Thermal over-closure of joints and rock masses and implications for HLW repositories

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Thermal OC (*'over-closure'*) effects in rock joints have been measured or interpreted in the case of the following:

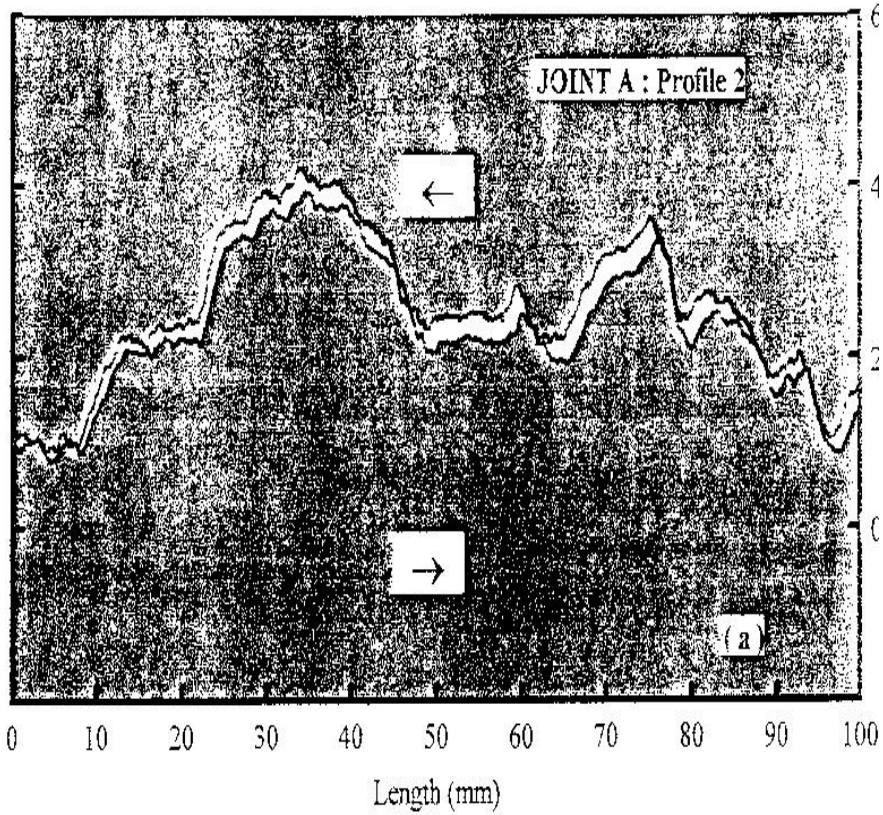
- rock joint and rock mass permeability reduction (until cooling)
- deformation modulus increase (following next item)
- thermal expansion coefficient reduction (joints close easier)
- seismic velocity increase (until cooling)
- shear strength increase (due to joint closure)
- numerical model predictions e.g. Adina code, compared to HMT rock *mass* measurements varying by factor of 1:2 or worse

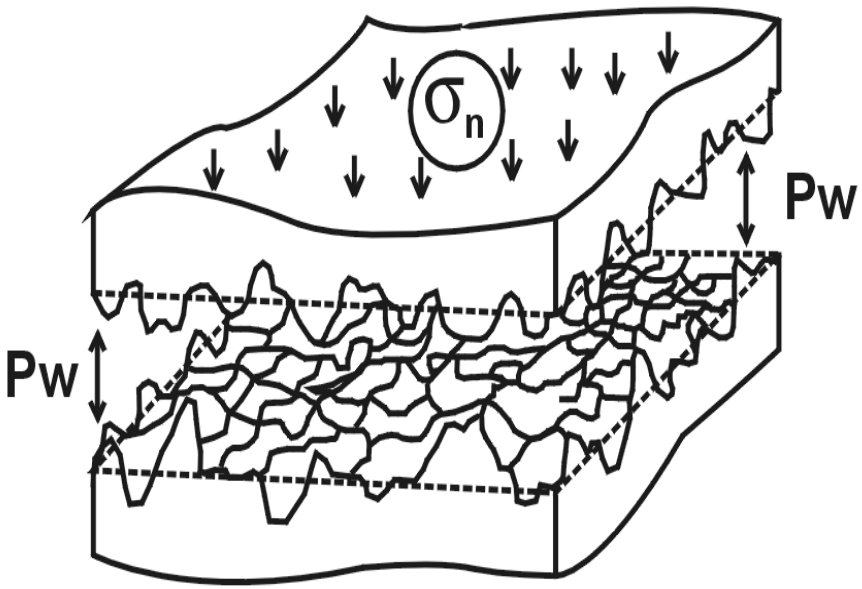
Few seem to have reckognised , acknowledged, or identified the cause of these phenomena

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

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

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

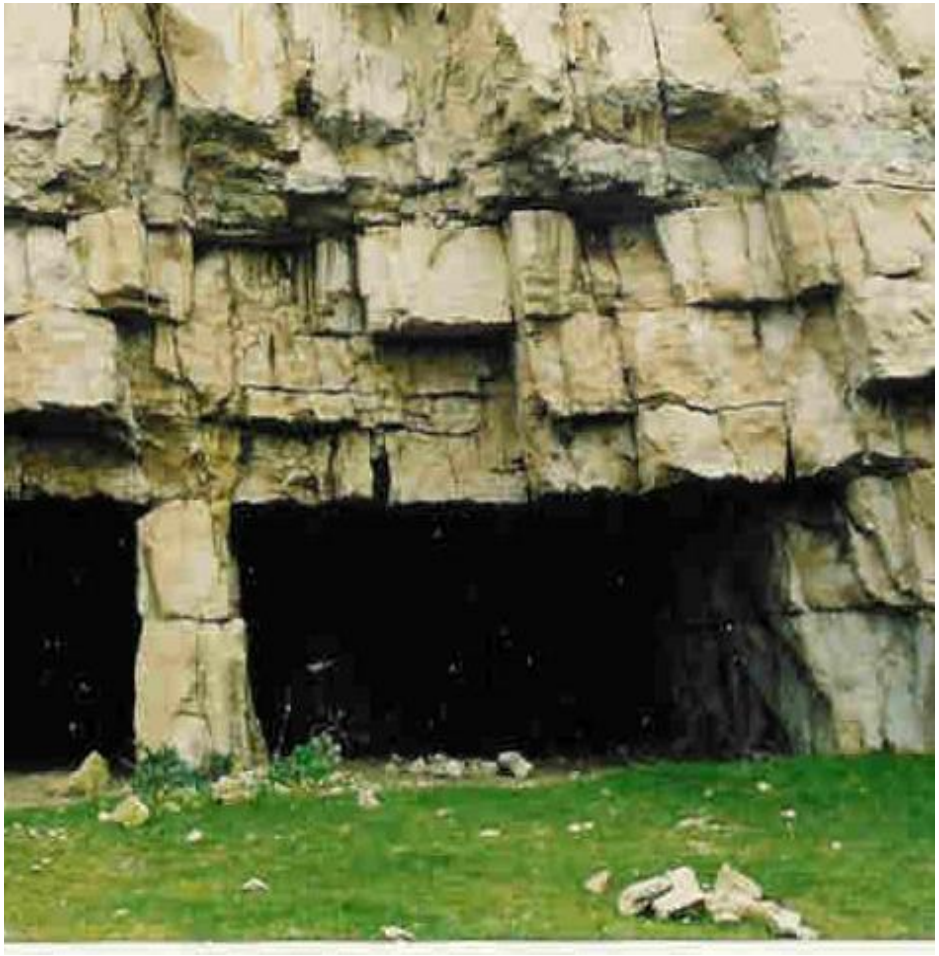


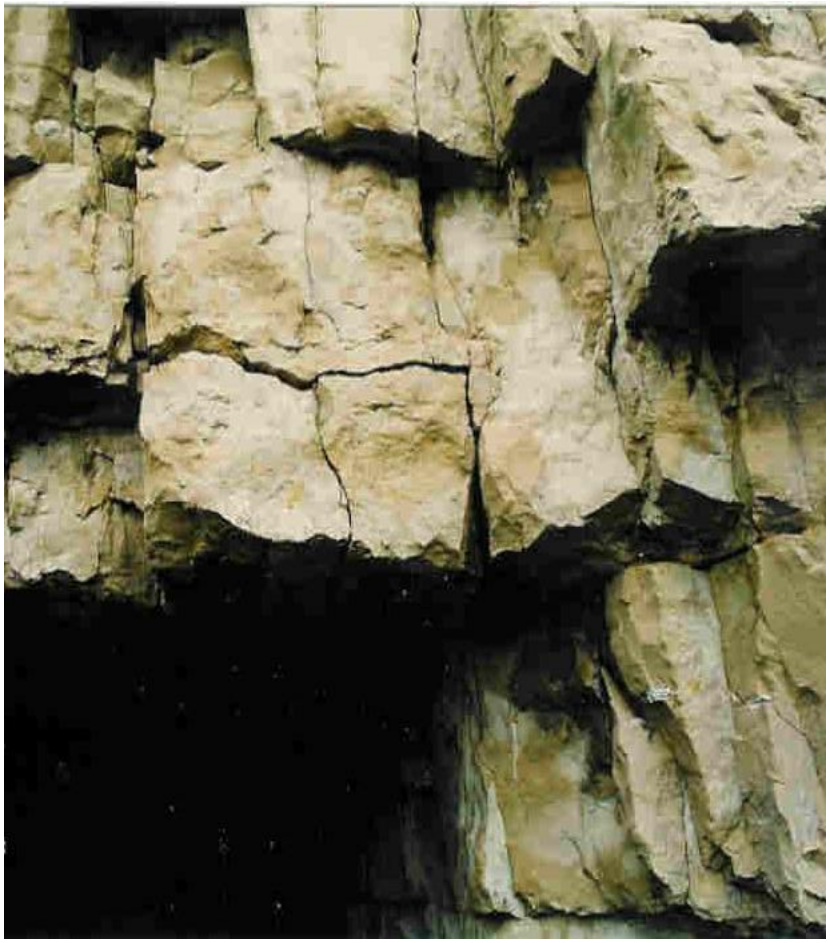


ARE THE JOINTS THAT REMAIN CLOSED EXHIBITING:
CEMENTATION?
OVER-CLOSURE?
OR NORMAL- CLOSURE?

THE TWO BLOCKS RETAINED BY ROUGHNESS AND DILATION FOR > 100 YEARS, WITH Jn = 9 (three sets) OBVIOUSLY *LOST* THE O-C EFFECT.

