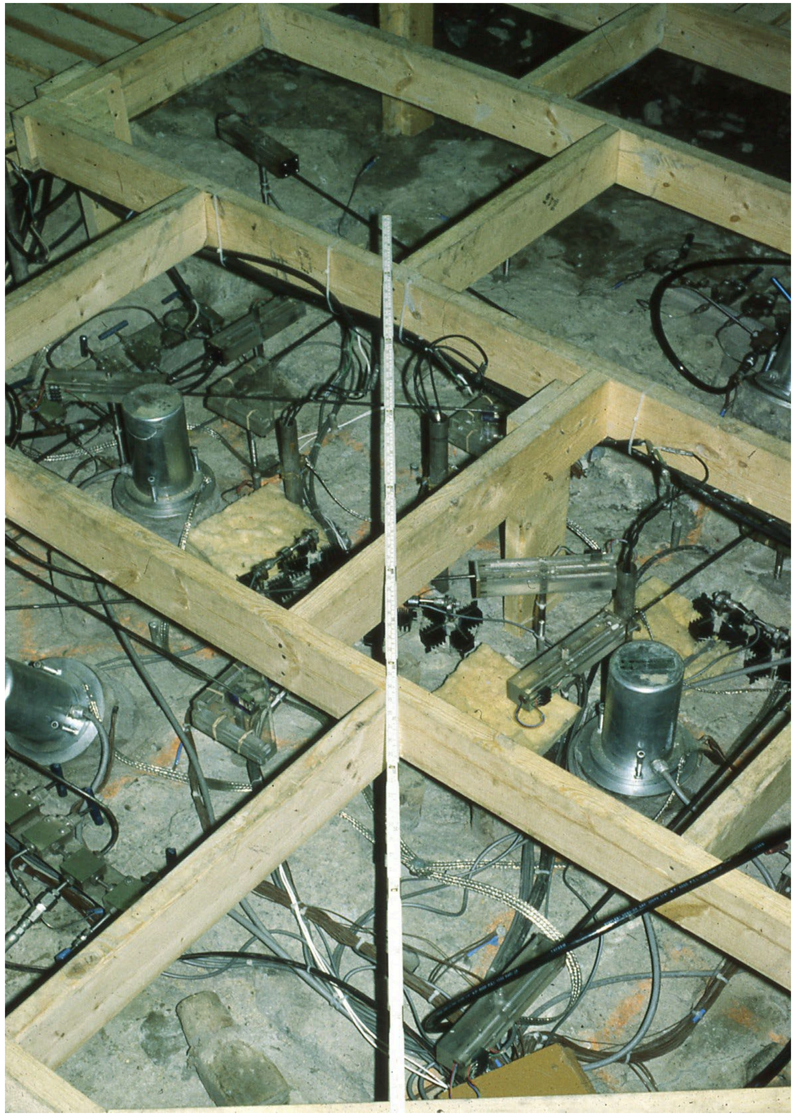
DIFFERENT SUPPORT NEEDS IN A REPOSITORY.

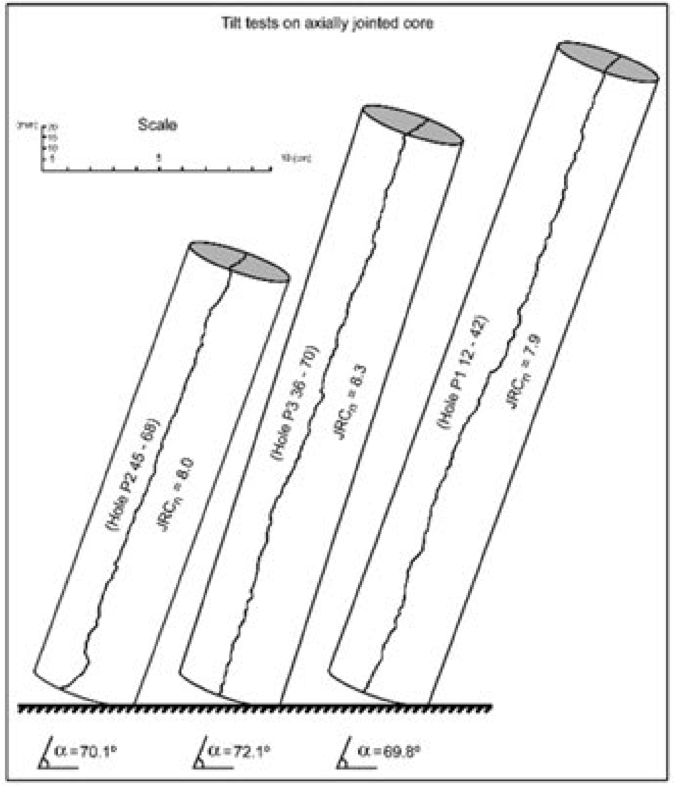
Barton, 1982

2) HEATED BLOCK TEST (TerraTek for ONWI 1980-1981) Hardin et al. 1981.

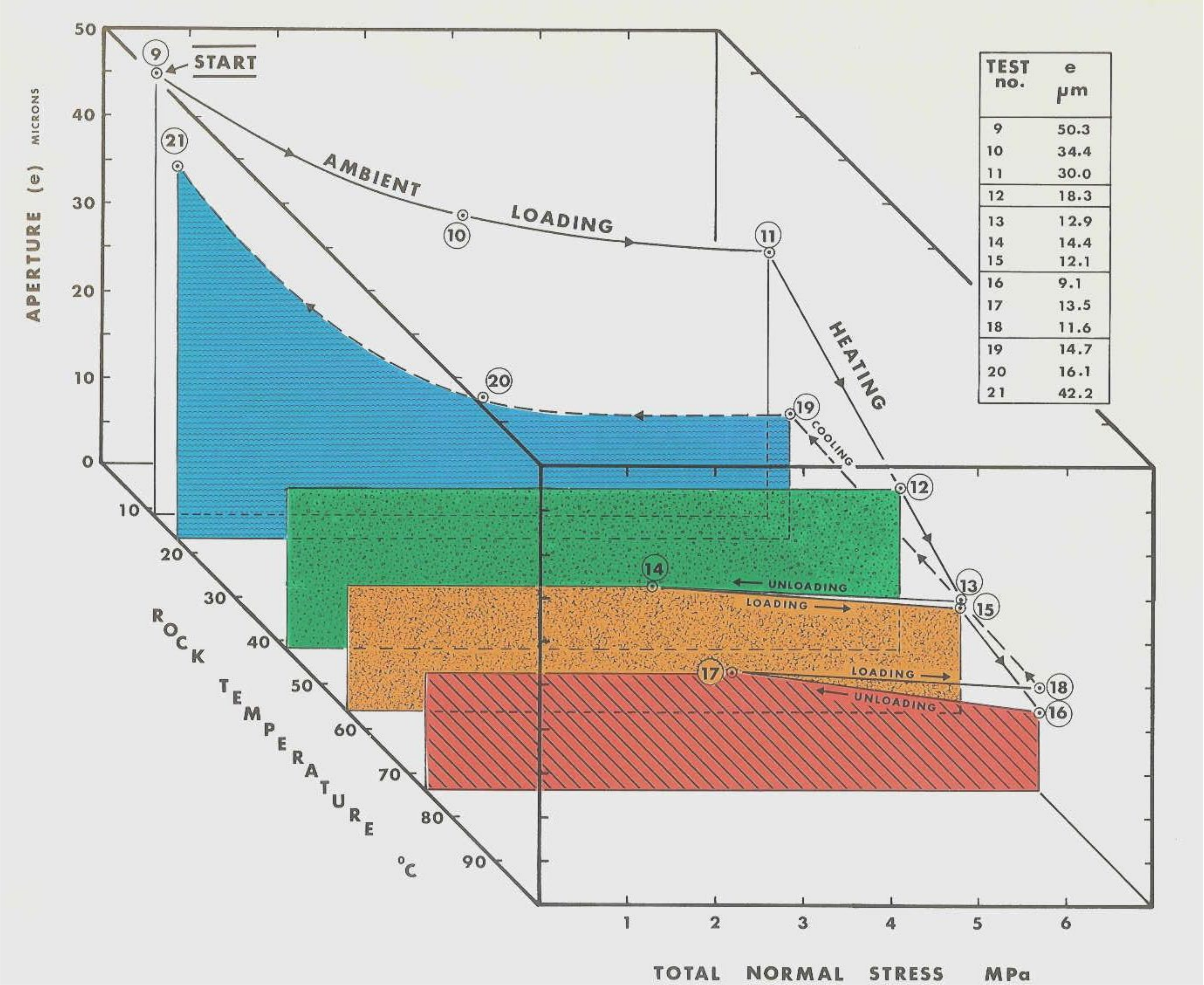








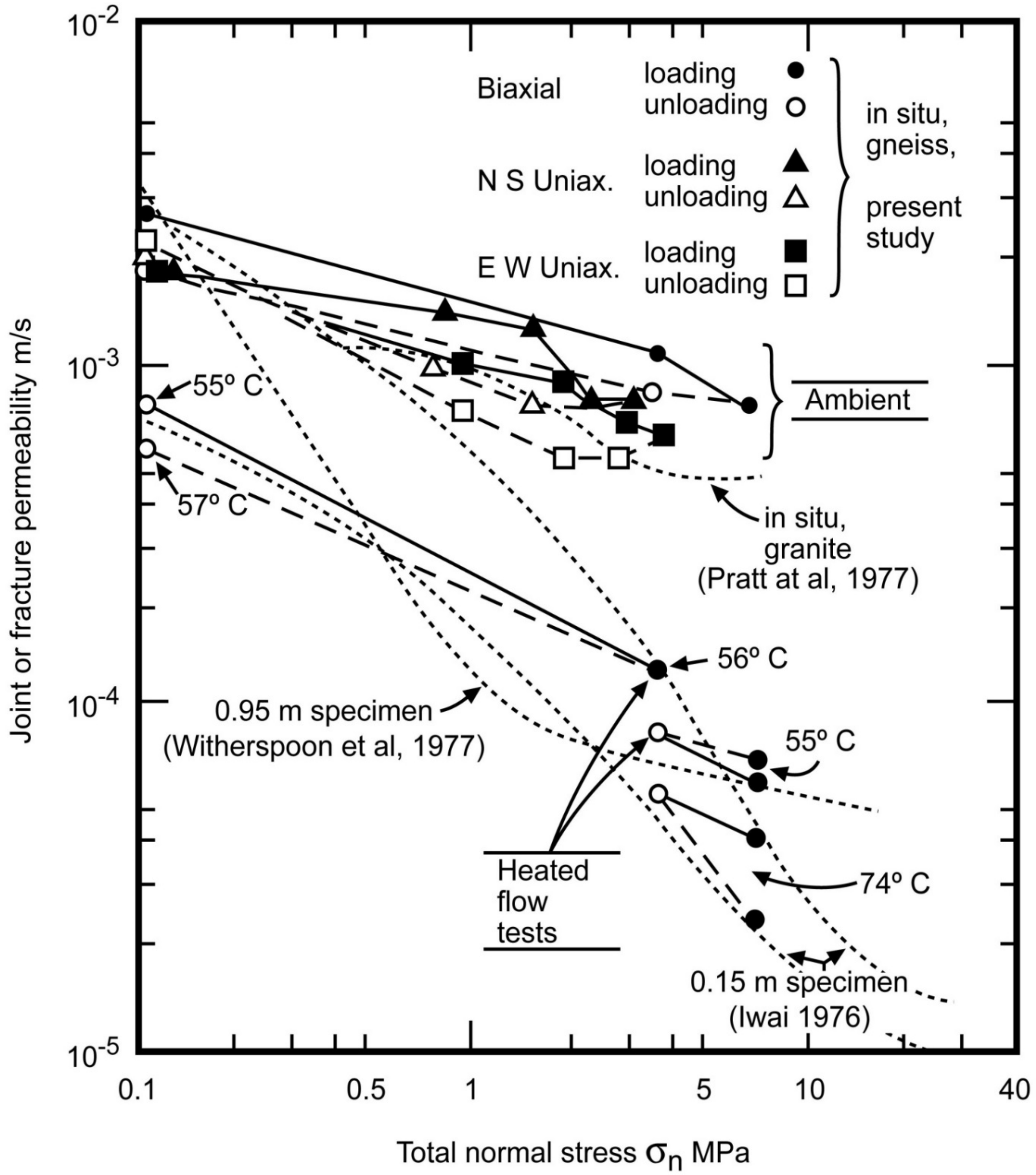
The 10 ‘standard’ samples of Barton & Choubey, 1977. Permeability tests were conducted in the rough diagonal joint shown on the right. Barton, 1982.



Results of HTM coupled testing:

FLOW (e) 50 – 9 µm
HEAT (15°-75°C)
NORMAL STRESS (0-7MPa).

Hardin et al. 1981
Barton, 1982.



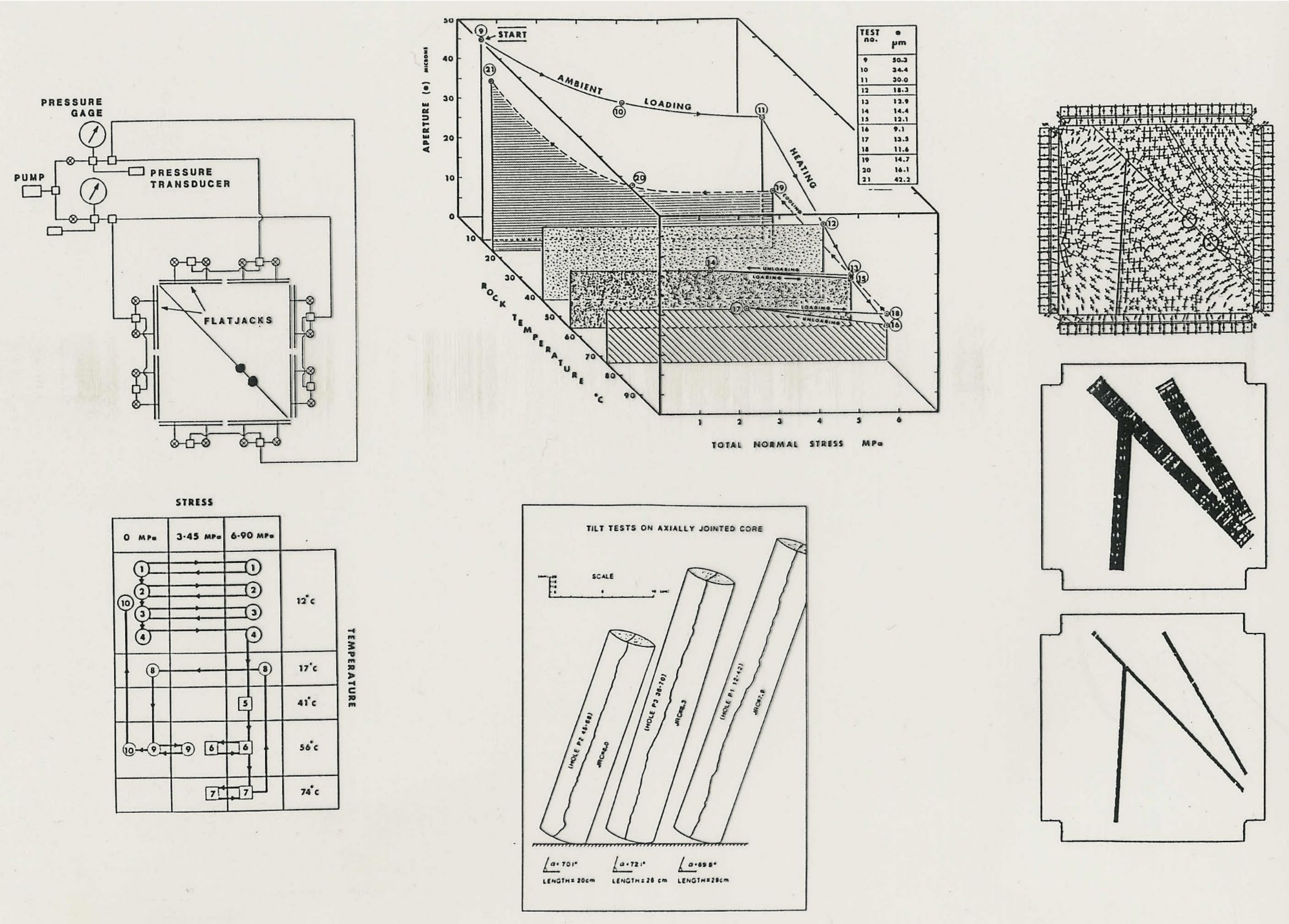
COMPARE AMBIENT CURVES WITH THE HEATED TESTS (lower curves).

Thermal over-closure.....no stress increase needs to be involved.

$\Delta e = 30 \rightarrow 9\mu m$

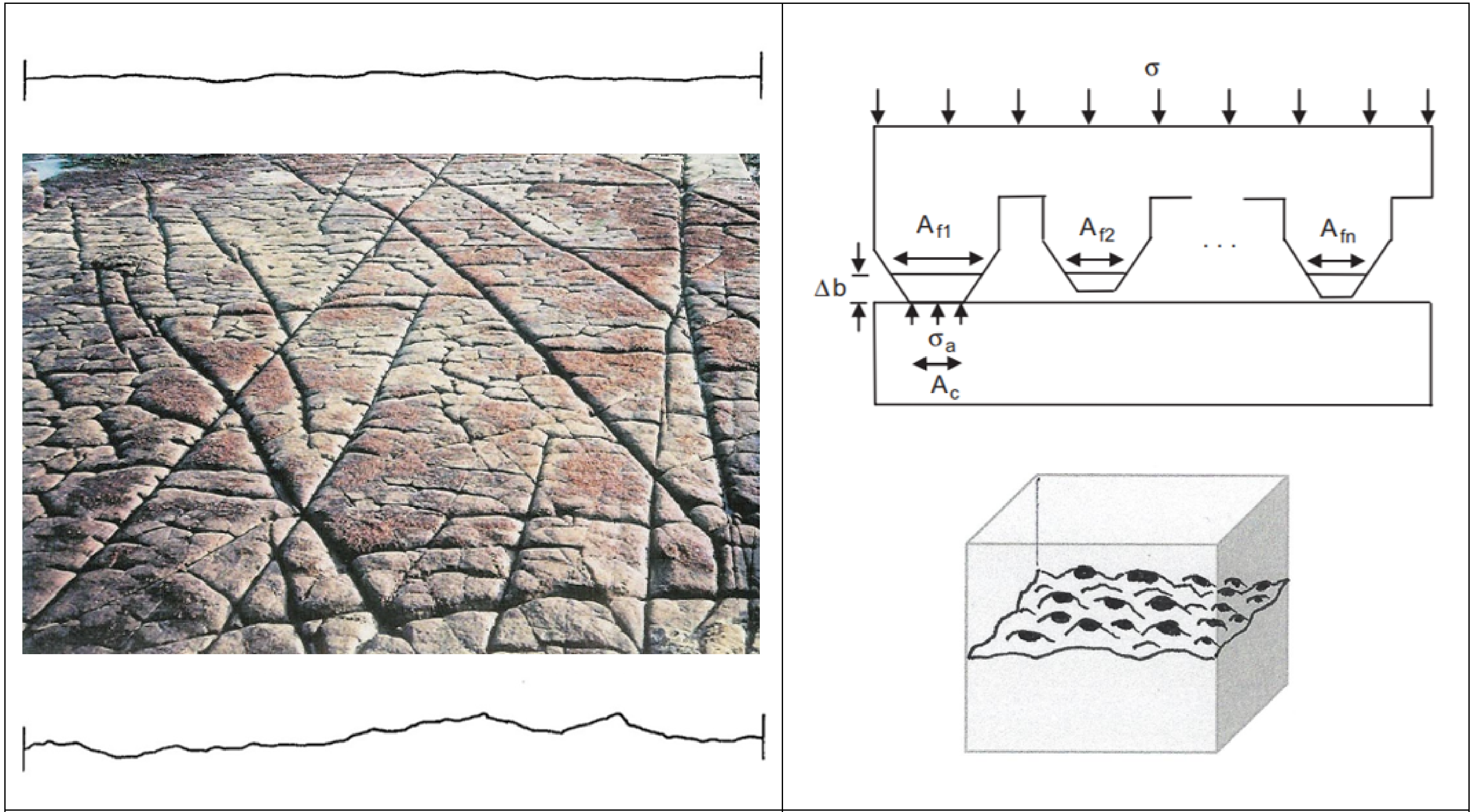
Δk: 1/10 x reduction)

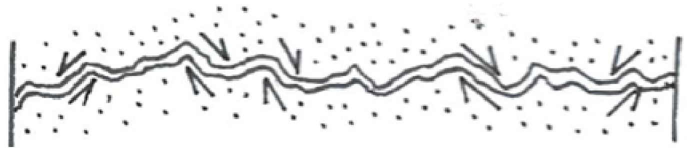
Barton, 1982.



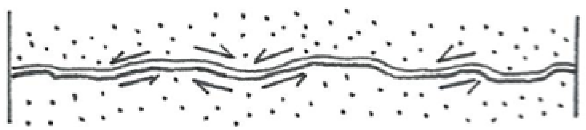
Heated block test and some permeability related UDEC-BB results (right).

Note differentiated apertures (E) and (e) in UDEC-BB model.





Frictional interlock – over-closure possible



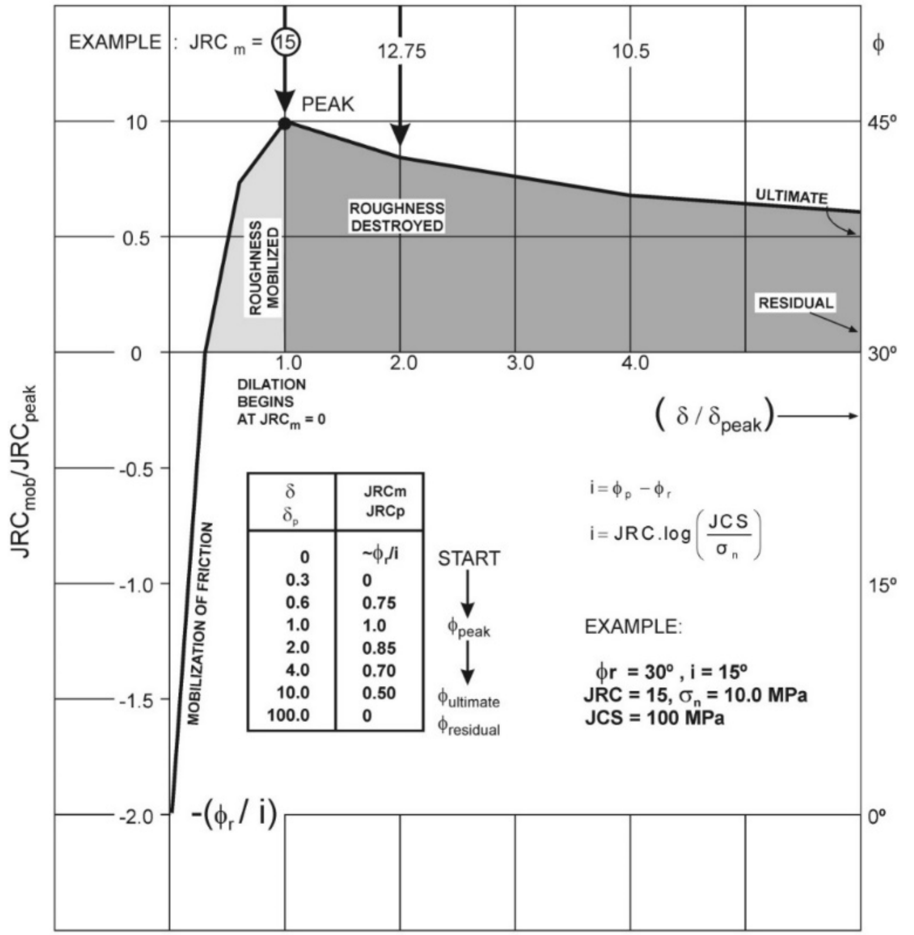
No frictional interlock – no over-closure

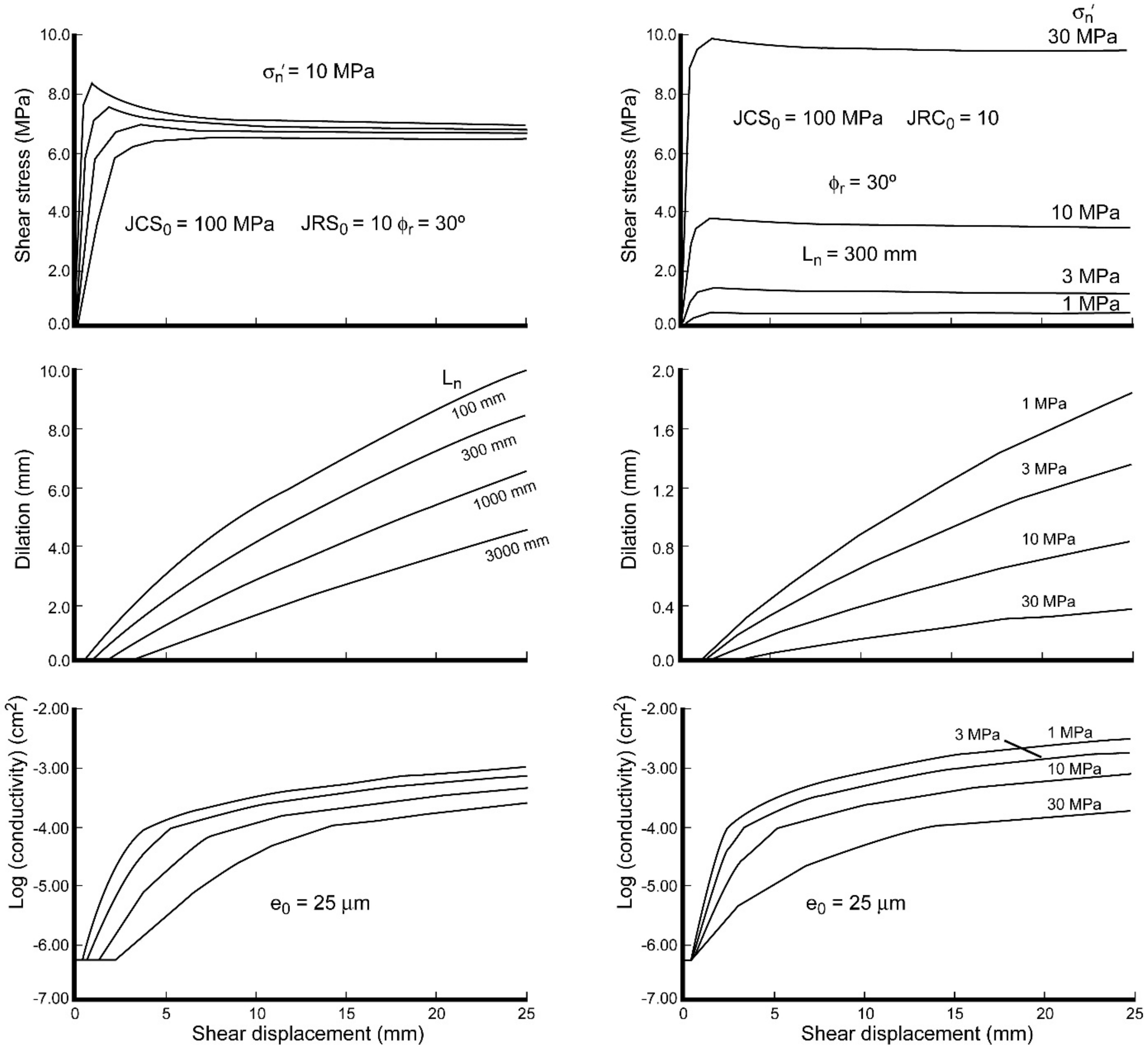
THE ROUGH DIAGONAL JOINT IN THE HEATED BLOCK TEST EXHIBITED THERMAL OVER-CLOSURE TENDENCIES.

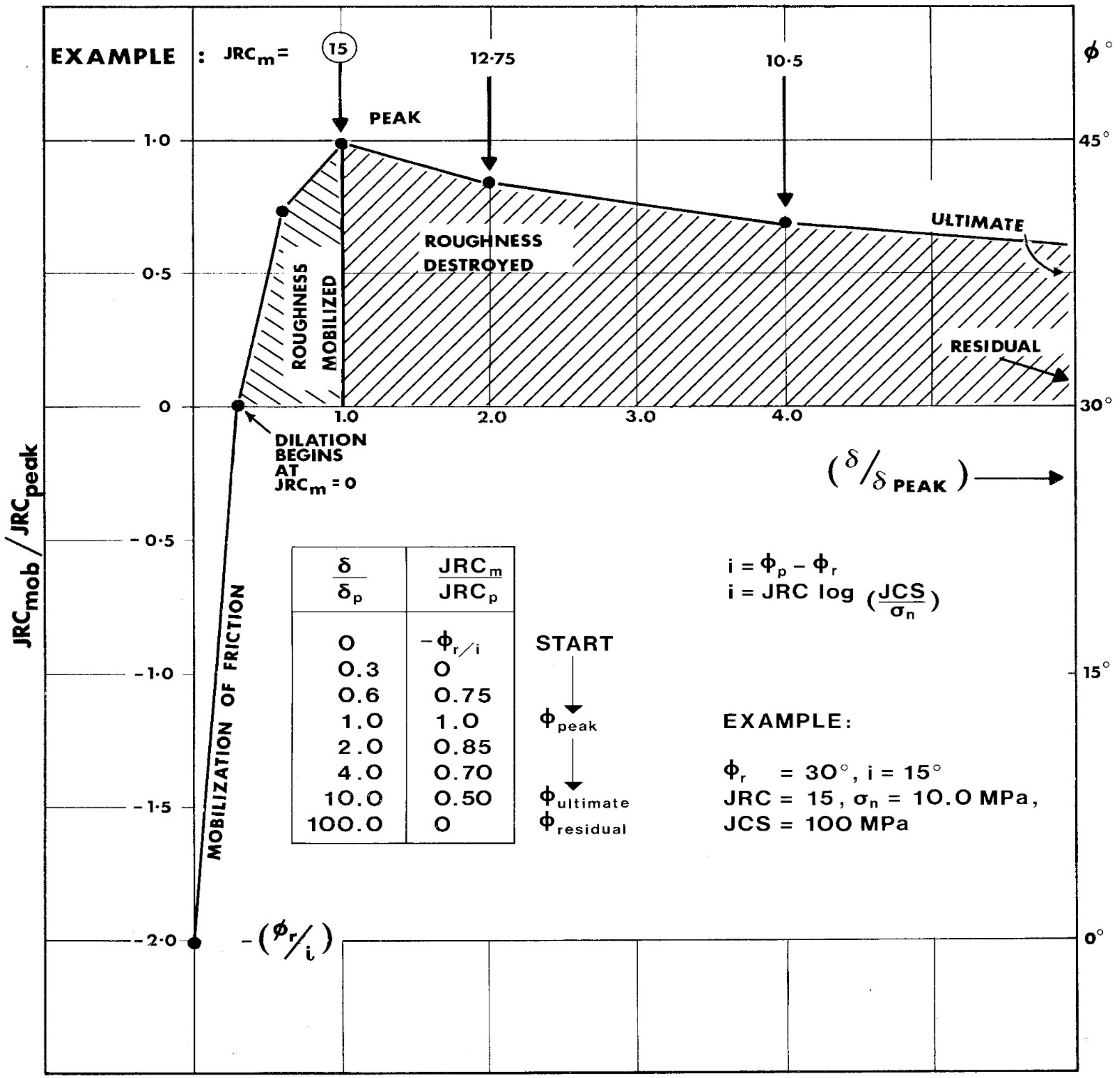
Bottom left: (friction interlock) is the most likely explanation.

(Remember 180° tilt test!)

3) AECL/CANMET TerraTek report on hydrothermomechanical coupling (Barton & Bakhtar, 1983/1987). Two volumes. Examples:



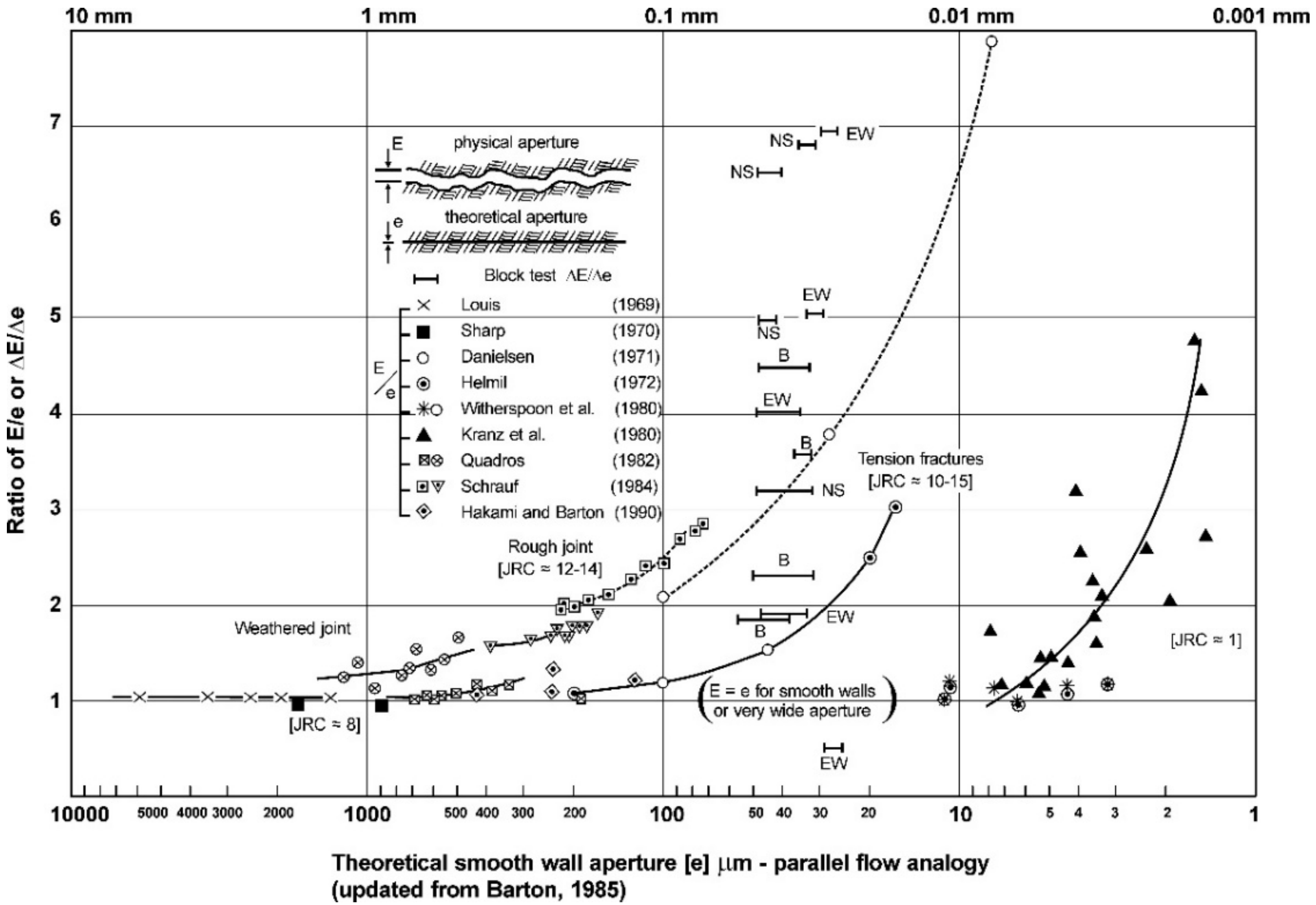


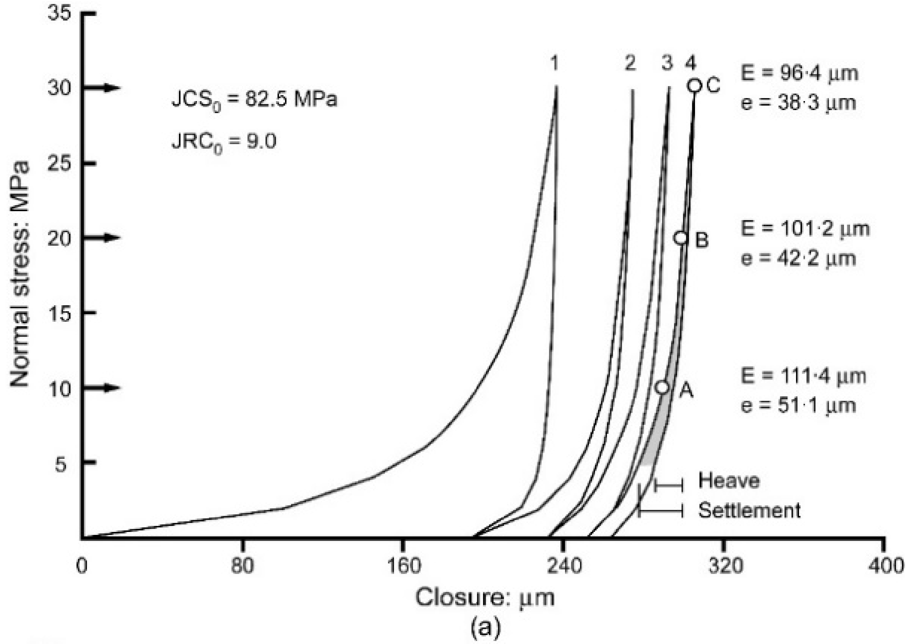


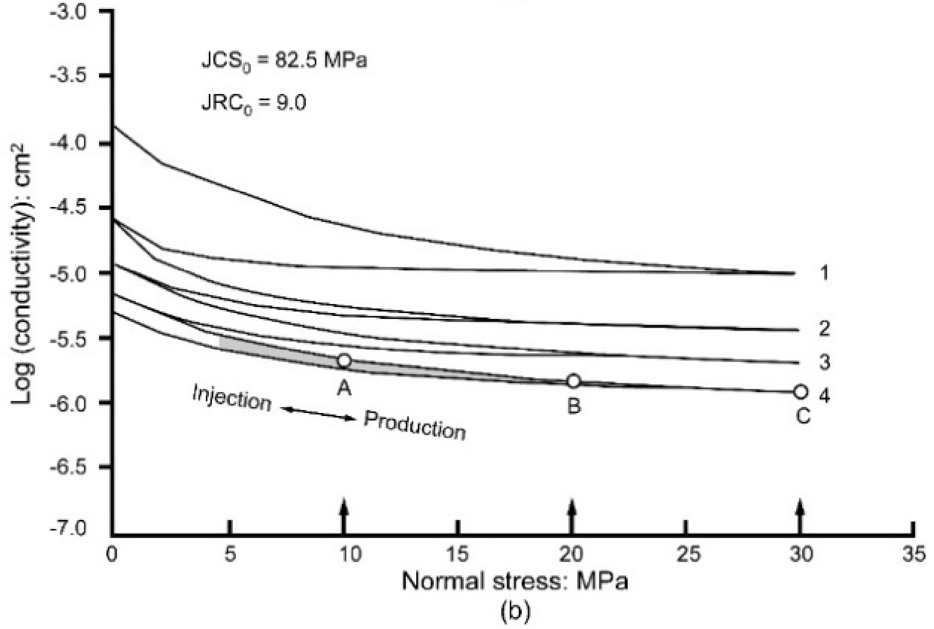
NOT JUST PEAK STRENGTH TO BE CONSIDERED- before and after peak is important.