OTHERS HAVE NOT LOST THE O-C EFFECTS, or are N-C due to tangential stress/arching ?

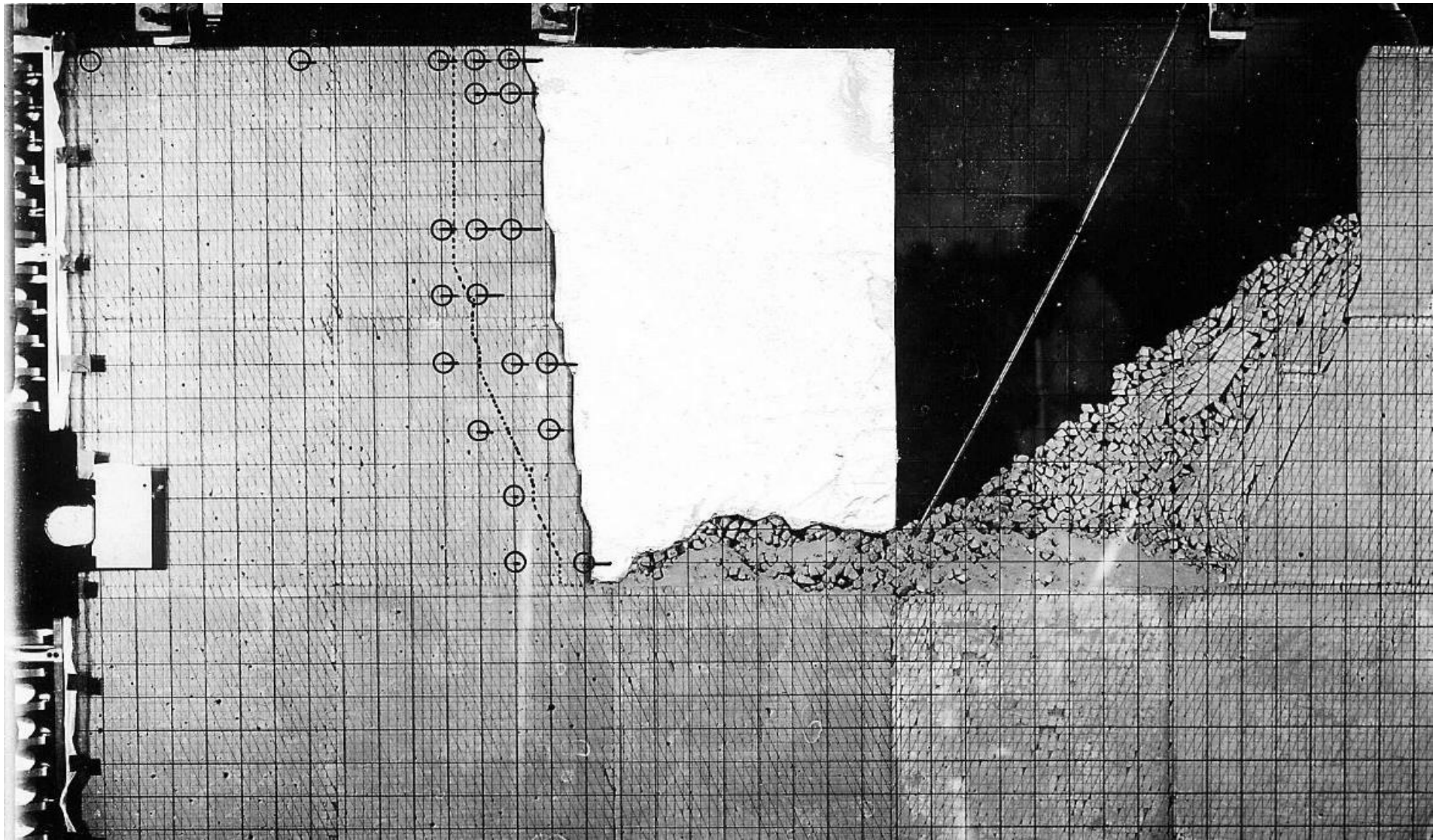




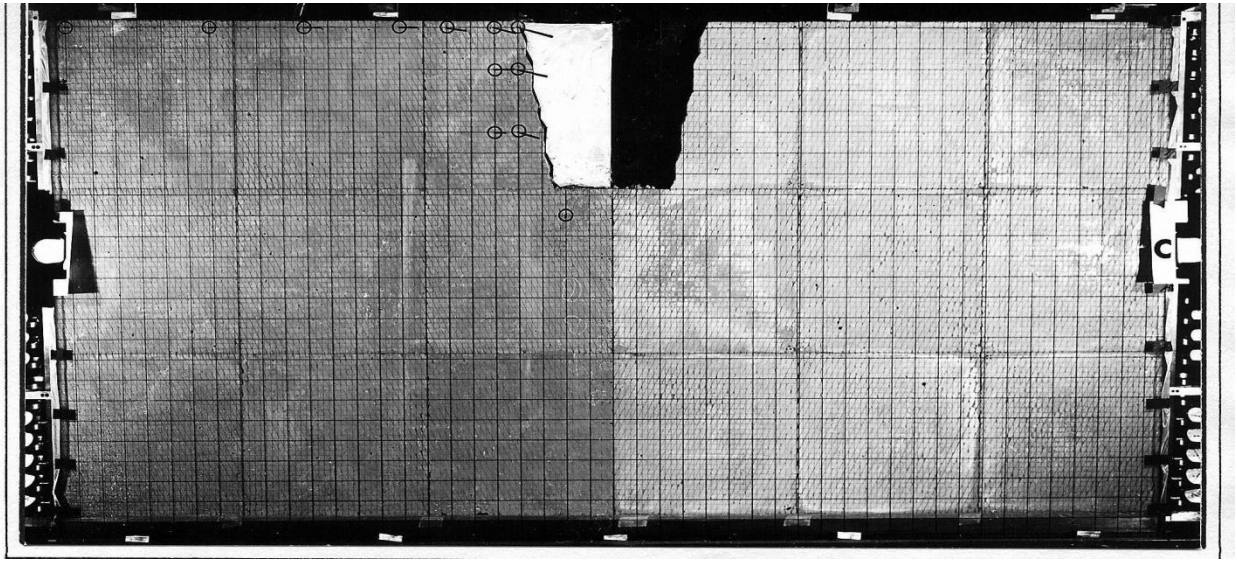
OUTLINE OF TOPIC

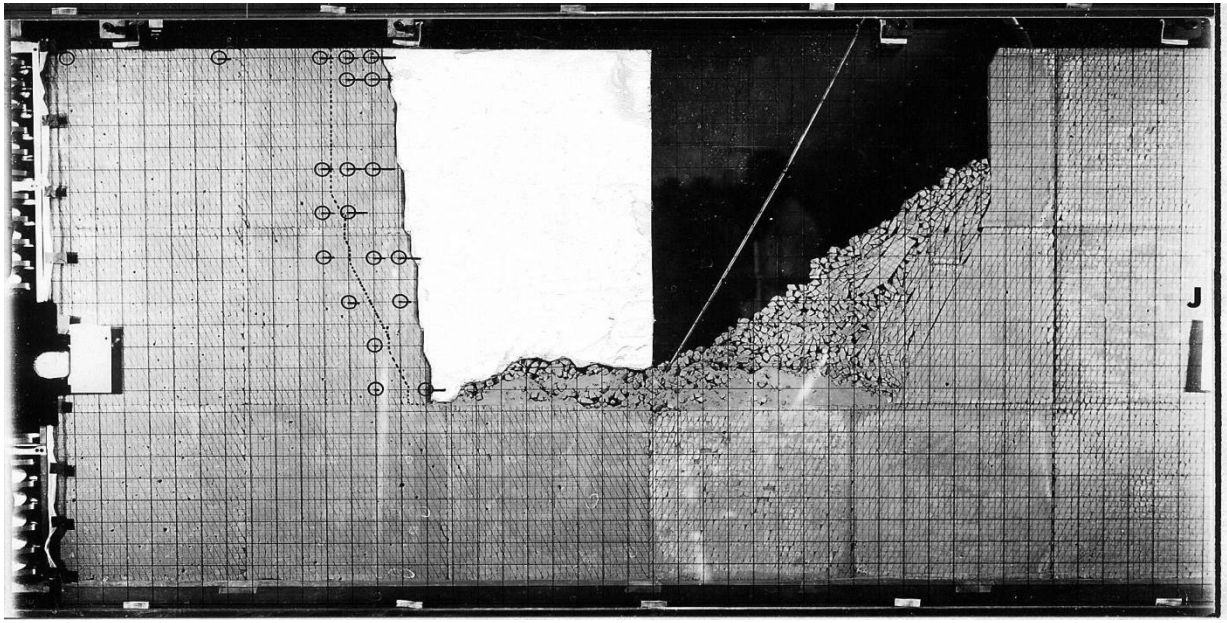
- Rough joints can be *over-closed*, and remain over-closed by a previous application of a higher normal stress.
- This is an exaggerated form of hysteresis.
- Rough joints in igneous and metamorphic rocks can *over-close* even due to temperature increase alone, due to better fit, which is something beyond hysteresis.
- The *rock mass* deformation moduli, thermal expansion coefficients, hydraulic apertures, and seismic velocities may each be affected.
- Well-controlled laboratory HTM tests, *in situ* HTM block tests, and large-scale heated rock mass tests, lasting several years at Stripa, Climax and Yucca Mountain, have produced evidence for this *extra* fully-coupled response.
- *Over-closed* laboratory direct shear tests give elevated strength envelopes in the case of tension fractures and joint replicas.
- Heating alone also increases the shear strength of natural joints.
- The coupled *thermal-OC* effect in HTM numerical modelling will require, as a minimum, thermal expansion coefficients that *include* rather than *exclude* relevant joint sets, if these have marked roughness and if they originated at elevated temperature.
- Elevated deformation moduli that attract higher stress must be expected.

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

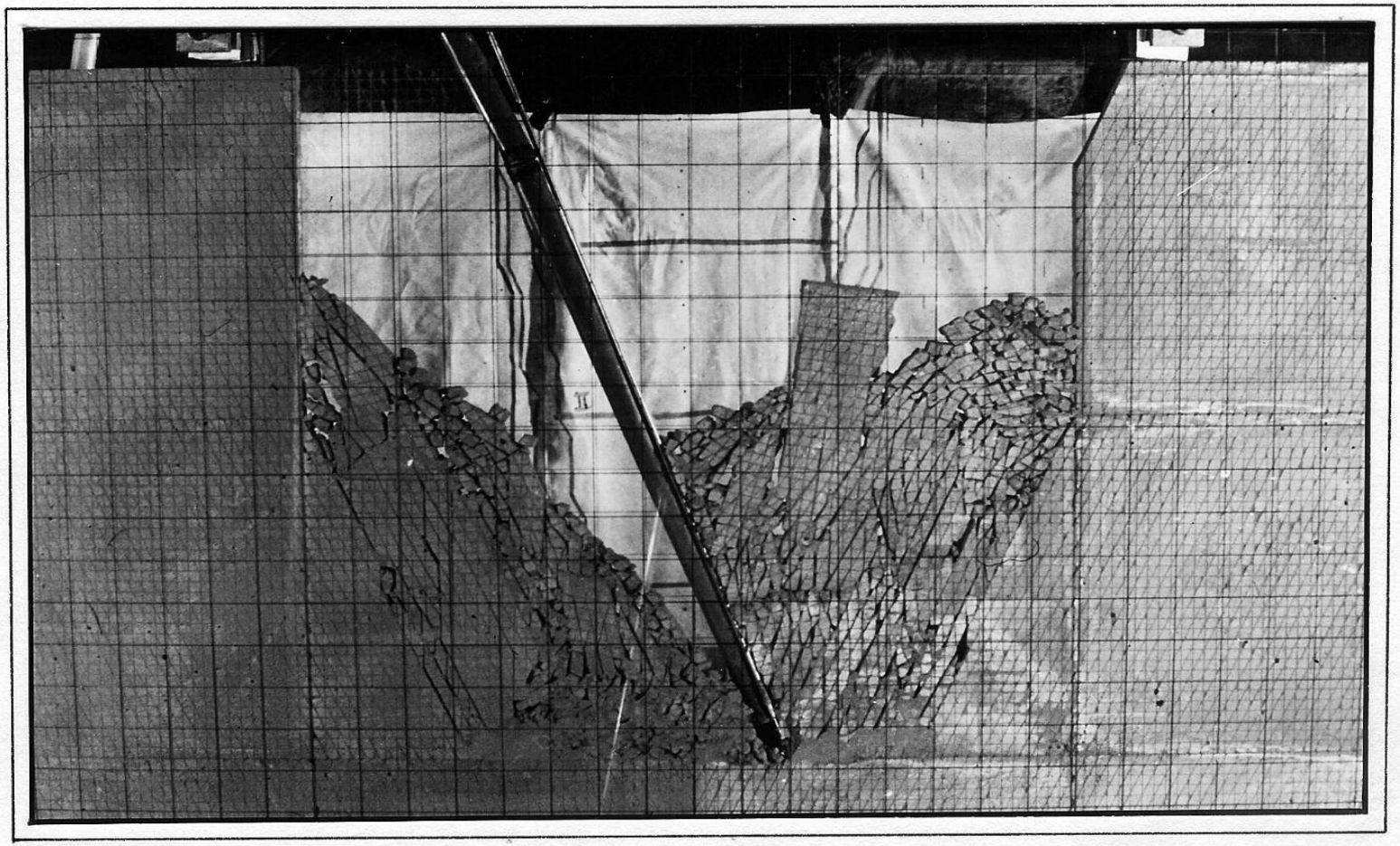


Model M2: medium horizontal stress
M3: high horizontal stress (40,000 blocks, each model)



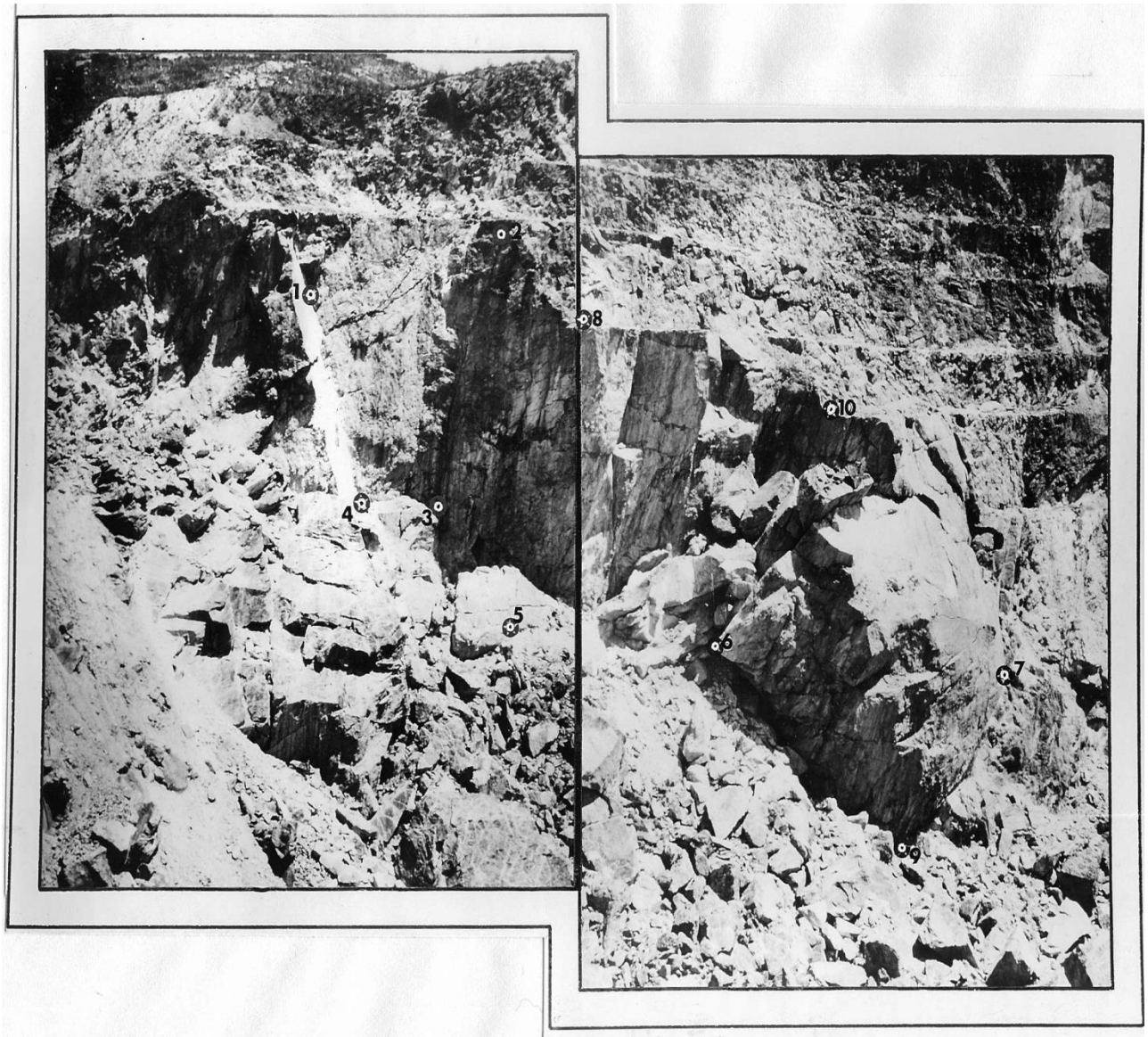


Note ’intact’ multi-fractured blocks, due to over-closure



Peña open-pit, Rio Tinto, Spain

A jointed block remains partly ‘intact’ after open-pit slope failure?

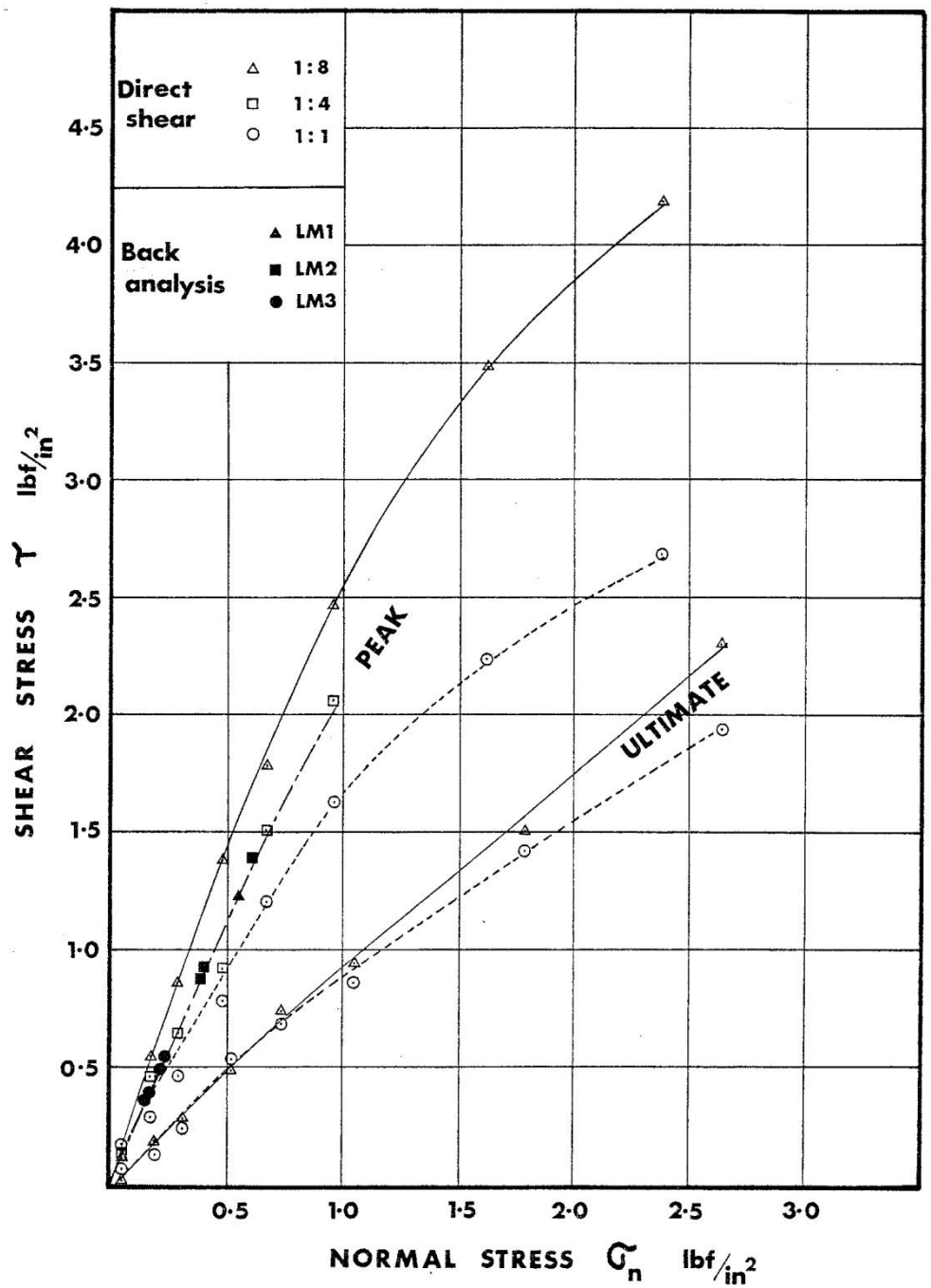


Slopes did not fail when expected, <u>based on *conventional* direct shear tests</u>