(Barton, 1982)

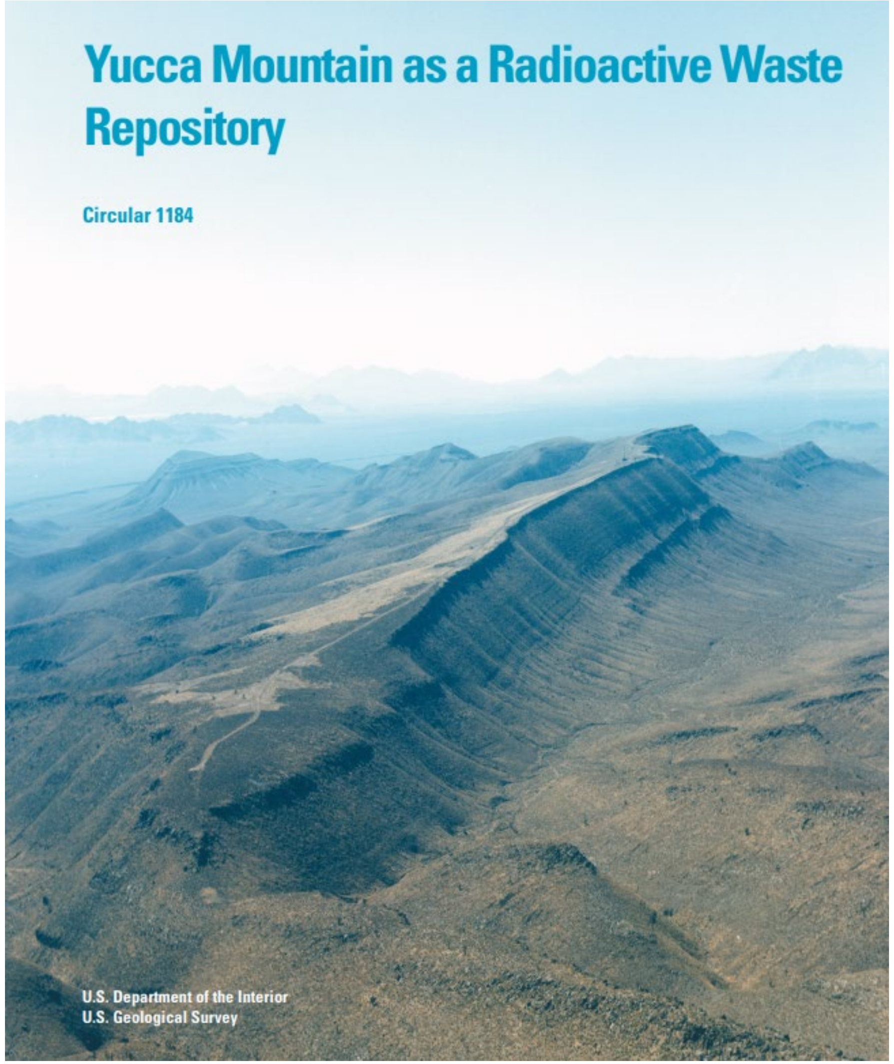
Differentiation of apertures e (hydraulic) and E (physical). AECL report. Also reproduced in Barton, Bandis, Bakhtar, 1985.



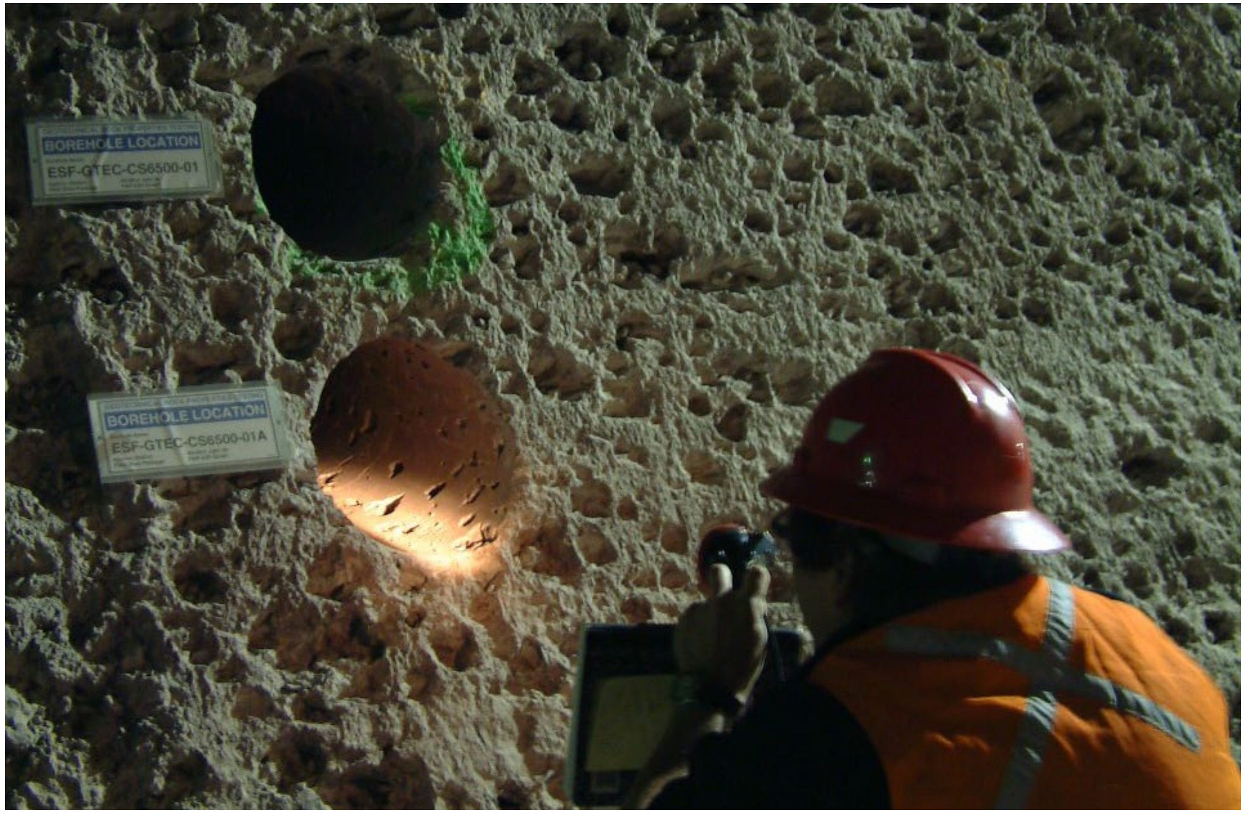




4. DoE: Reviews of two consortia's (Bechtel, TRW) rock mass characterization of Yucca Mountain Site, USA 1998 NB/ NGI, 2001 NB/ NB&A.

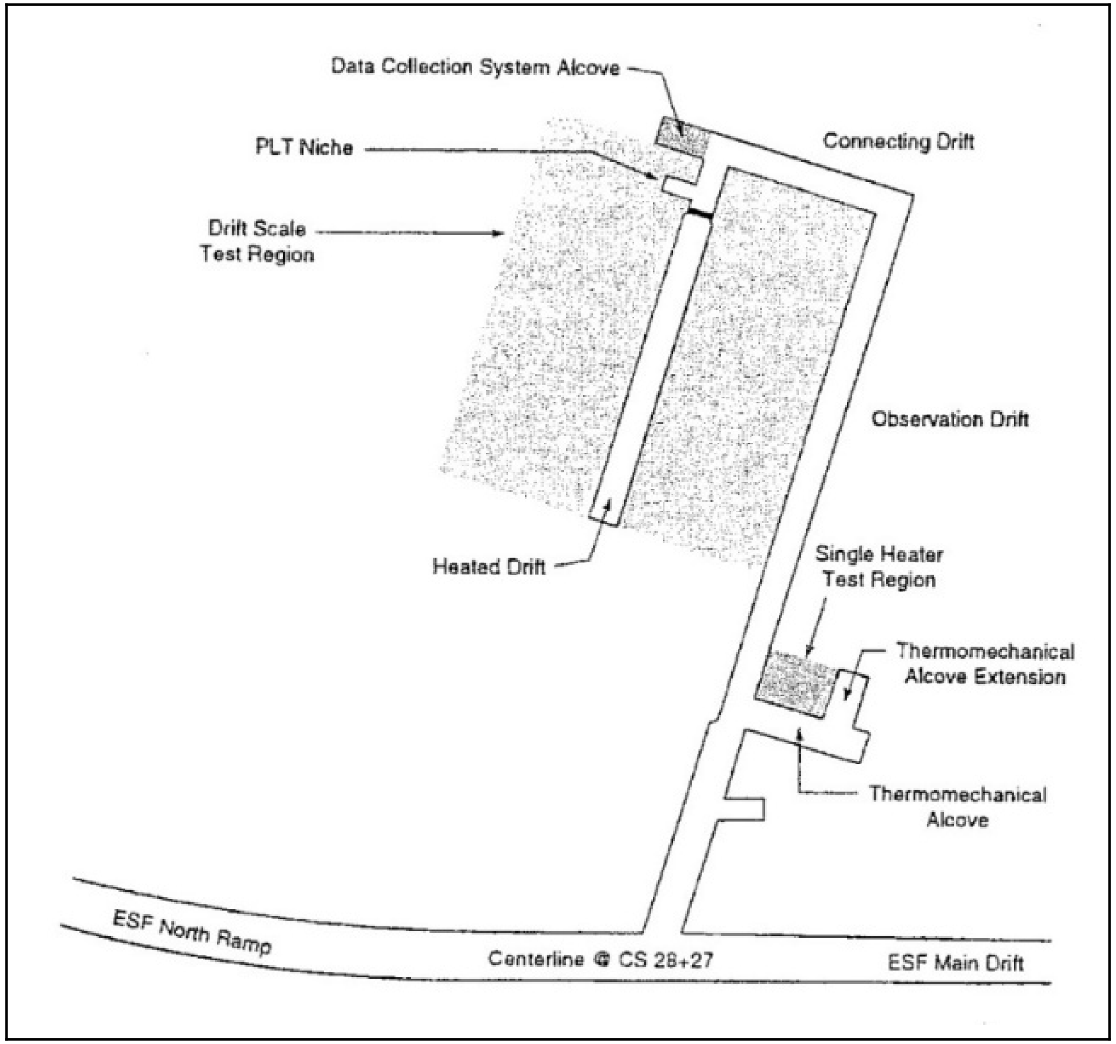


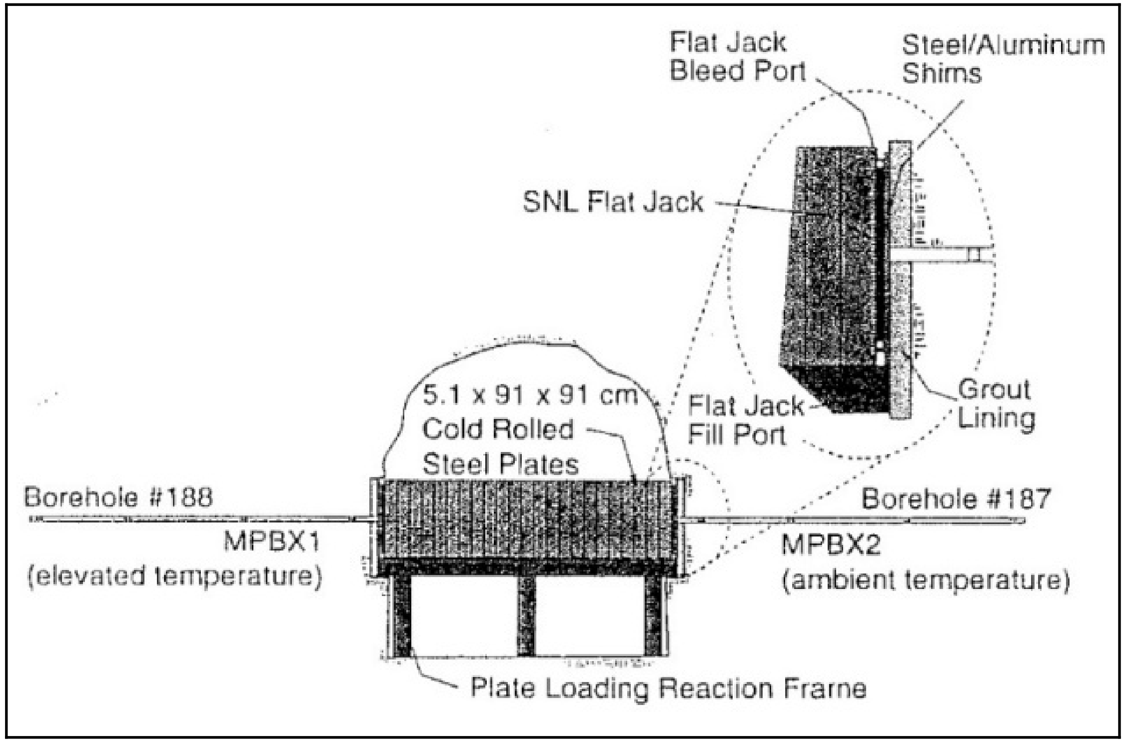
Two distinct geologies in the welded tuff: the non-lithophysal (without voids, typically jointed) and the lithophysal (with a major unconnected porosity due to gas filled voids). The majority of the (previously) planned repository in the Nevada Test Site area was ***in the medium with voids.***



YUCCA MT joints. Distinctly planar (low JRC =2) and distinctly rough (high JRC =15) joint sets. Some very conservative 3DEC numerical modelling in USA considered only the smoother joints and had input errors (incompatible dilation and shear strength).

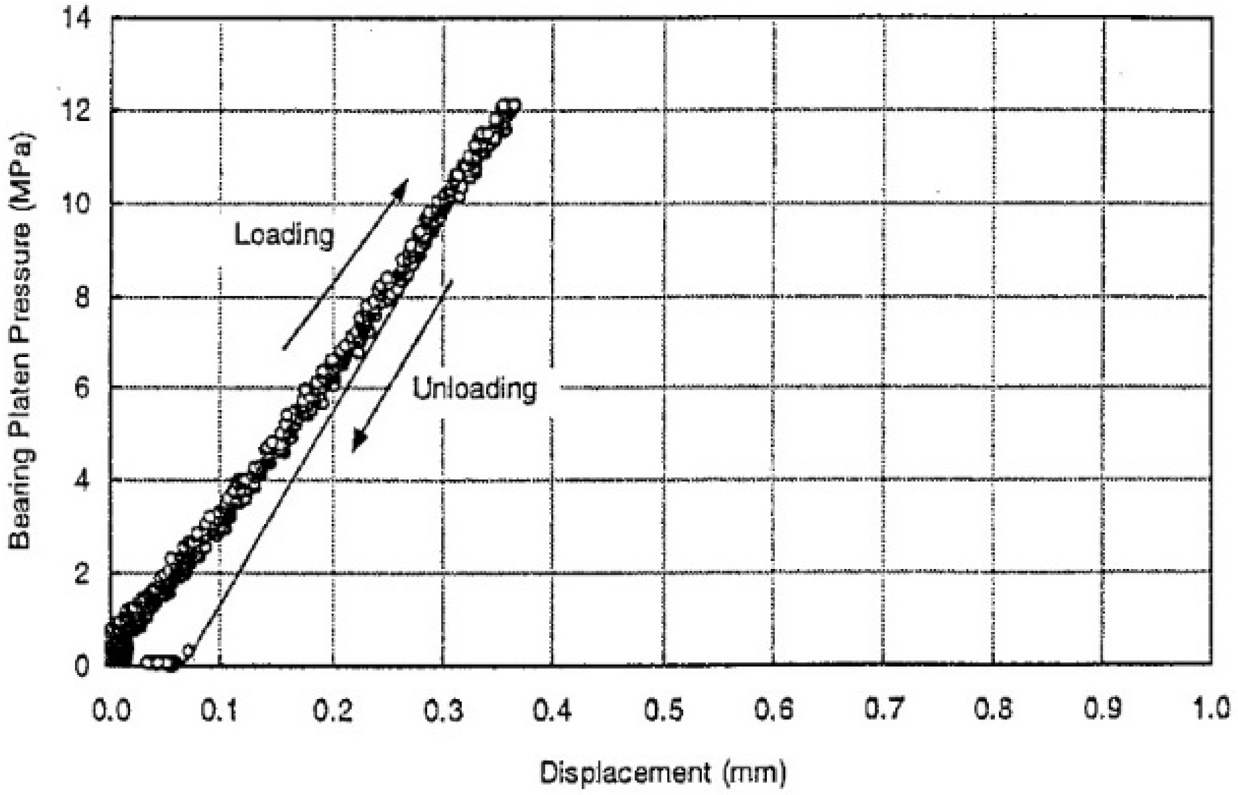
Opportunity to see unique (?) thermal testing in situ. Note 'thermal over-closure' effect on deformation moduli, contrasting 'hot' and 'cold' sides of drift (next screen).

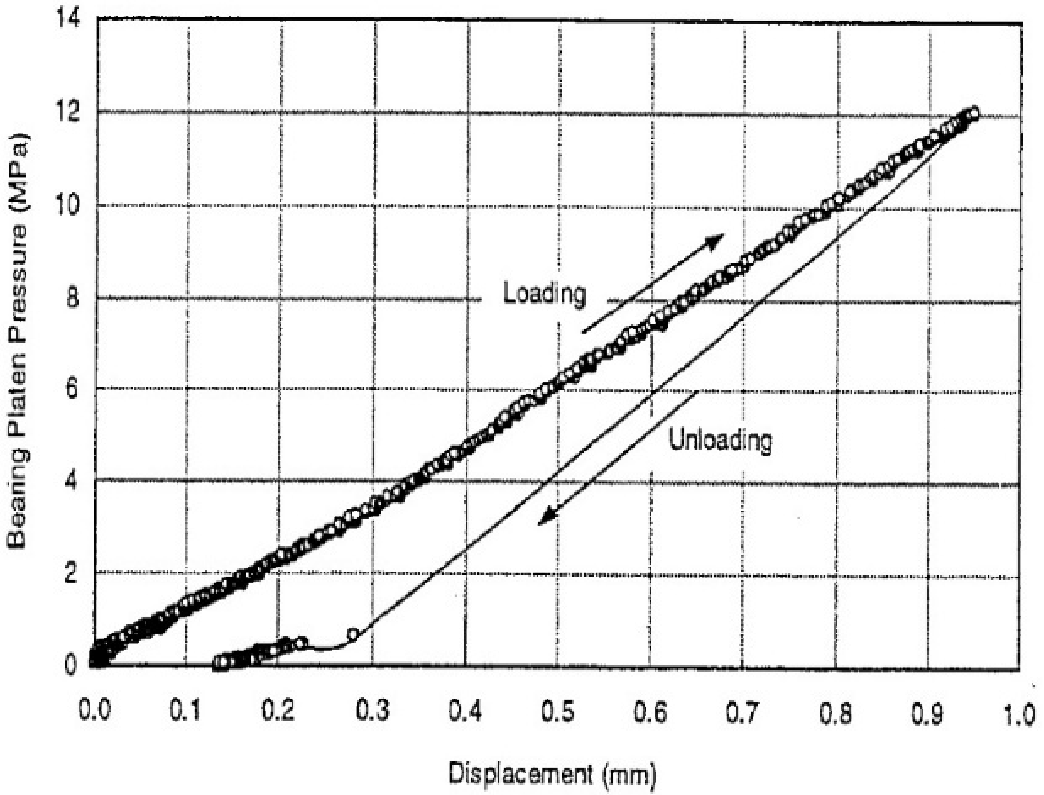




YUCCA MOUNTAIN ESF PLATE-LOAD TEST. Hot side and cool side of the drift showed distinctly different deformation moduli (due to thermal over-closure). See Barton, 2020.

E_{mass} (heated) = 24.5 Gpa E_{mass} (ambient) = 11.4 GPa   (George et al., 1999)





4b. THERMAL OVER-CLOSURE OF ROUGHER JOINT SETS

– consequences for HLW disposal strategies and HTM modelling.

THERMAL OC (*'OVER-CLOSURE'*) EFFECTS IN ROCK JOINTS HAVE BEEN MEASURED OR INTERPRETED IN THE CASE OF THE FOLLOWING:

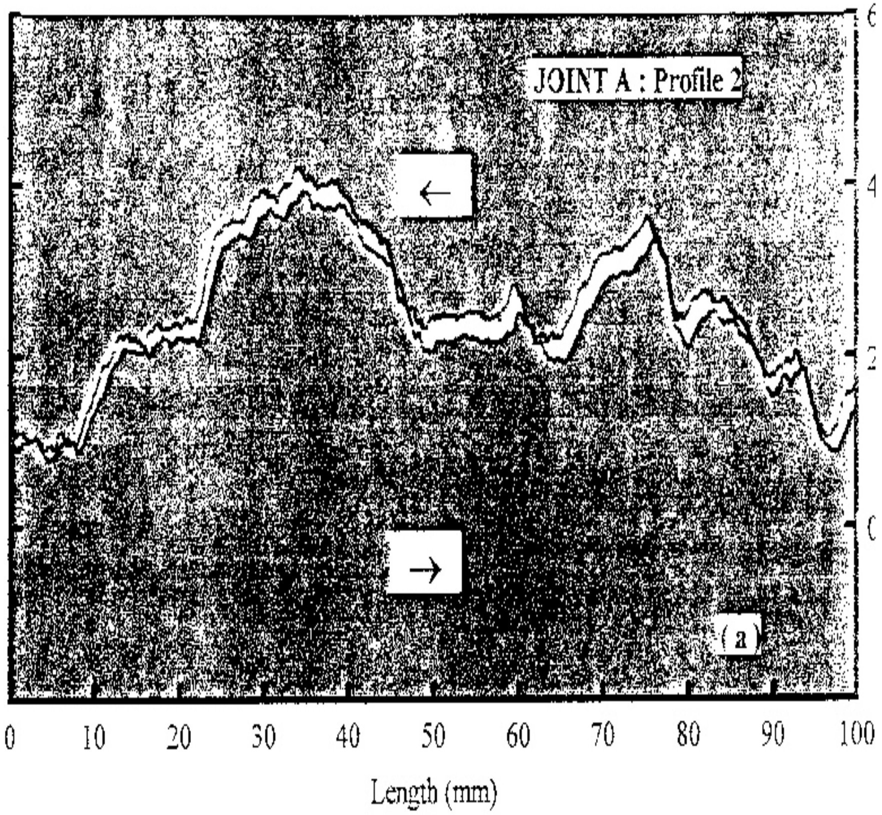
- **ROCK JOINT AND ROCK MASS PERMEABILITY REDUCTION (UNTIL COOLING)**
- **DEFORMATION MODULUS INCREASE (PREVIOUS ITEM)**
- **THERMAL EXPANSION COEFFICIENT REDUCTION (JOINTS CLOSE EASIER)**
- **SEISMIC VELOCITY INCREASE (UNTIL COOLING)**
- **SHEAR STRENGTH INCREASE (DUE TO JOINT CLOSURE)**
- **NUMERICAL MODEL PREDICTIONS E.G. ADINA CODE, COMPARED TO HMT ROCK *MASS* MEASUREMENTS VARYING BY FACTOR OF 1:2 OR WORSE**

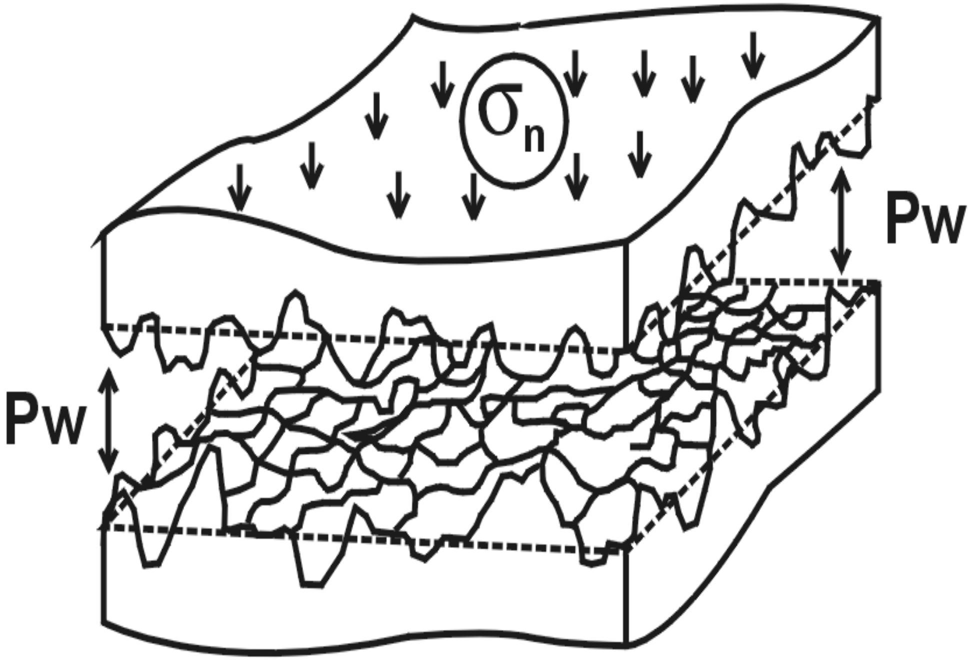
FEW SEEM TO HAVE RECKOGNISED , ACKNOWLEDGED, OR IDENTIFIED THE CAUSE OF THESE PHENOMENA

THE MECHANISM OF JOINT CLOSURE IS NOT AS 'SIMPLE' AS WE ASSUME.

WITH HIGH JRC (*in the <u>shearing</u> direction*),
THIS ROUGHNESS WILL ALSO ADD
NON-LINEARITY (*in the <u>closure</u> direction*)*.......as we know fom Kn-studies.*

WHAT IF HEATING *MAKES THE ROUGHNESS PROFILES FIT BETTER??*





Rough joints can be *over-closed*, and remain over-closed by a previous application of a higher normal stress.

This is an exaggerated form of hysteresis.

Rough joints in igneous and metamorphic rocks can *over-close* even due to temperature increase alone, due to better fit, which is something beyond hysteresis.

The *rock mass* deformation moduli, thermal expansion coefficients, hydraulic apertures, and seismic velocities may each be affected.

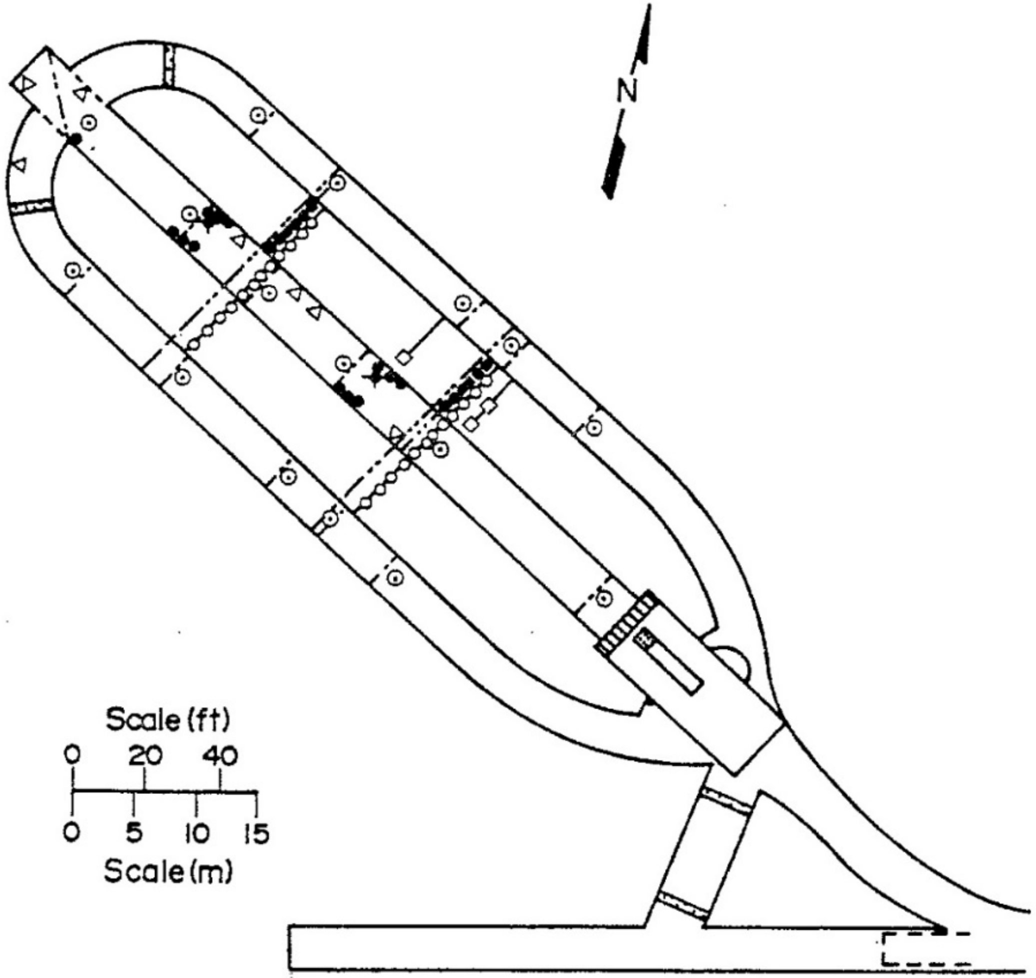
Barton, 2020 (TUST)

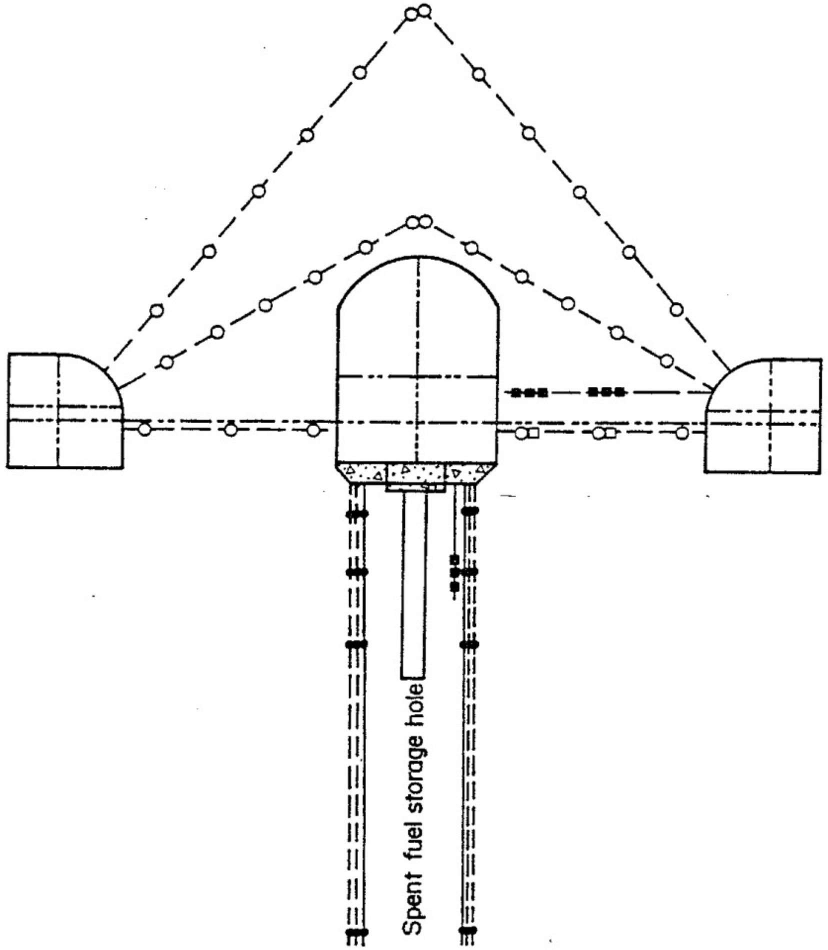
MANY EXAMPLES OF THERMAL *OVER-CLOSURE (See Barton, 2020, TUST).*

- CONDUCTING APERTURE DECREASES IN TERRA TEK / CSM HTM BLOCK TEST (FOR ONWI)
- JOINT CLOSURES IN HTM COUPLED STRESS FLOW TESTS (CSFT) (FOR AECL/URL)
- CONDUCTING APERTURE REDUCTIONS FROM HTM BLOCK TEST IN G-TUNNEL (FOR SANDIA NATIONAL LABORATORY)
- (REDUCED THERMAL EXPANSION COEFFICIENTS AT NSTF HANFORD (FOR ROCKWELL-HANFORD)
- REDUCED VP AND VS AFTER LONG-TERM HEATED/COOLED BOREHOLE TEST AT STRIPA (FOR SKB). POOR MODEL PREDICTION DUE TO THERMAL JOINT OVER-CLOSURE AND CHANGED MODULI
- (INCREASED COHESIVE AND FRICTIONAL STRENGTH OF JOINTS IN WELDED TUFF THAT HAVE BEEN HEATED. SANDIA N.L)
- HEATED MINE-BY (SPENT FUEL TEST) AT CLIMAX (FOR LAWRENCE LIVERMORE). POOR MODEL PREDICTION DUE TO HIGHER FINAL MODULI, LOWER THERMAL EXPANSION COEFFICIENTS, DUE TO THERMAL OVER-CLOSURE OF JOINTS
- HEATED AND AMBIENT SIDES OF PLATE LOAD TEST AT YUCCA MOUNTAIN (FOR DOE). WIDELY DIFFERENT MODULI IN THE AMBIENT AND HEATED SIDES OF THE SAME DRIFT

CLIMAX MINE (quartz monzonite) HEATED MINE-BY at 400 m depth, as part of the SPENT FUEL TEST (Yow and Wilder, 1993)

Measured deformations ¼ to ½ of those calculated by ADINA (discrepancies in thermal moduli and thermal expansion coefficients)

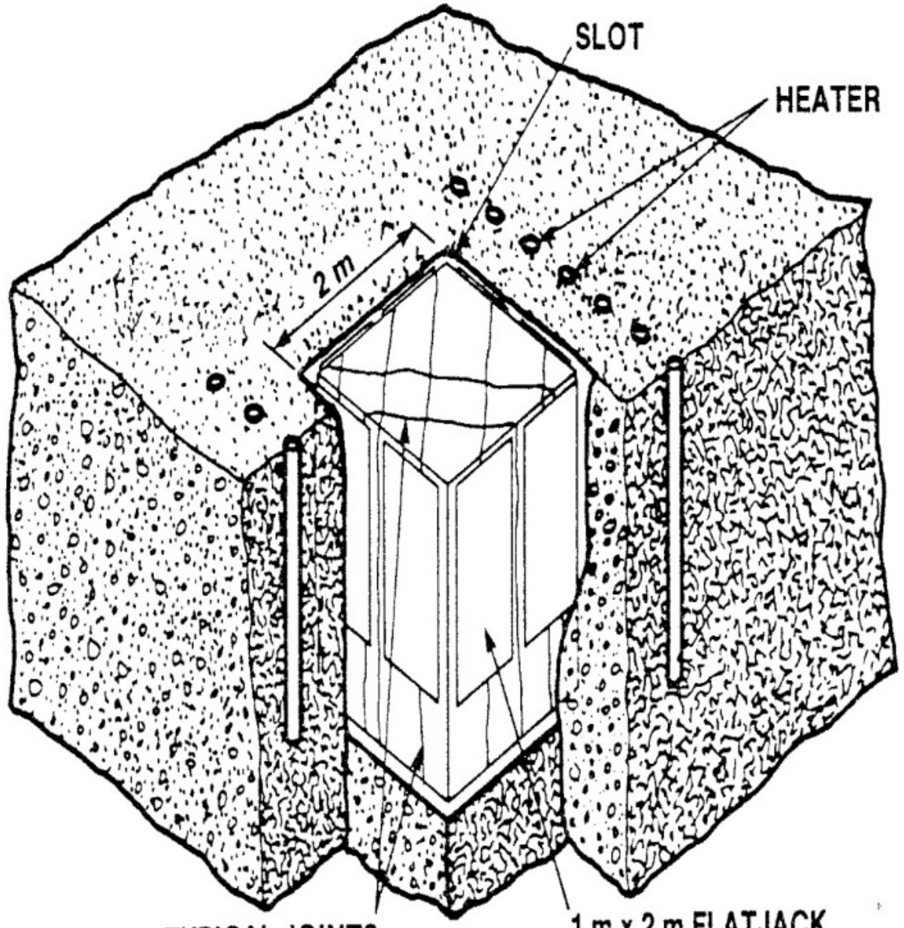


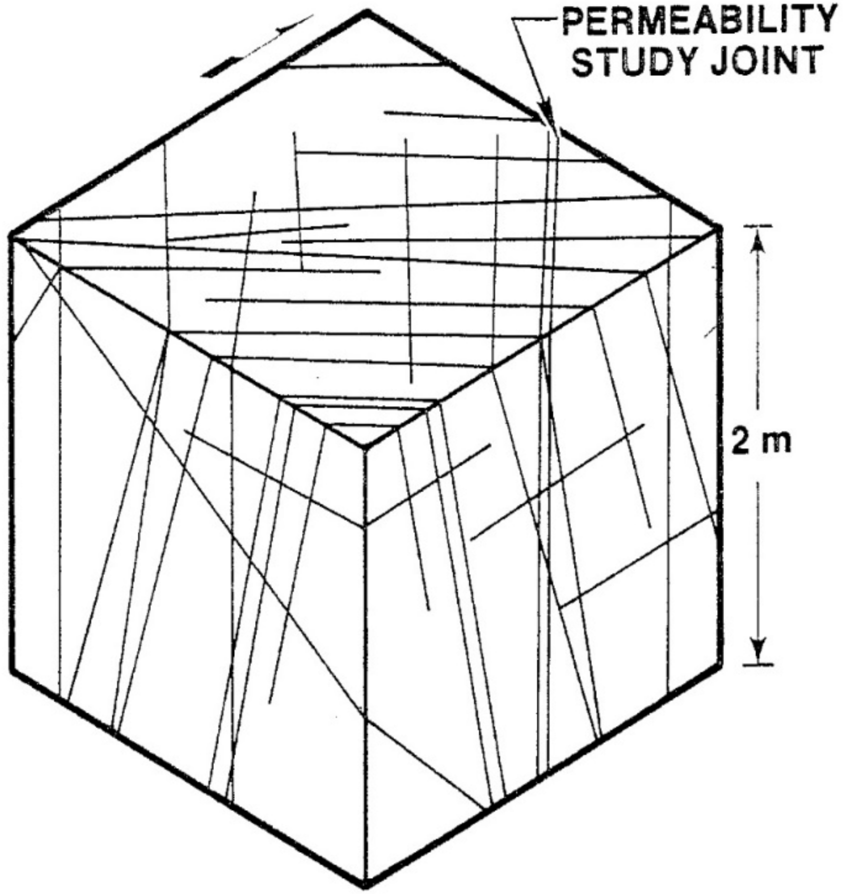


G-tunnel (NTS) HMT block test (SAIC, for Sandia)

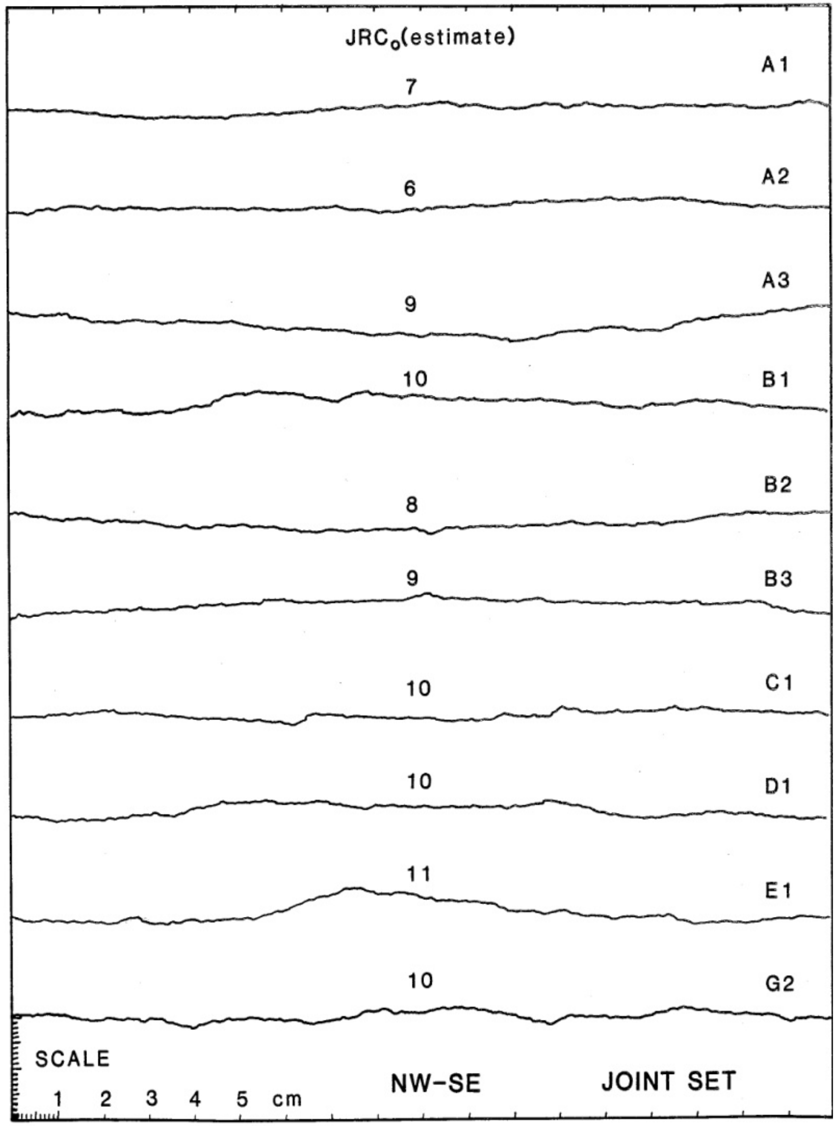
(Reduced hydraulic apertures due to heating: 60 to 35 µm)

Zimmerman et al. 1986





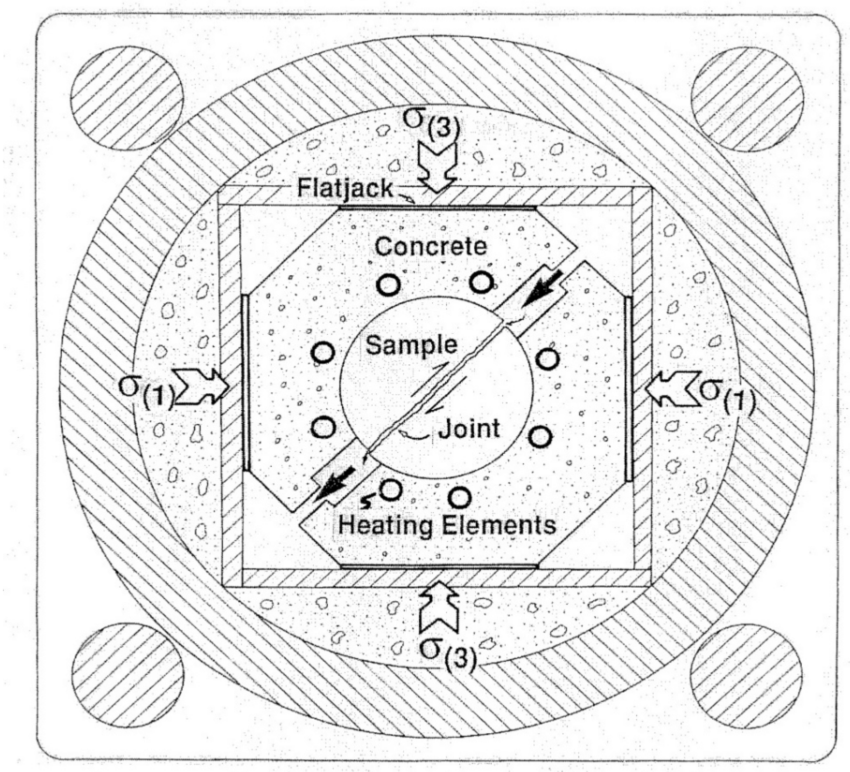
TYPICAL JOINT ROUGHNESS AT THE G-TUNNEL HEATED BLOCK TEST. Barton et al. 1983.