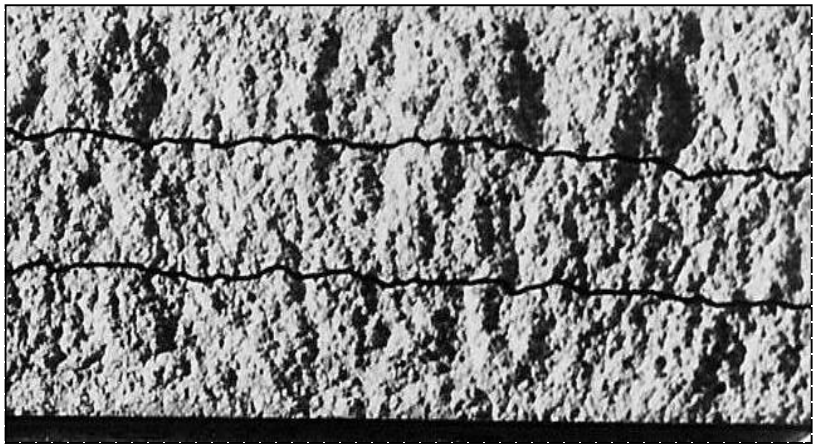
- *Conventional* meant normal stress σ_n application of the same magnitude as that acting beneath the slope

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

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



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

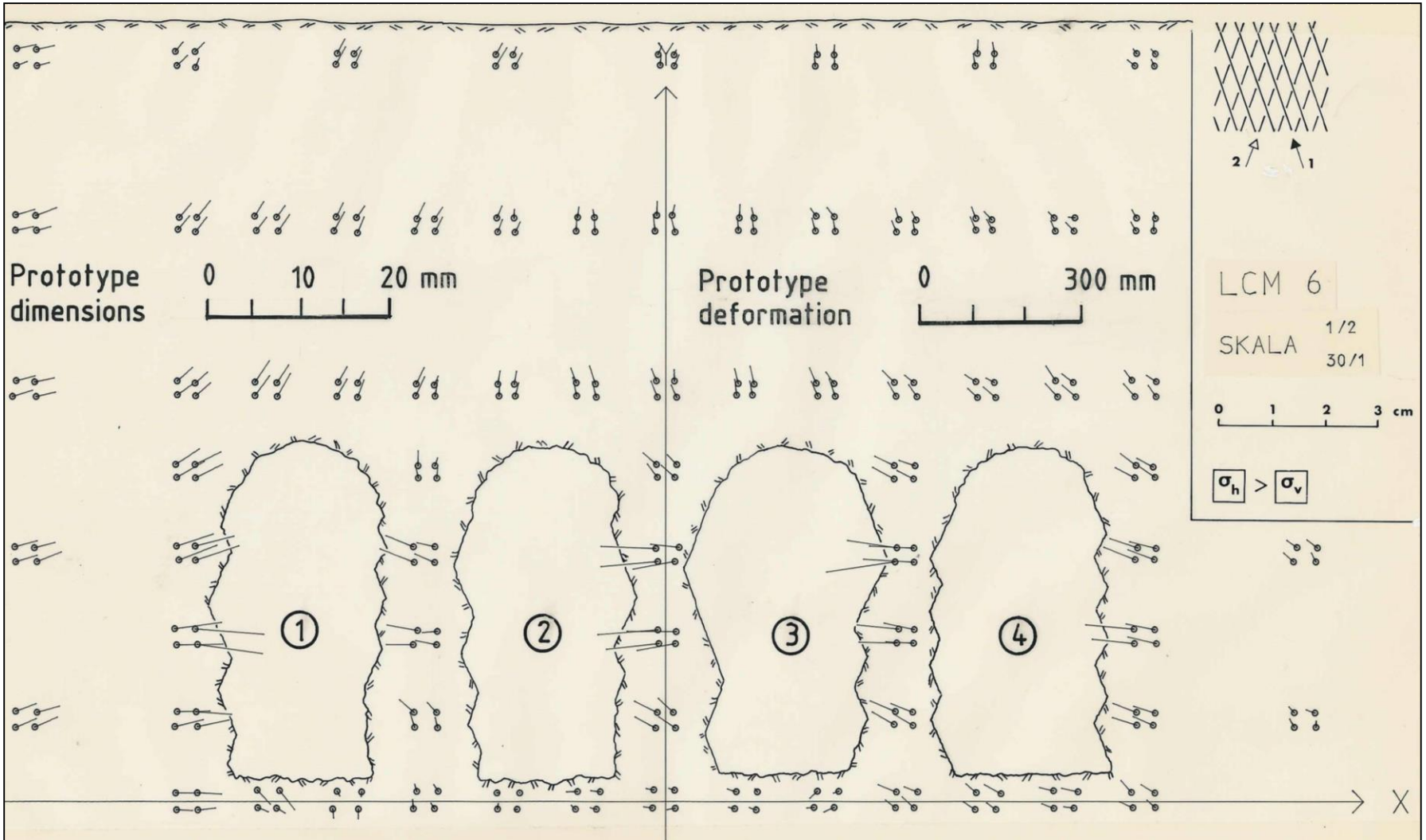


20,000-block models of 'rock caverns'
(Barton and Hansteen, 1979)

.....extreme hysteresis (= over-closure) again experienced....

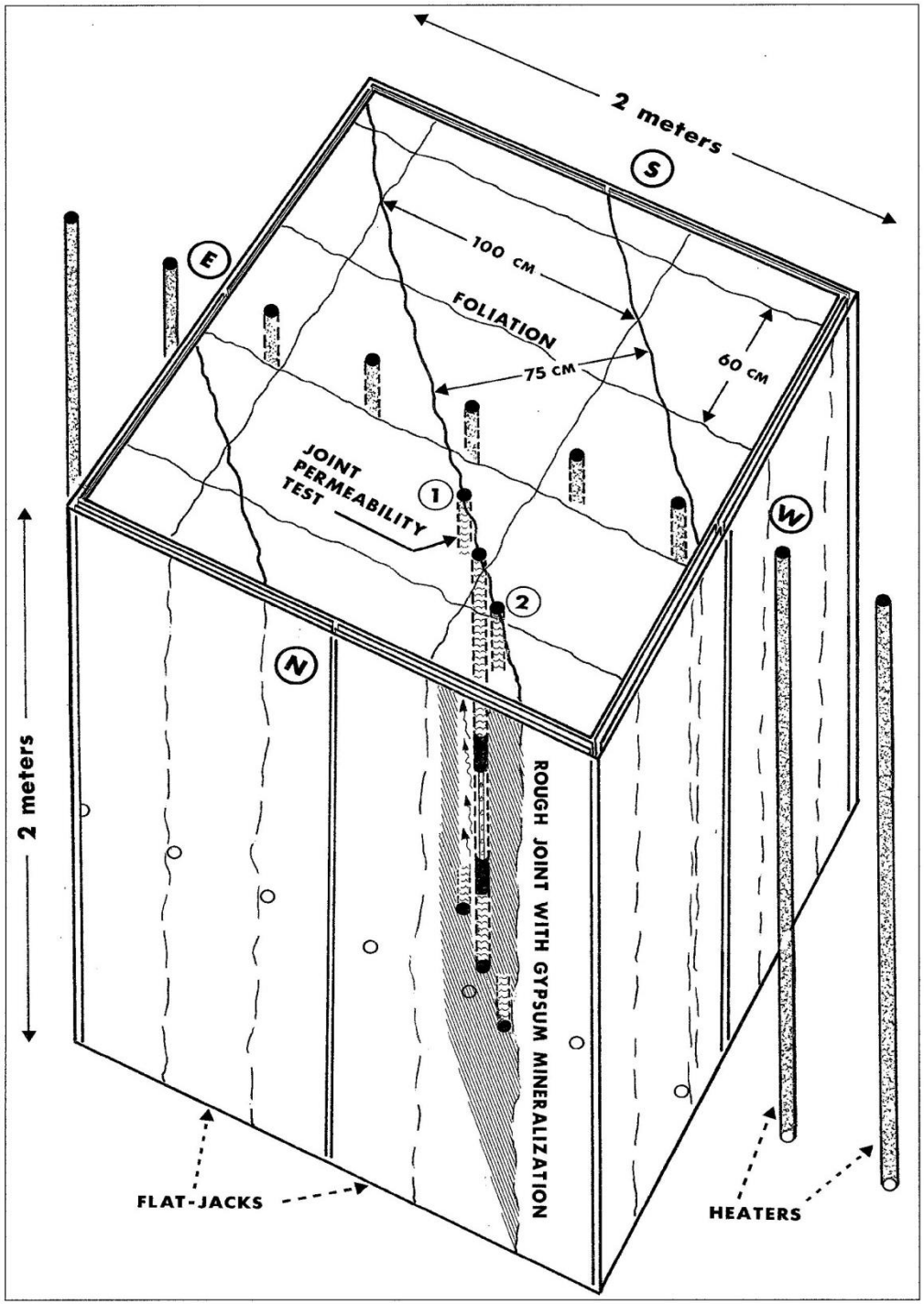
(DEFORMATIONS DIRECTED ONLY TOWARDS THE LAST EXCAVATION)

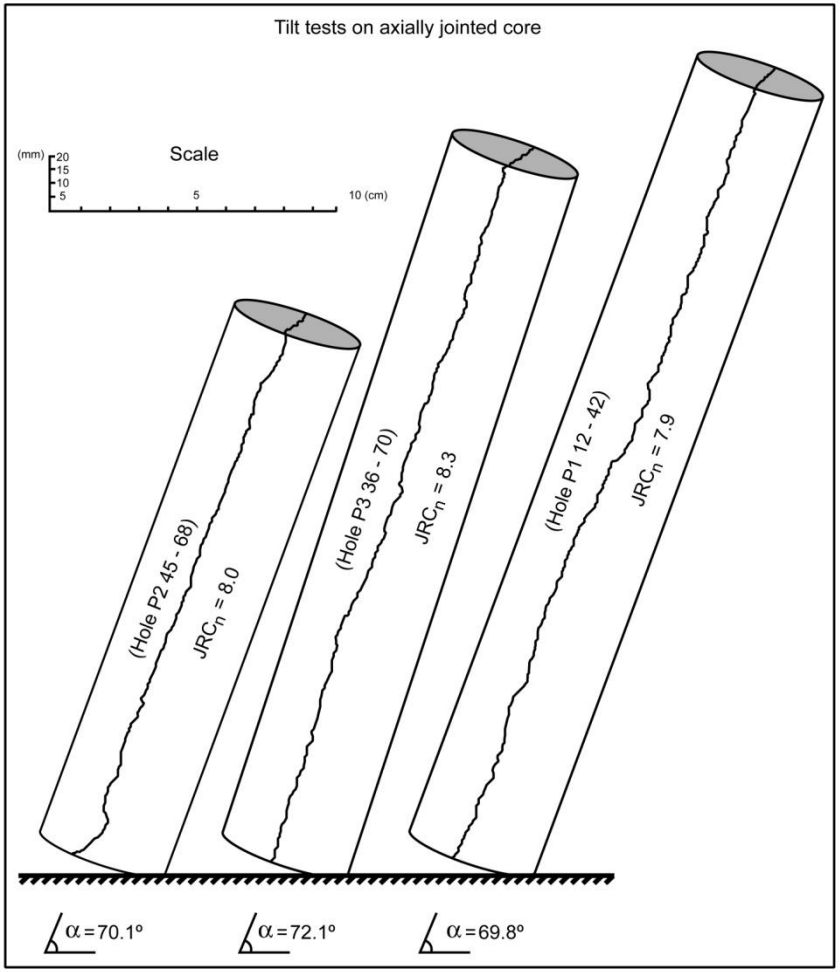
(order of excavation 1-2-3-4)



MANY EXAMPLES OF THERMAL *OVER-CLOSURE*

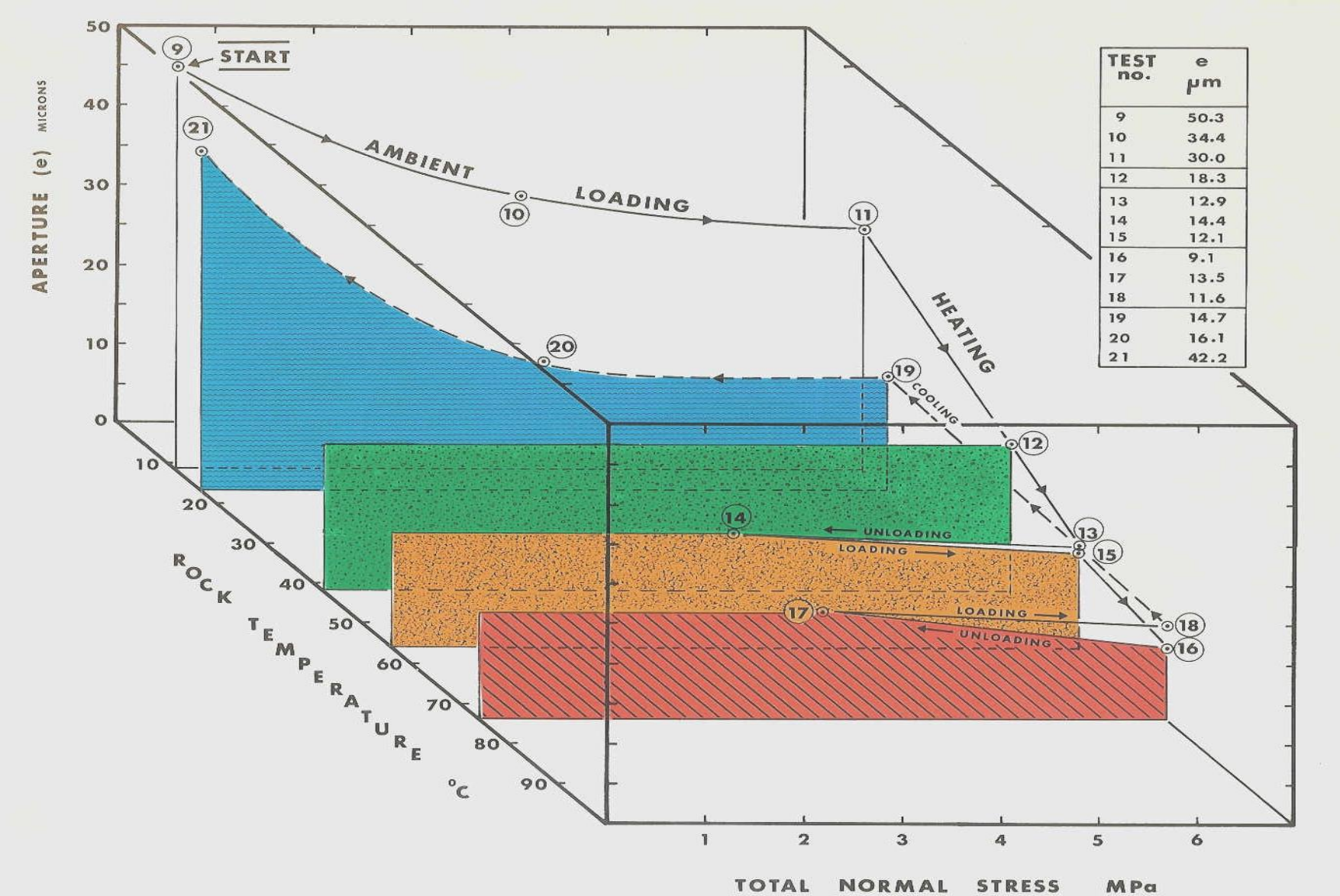
- Conducting aperture decreases in Terra Tek / CSM HTM block test (for ONWI)
- Joint closures in HTM coupled stress flow tests (CSFT) (for AECL/URL)
- Conducting aperture reductions from HTM block test in G-Tunnel (for Sandia National Laboratory)
- (Reduced thermal expansion coefficients at NSTF Hanford (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


2 meters
S
E
100 CM
FOLIATION
75 CM
60 CM
JOINT PERMEABILITY TEST
1
2
W
N
2 meters
ROUGH JOINT WITH GYPSUM MINERALIZATION
FLAT-JACKS
HEATERS

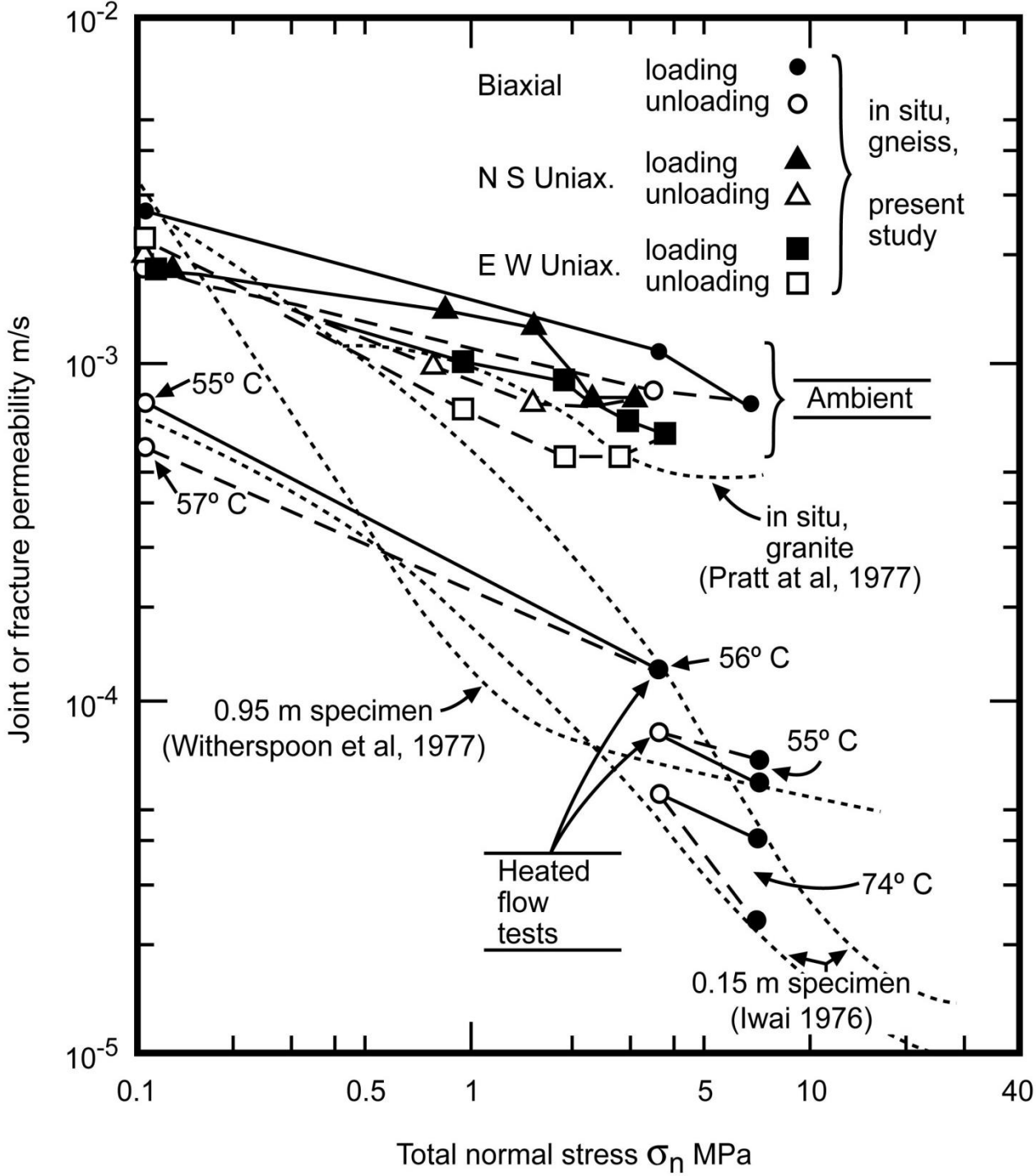

Tilt tests on axially jointed core
Scale
(mm)
20
15
10
5
5
10 (cm)
(Hole P2 45 - 68)
JRCn = 8.0
(Hole P3 36 - 70)
JRCn = 8.3
(Hole P1 12 - 42)
JRCn = 7.9
α = 70.1°
α = 72.1°
α = 69.8°