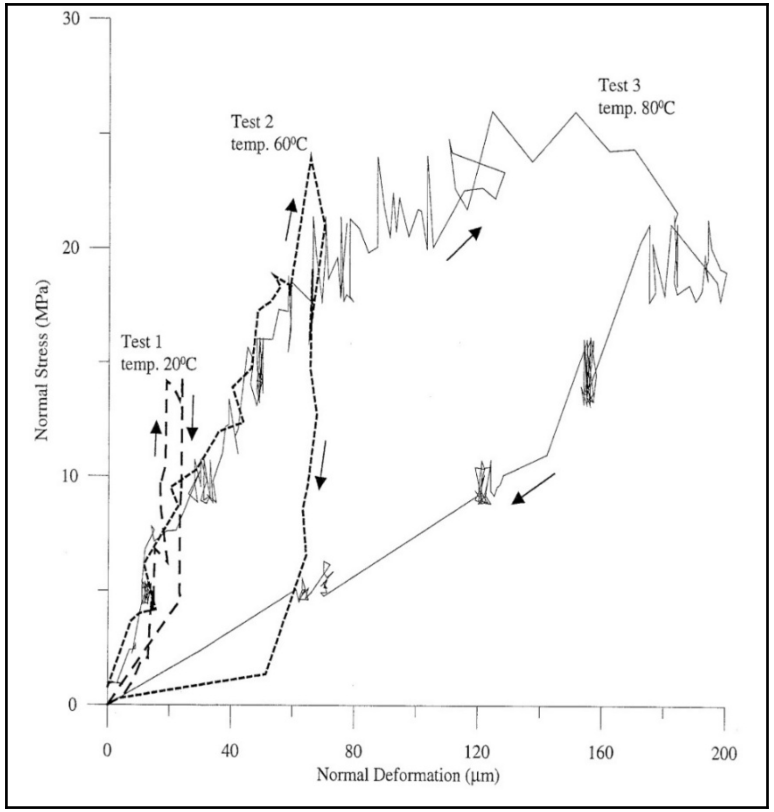


Three tests on joints in granite from URL in Canada, loaded to 14, 19 and 26 MPa in NGI's CSFT apparatus (Makurat, 1985, 1989)

On the 4th load cycle of each test, joint closures (ΔE) = 24μm, 54μm and 151μm were recorded at 20ºC, 60ºC and 80ºC

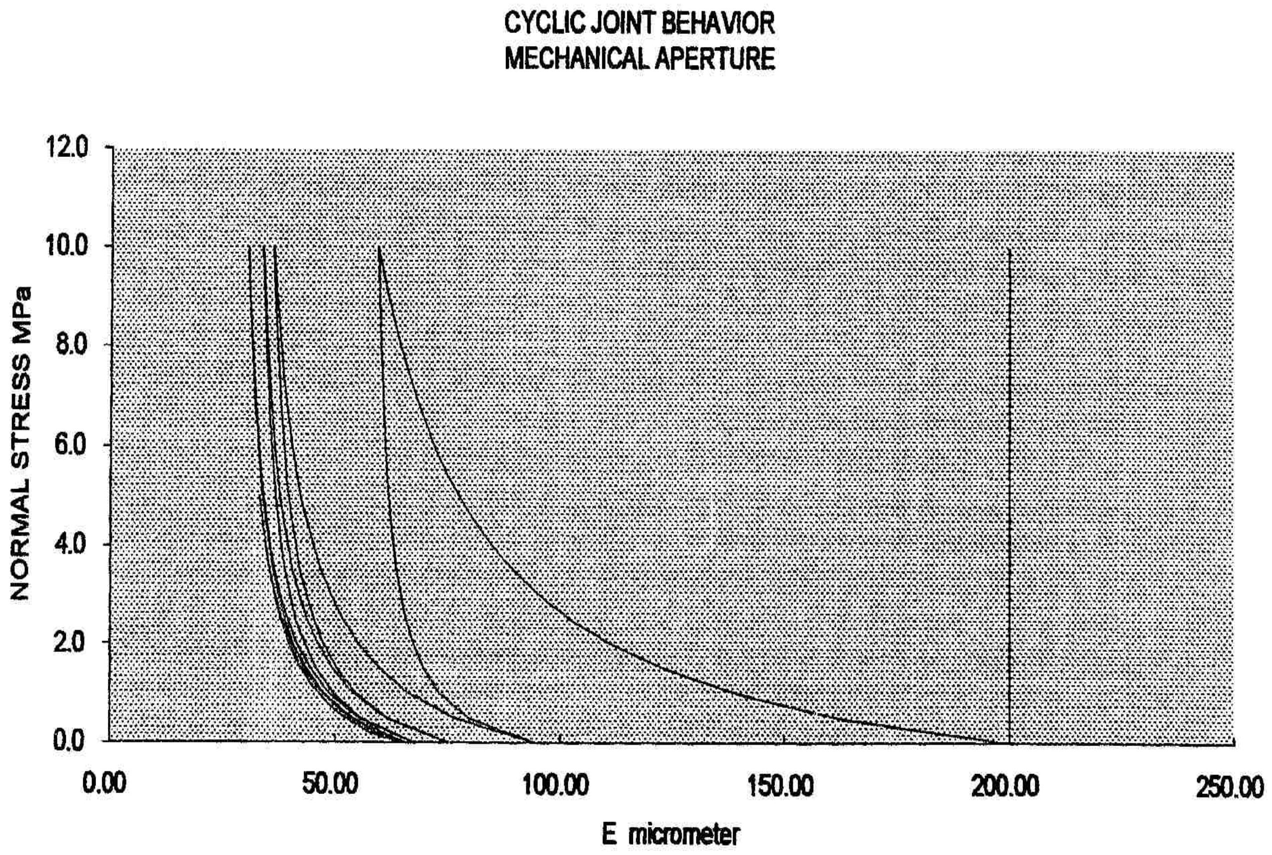
(i.e. increases out of proportion to stress increases....when stiffening)

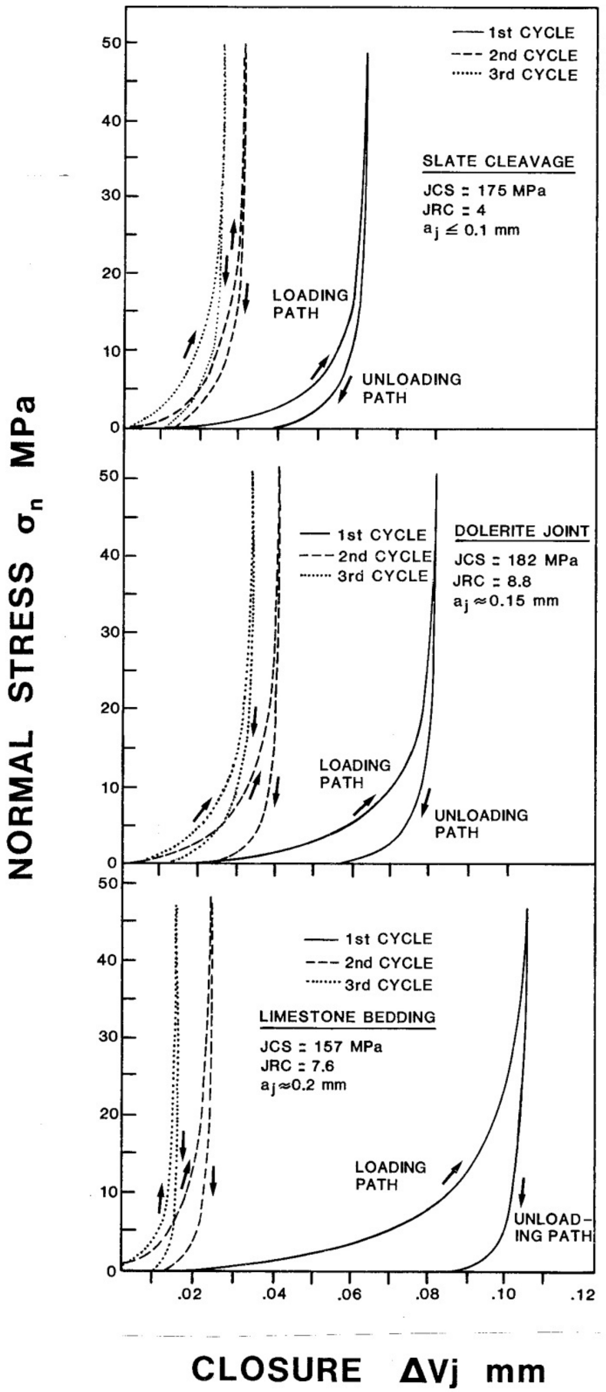




Bandis normal closure tests (Bandis et al.1983) show over-closure (i.e. hysteresis) when the roughness is significant.

The BB-model has yet to be modified to account for *thermal over-closure – but 4th-cycle non-linearity and hysteresis is modelled.*





ONE MAY *ONLY* NEED TEMPERATURE RISE FOR THE T-O-C EFFECT TO OCCUR

- This should not be a surprise – joints were probably formed at higher temperature than today's ambient level of 10°C or 20°C. (Barton, 1982).

- Why?...Anisotropic thermal expansion/contraction of constituent minerals in opposing joint walls....the joint's memory of warmer conditions at it's birth?... a primeval 'finger-print' of 3D-roughness.

- The 3D roughness *finger-print*, though very recognizable, would be subtly altered in its finer details by today's cooler conditions.

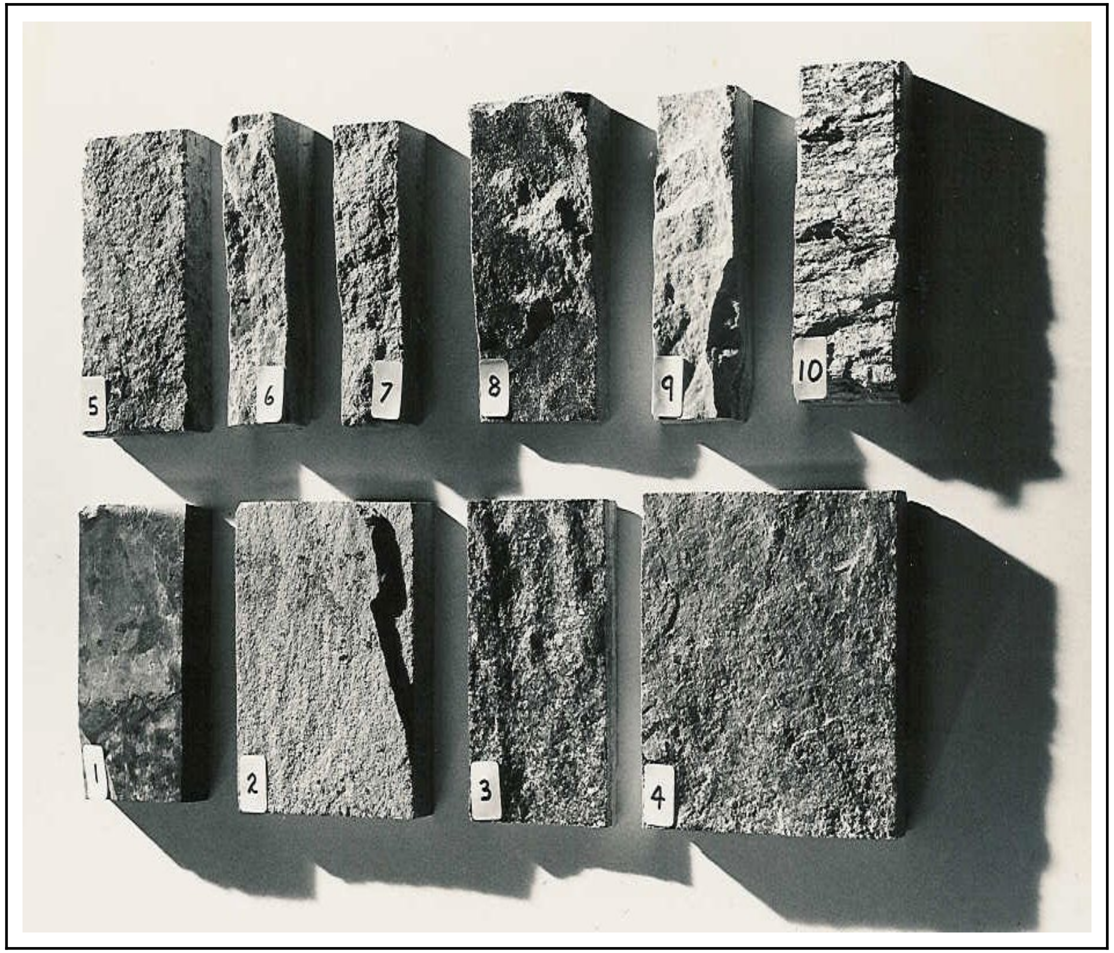
JRC_O (small-scale)

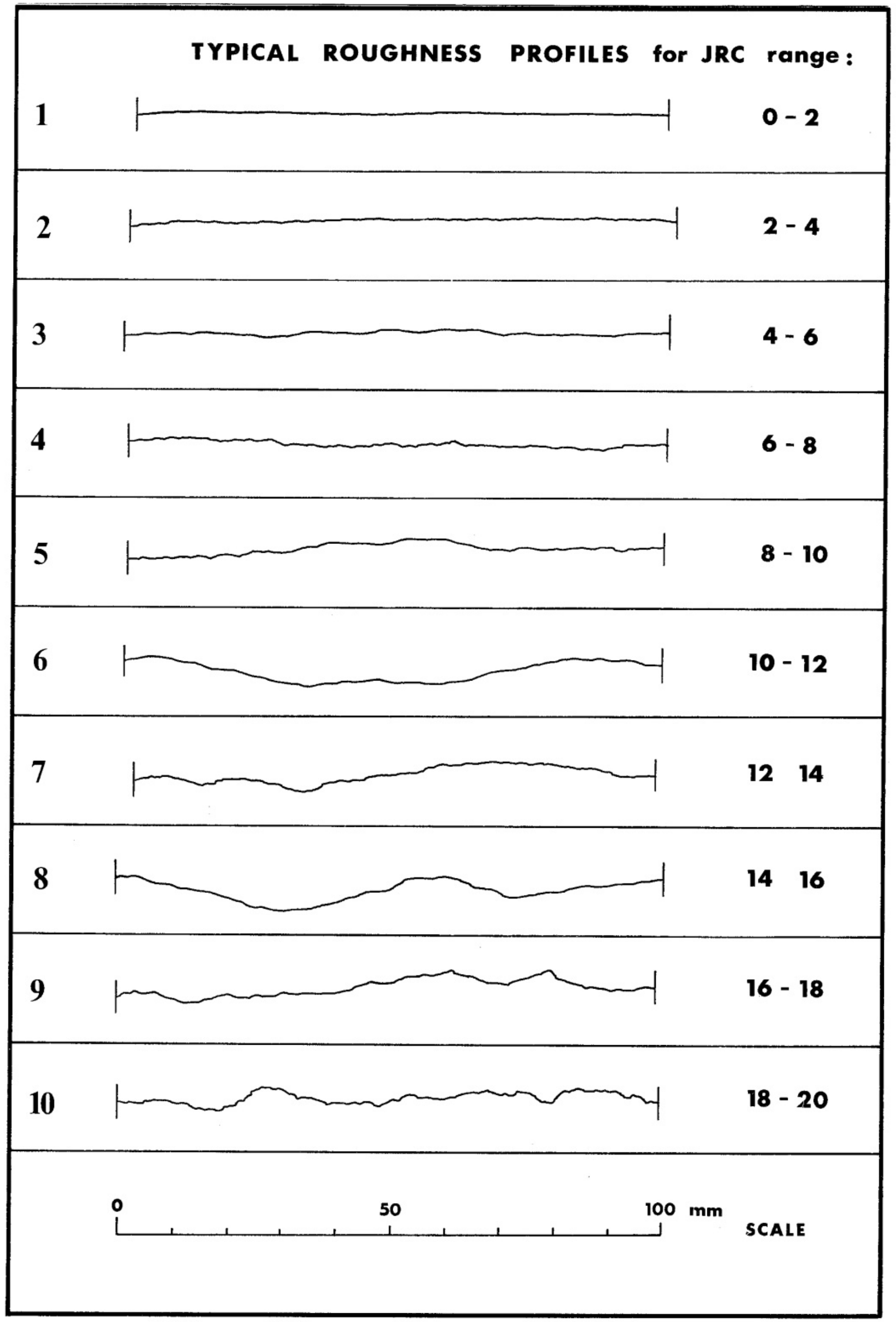
- JOINT ROUGHNESS IS GOING TO BE THE ALL-IMPORTANT DISCRIMINATOR IN THIS INTERLOCK MECHANISM, WHICH RESEMBLES THE EFFECT OF A 'PERPENDICULAR-JRC'.

- THE INFLUENCE OF THIS PERPENDICULAR ROUGHNESS IS EASY TO SEE WHEN TILT TESTING.

- WITH SUFFICIENT ROUGHNESS 'TENSILE STRENGTH' IS EXHIBITED. *VERY ROUGH* JOINTS GIVE *180° (!) TILT ANGLES (despite very low initial normal stress)*

O-C beyond JRC_0 = 10?
or beyond JRC_0 = 15?





EXAMPLES OF A PLANAR JOINT AND A ROUGH JOINT, WITH RESPECTIVELY ZERO-AND- A-HIGH-PROBABILITY OF OVER-CLOSURE PHENOMENA

(JRC = 1 and 15)

DoE test labs, Denver. NB back-analysis of DST's.

IN CONNECTION WITH NUCLEAR WASTE (AND GEOTHERMAL DEVELOPMENT)

IF ROUGH SHORTER JOINTS REMAINED OVER-CLOSED DURING COOLING, WHERE WOULD CONTRACTION BE CONCENTRATED?

BIG PERMEABILITY INCREASE AND LOSS OF SHEAR STRENGTH WHERE LEAST NEEDED.

LONG TERM IMPLICATIONS

- THE LONG TERM IMPLICATION IS THAT IN THE COOLING PHASE OF AN HLW REPOSITORY, ONE MAY EXPERIENCE ROUGHER JOINTS THAT ARE OVER-CLOSED AND STABLE.

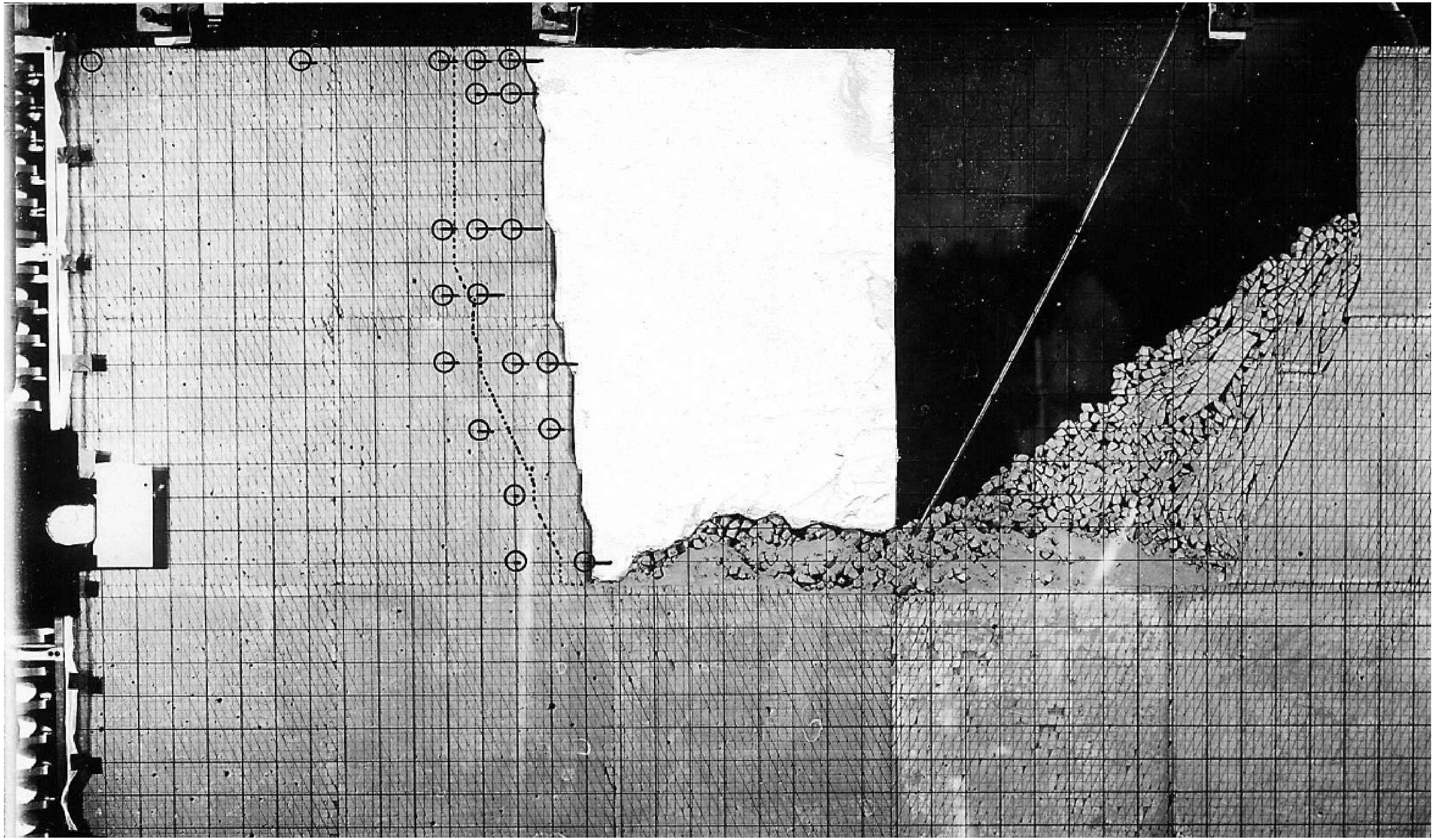
- SMOOTHER AND PROBABLY MORE CONTINUOUS FEATURES WILL TEND TO OPEN TO COMPENSATE FOR THE COOLING, THEREBY POTENTIALLY LOSING STRENGTH AND GAINING PERMEABILITY.

- OVER-CLOSURE (of joints) DOES NOT YET APPEAR IN THE ROCK MECHANICS VOCABULARY – AFTER 40 YEARS OF APPARENT NEGLECT BY THE COMMUNITY.

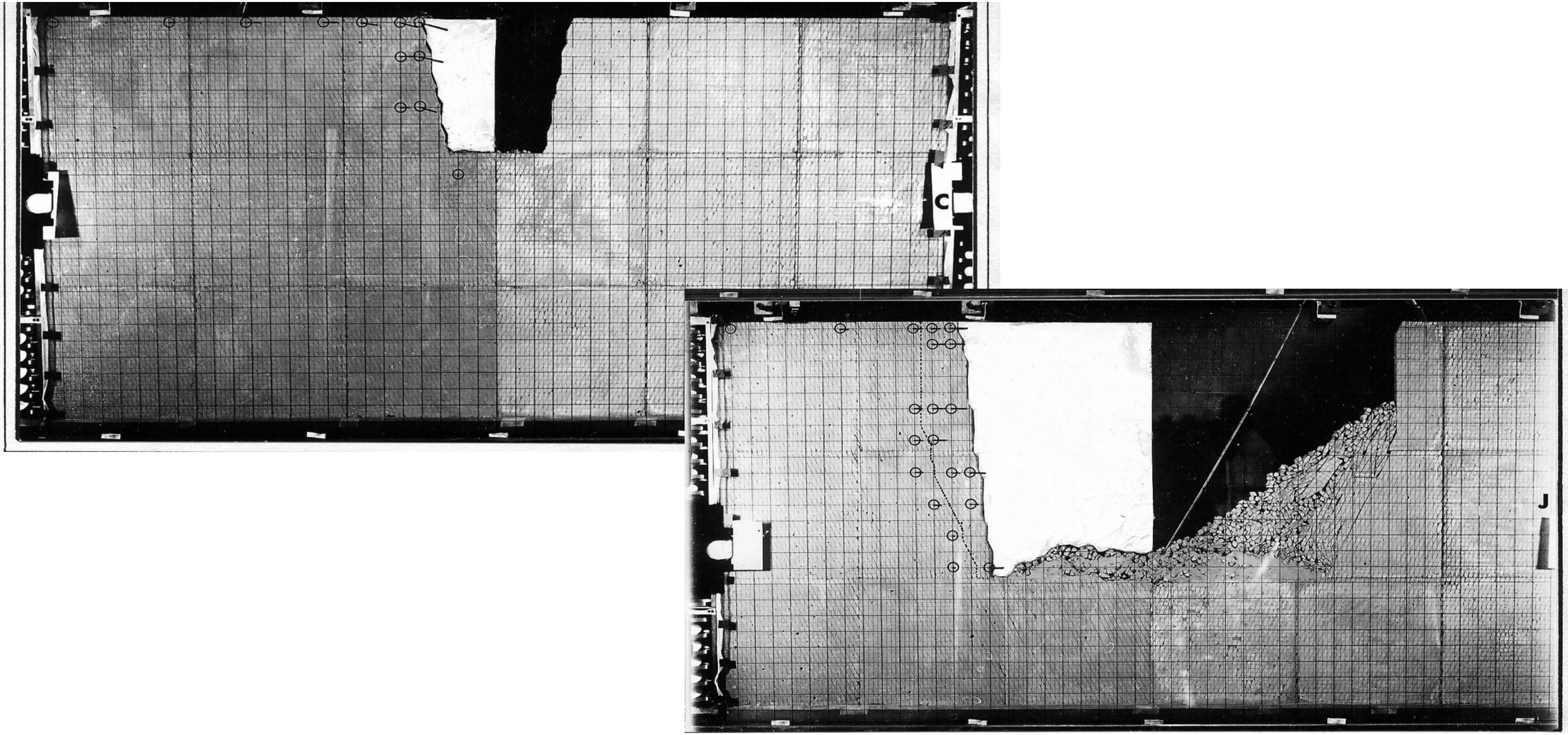
- HMT LABORATORY TESTING OF JOINTS IS NEEDED - OUR DATA IS VERY LIMITED. MUST TEST JOINTS WITH A WIDE RANGE OF JRC_O

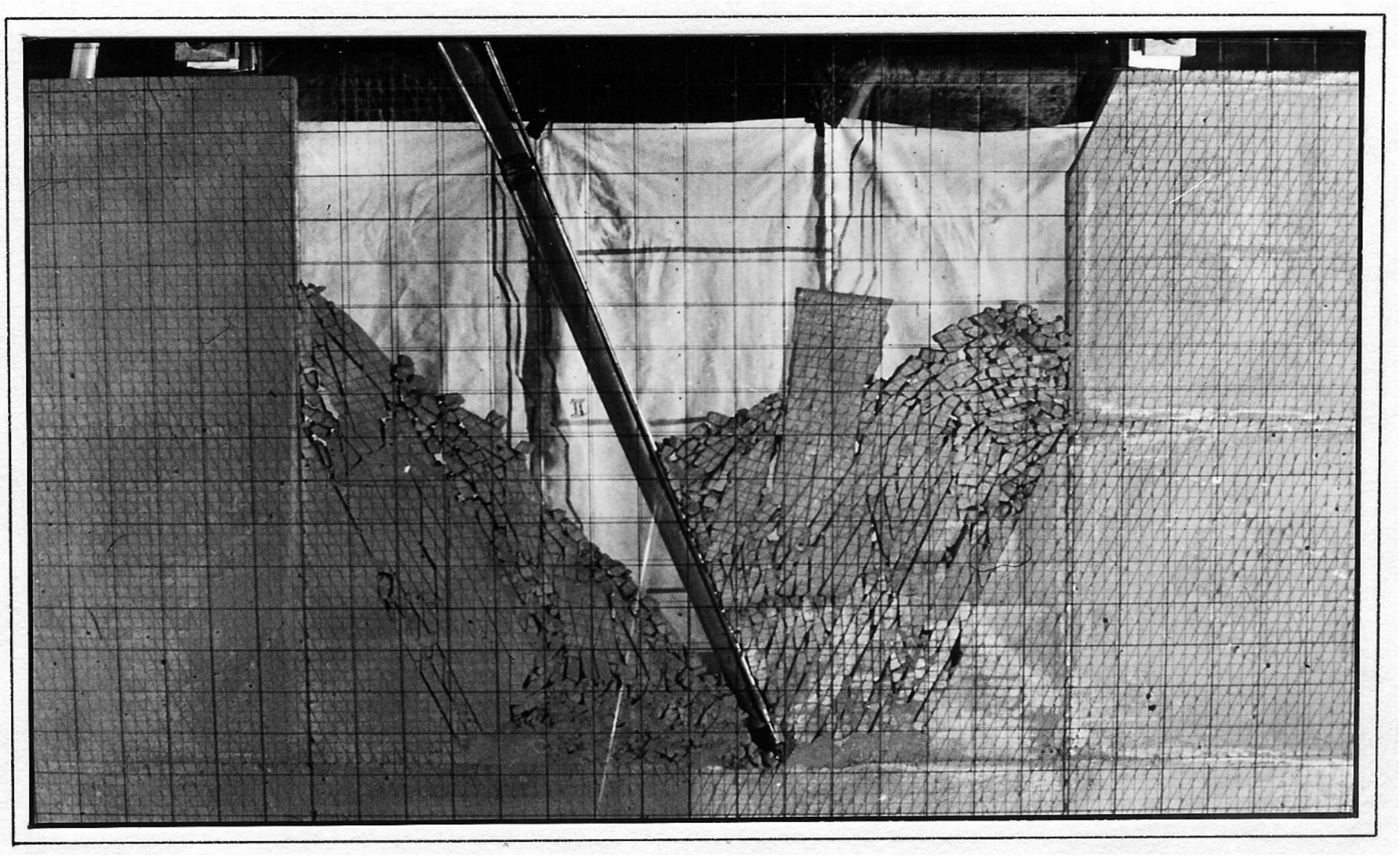
- THE O-C MECHANISM CANNOT BE IGNORED – THAT WOULD BE *NON*-CONSERVATIVE. IT'S EFFECT ON INPUT DATA AND THEREFORE ON MODEL PREDICTIONS HAS BEEN DEMONSTRATED AS SERIOUS (e.g. Stripa, Climax)

A LOOK BACK A LONG TIME! A doctoral thesis problem (1968-1970)
40,000-block tension fracture model 'rock slopes'. AMBIENT PROBLEMS.
Ph.D. Topic: 'Steep excavated rock slopes'......NOT FAILING WHEN EXPECTED!!



Model M2: medium horizontal stress : more logical down-dip deform.
M3: high horizontal stress a lot of OC. (40,000 blocks in each model)
Barton, 1971





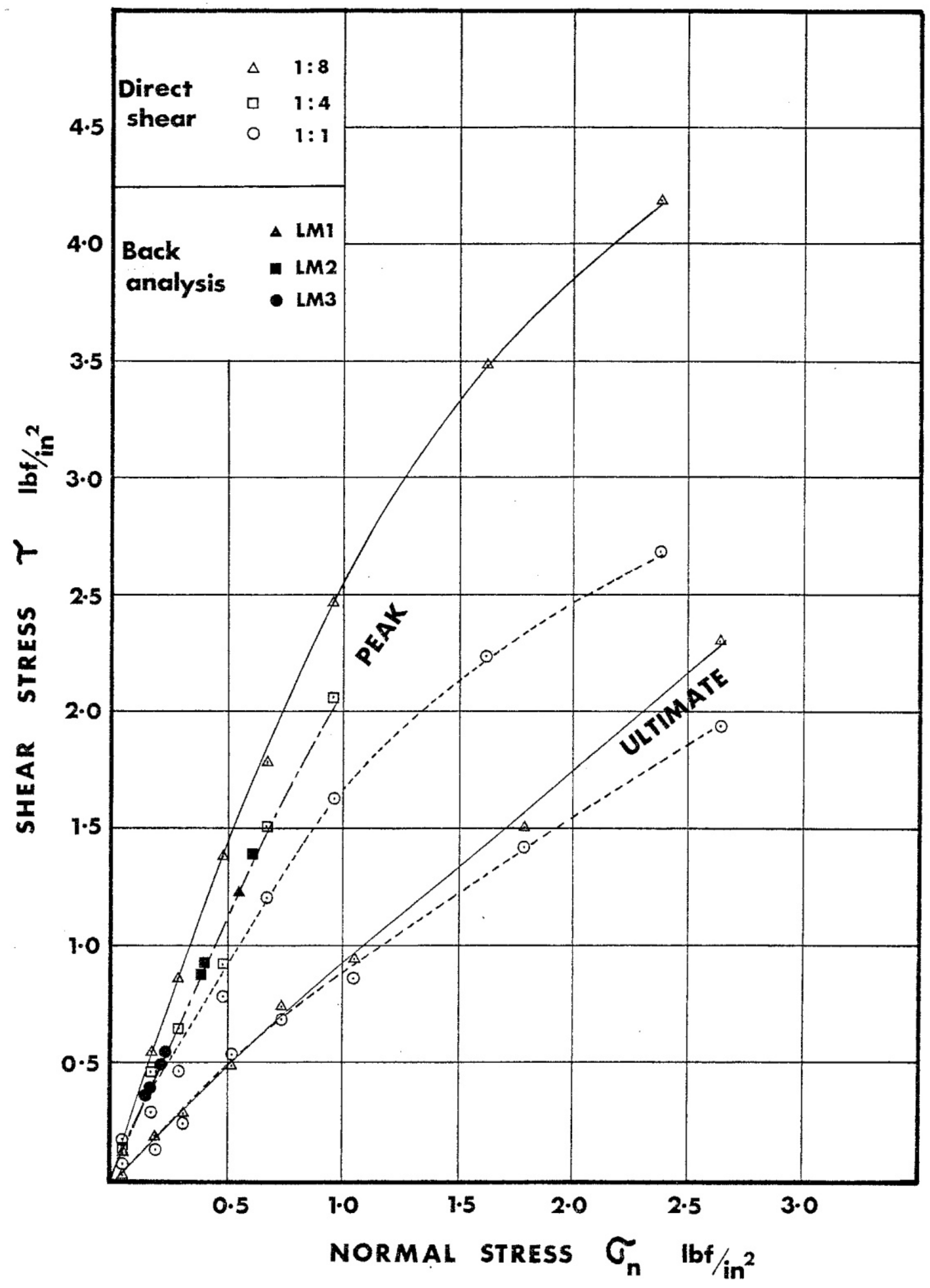
Note 'intact' multi-fractured blocks, due to over-closure.