(One of the) TerraTek HTM block test results (1980,1981)

Note conducting aperture **reduction with temperature alone**
(and near-maintenance when unloaded or cooled)



TEST no.	e µm
9	50.3
10	34.4
11	30.0
12	18.3
13	12.9
14	14.4
15	12.1
16	9.1
17	13.5
18	11.6
19	14.7
20	16.1
21	42.2



Thermal over-closure.....no stress increase involved

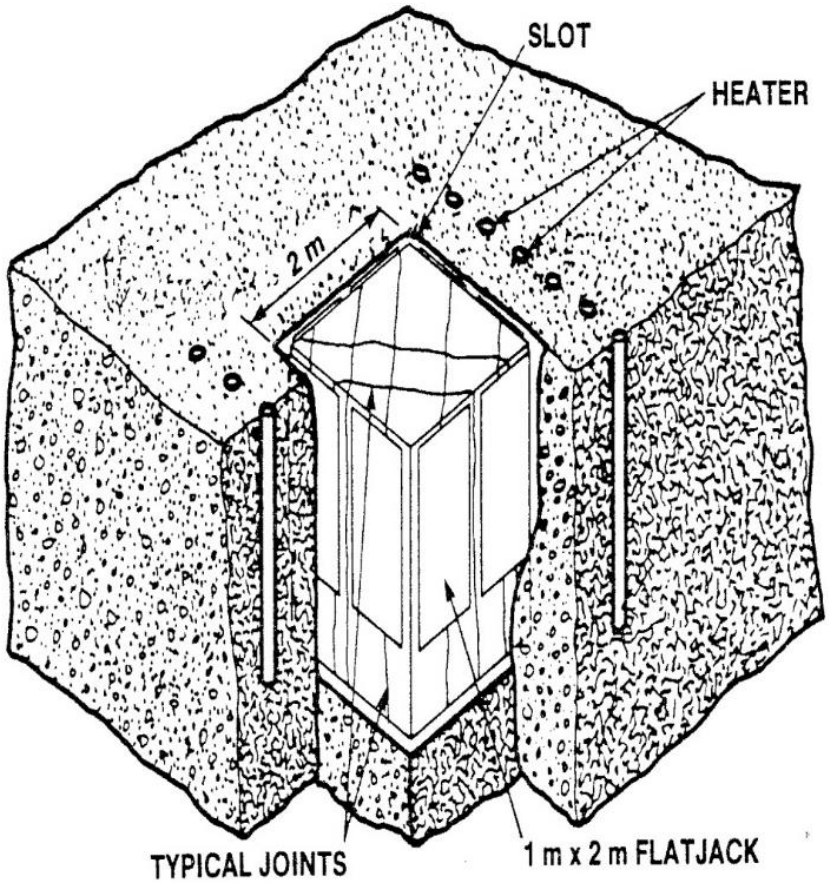
$\Delta e = 30 \rightarrow 9\mu m$

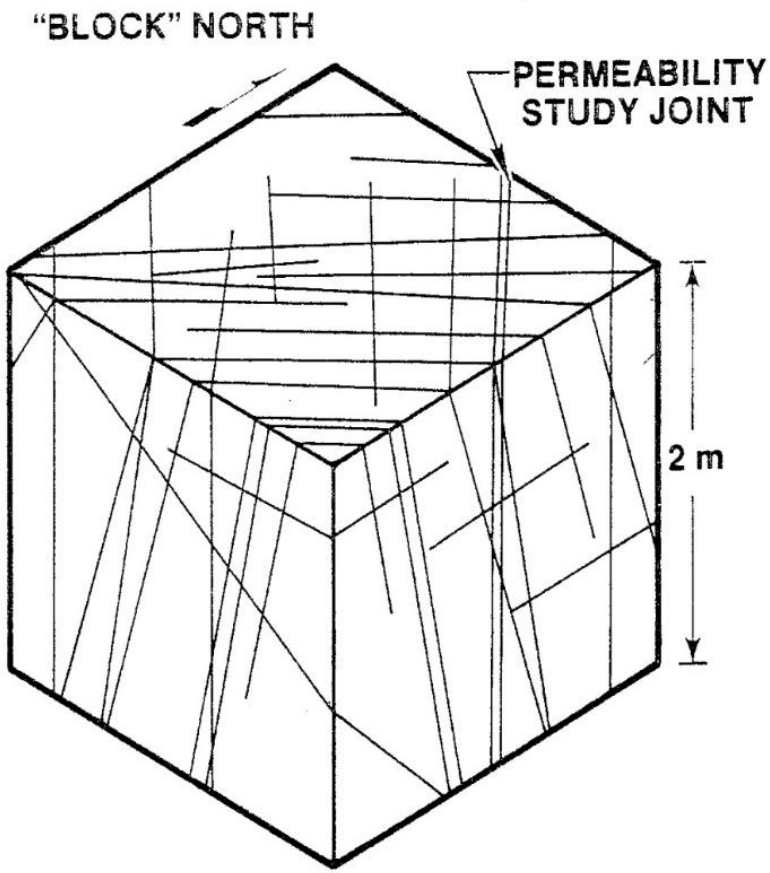
Δk: 1/10 x reduction)

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

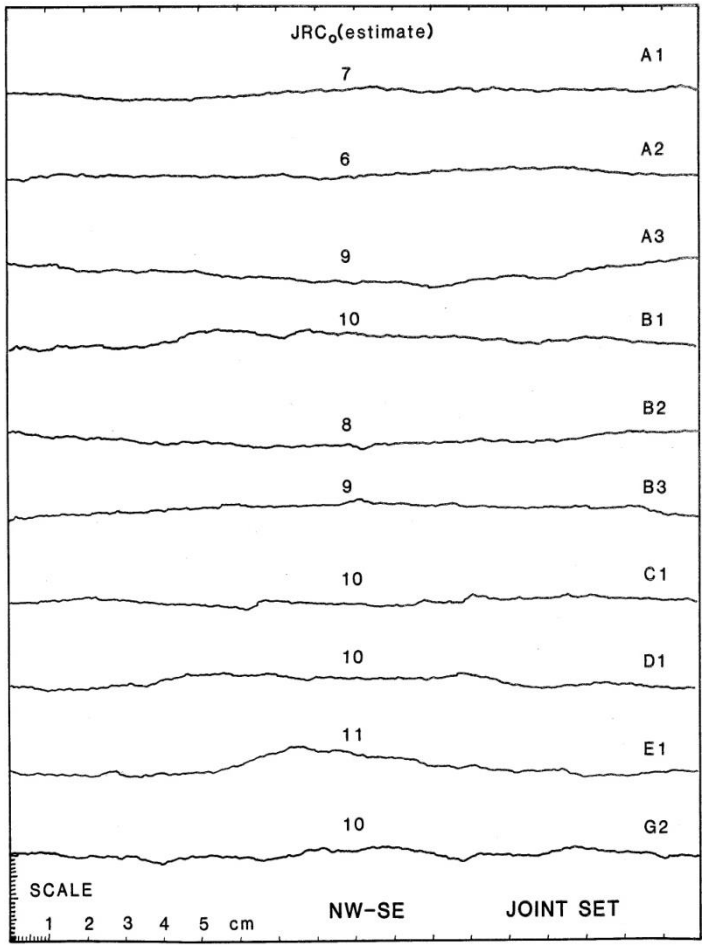
(Reduced hydraulic apertures due to heating: 60 to 35 μm)

Zimmerman et al. 1986





TYPICAL JOINT ROUGHNESS AT THE G-TUNNEL HEATED BLOCK TEST



ONE MAY *ONLY* NEED TEMPERATURE RISE FOR THE 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).

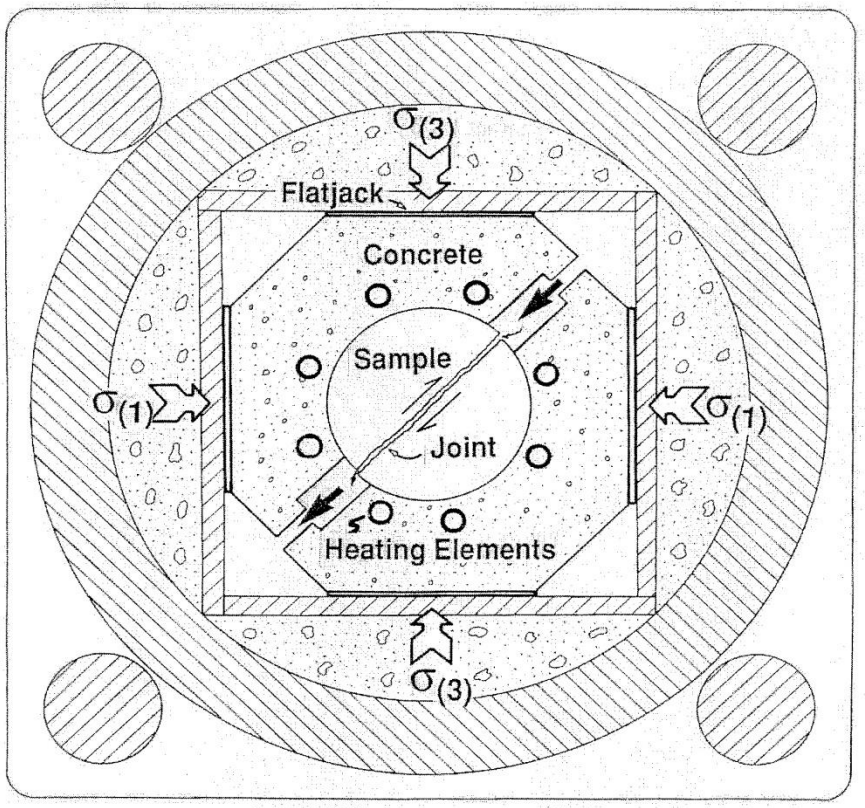
- Why?...Anisotropic thermal expansion/contraction of constituent minerals in opposing joint walls....the joint's memory of warmer conditions at it's birth?... a primeval 'finger-print' of 3D-roughness.

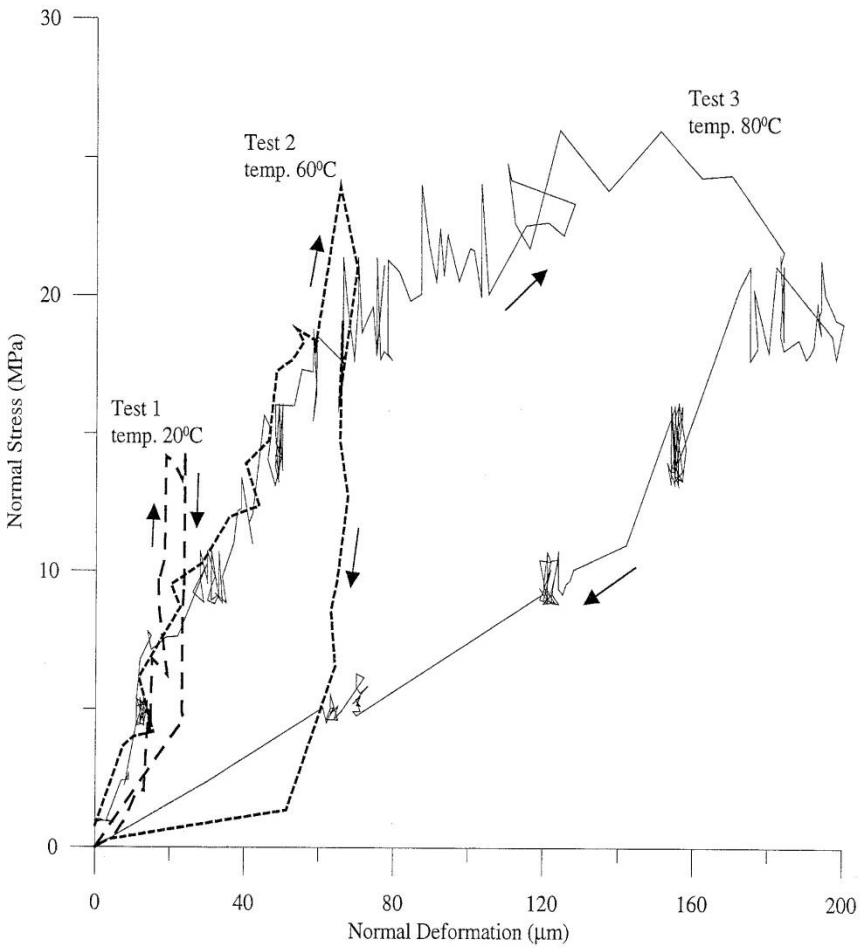
- The 3D roughness *finger-print*, though very recognizable, would be subtly altered in its finer details by today's cooler conditions.

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 recorded at 20ºC, 60ºC and 80ºC

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



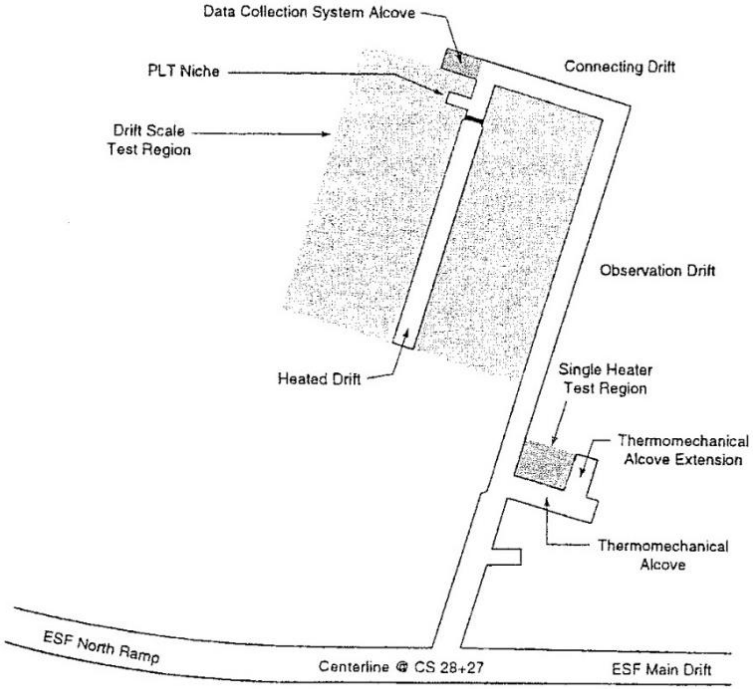


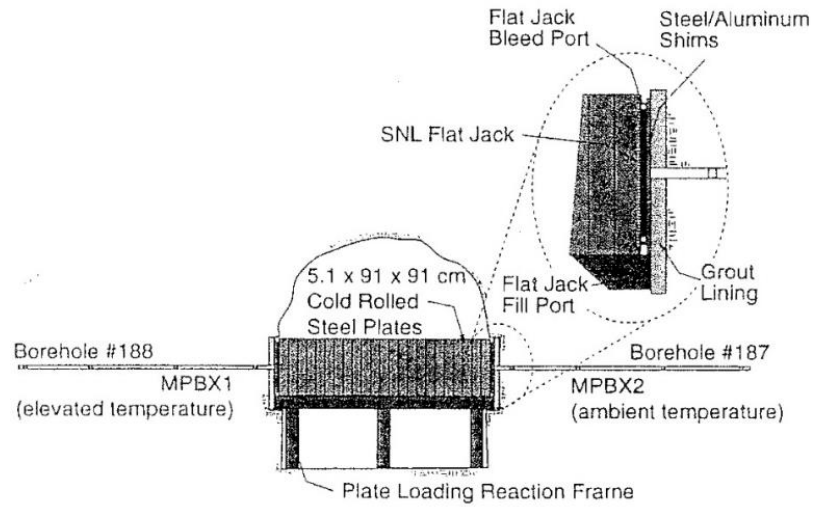
YUCCA MOUNTAIN ESF plate-load test

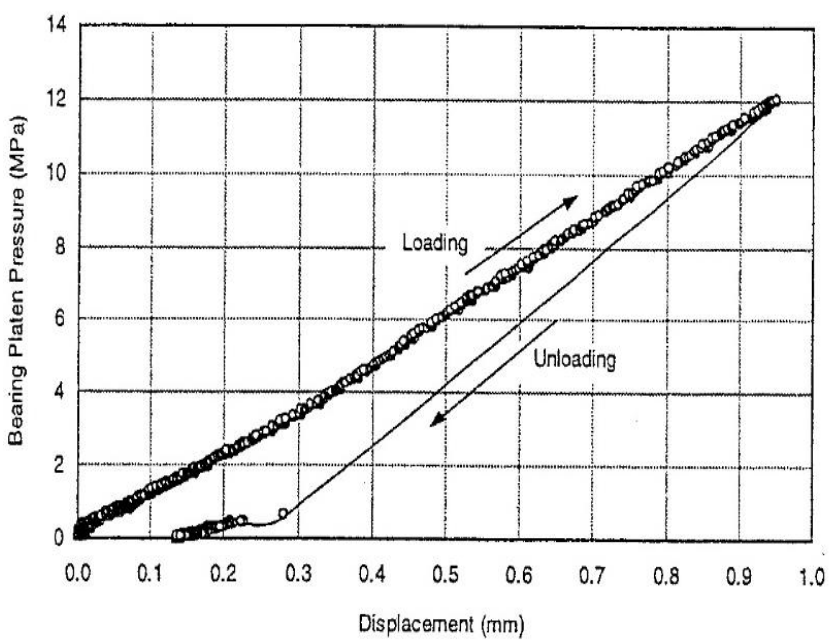
E_{mass} (heated) = 24.5

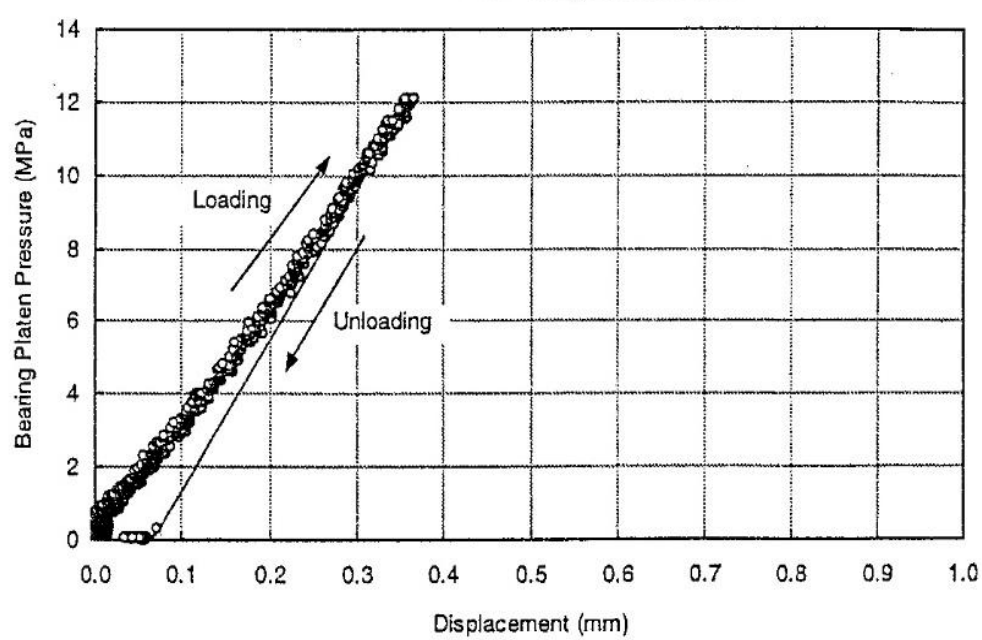
E_{mass} (ambient) = 11.4 GPa

(George et al., 1999)