SLOPES DID NOT FAIL WHEN EXPECTED, BASED ON *CONVENTIONAL* DIRECT SHEAR TESTS

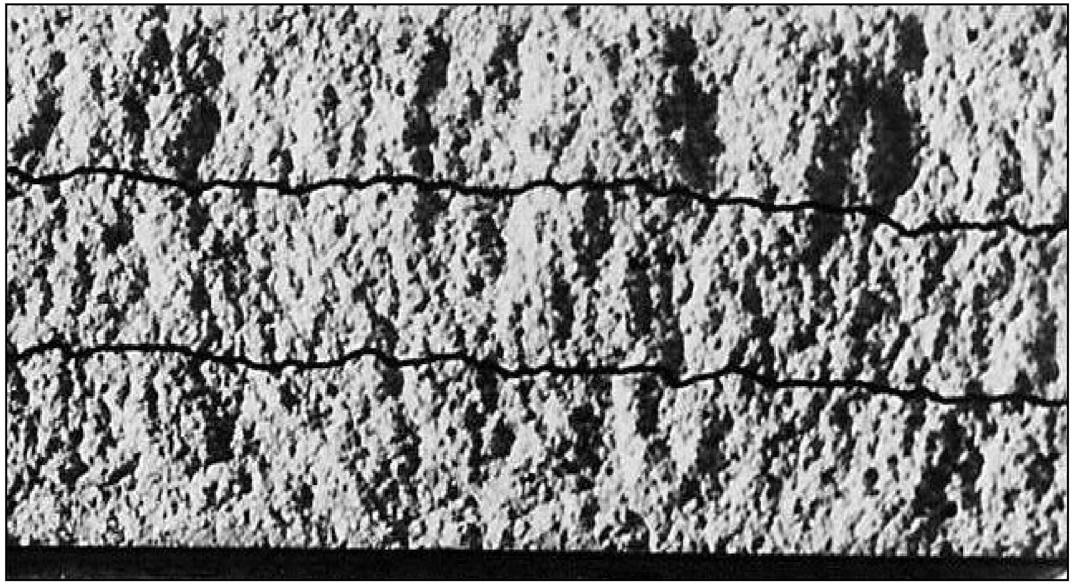
- *Conventional* meant normal stress σ_n application of the same magnitude as that expected beneath the slope during excavation.

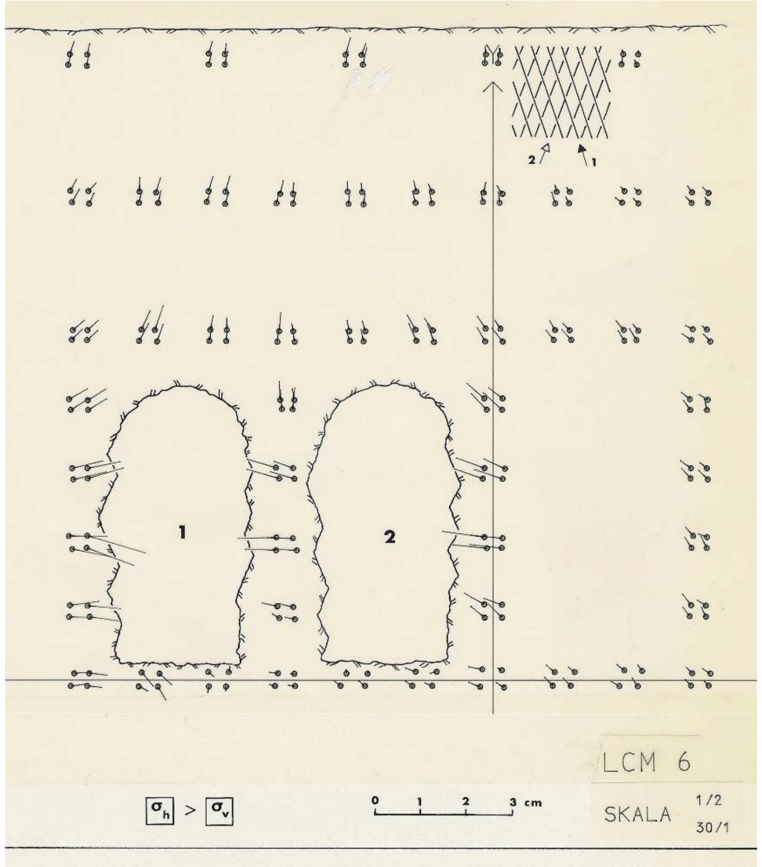
- What about the normal stress level acting before the slopes were constructed?

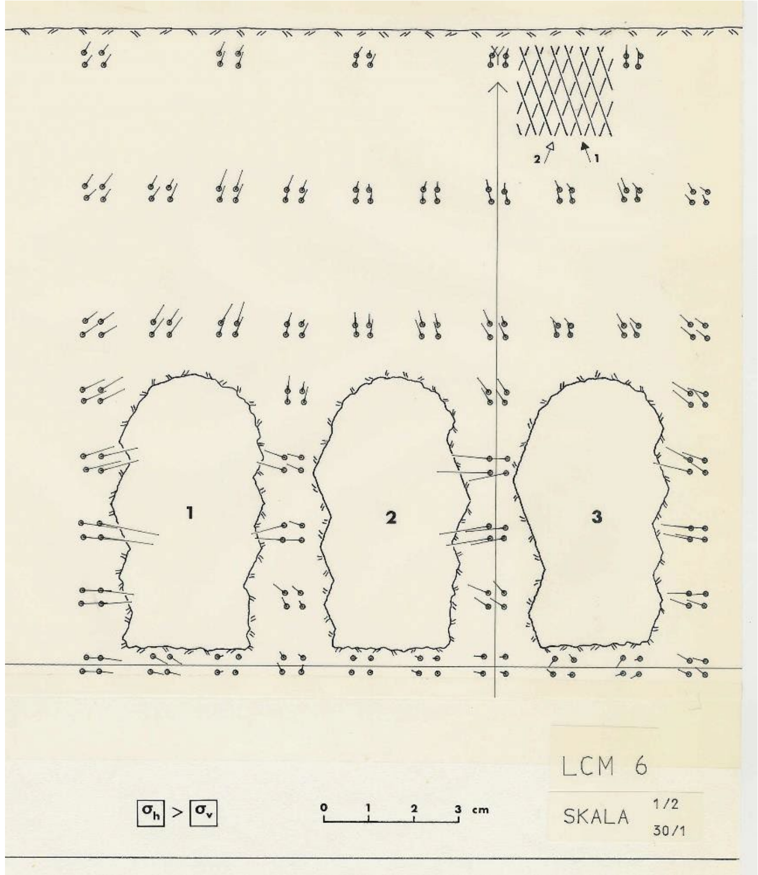
- See direct shear test envelopes: 1:1 (conventional) SEE NEXT SCREEN
- 4:1 (pre-consolidated).......as with medium horizontal stress
- 8:1 (pre-consolidated).......as with high horizontal stress



Conventional (1:1) and pre-closed, therefore *'over-closed'* direct shear tests.
(Barton, 1971)



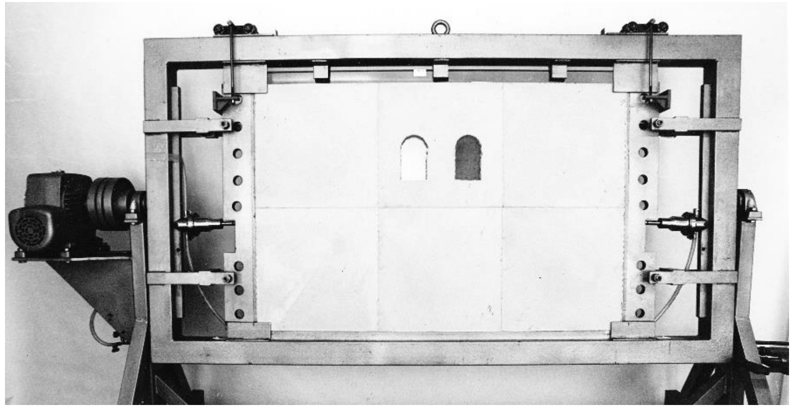


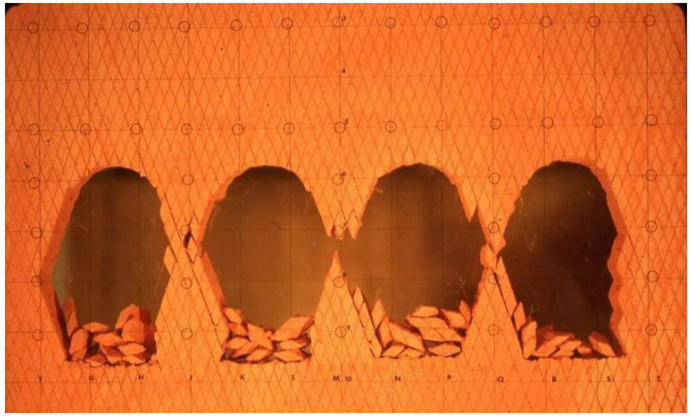


NOTE: NO REVERSAL OF DEFORMATIONS in PREVIOUS PILLAR.

Over-closure here is purely an M response. But can get T and TM responses in crystalline rocks.

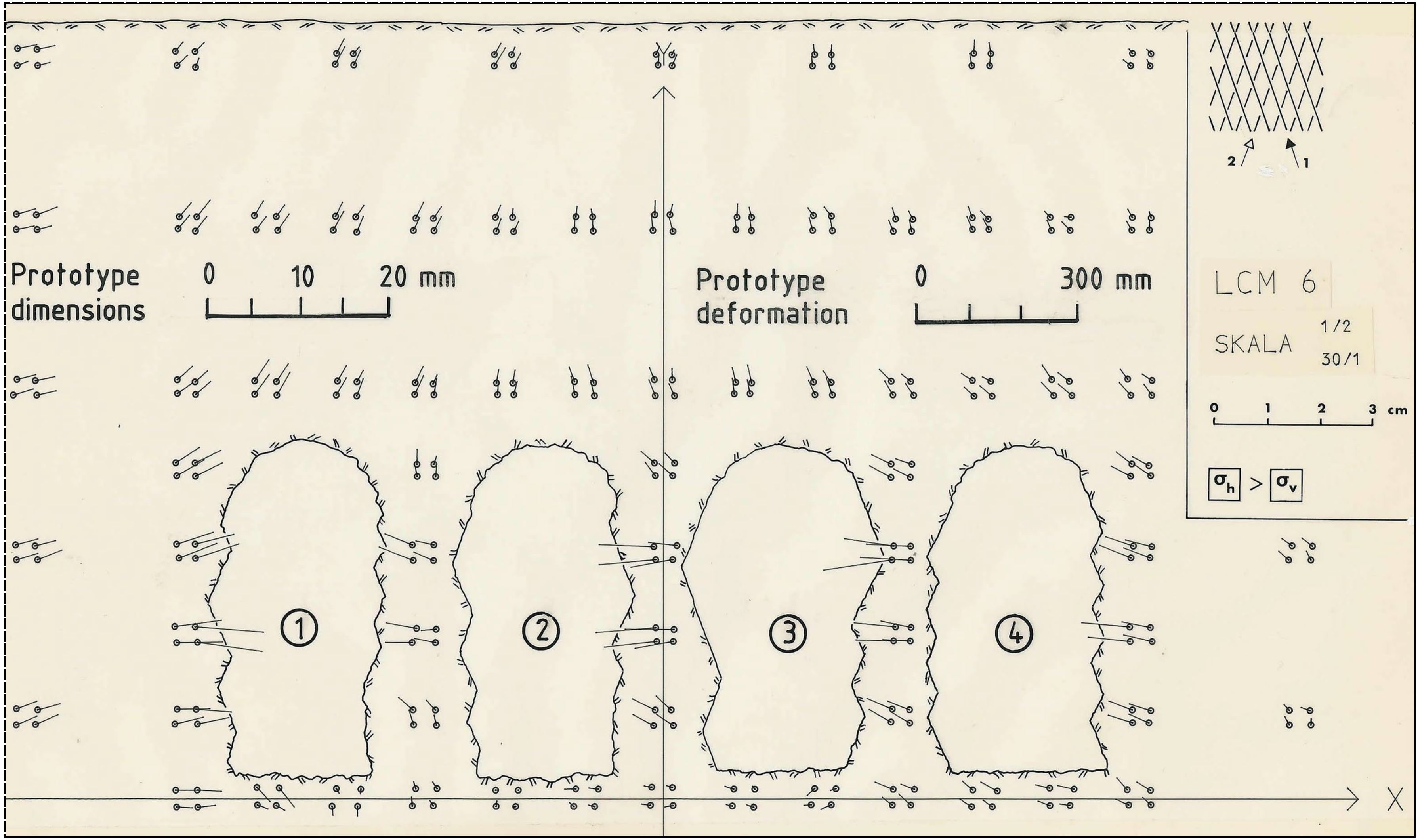
Barton and Hansteen, 1979



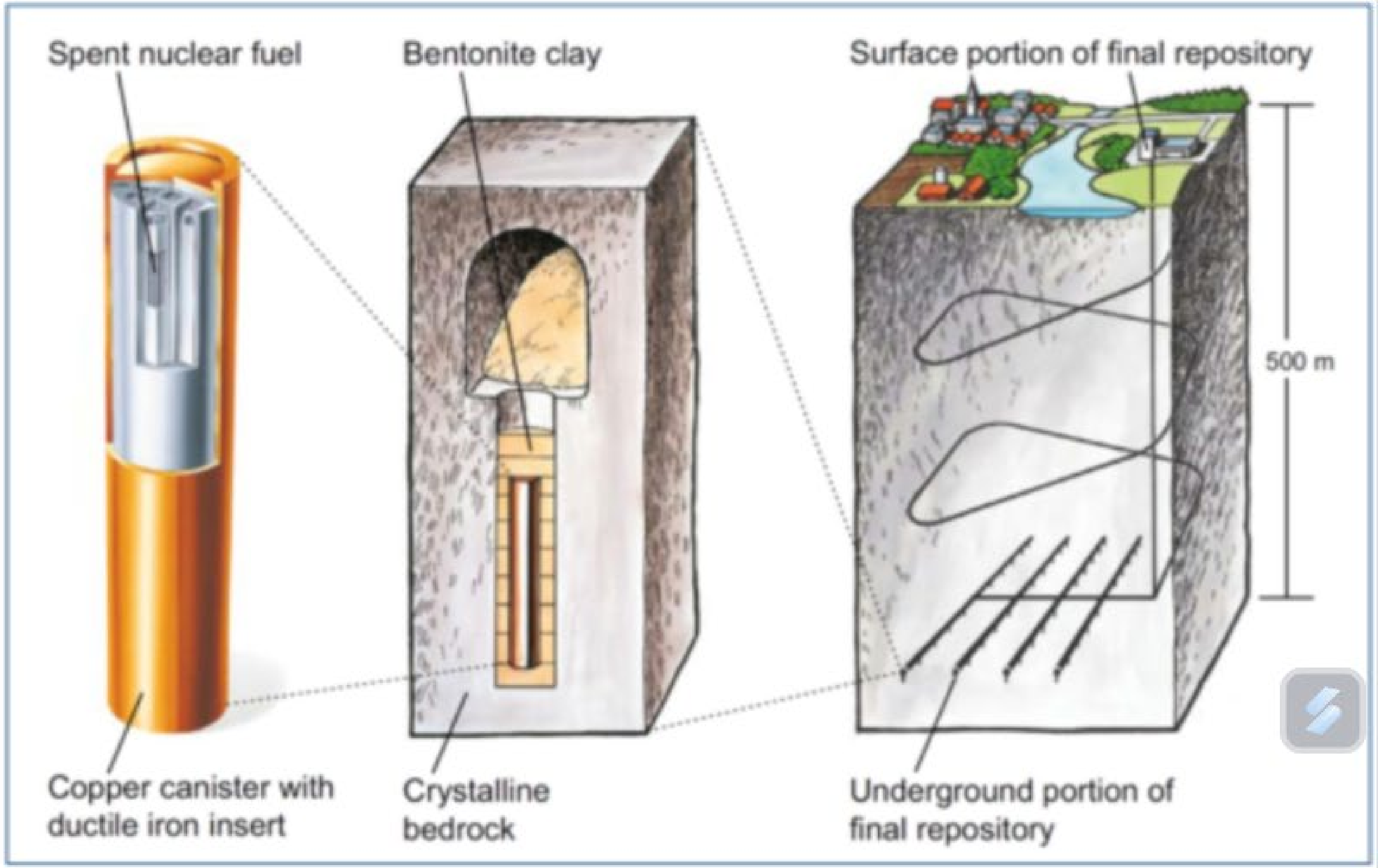


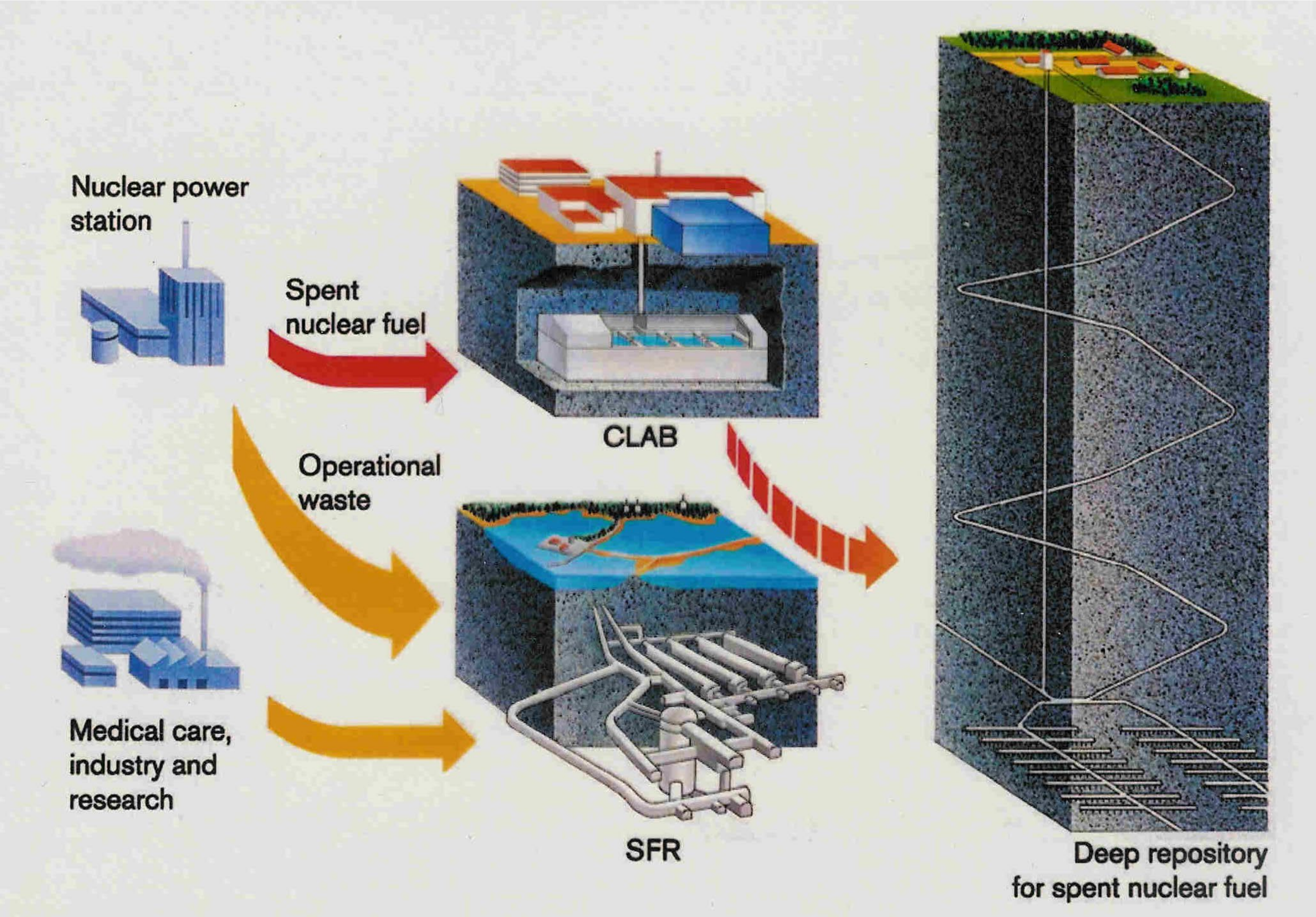
Left: Response to modelled earthquake shaking.

20,000-block models of 'rock caverns' (Barton and Hansteen, 1979)
Extreme hysteresis (= over-closure) were experienced.
(DEFORMATIONS DIRECTED ONLY TOWARDS THE LAST EXCAVATION)
(order of excavation 1-2-3-4)



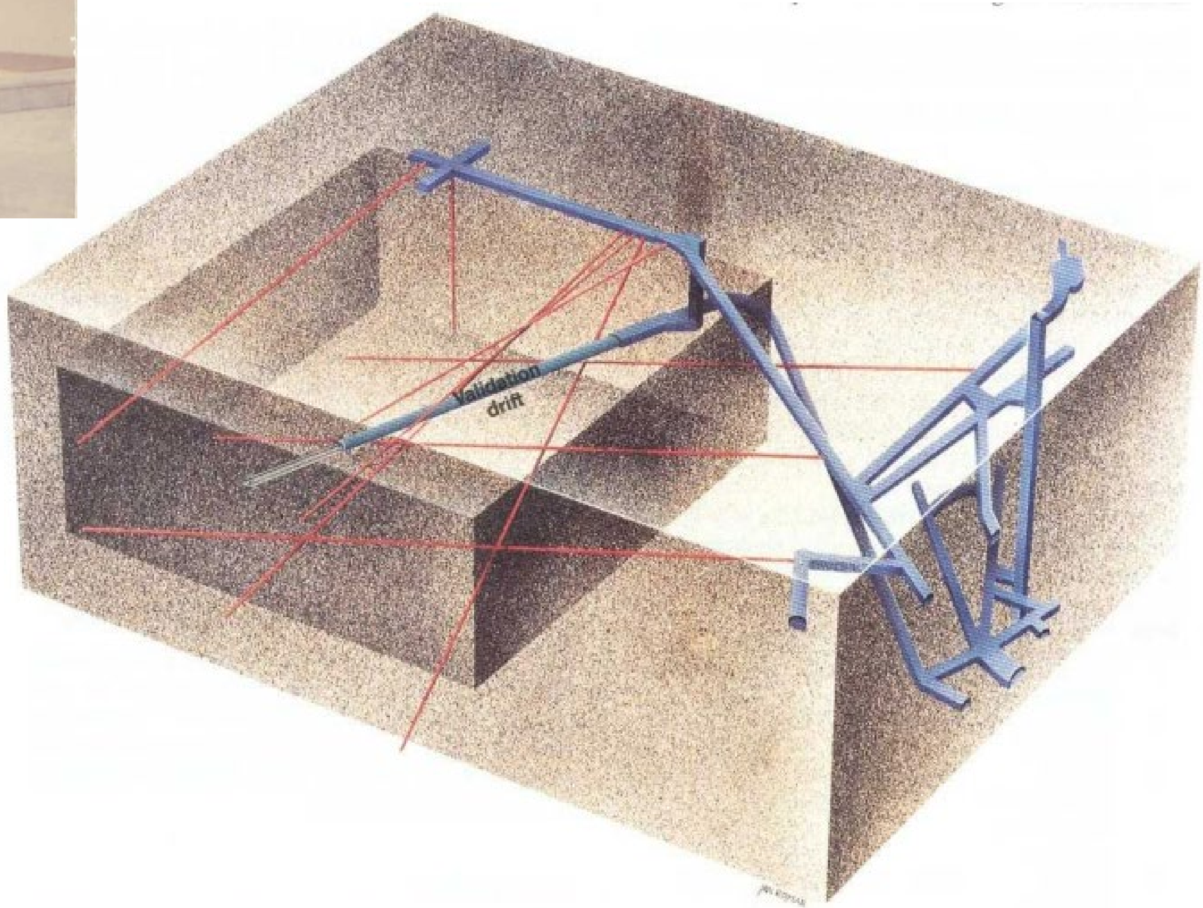
5. SKB: Swedish Nuclear Fuels studies: Stripa SCV site characterization and validation (NGI,1986 -1990).



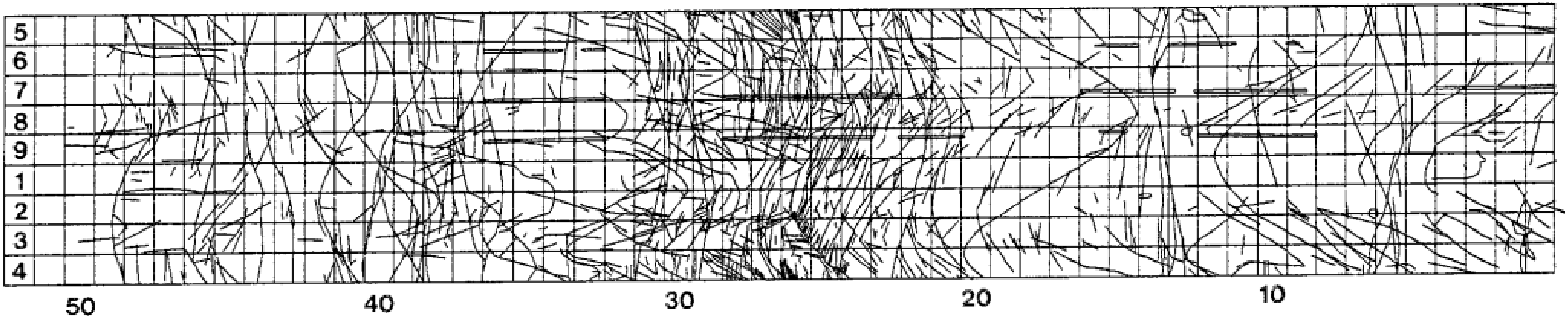


SKB has played a leading international role in researching nuclear waste disposal challenges, using multiple teams of international experts.

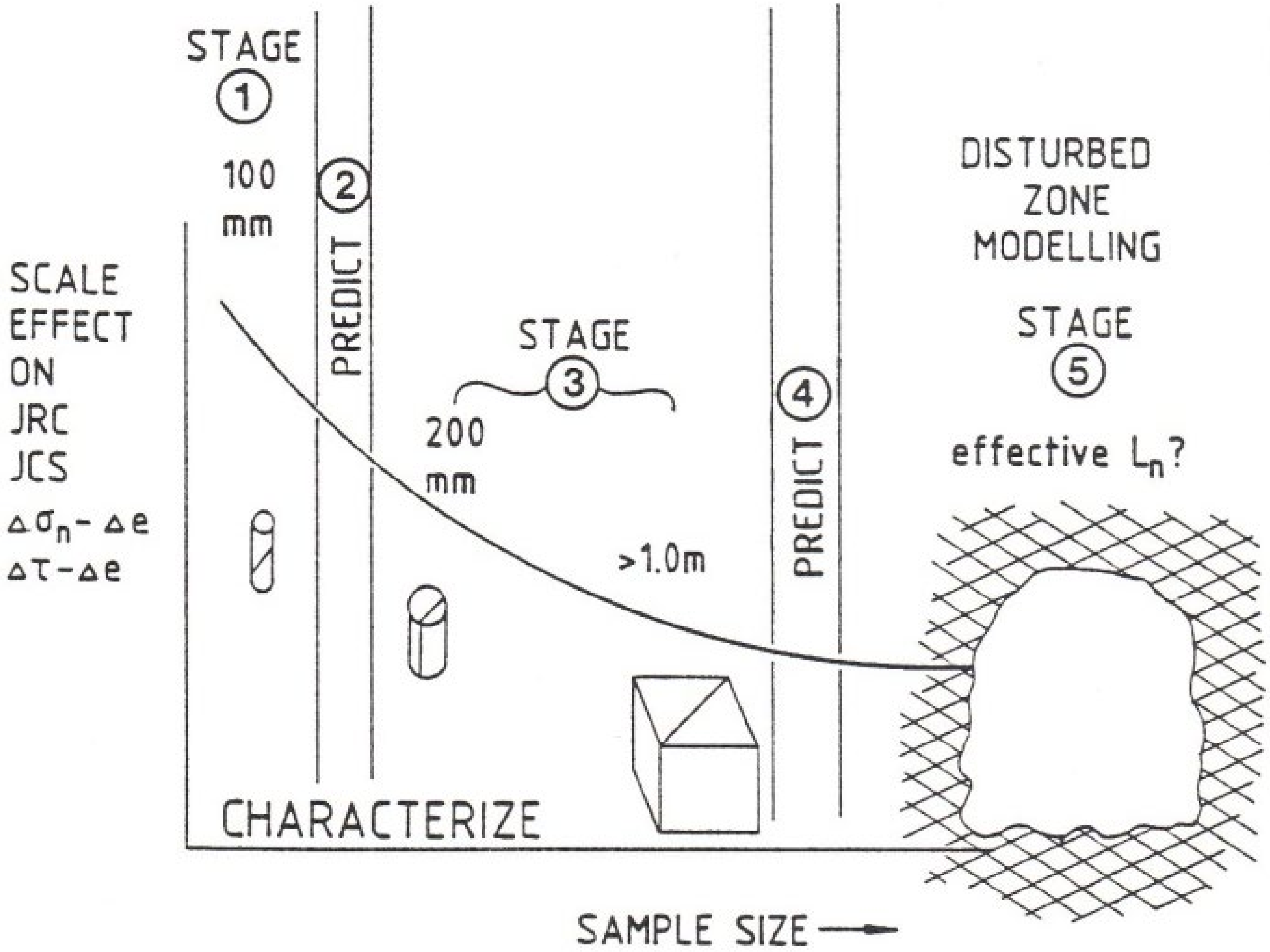
Most of the ‘principal investigators’ for the Stripa SCV project 1987-1990.



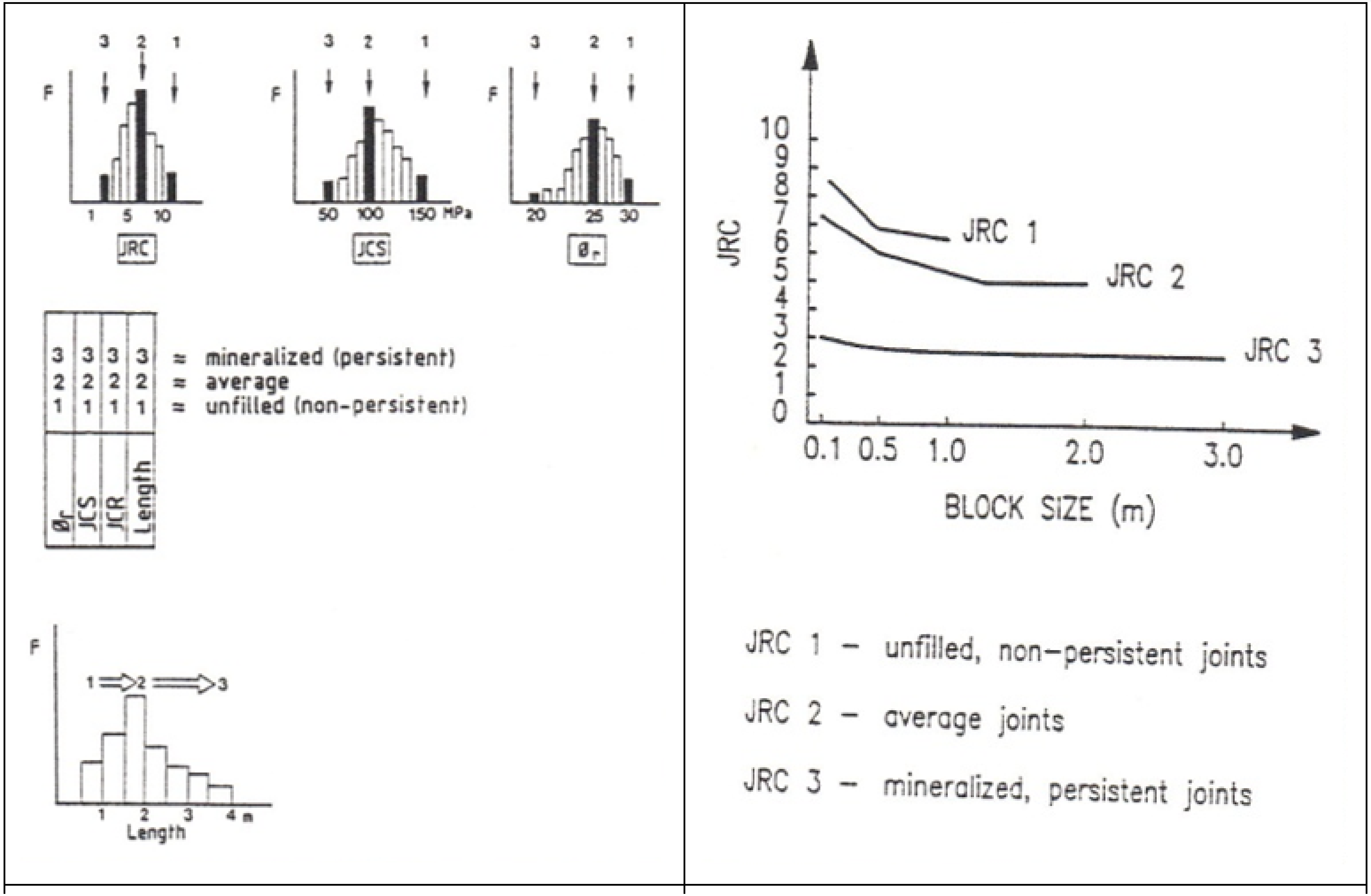
THE VALIDATION DRIFT WITH finally RECORDED JOINTING. 360° image. Hydraulic modellers (Dersowitz, Herbert) used FRACMAN and NAPSAC models, based on multiple future-drift-parallel borehole testing. The drift was covered in 2x2m plastic sheets to locate and measure all inflow.



- An important finding: due to the small 2.0 x 2.5m drift, there was insufficient deformation for 'normal' EDZ-related joint shear/dilation (NGI models showed this). All hydraulic models were strongly in error: because of no normal closure allowance. Inflow was almost limited to the fracture zone. Some sited dewatering/gas emission to explain reduced inflow

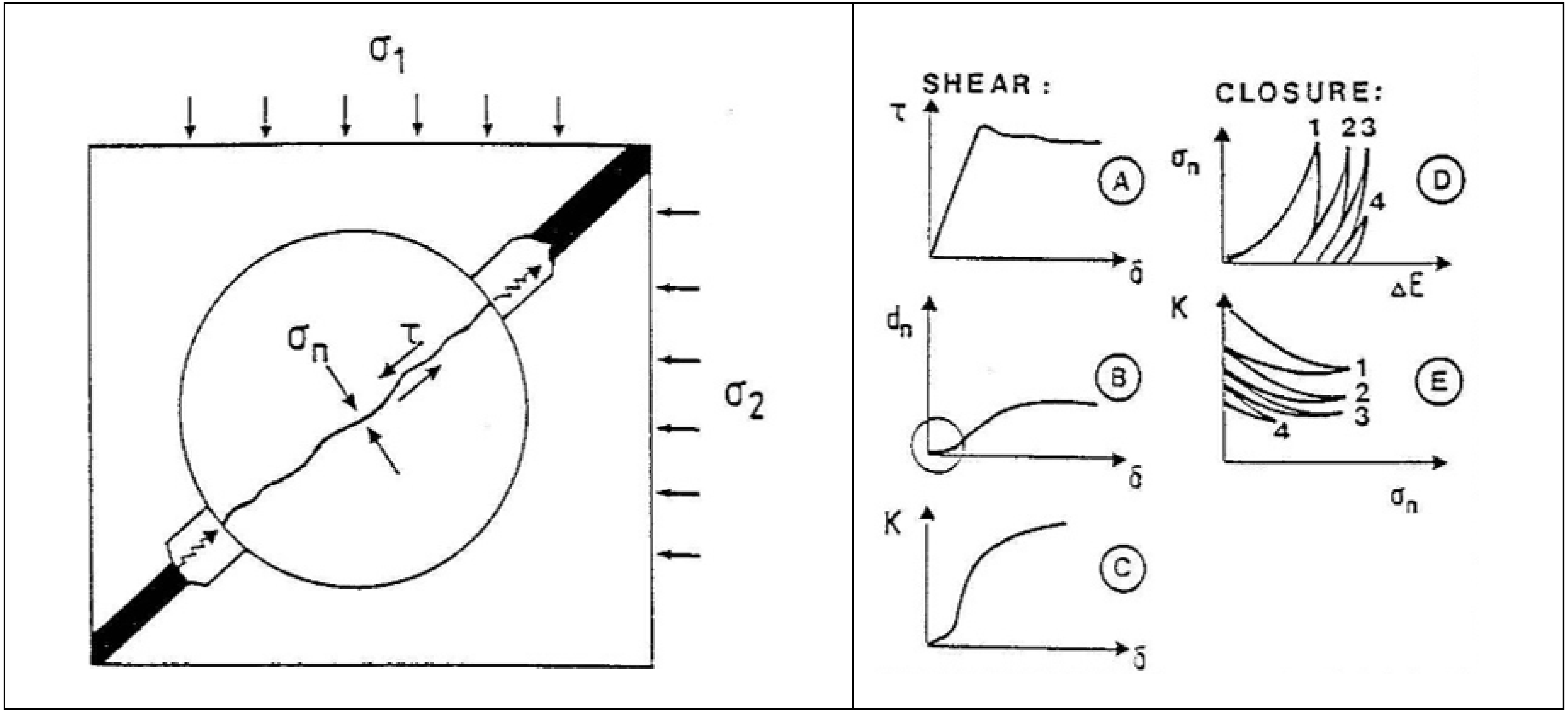


The NGI rock mechanics part of the Stripa SCV (site characterization and validation) project.



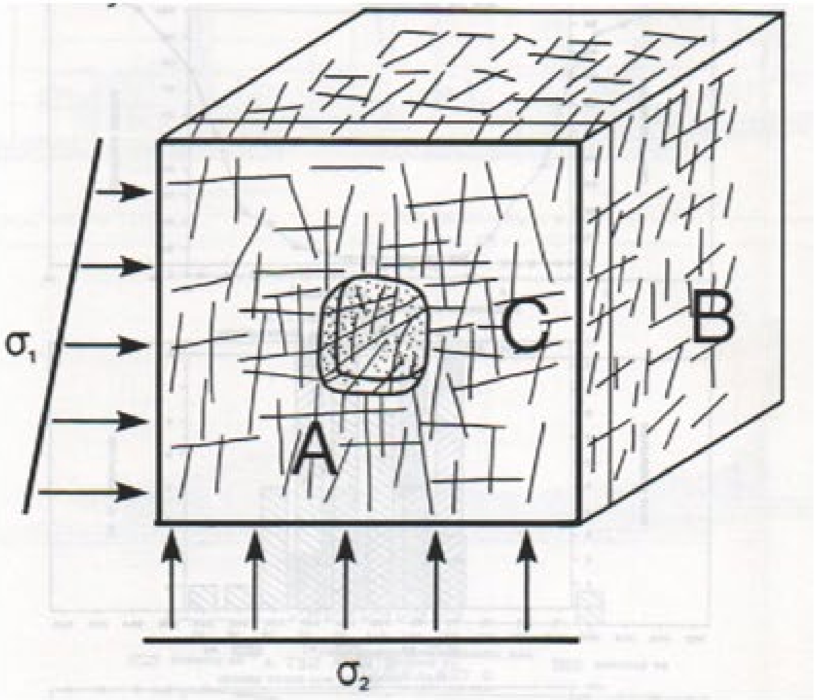
Stage 1 of NGI's SCV contribution was joint characterization in preparation for coupled (M-H) UDEC-BB modelling of the test tunnel, based on initially limited core logging and testing.

The larger CSFT test was the 3rd Stage of NGI's SCV, plus a 1mx1m in situ block test in the Stripa test drift.



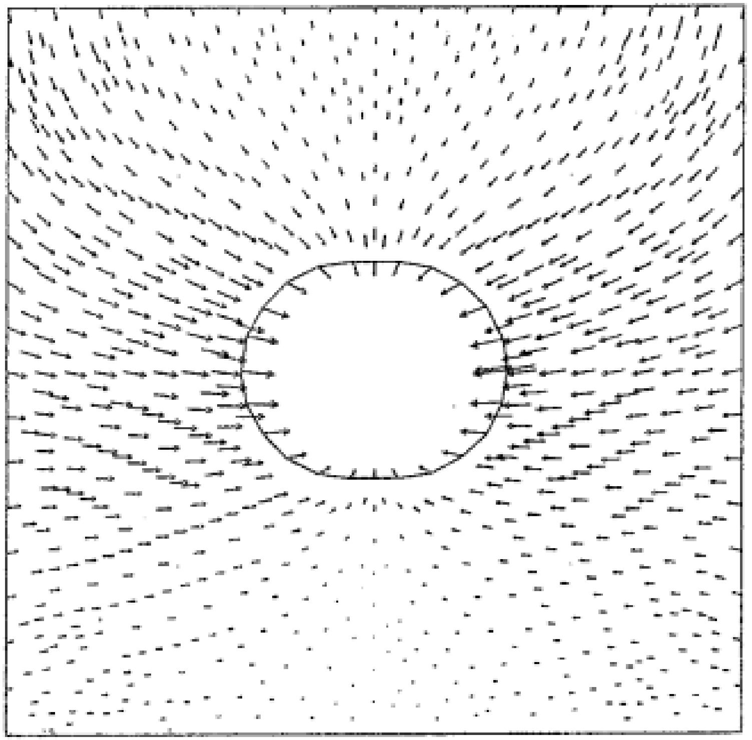
Allowance was made for individual joint set JRC, JCS, ϕ_r and for block-size scaling.

Group \ Block size (m)	0.1	0.5	1.0	2.0	3.0
JRC 3	3	2.7	2.6	2.5	2.5
JRC 2	7.25	5.6	5.2	4.7	
JRC 1	8.5	6.5	5.8		

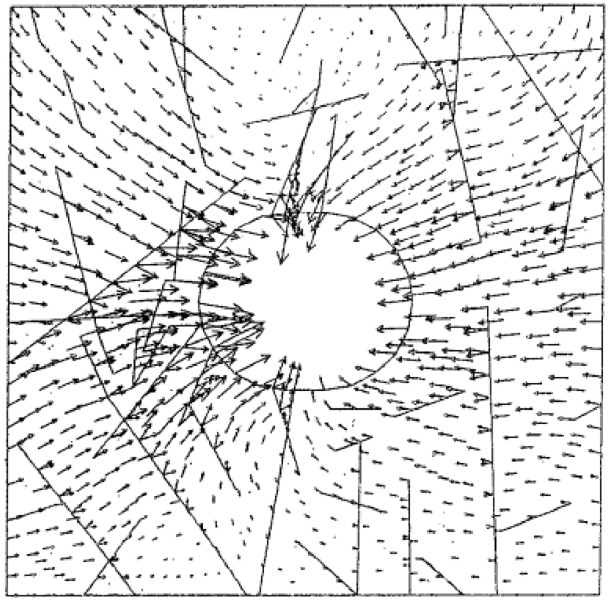


NGI's UDEC-BB modelling with stochastically generated jointing from Harwell's NAPSAP models (Karstein Monsen and Alan Herbert).

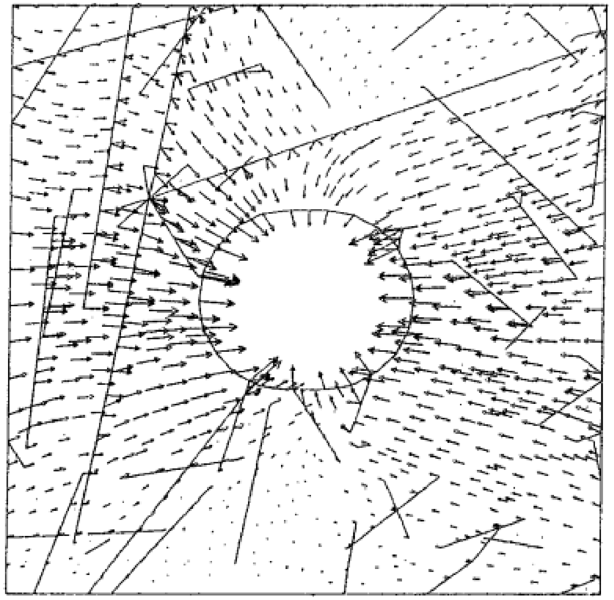
See Barton et al. 1991.



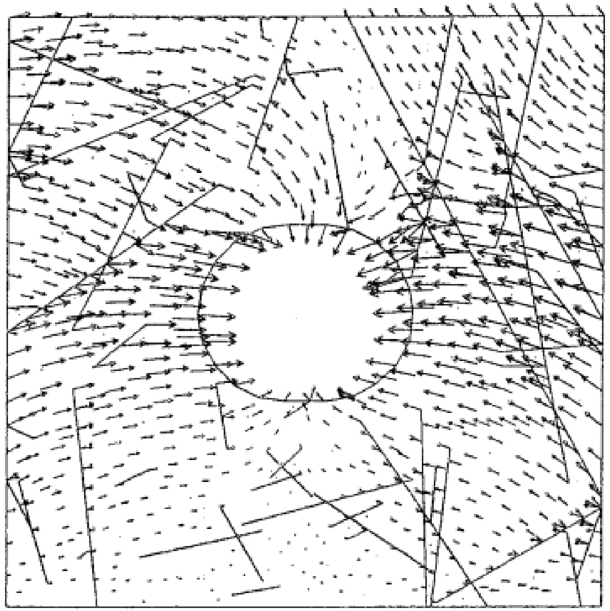
Continuum model



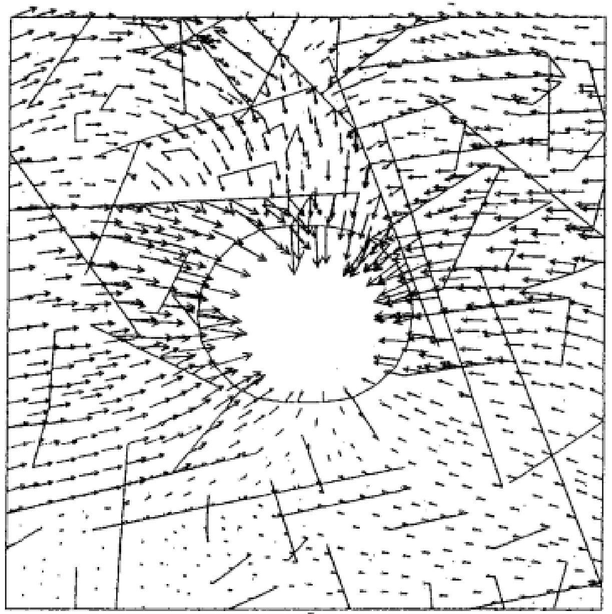
Model 5



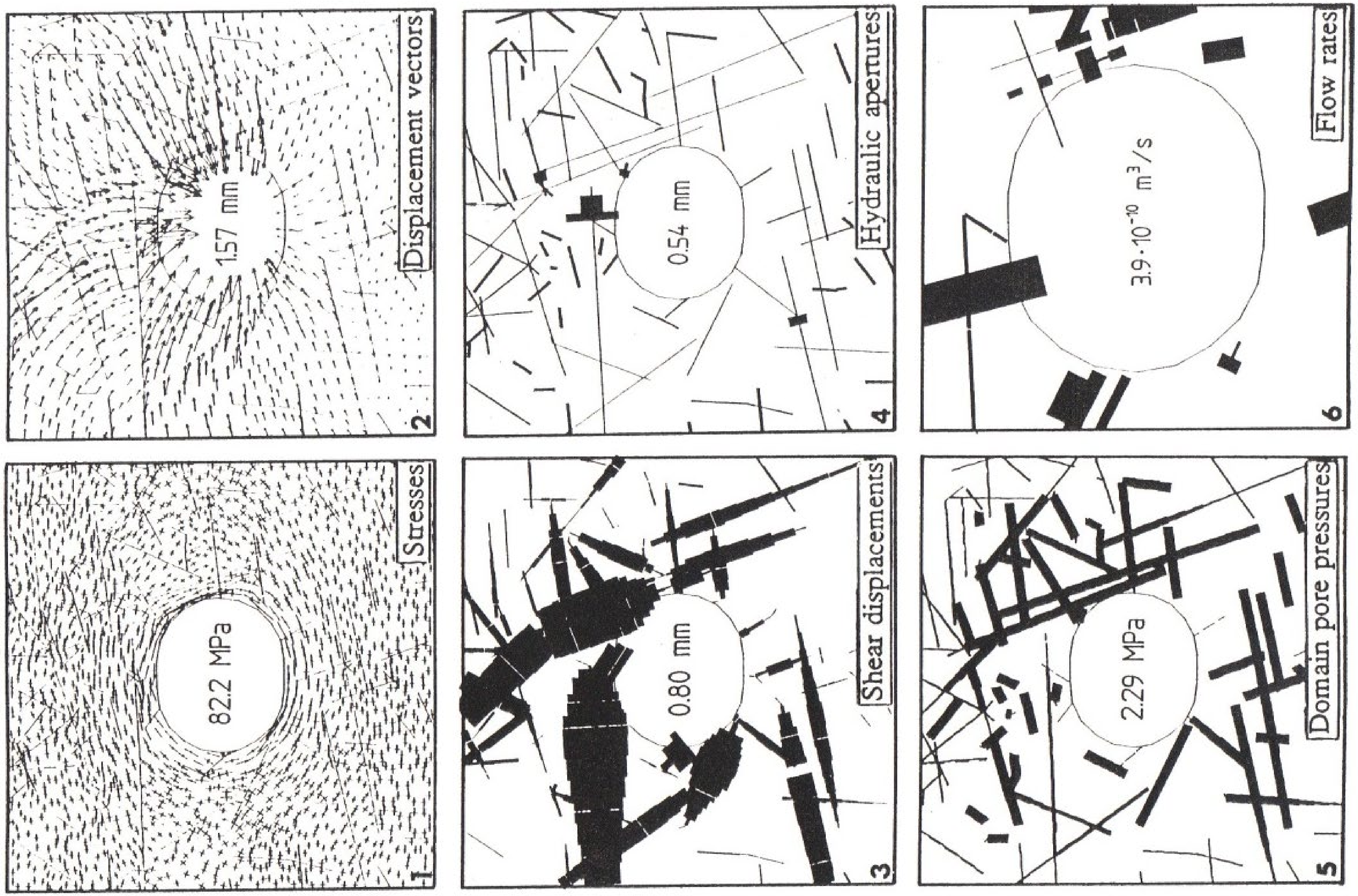
Model 6



Model 7



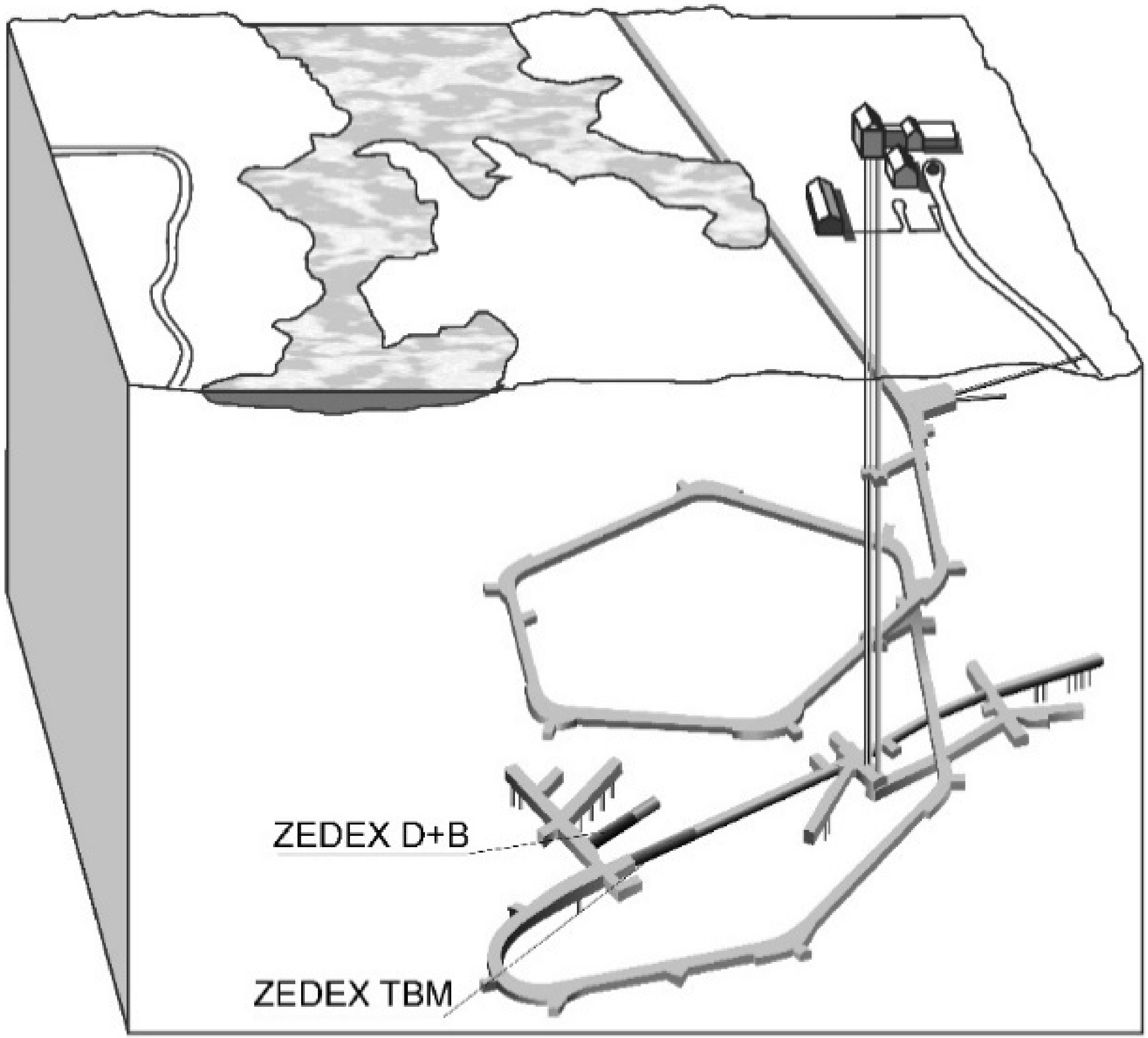
Model 8



One of NGI's M-H coupled UDEC-BB models.

6. Äspö ZEDEX D+B, velocity, modulus. APSE pillar study, tunnel characterization, parameter estimation. 1991 -1994

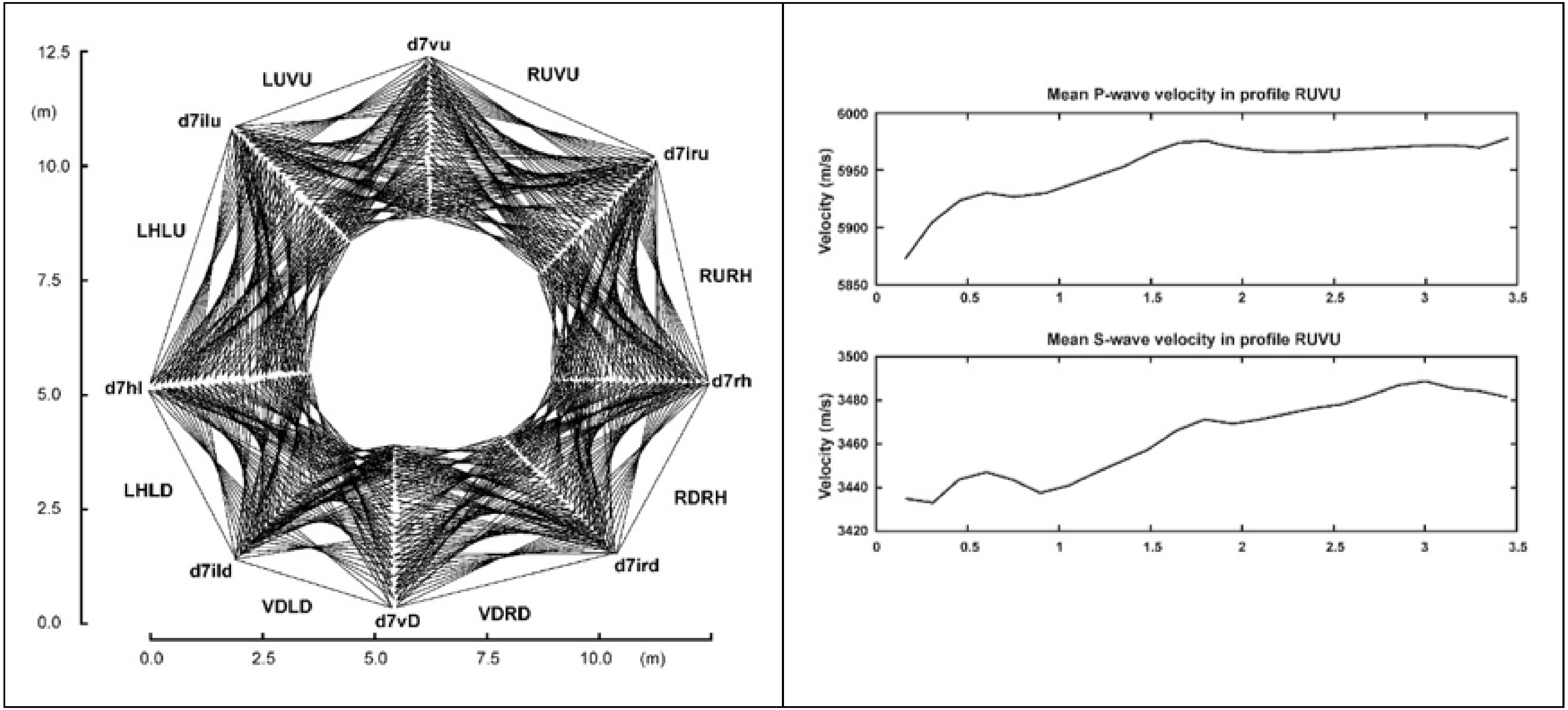
NGI/NB ZEDEX D+B involvement

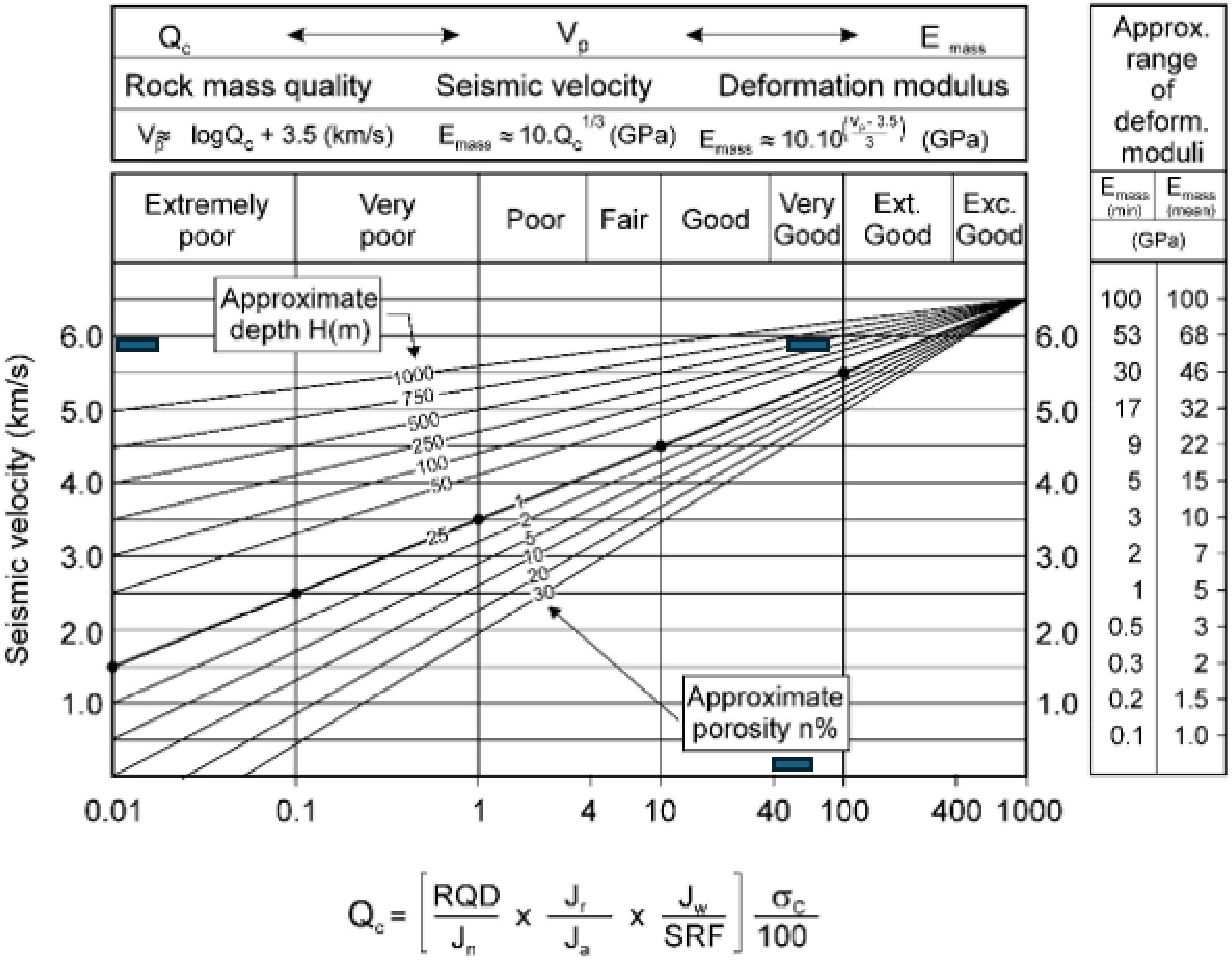


With Brazilian visitors near and above Äspö. **‘Cleaned pavement’** in forest *for observation of the rock mass.* Rolf Christiansson of SKB is our guide.

Cross-hole seismic tomography for ZEDEX. Note reduced velocity in EDZ caused (also) by drill-and-blast effect.

Cosma and Enescu, 1996.



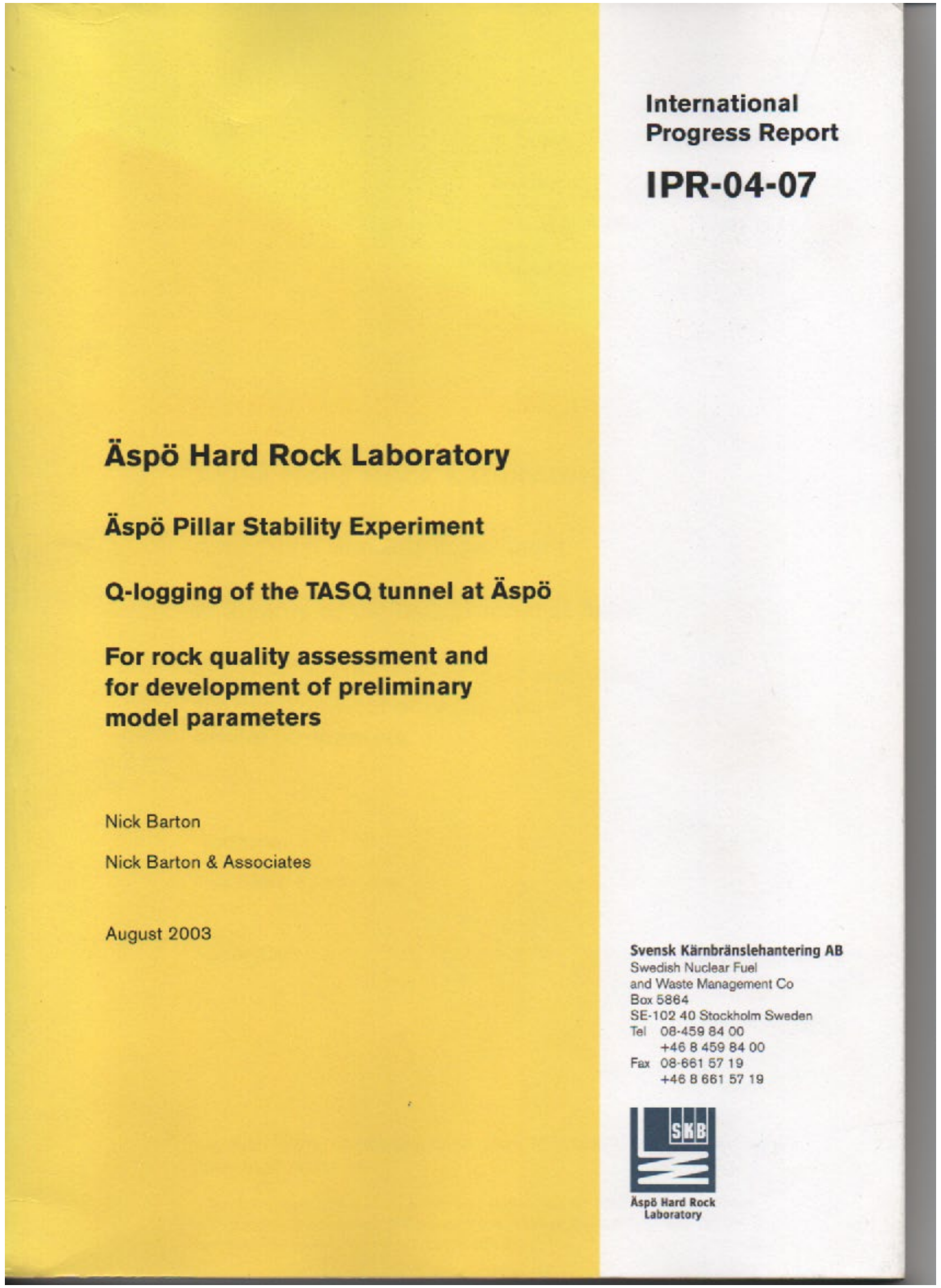


Empirically derived correlations between Qc, Vp and Emass (=M). Barton, 1995, 2000, 2002.

800m of relevant core within the ZEDEX PROJECT, logged by Løset of NGI showed Q mean = 40.

With UCS or σc ≈200MPa, this gives Qc = 80.

CORRELATES WITH VP = 5.8 – 5.9 km/s as X-hole measured at 500m depth.



International
Progress Report

IPR-04-07

Äspö Hard Rock Laboratory

Äspö Pillar Stability Experiment

Q-logging of the TASQ tunnel at Äspö

For rock quality assessment and for development of preliminary model parameters

Nick Barton

Nick Barton & Associates

August 2003

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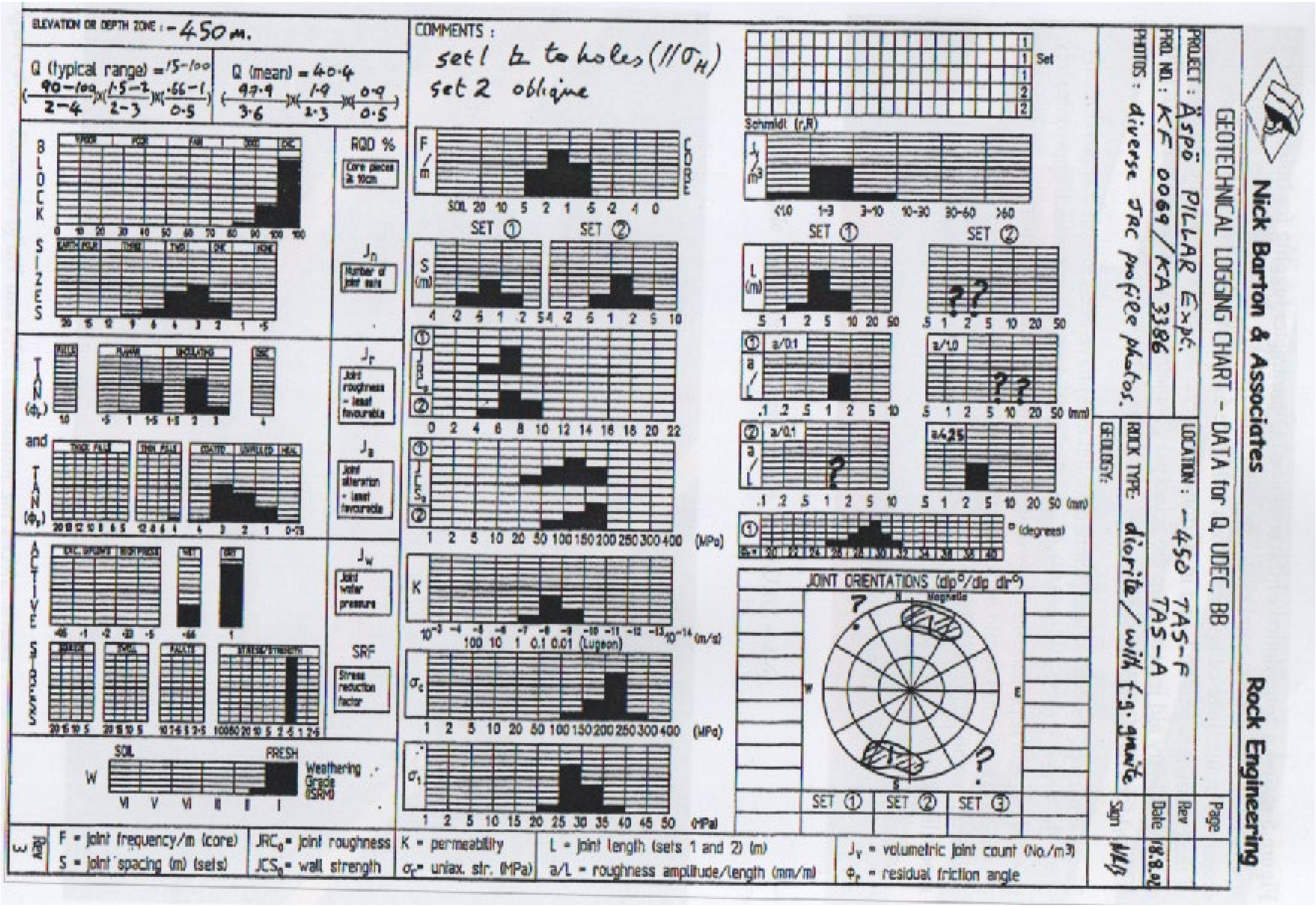
Äspö Hard Rock
Laboratory

Figure 4-3. Example of a/L and JRC estimation, set 2 (JRC ≈ 6-8).

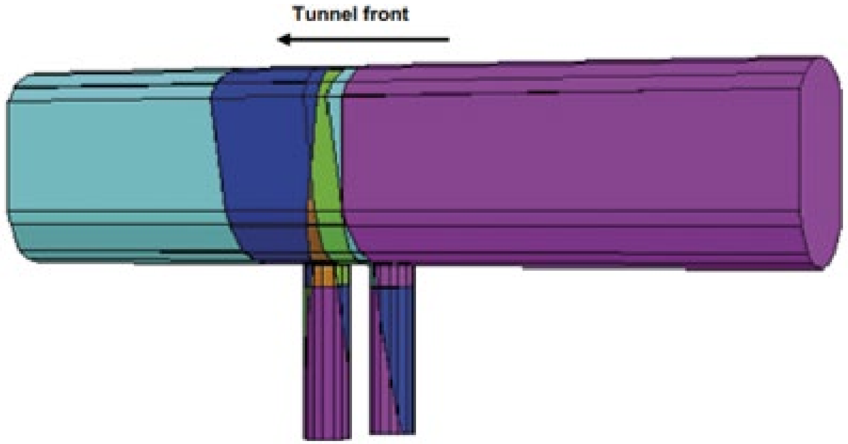
Before logging in the APSE tunnel, two axis parallel boreholes were Q-logged.

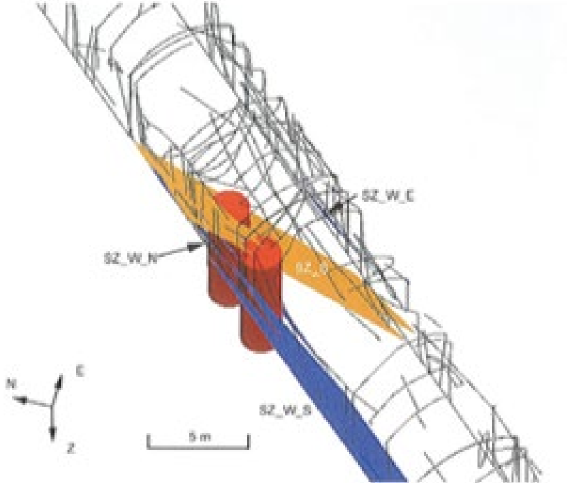


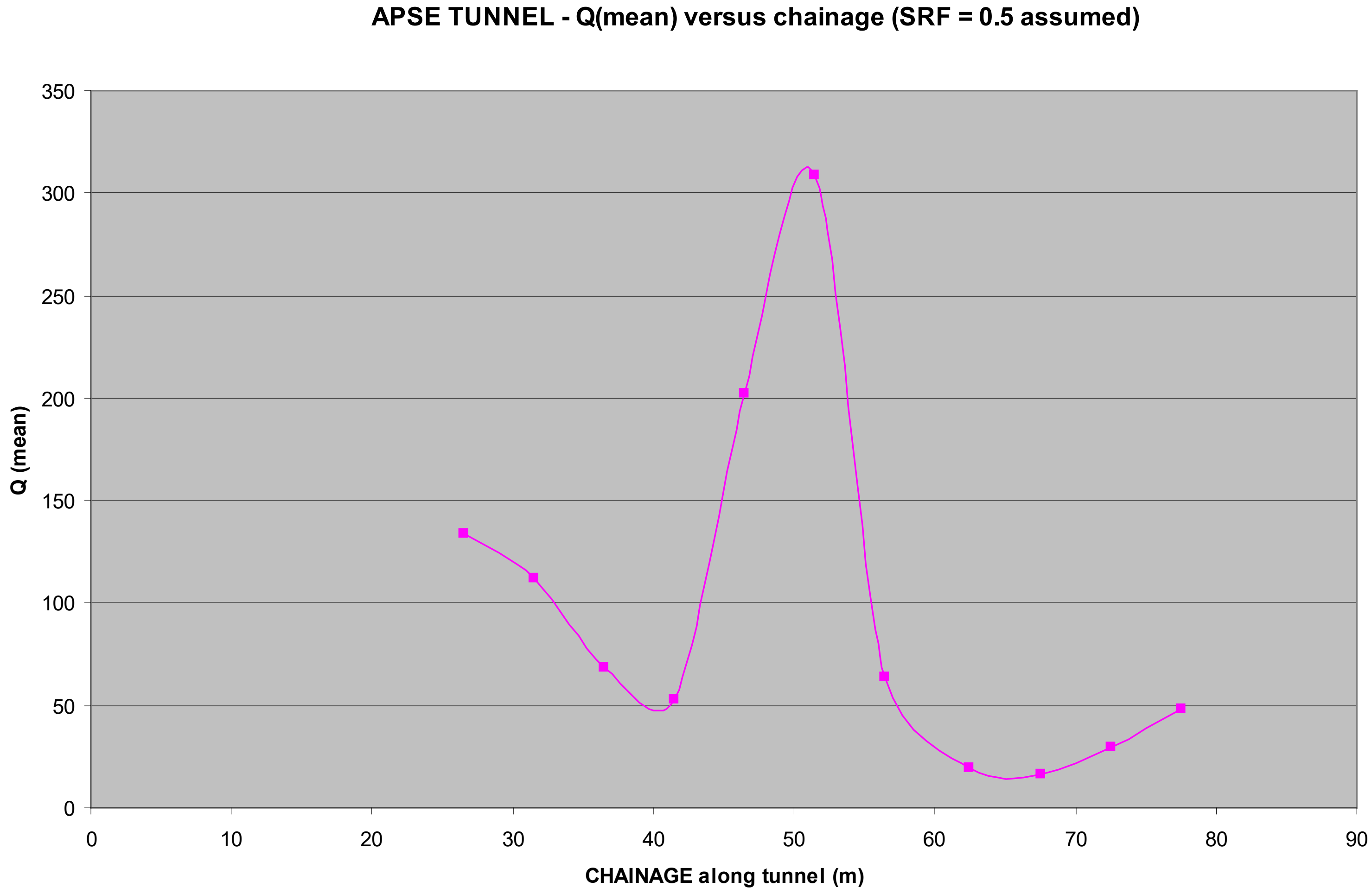
Comprehensive histogram logging of two axis-parallel boreholes prior to entry in APSE.

Q-histograms on the left.

Q-value distribution in APSE (pillar stability) tunnel at Äspö

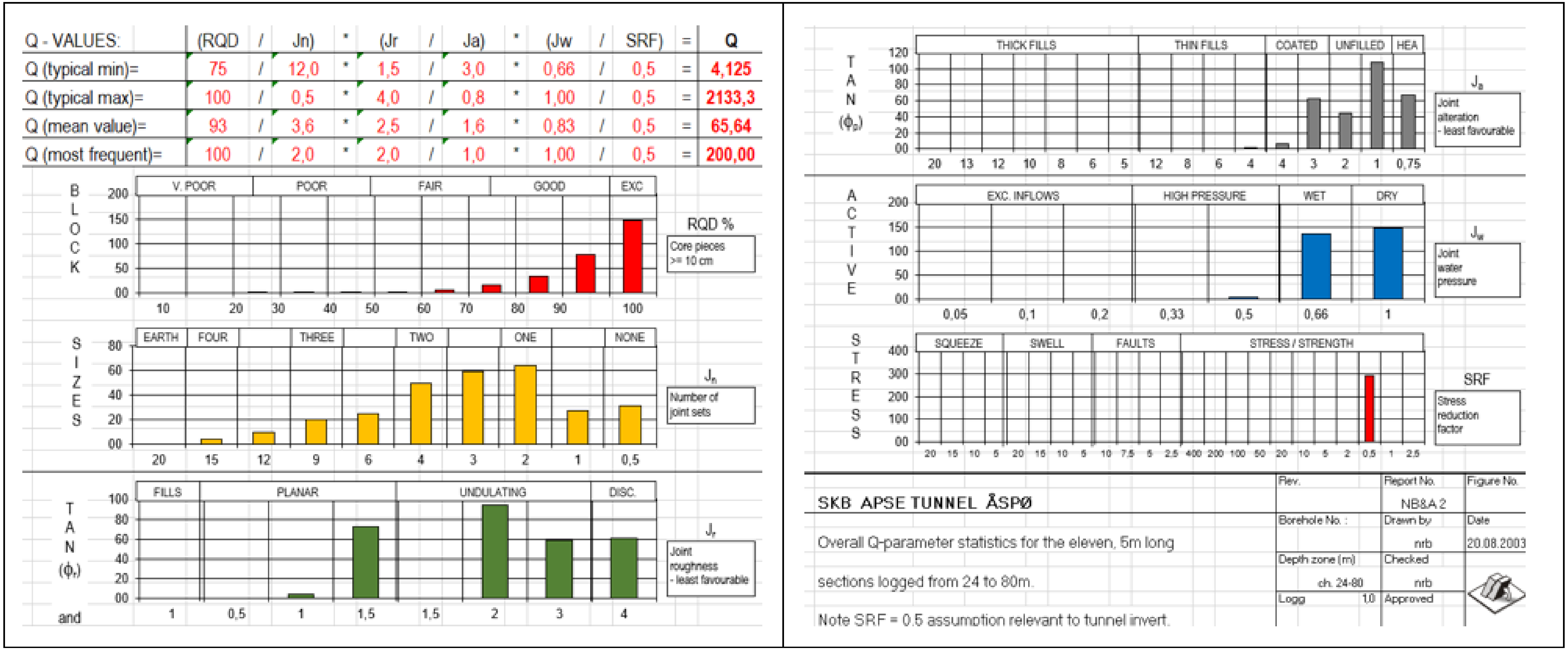






Q-parameter statistics for SKB's APSE tunnel.

Barton, 2003.



Details of Q-parameters in APSE tunnel

Q-parameter statistics for seven, 5m long sections logged from ***24 to 59m***.

Q - VALUES: (RQD / J_n) * (J_r / J_a) * (J_w / SRF) = Q
Q (typical min)= 75 / 6.0 * 1.5 / 3.0 * 0.50 / 0.5 = 8.250
Q (typical max)= 100 / 0.5 * 4.0 / 0.8 * 1.00 / 0.5 = 2133.0
Q (mean value)= 94 / 2.5 * 2.6 / 1.5 * 0.85 / 0.5 = 110.76
Q (most frequent)= 100 / 2.0 * 2.0 / 1.0 * 1.00 / 0.5 = 200.00

Q-parameter statistics for the four, 5m long sections logged from ***60 to 80m***.

Q - VALUES: (RQD / J_n) * (J_r / J_a) * (J_w / SRF) = **Q**
Q (typical min)= 75 / 15.0 * 1.5 / 4.0 * 0.66 / 0.5 = **2.475**
Q (typical max)= 100 / 1.0 * 4.0 / 0.8 * 1.00 / 0.5 = **1066.7**
Q (mean value)= 91 / 6.7 * 2.2 / 1.9 * 0.79 / 0.5 = **25.10**
Q (most frequent)= 100 / 6.5 * 2.0 / 1.0 * 0.66 / 0.5 = **40.62**

(Note SRF = 0.5 assumption for relevance to tunnel invert)

Stressed (500m depth) estimates of V_P and E_{mass} based on Q_c correlations range from 5.8 to 6.0 km/s and 59 to 66 GPa respectively.

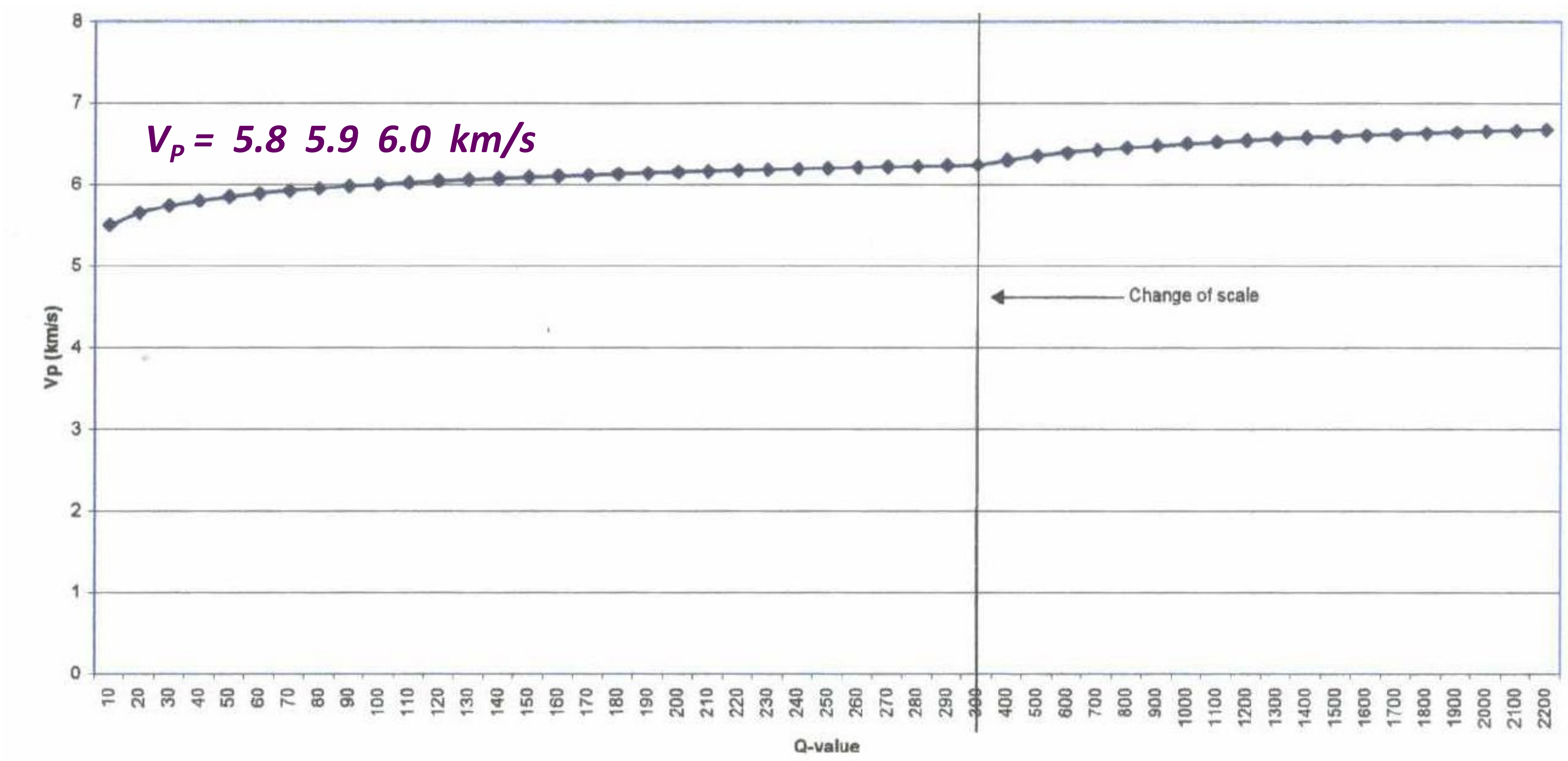
A more stressed (1000m depth) model, ***perhaps*** equivalent to σ_1 stress levels (rather than σ_2, σ_3 levels) suggested V_P ranges of 6.1 to 6.2 km/s, and E_{mass} ranges of 74 to 79 GPa. (See following curves).

The following empirical equation can be used for near-surface correlation between V_P and Q_C.

$$V_P \approx 3.5 + \log Q_c$$

Stress effects are important components of both V_P and deformation modulus E_m. The following is an approximation for 500m depth (or equivalent stress):

$$V_P \approx 5.0 + 0.5 \log Q_c$$

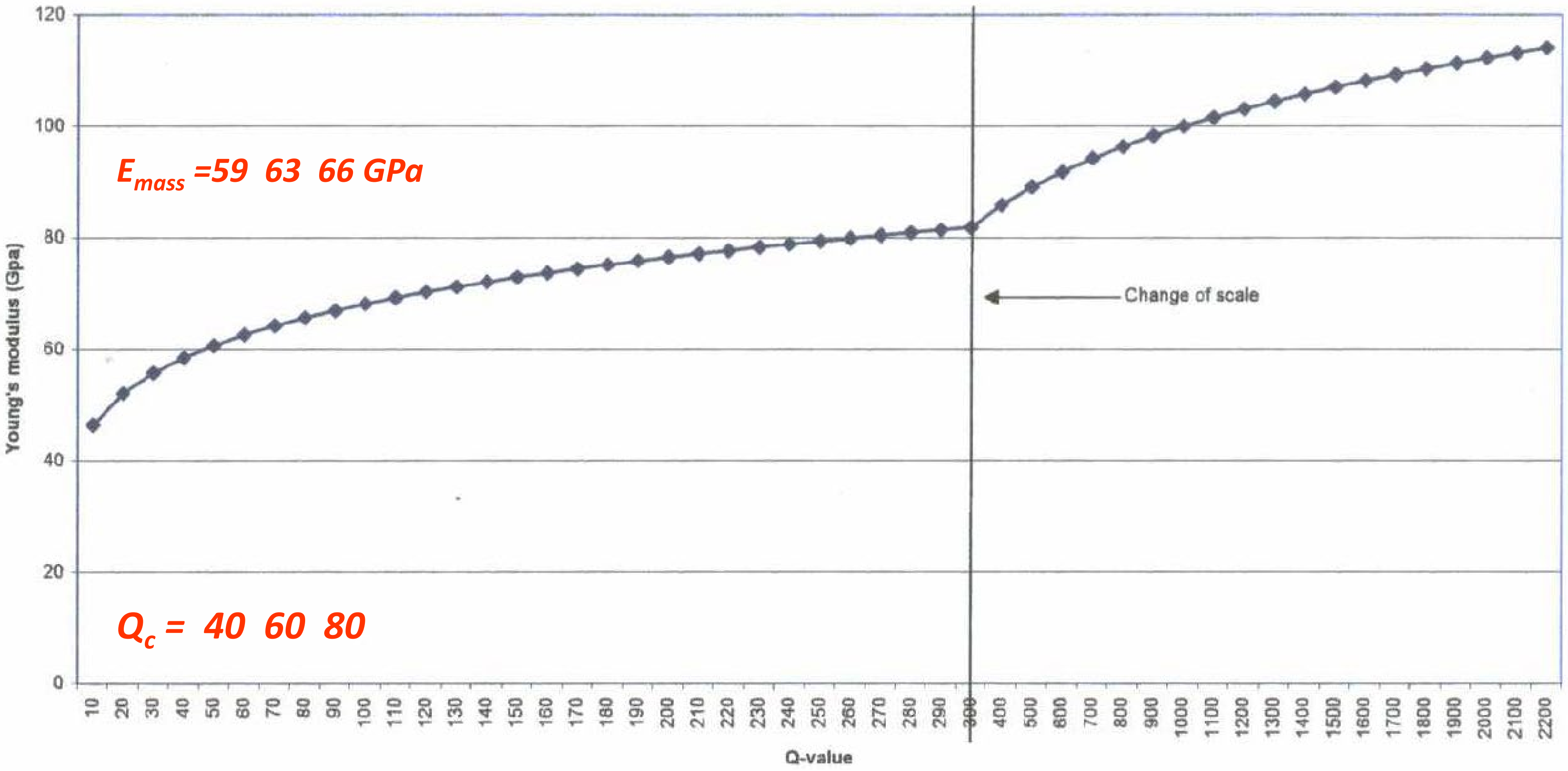


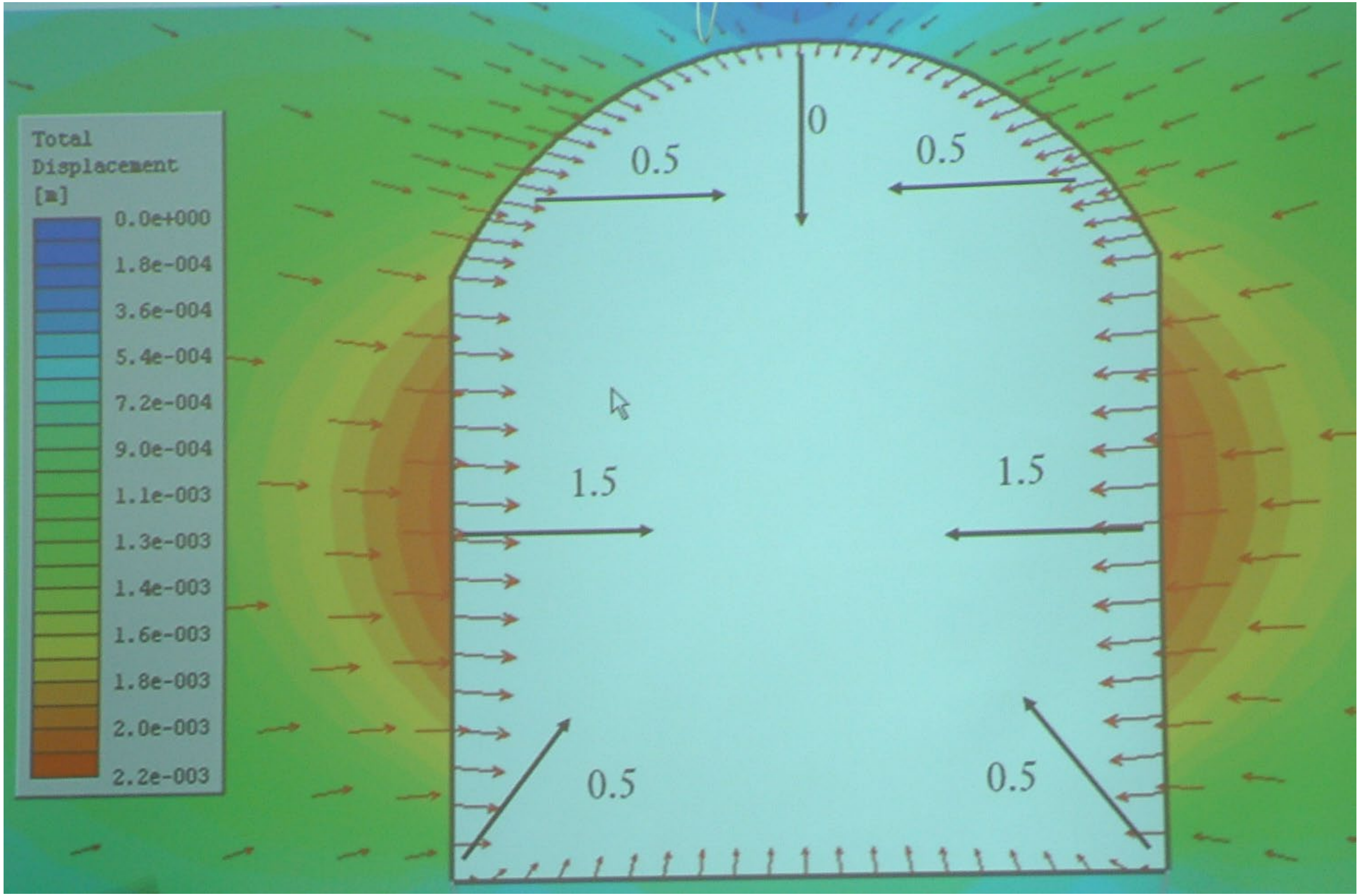
The following empirical equation can be used for near-surface correlation between E_{mass} and Q_c.

$$E_{mass} \approx 10\, Q_c^{1/3}$$

Stress effects are also an important component of deformation modulus E_m. The following is an approximation for 500m depth (or equivalent stress):

$$E_{mass} \approx 10^{(4.5 + 0.5\, Qc)/3}$$





Christer/SKB intact rock modelling with Q-value estimates of deformation modulus.

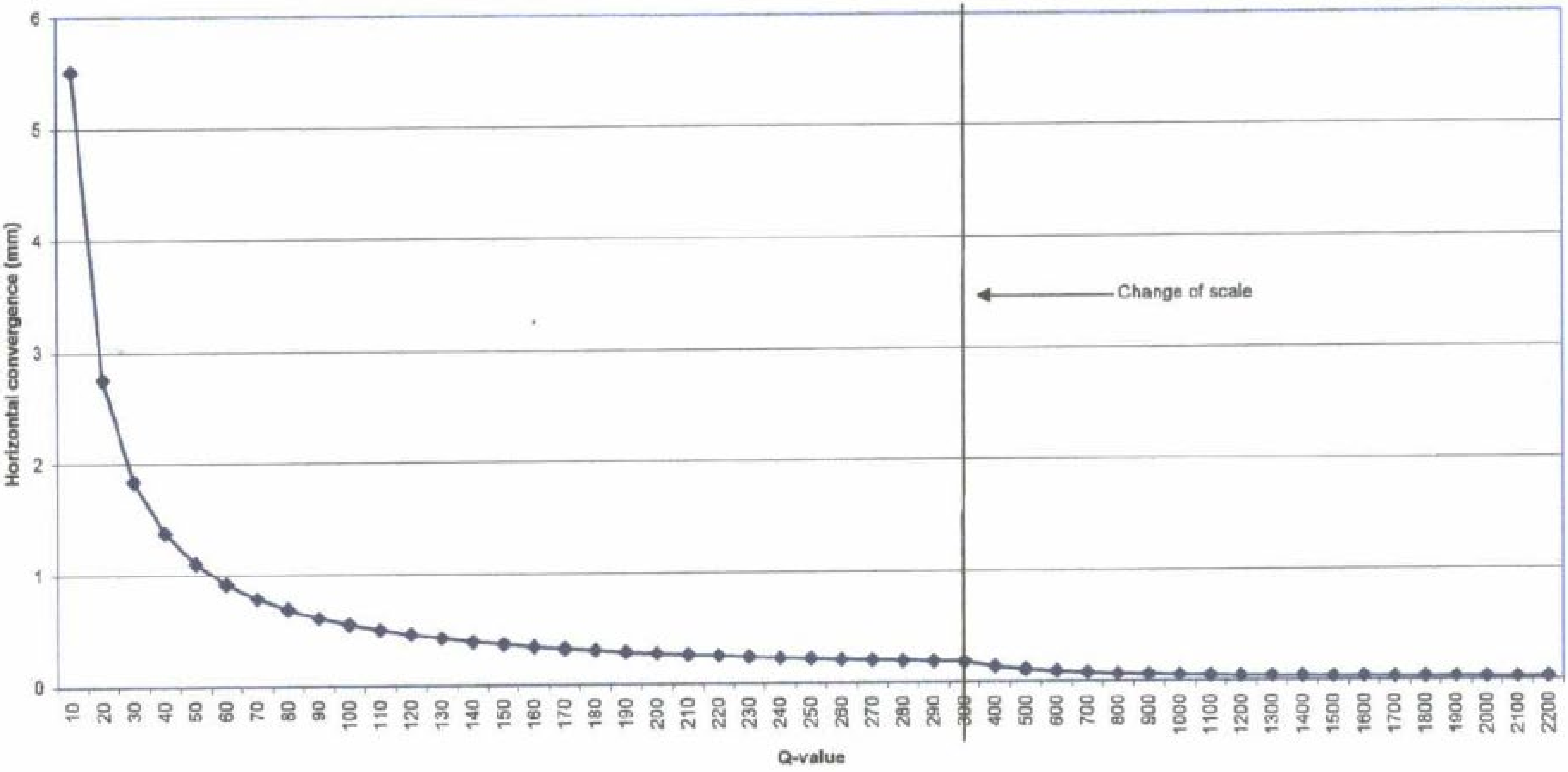
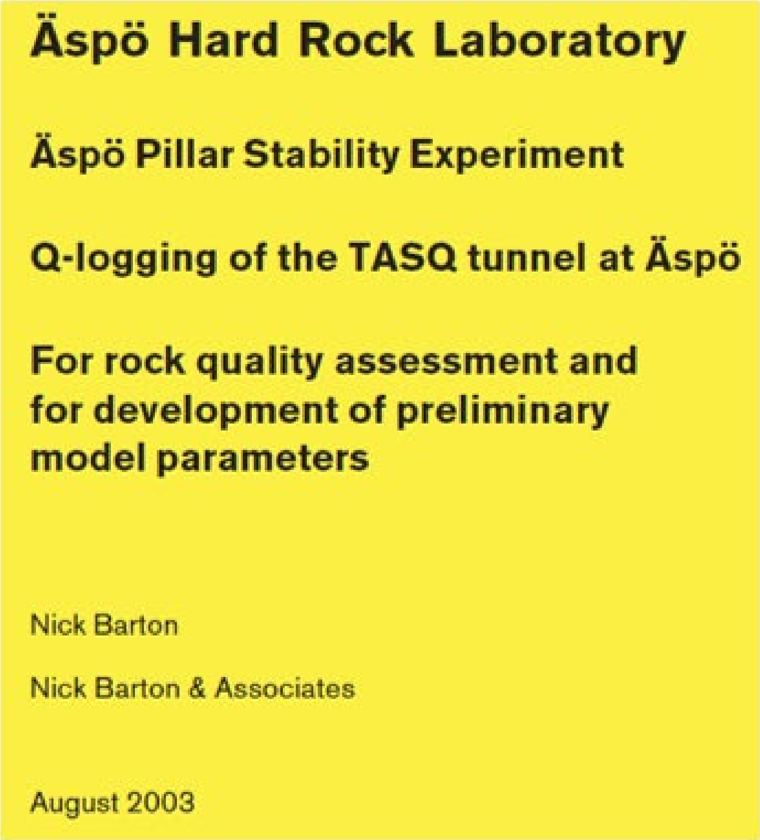


Figure 9. Plot of horizontal deformations versus Q-value using equation: $\Delta h = 2 \times HEIGHT/100Q(\sigma_H/\sigma_c)$. Used parameters: Height = 7500, σ_H = 27 MPa, σ_c = 200 MPa.

NB report includes observations of the results of grouting experiments in the APSE TUNNEL. Only one joint set was injected successfully due to insufficient pressure.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For rock quality assessment and for development of preliminary model parameters

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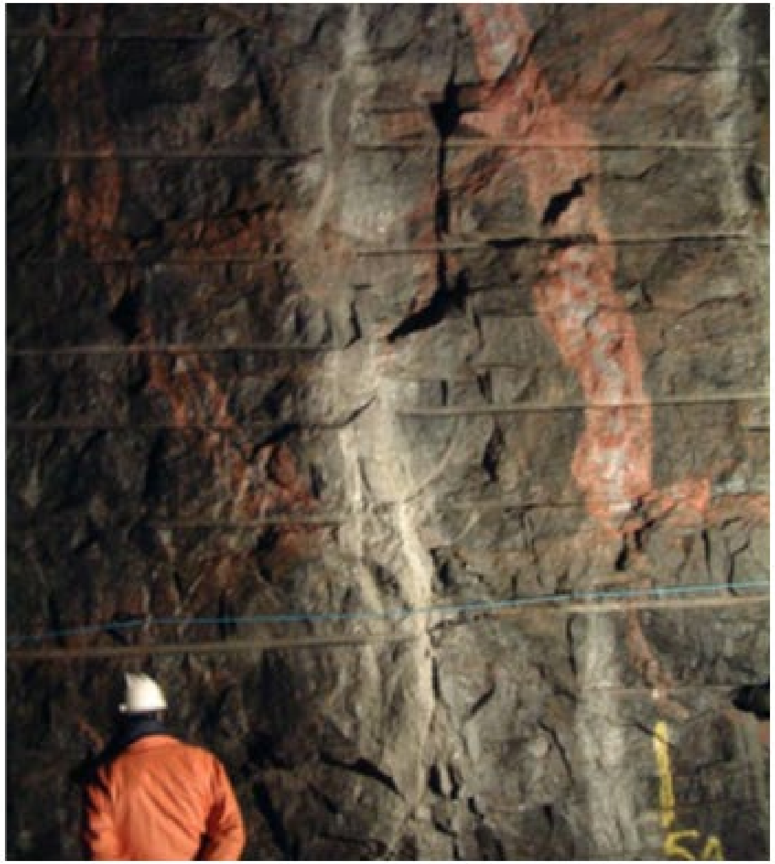
August 2003

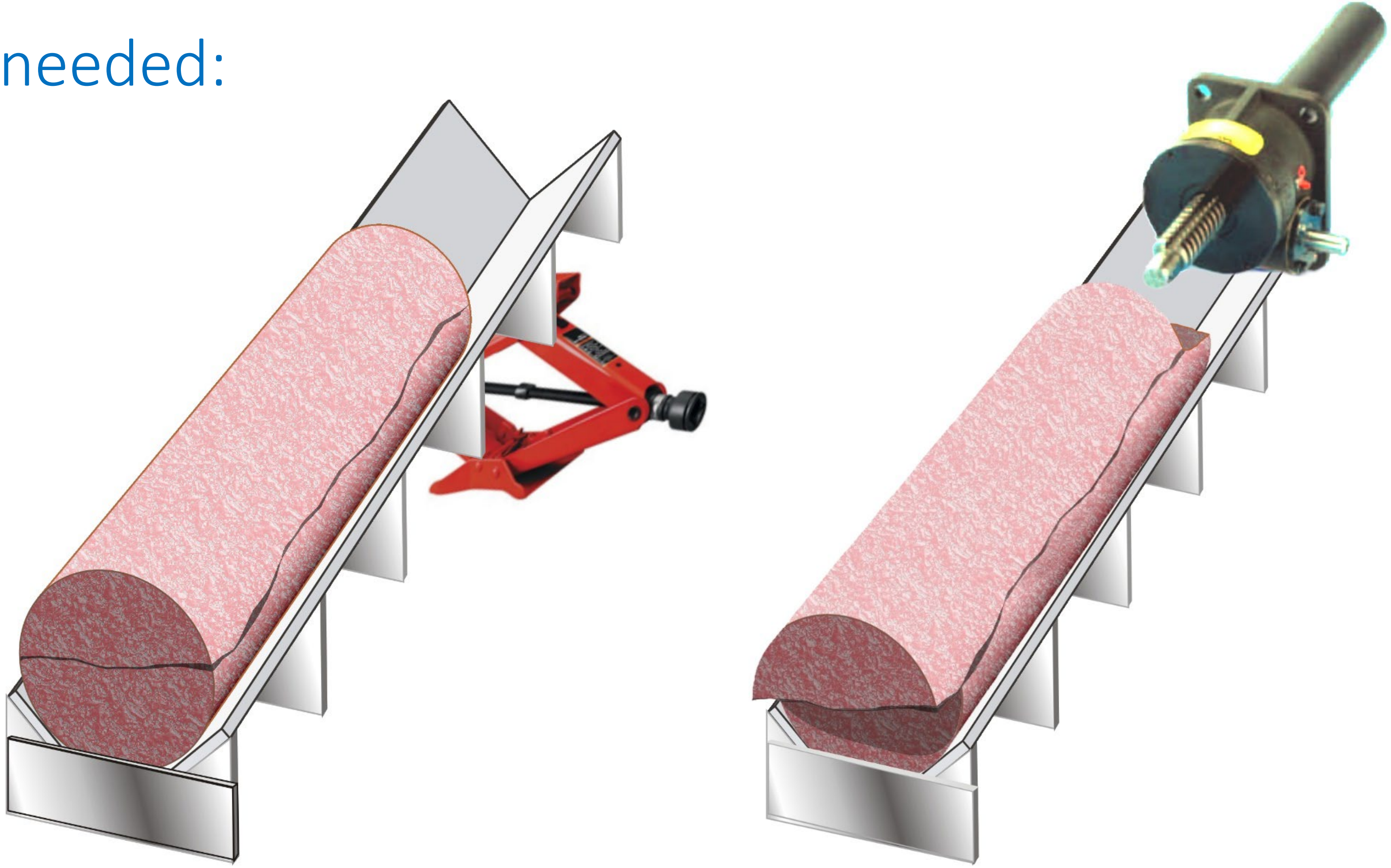


Modelling joints at Äspö: if rough joints remained TOC closed during cooling phase, deformation/opening would be on **these more planar sets**. Need to test for JRC_0 and JRC_n.

NB Suggestion to SKB for index testing of large diameter (and long L = 1-3m) over-cored joints.

In situ (JRCn) data needed:

TILT or PUSH tests:



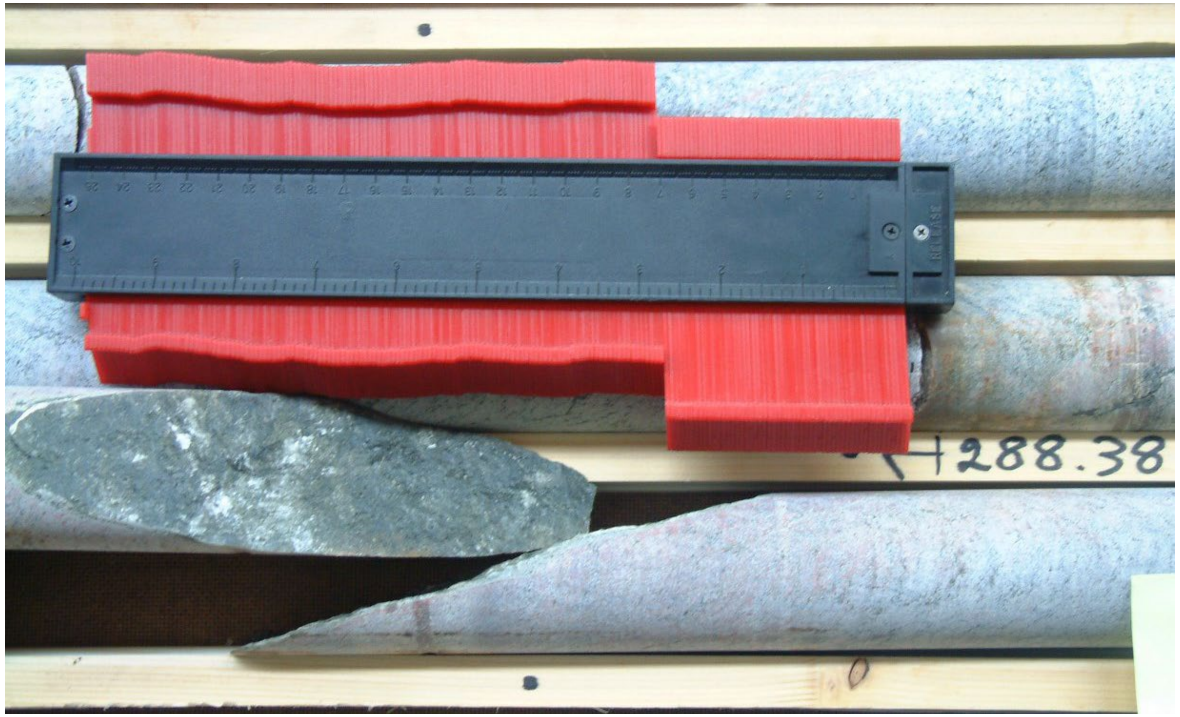
7. Simpevarp, surface and 2x 1000m deep borehole cores: Q-histogram 2003-4

8. Forsmark: surface and 2x 1000m deep borehole cores: Q-histogram 2007 – 2008

- 1,000m of core for inspection in SKB core shed.

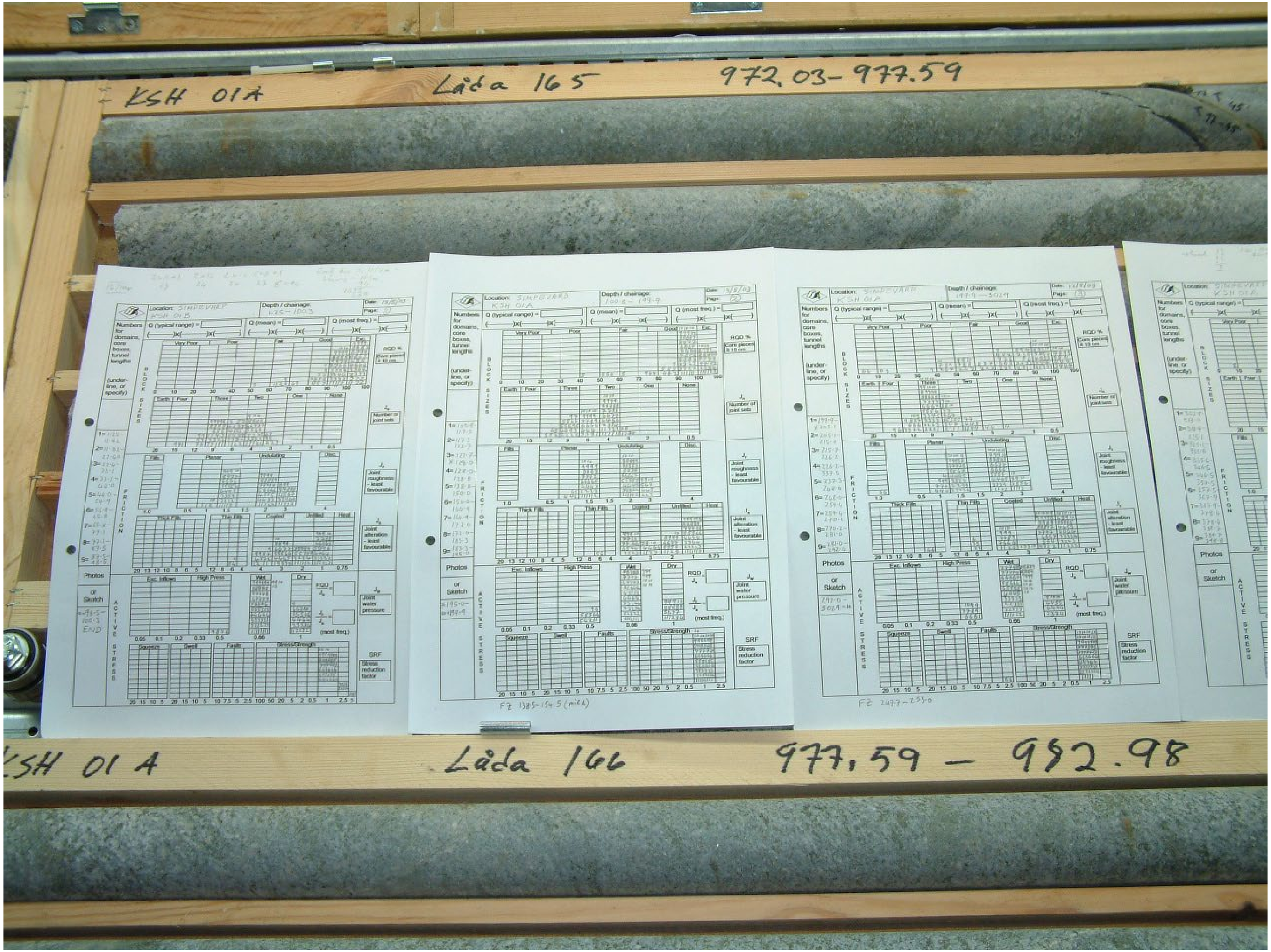
- (This speeds logging by a factor of 5 to 10 compared to finding and opening each core box individually!)

- Typical massive core representing the best quality



Recording Jr and optional JRC (using a/L method) at Simpevarp.

An example of a 'fracture zone' relative to the high Q core. (KSH-01A) ca. 400-410m depth

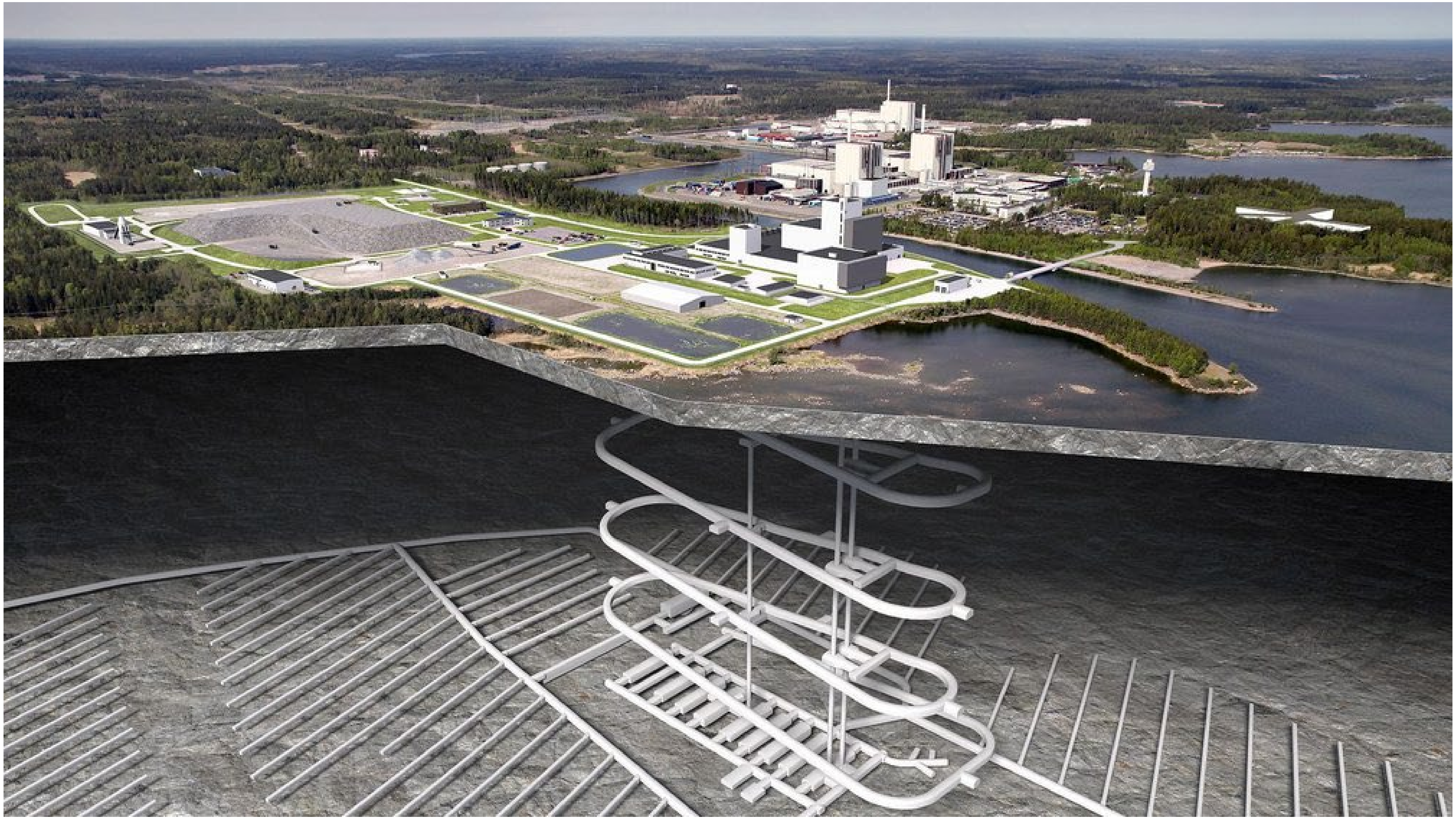


NB Q-histogram logging of deep core at Simpevarp

(KSH 01A)

Latest SKB deep repository image (Implenia contract).

(Discuss stress anisotropy issues).



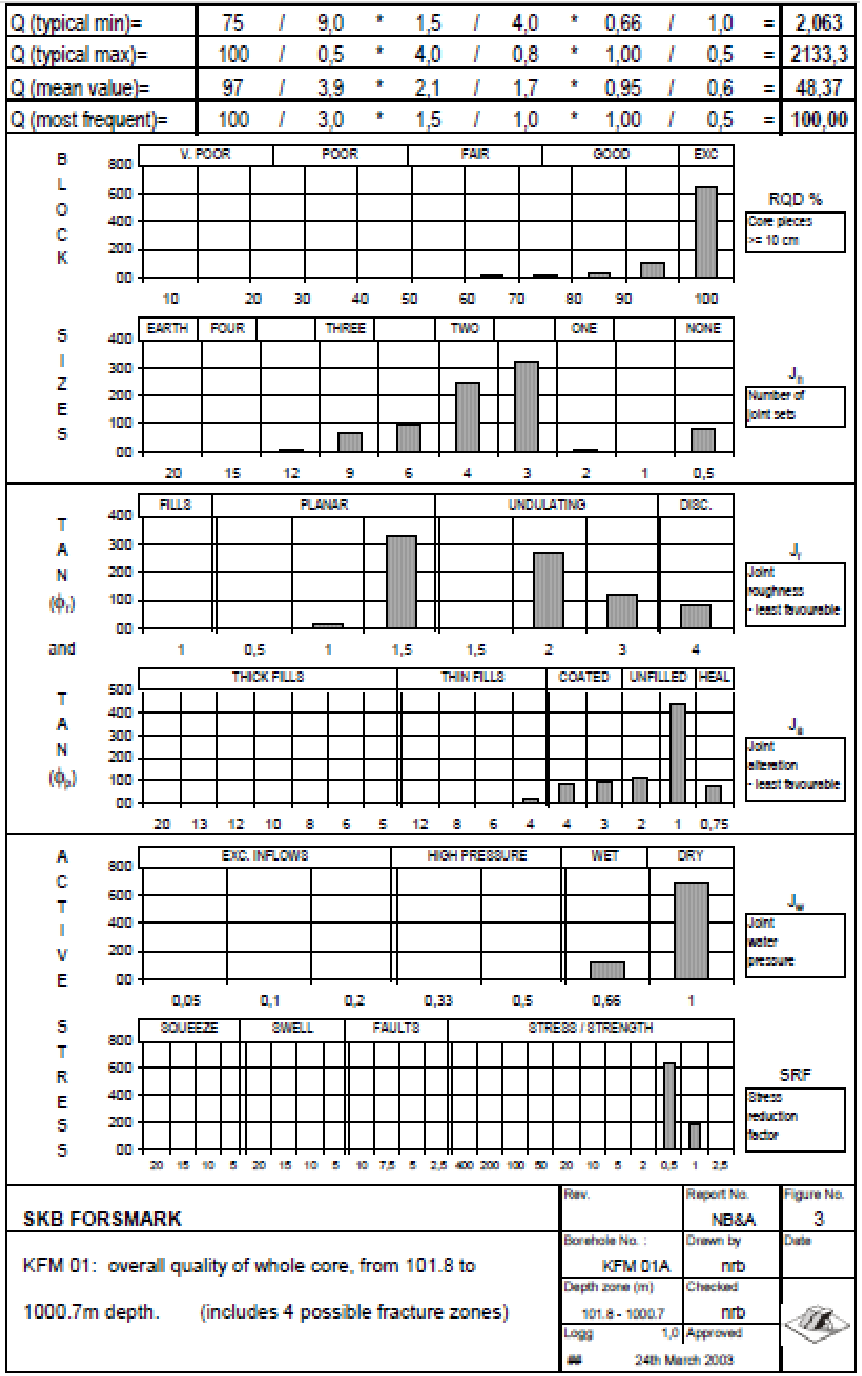
KFM 01A

Q-logging

Nick Barton, Nick Barton & Associates

March 2003

- 'The overall quality of this first Forsmark 900m core is very good to excellent, with Q(mean) of 48.4, and a most frequent Q-value of 100. The range of quality is from 2.1 to 2130, which is the complete upper half of the six order of magnitude Q scale. Even the relatively fracture(d) zones, representing some 13% of the 900 m cored, have a combined Q(mean) of 13.9 and a range of quality of 2.1 to 150'.

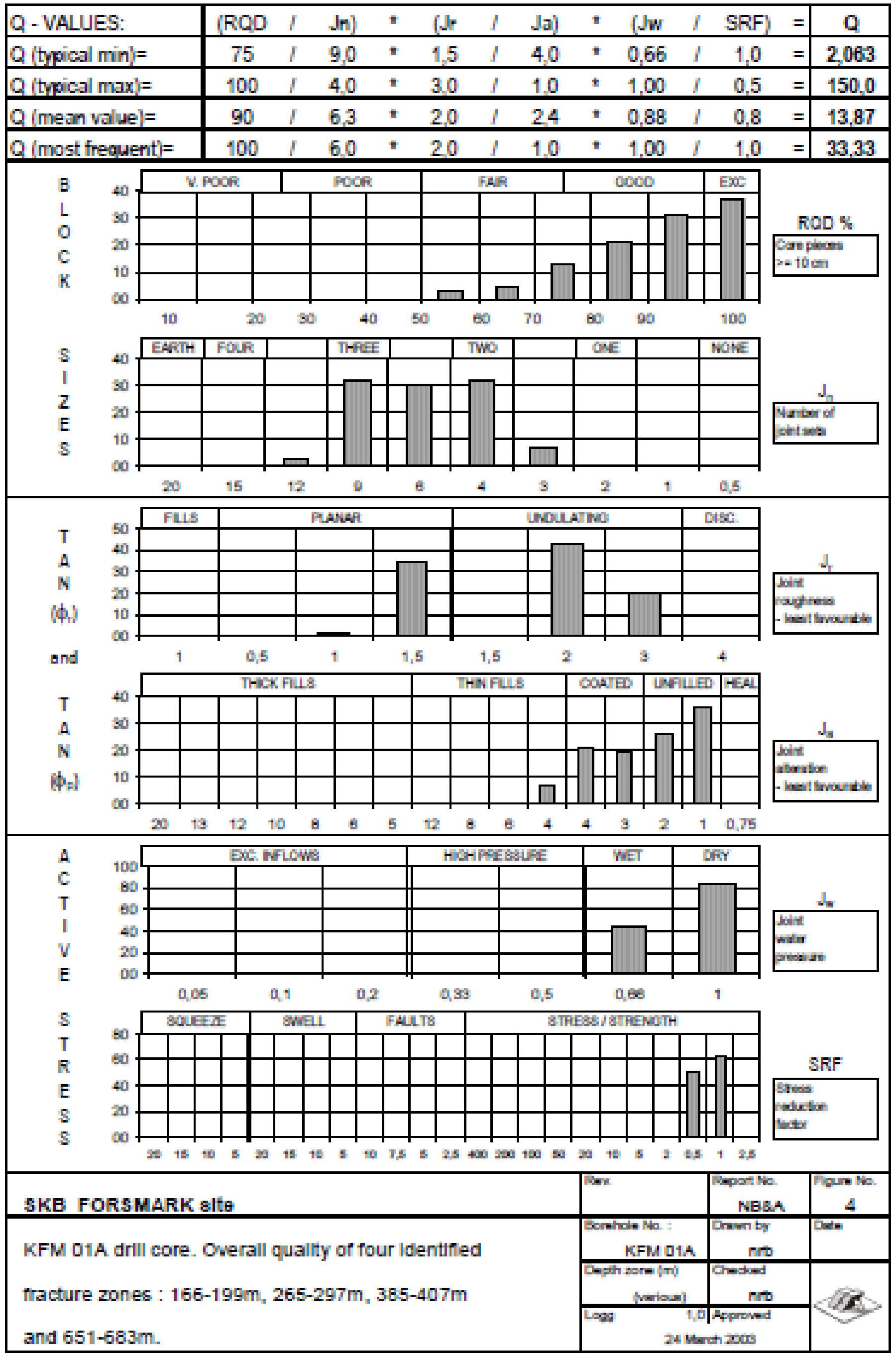


Borehole KFM-01A

Left: overall quality.

Right: fracture zones separately

900m



Joints in KFM 01A.

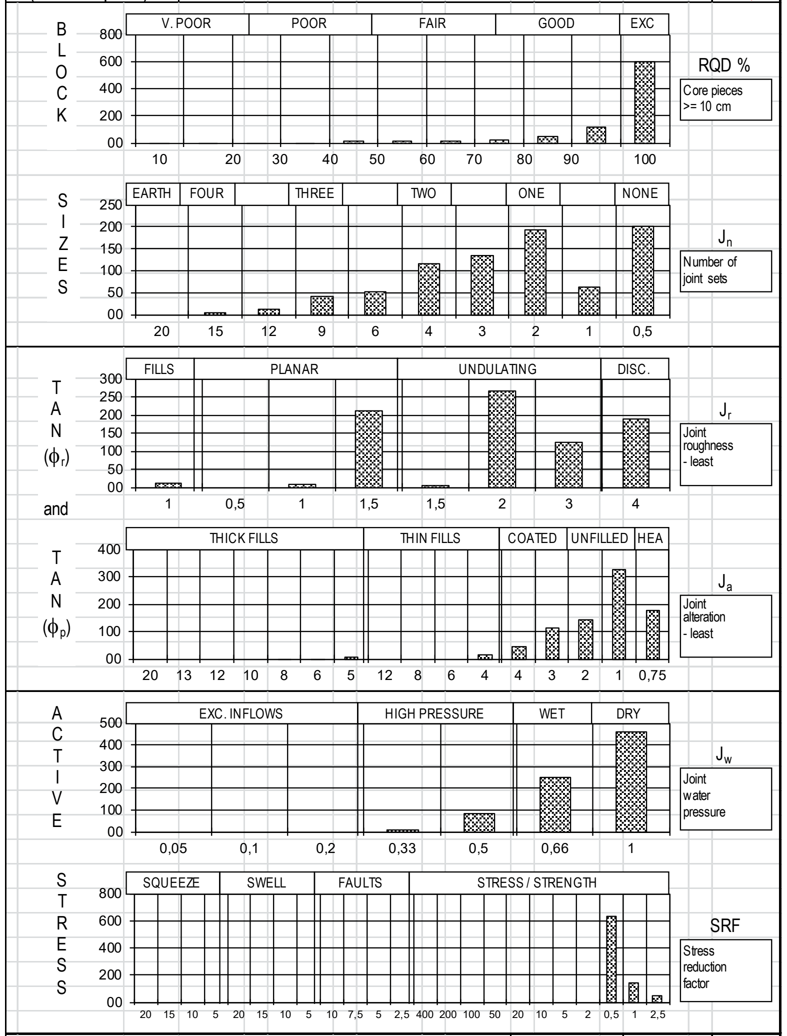
Jr = 1, 2 and 3

Forsmark borehole KFM 02A

left: OVER-ALL QUALITY, 900m OF CORE.

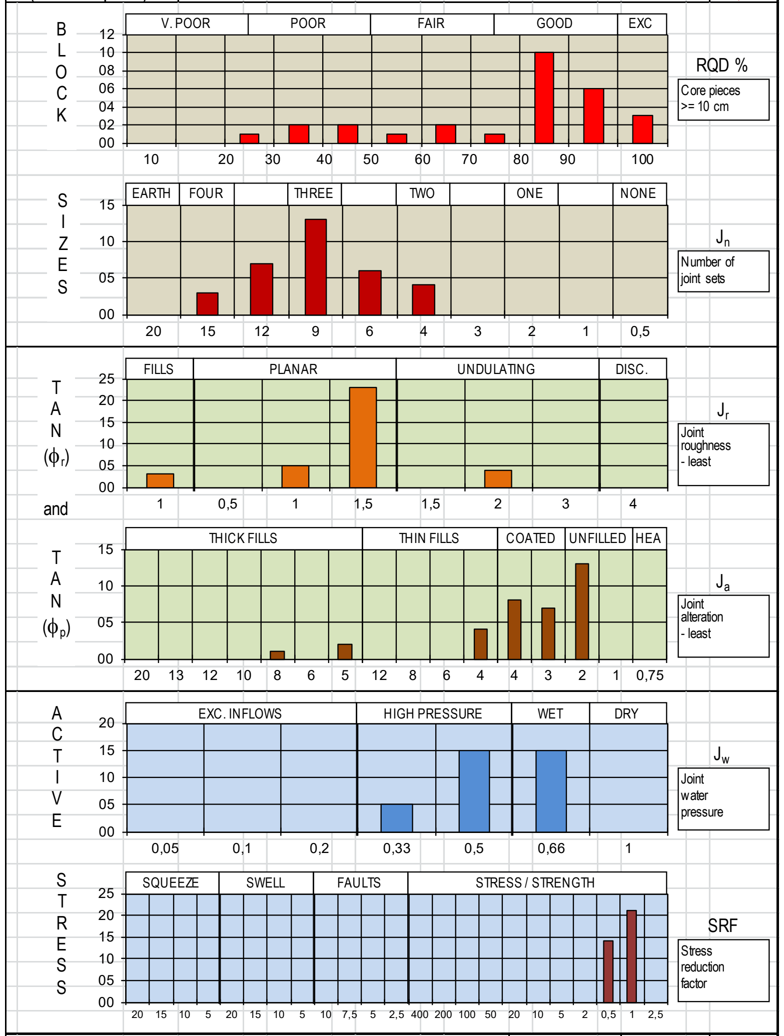
right: FRACTURE ZONES,

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	75	/	9,0	*	1,5	/	4,0	*	0,50	/	1,0	=	1,563
Q (typical max)=	100	/	0,5	*	4,0	/	0,8	*	1,00	/	0,5	=	2133,3
Q (mean value)=	95	/	2,8	*	2,5	/	1,7	*	0,83	/	0,7	=	60,86
Q (most frequent)=	100	/	0,5	*	2,0	/	1,0	*	1,00	/	0,5	=	800,00



SKB FORSMARK	Rev.	Report No. NB&A 2	Figure No.
KFM 02A : overall quality, from 101.0 to 1002.4m,	Borehole No. : KFM 02A	Drawn by nrb	Date #######
(includes six minor, more fractured zones and two porous	Depth zone (m) 101.0 - 1002.4	Checked nrb	
zones).	Logg 1,0	Approved	

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	25	/	15,0	*	1,0	/	8,0	*	0,33	/	1,0	=	0,069
Q (typical max)=	100	/	4,0	*	2,0	/	2,0	*	0,66	/	0,5	=	33,0
Q (mean value)=	77	/	9,0	*	1,4	/	3,2	*	0,54	/	0,8	=	2,60
Q (most frequent)=	85	/	9,0	*	1,5	/	2,0	*	0,58	/	1,0	=	4,11



SKB FORSMARK site KFM 02A	Rev.	Report No. NB&A 2	Figure No.
Combined quality of six fracture(d) zones : 116-122m,	Borehole No. : KFM 02A	Drawn by nrb	Date #######
417-427.5m, 493-501.7m, 512-518m, 893-899m, and	Depth zone (m) 116-905 m	Checked nrb	
903-904.7m		Approved	

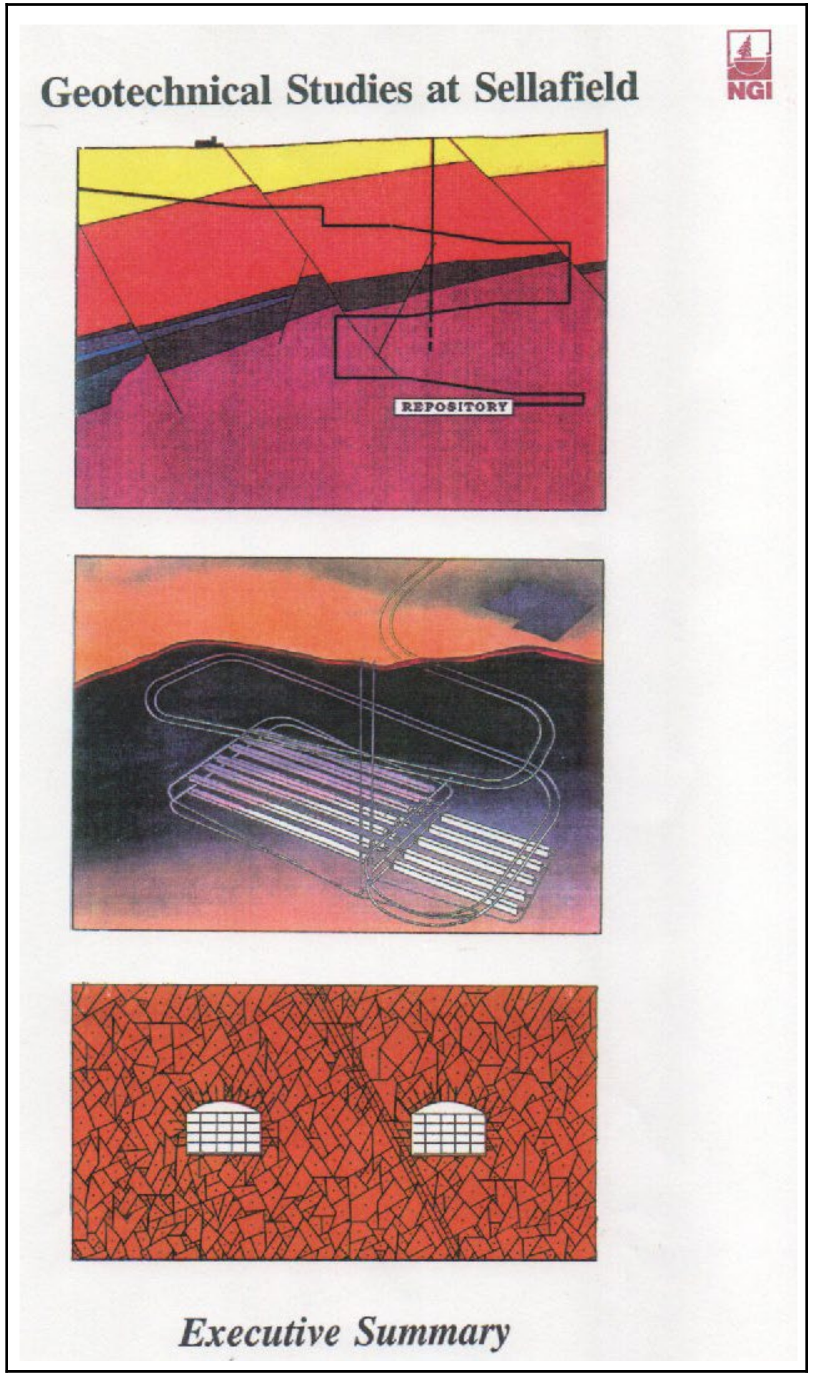
Surface Q-hist logging above future Forsmark repository.

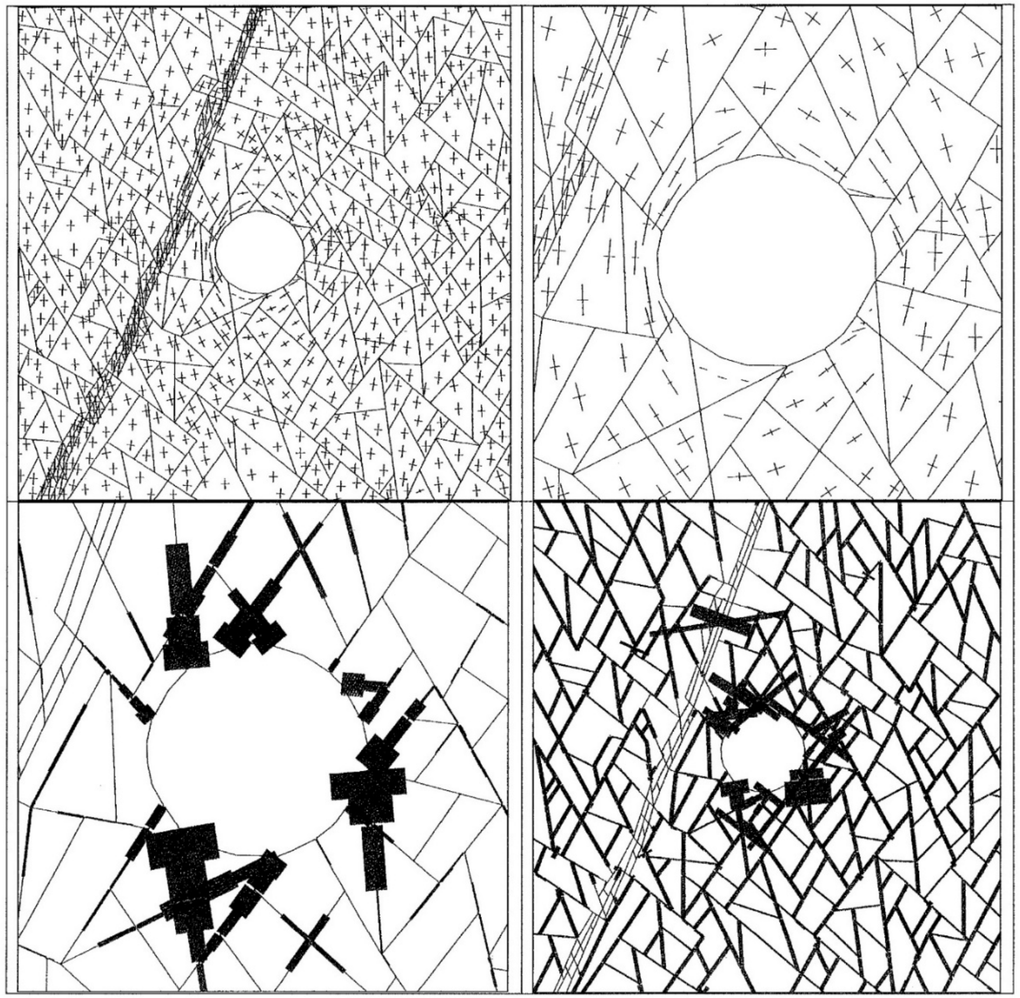
Simple roughness profiling above future repository.

a/L gives JRC_n estimate.

(And helps with Jr of course)

9. UK Nirex Geotechnical Consultant: Sellafield Repository and RCF studies. NGI/Atkins. 1990 -1996.





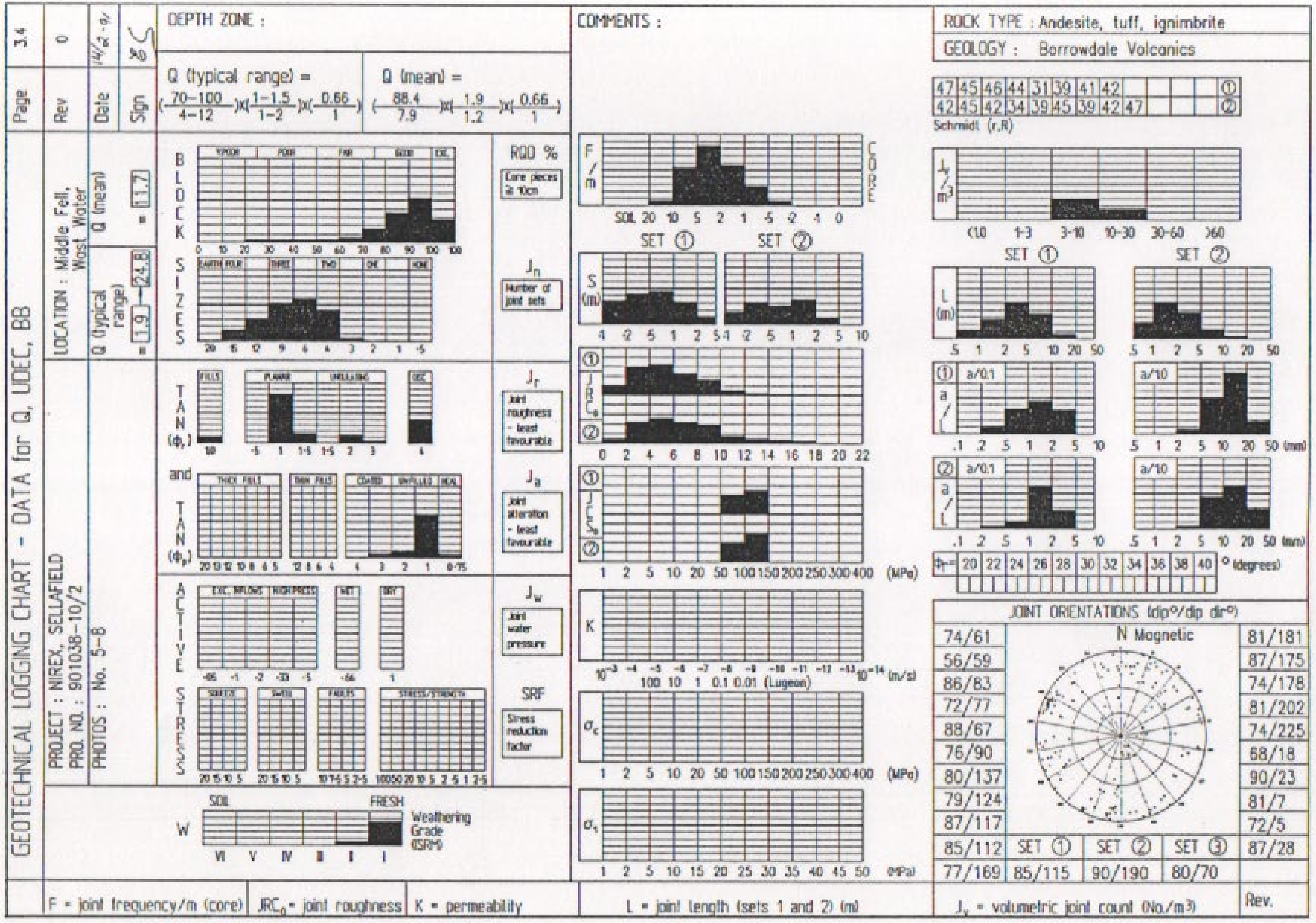


Figure 2.5 Geotechnical logging data for the BVG, based on Phase II field mapping (NGI 901038-10/2)

NOTE: EXPOSURE LOGGING IN LAKE DISTRICT NATIONAL PARK

Unusual large range of JRC even for one joint set.

Figure 3.8 *Photographs of joints in BVG, BH2, BH4 and BH5, from depths between 570 m and 796 m. Examples of steepest (J1) joints (top left), four J2 joints (dip 50-75°) and one J3 joint (bottom left) (NGI 901038-18/2 and 28/7, NGI 931005-11/1)*

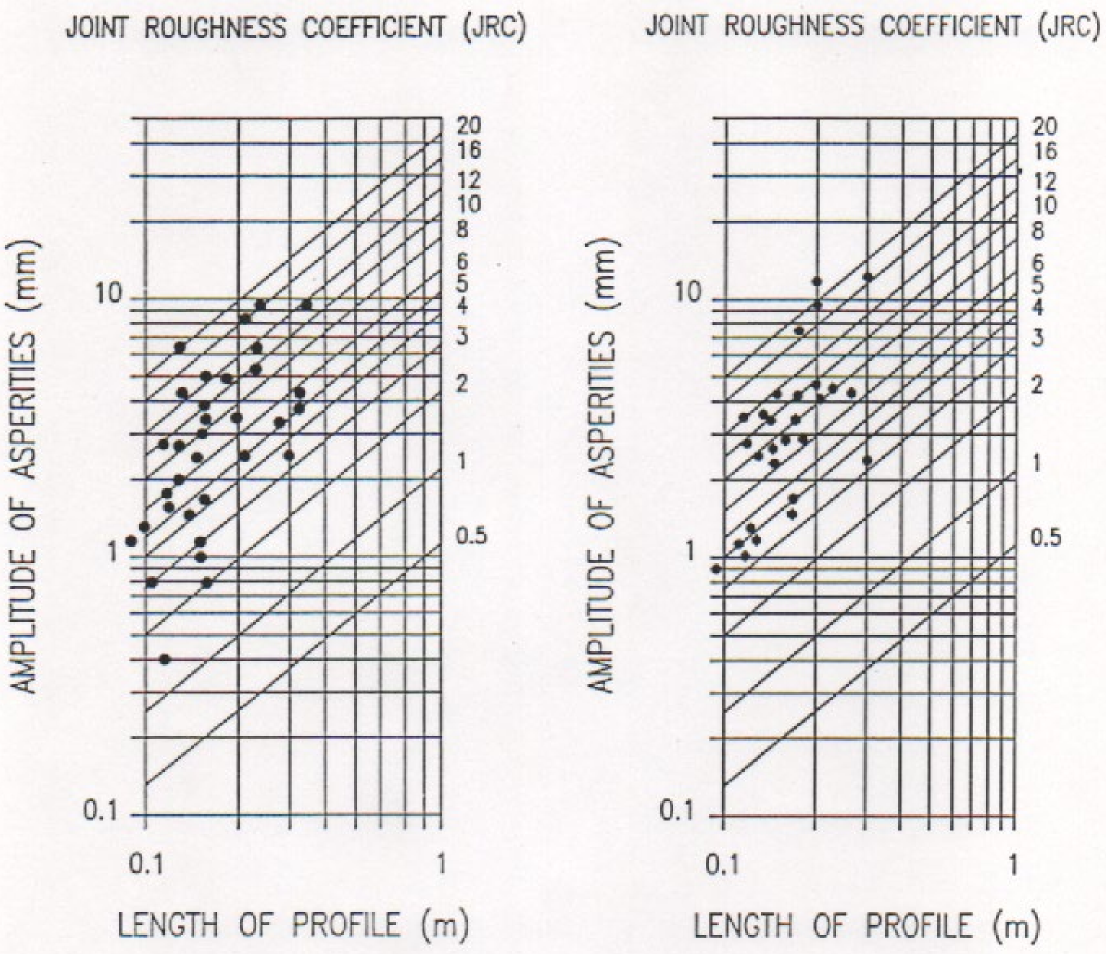
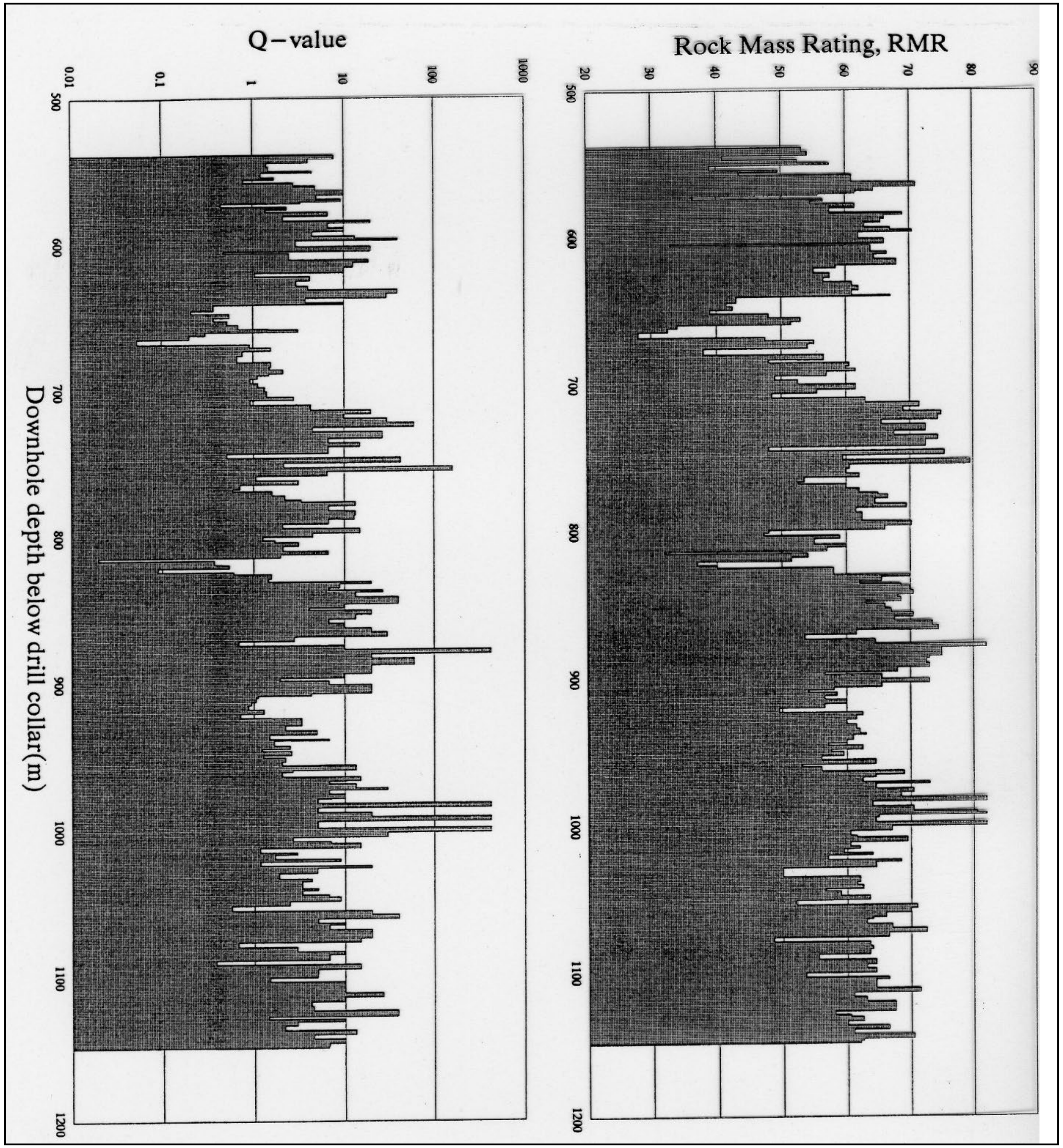


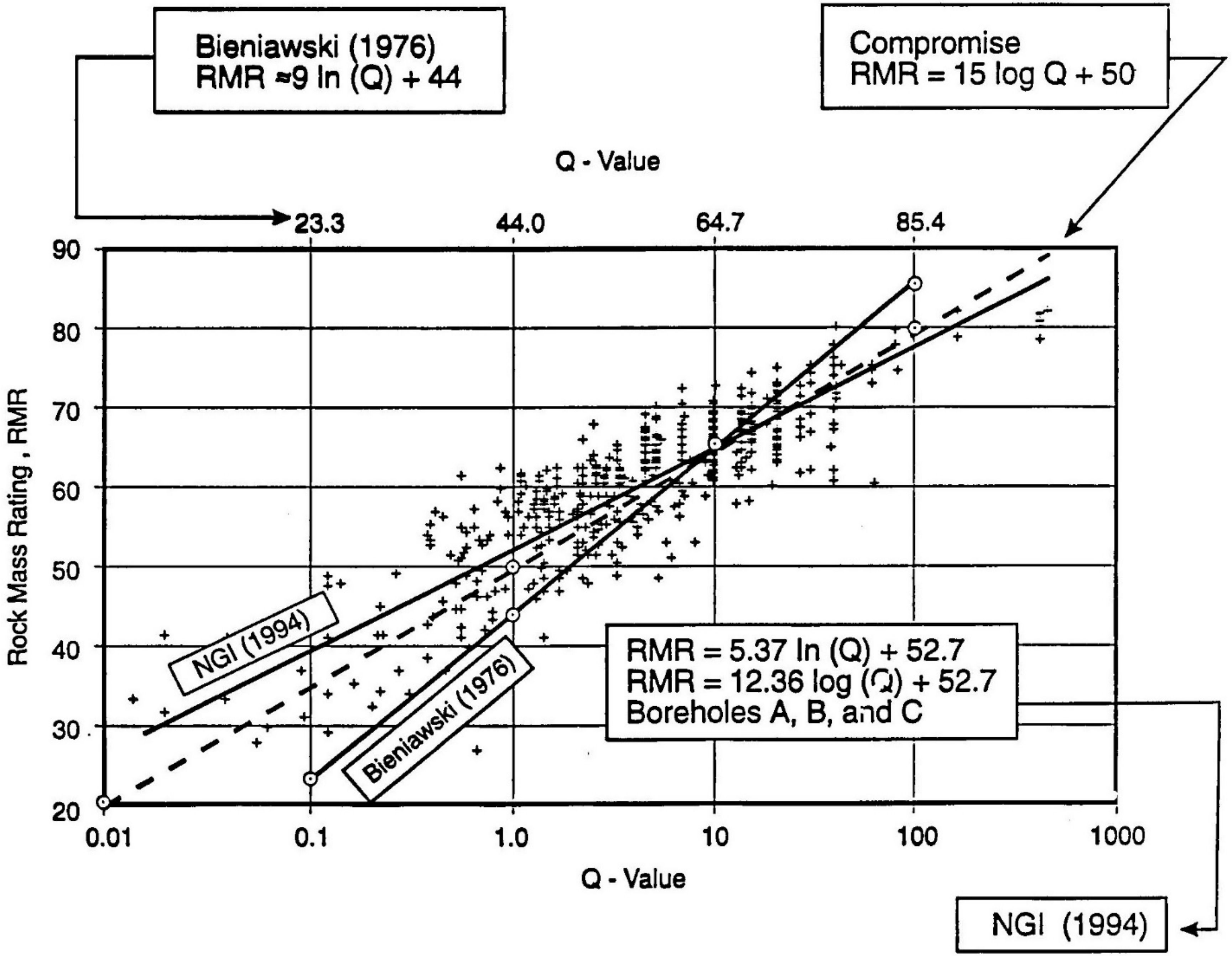
Figure 3.11 *Roughness amplitude measurements on J2 joints in the BVG from BH4 and BH5*



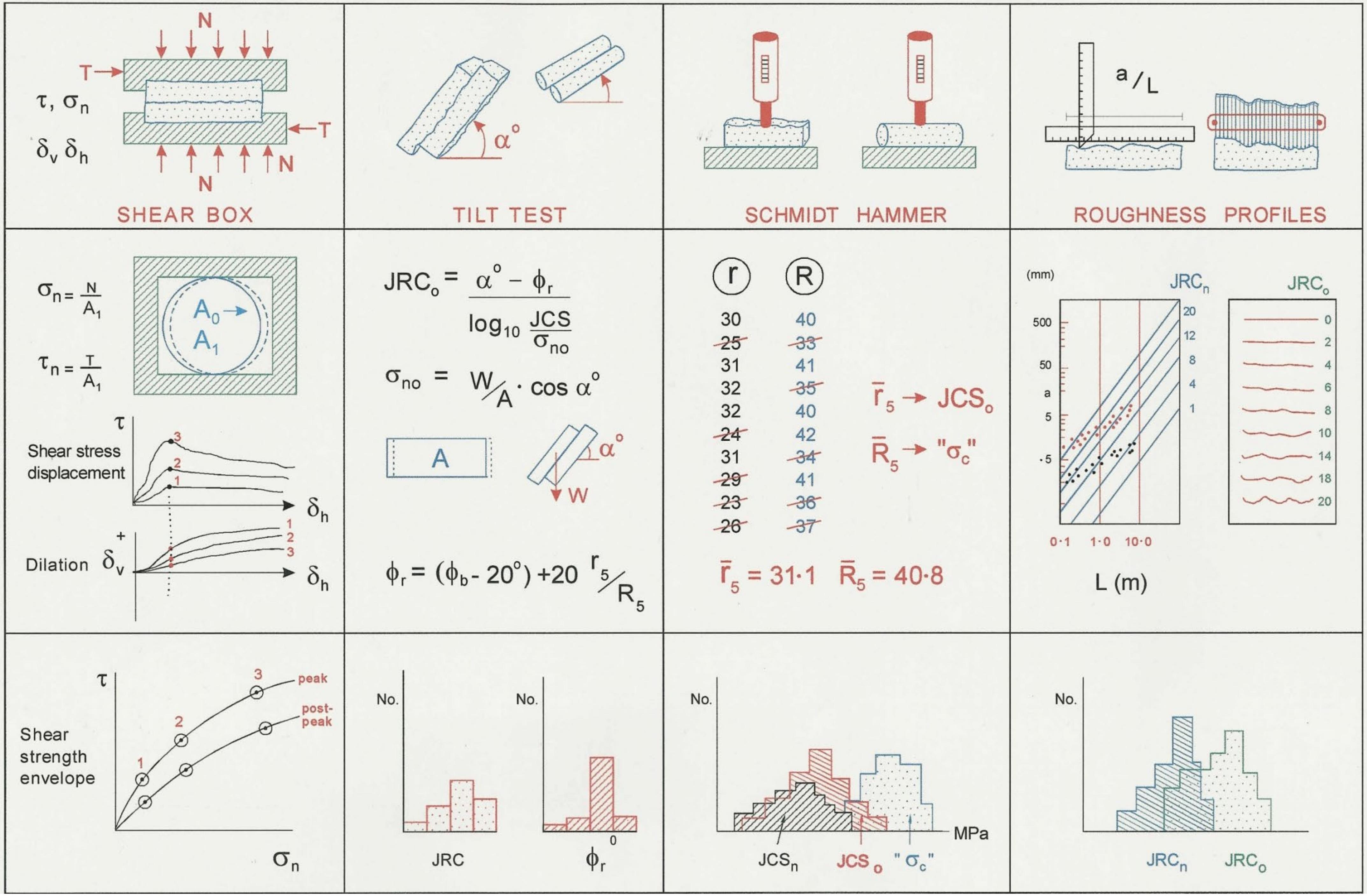
Visual comparison of Q-depth, and RMR-depth logs. (NGI 1994, UK Nirex, Sellafield).

NGI/ATKINS logged >10km of core at Sellafield, and we could also compare with deep cross-hole seismic. (Vp-Qc-depth)

Barton, 1995.



RMR and Q are rather different, though may 'correlate' in central areas of quality.



MUCH USED AT SELLAFIELD

INDEX TESTS for collecting fundamental input for estimation of:

shear-strength, dilation, deformation, closure, aperture (s)

(i.e. BB-model M-H coupled input)

During UDEC-BB modelling approximation we ‘moved’ the models around in this vertical geologic-plane approximation.

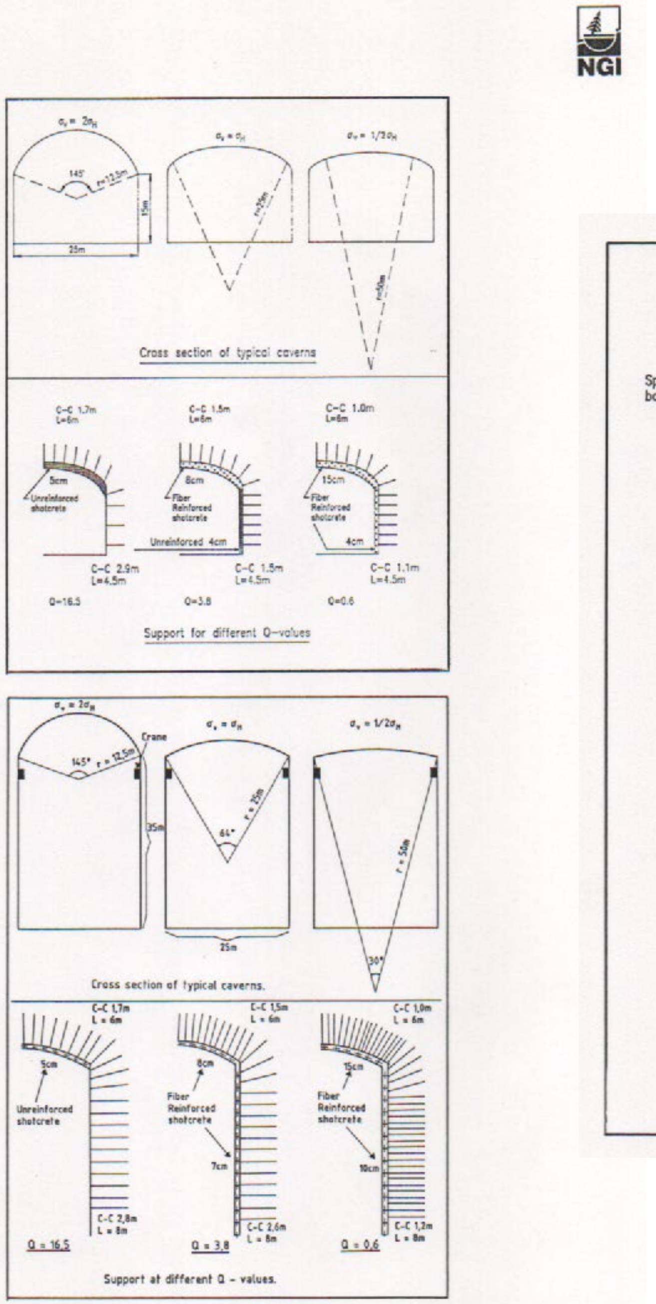
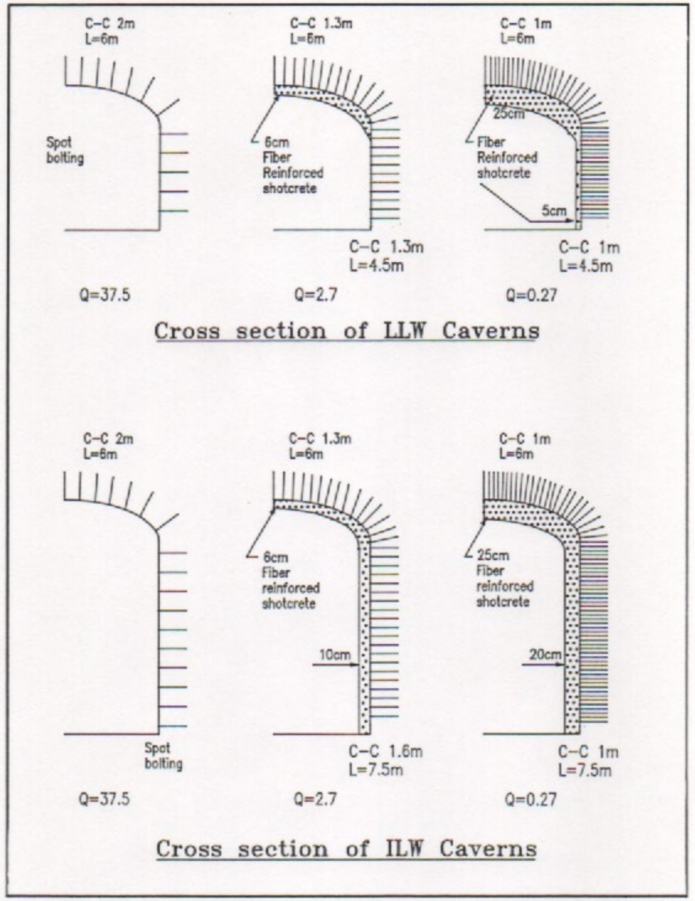


Figure 5.1 Preliminary rock reinforcement designs for 25 x 35 m and 25 x 15 m caverns (NGI 901038-6 and 15/1)



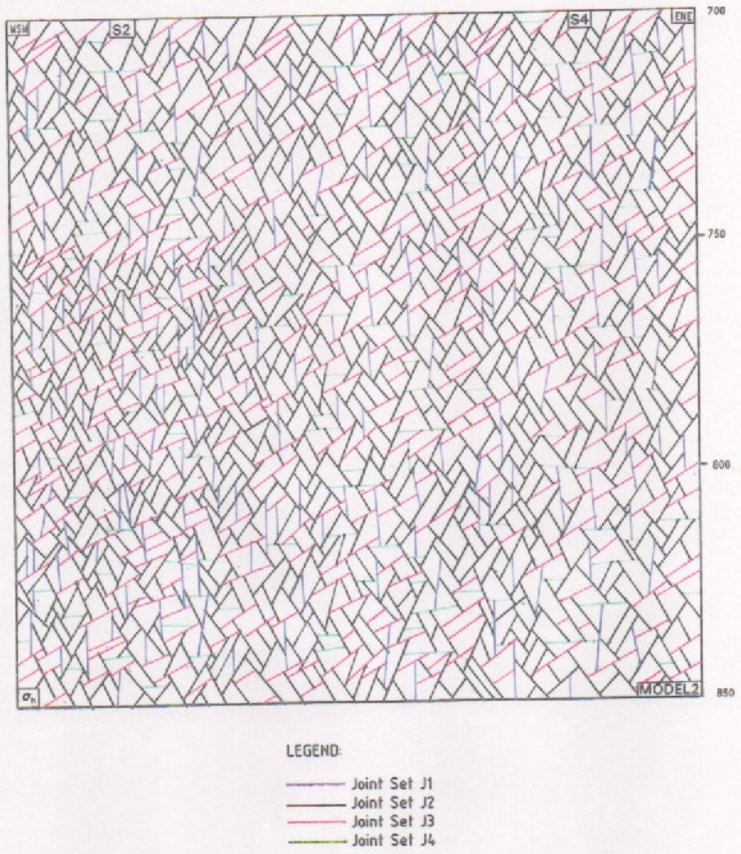


Figure 5.13 Colour code for joint set nomenclature. Low stress joint model (NGI 901038-33/1)

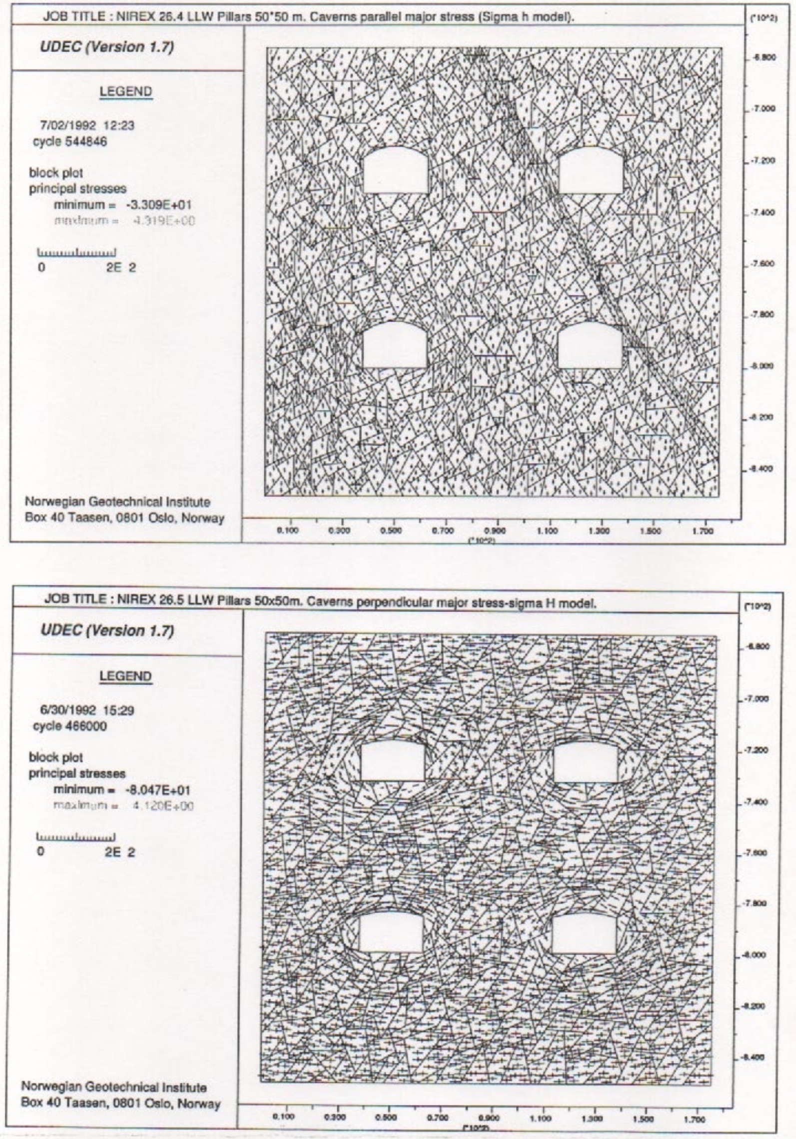


Figure 5.21 Principal stresses induced in LLW bolted cavern; σ_h and σ_H cases (NGI 901038-26/1)

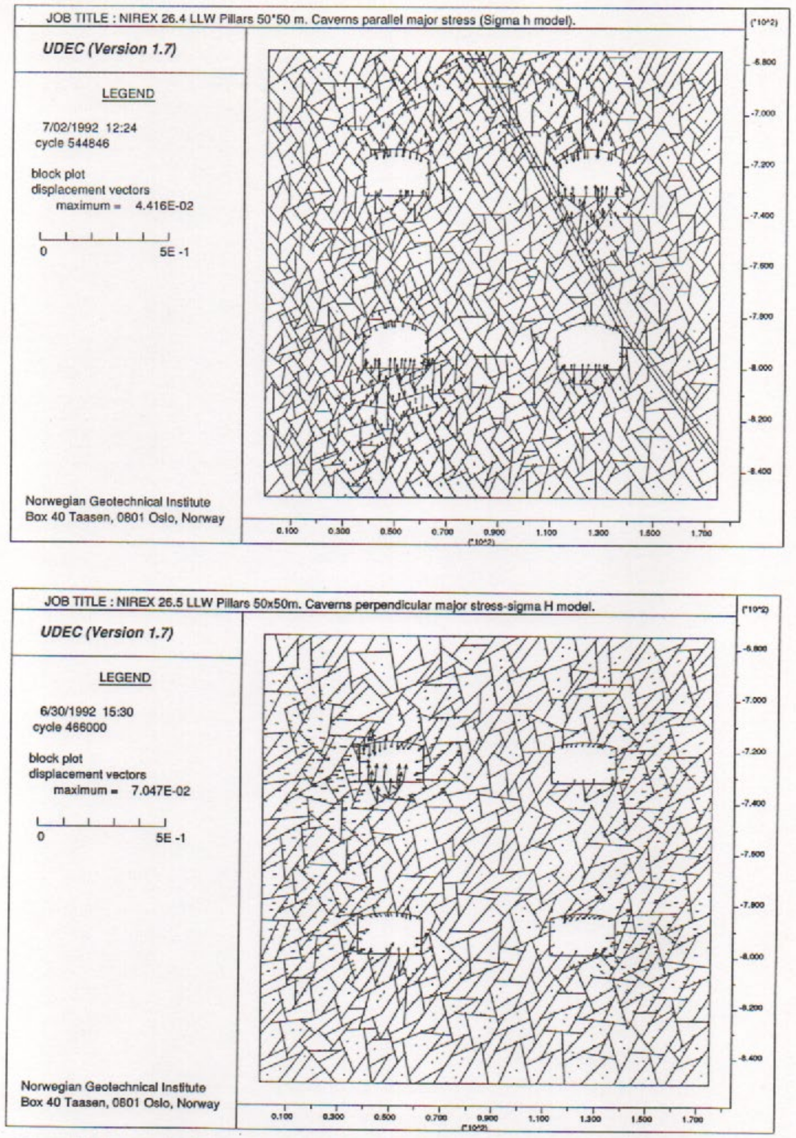


Figure 5.22 Displacement vectors caused by LLW cavern excavations; bolted models, σ_h and σ_H cases (NGI 901038-26/1)

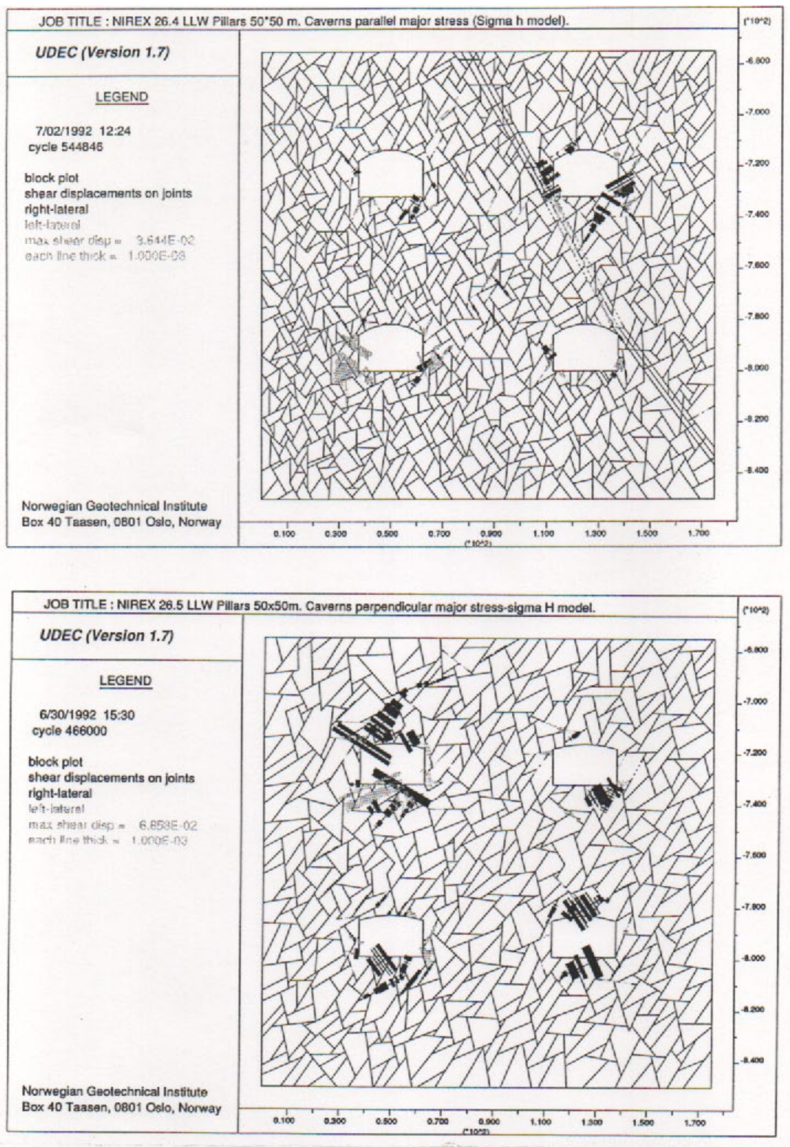
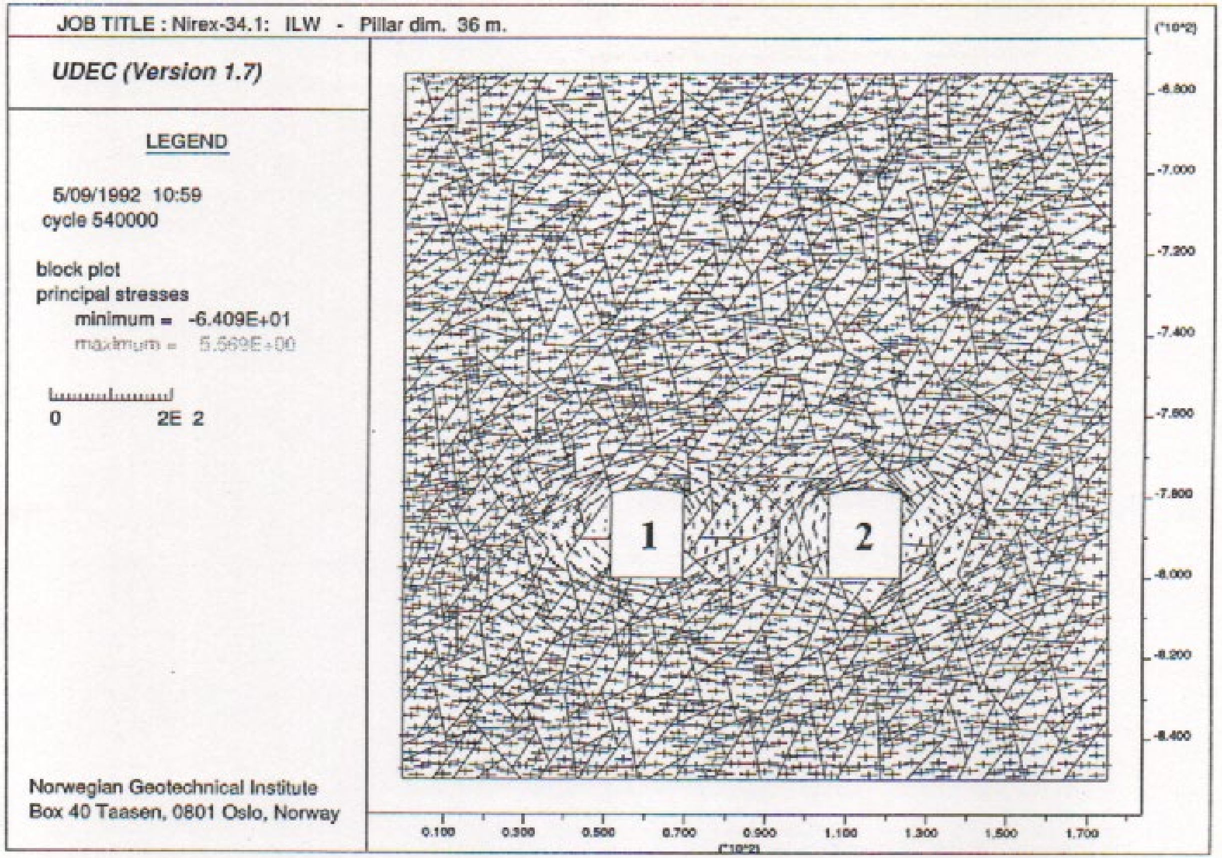


Figure 5.23 Joint shear displacements caused by LLW cavern excavations; bolted models, σ_h and σ_H cases (NGI 901038-26/1)

Multi-cavern LLW: stresses, displacements, joint shearing, low (top) and high stress models.

Twin-cavern high stress ILW models.



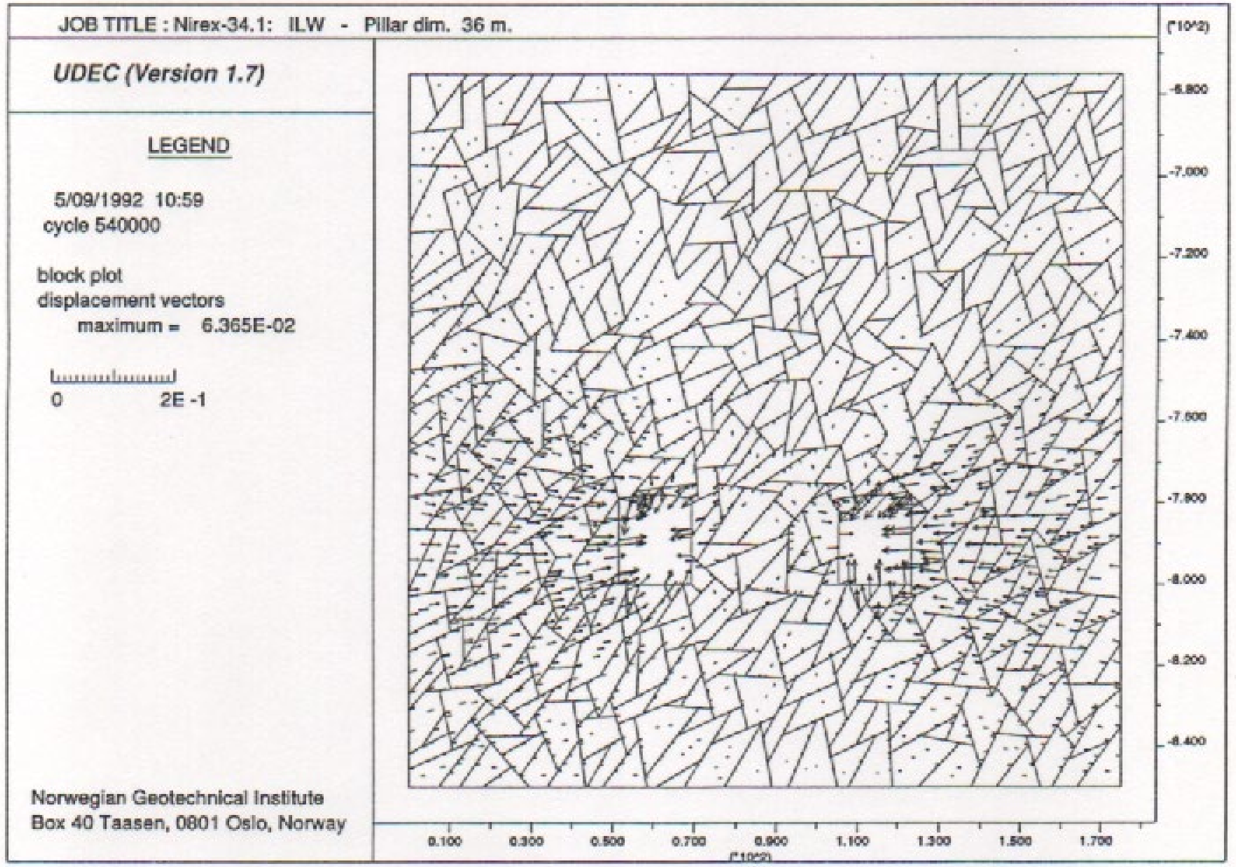
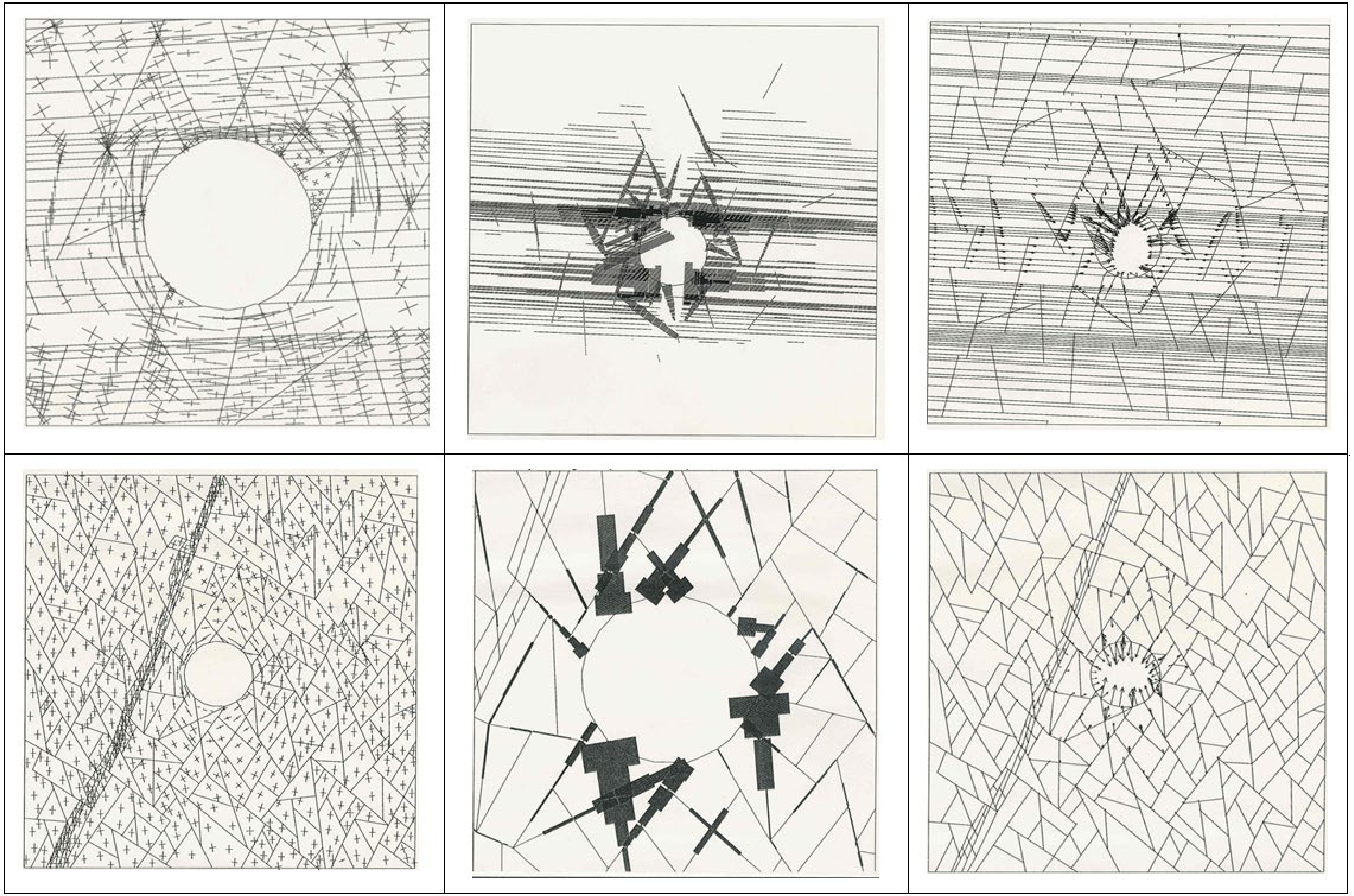


Figure 5.27 Principal stresses and displacements for unbolted ILW caverns with 36 m pillar (NGI 901038-34/1)



FINALLY:

SELECTED UDEC-BB STUDIES OF 250M DEEP AND 700M DEEP SECTIONS OF A PLANNED TBM SPIRAL ACCESS TUNNEL.

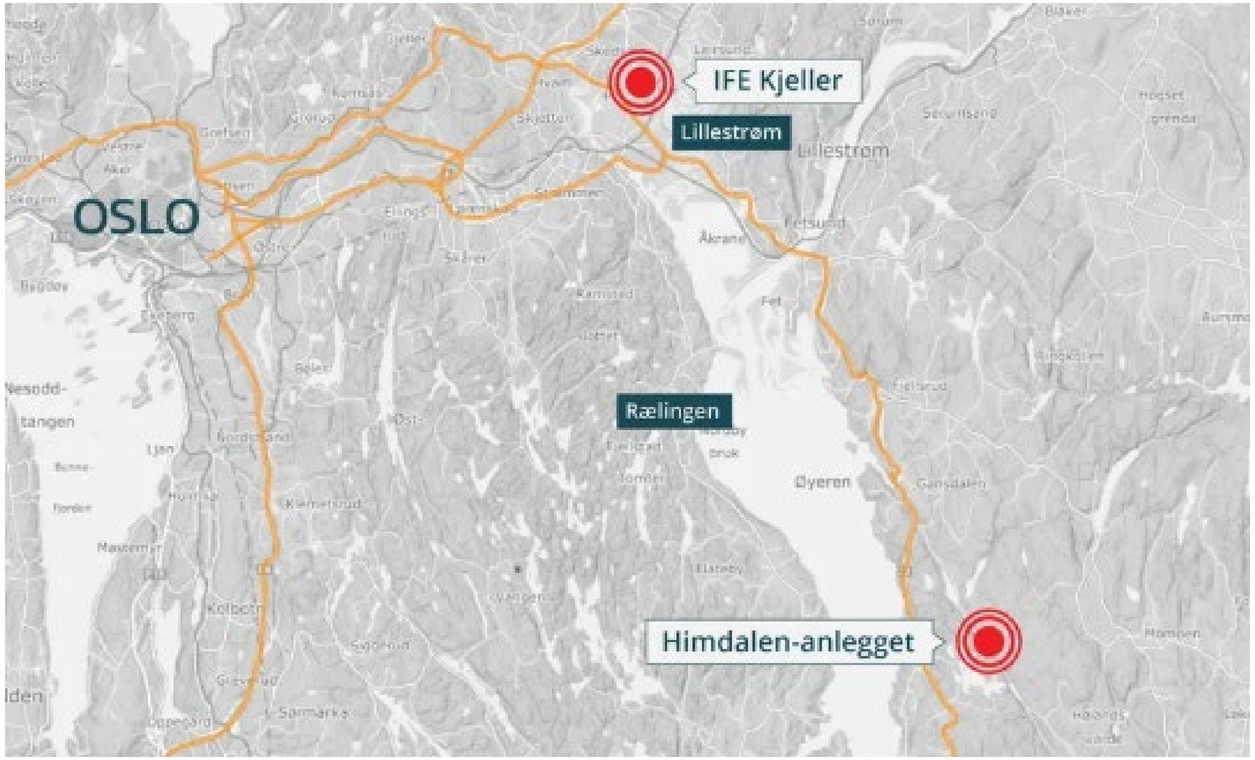
TOP: Interbedded St Bees sandstones and siltstones.

BOTTOM: Borrowdale welded tuffs-ignimbrites.

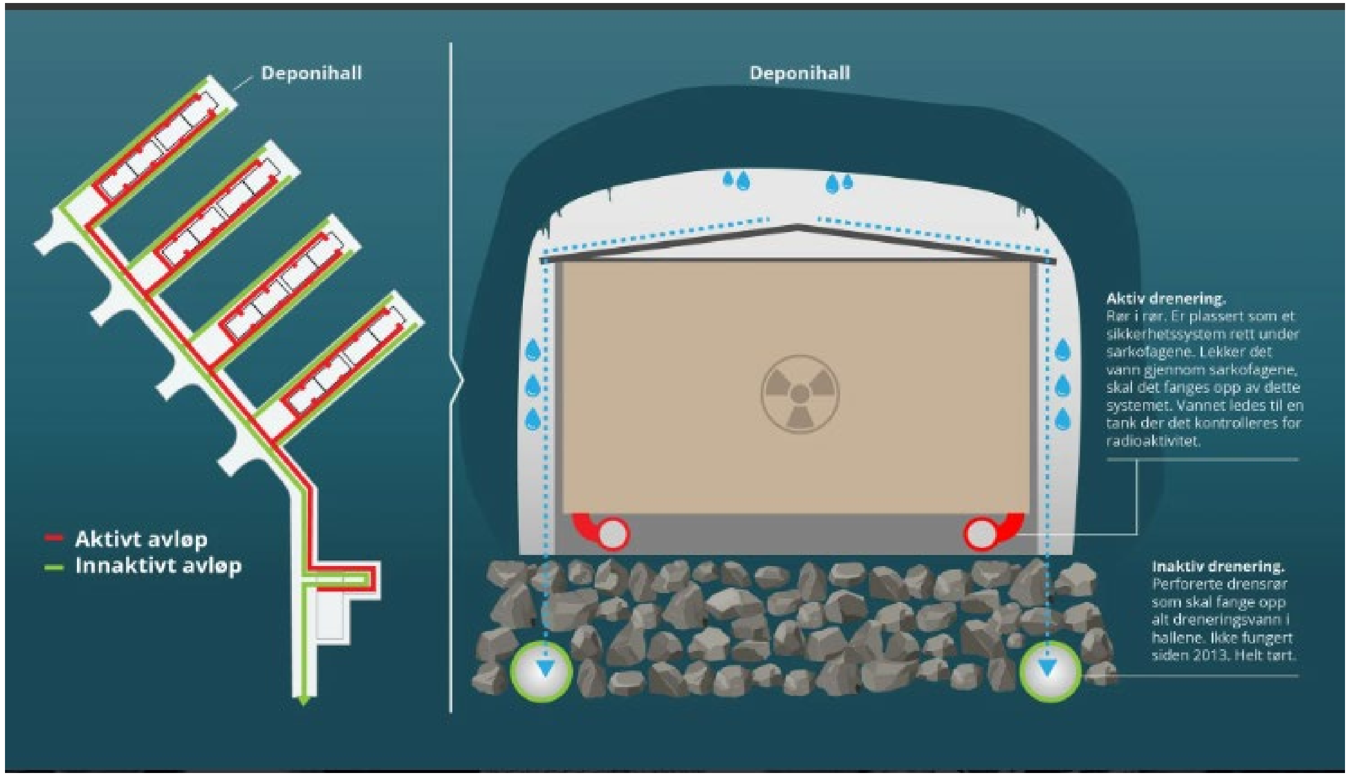
PLANNED SELLAFIELD LLW/ILW NUCLEAR WASTE REPOSITORY ACCESS. NGI UK Nirex project 1990-1996.

10. Norwegian Himdalen ILW ‘repository’.

(NB opposition: local support in public meeting, also requested advice to Shadow Minister in Parliament vs. Stoltenberg, at that time Norway’s Environment Minister)



Leakage into river! Discarded after 30 years. Many NB and other's warnings!



SINGLE-SHELL NMT – Q-BASED SUPPORT SELECTION. PRE-INJECTED TUNNEL