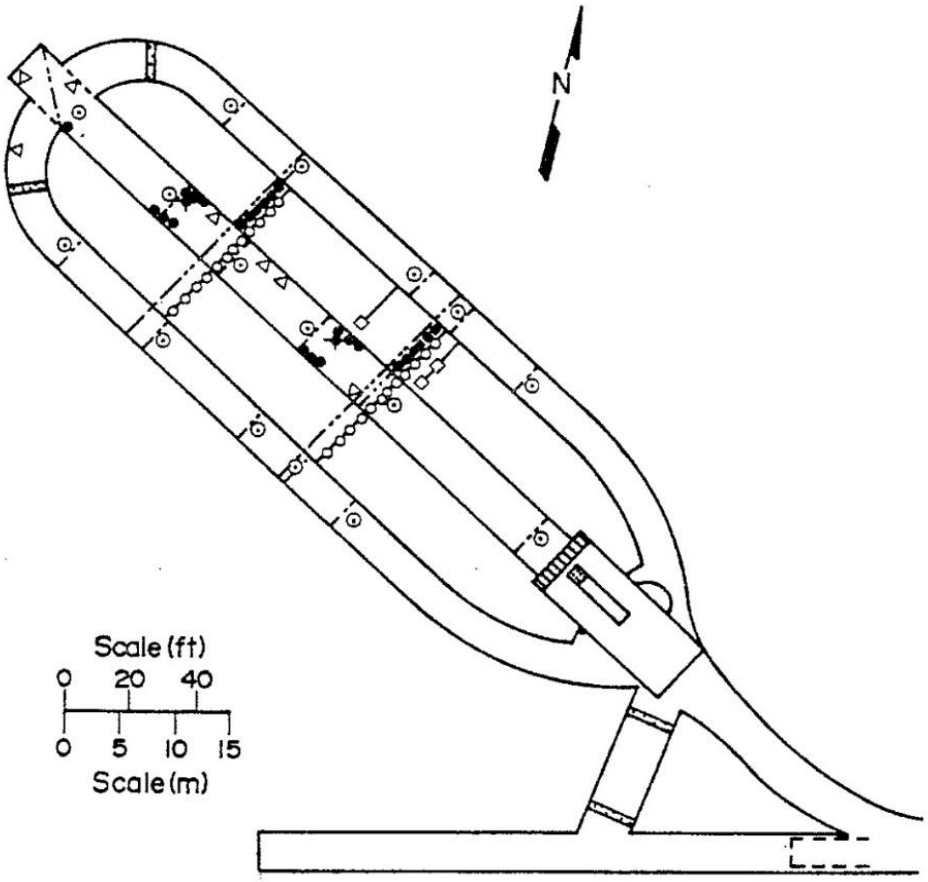


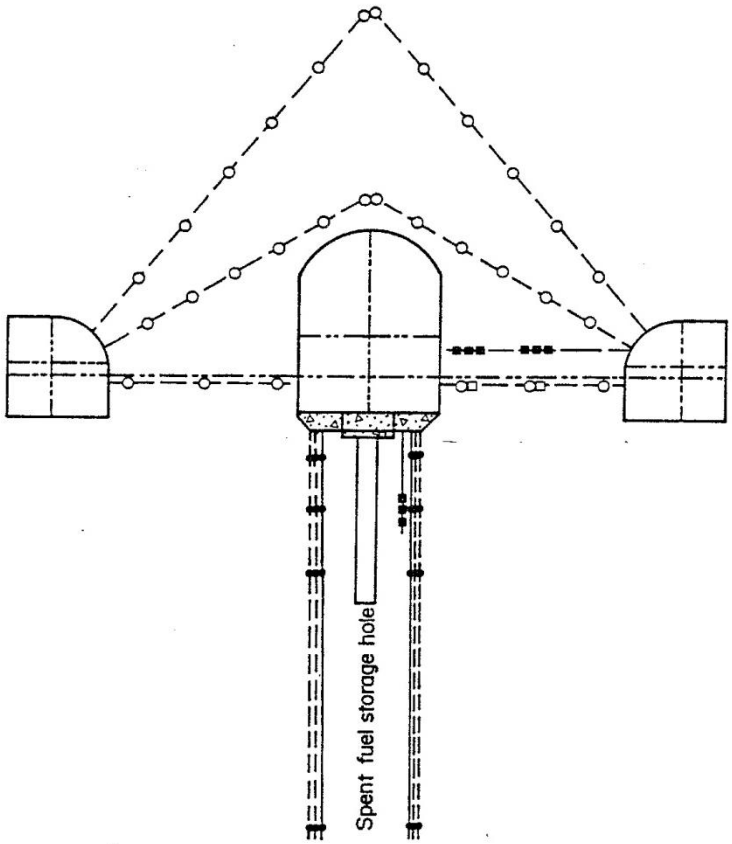




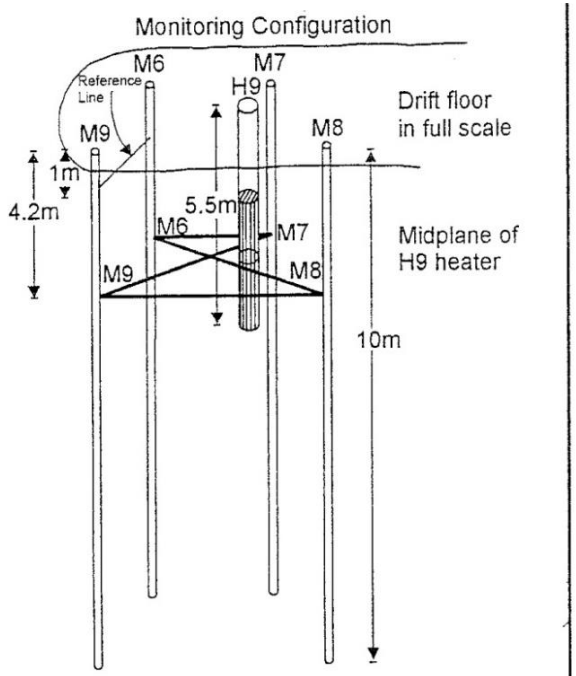
CLIMAX MINE (quartz monzonite) HEATED MINE-BY at 400 m depth, as part of the SPENT FUEL TEST (Yow and Wilder, 1993)

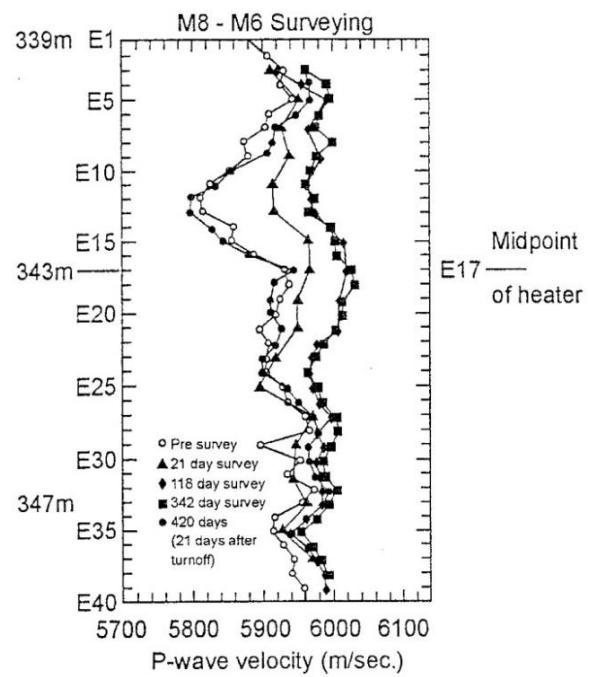
Measured deformations ¼ to ½ of those calculated by ADINA (discrepancies in thermal moduli and thermal expansion coefficients)

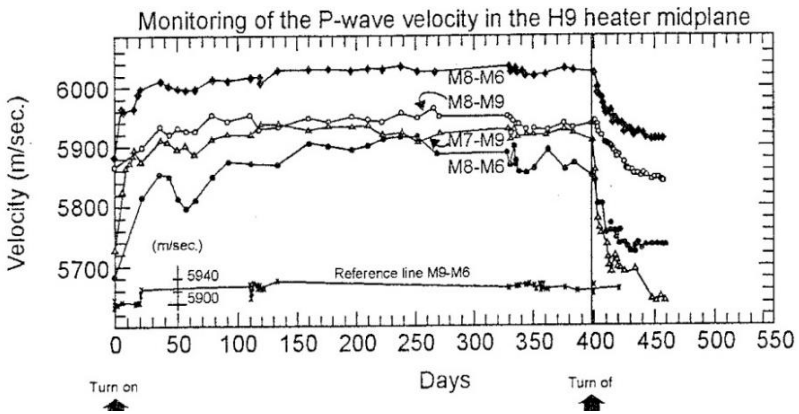




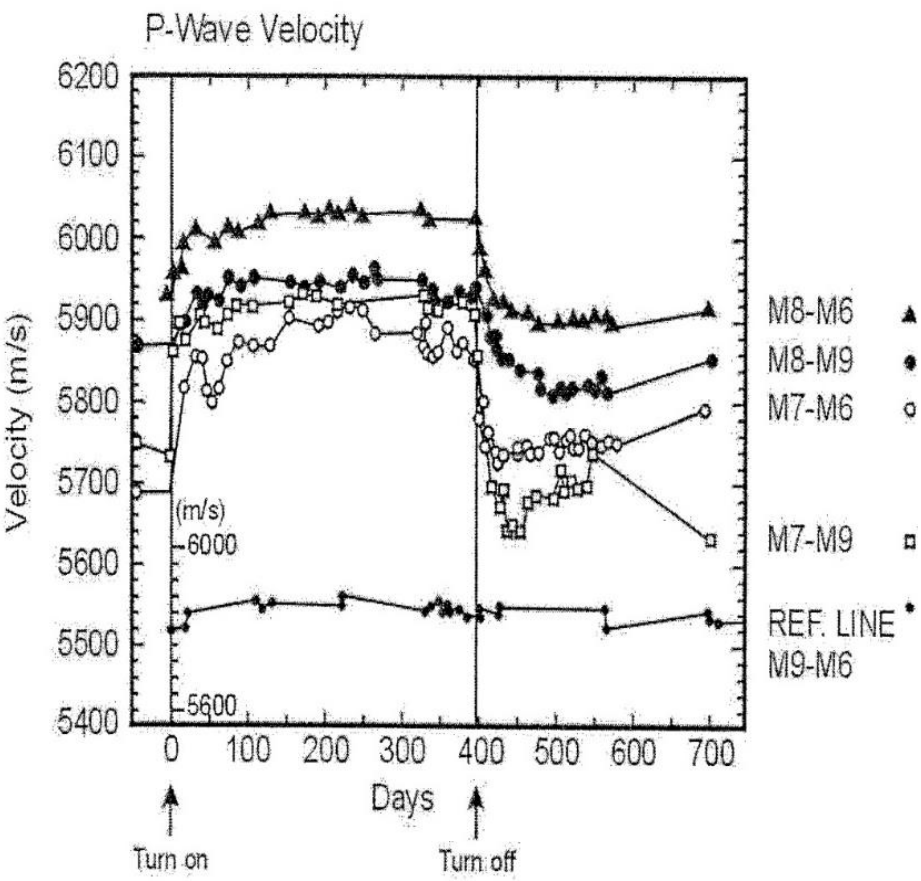
BOREHOLE HEATER TEST AT STRIPA.....1st 400 days heating
(monotored by cross-hole seismic: Paulsson and King, 1980)

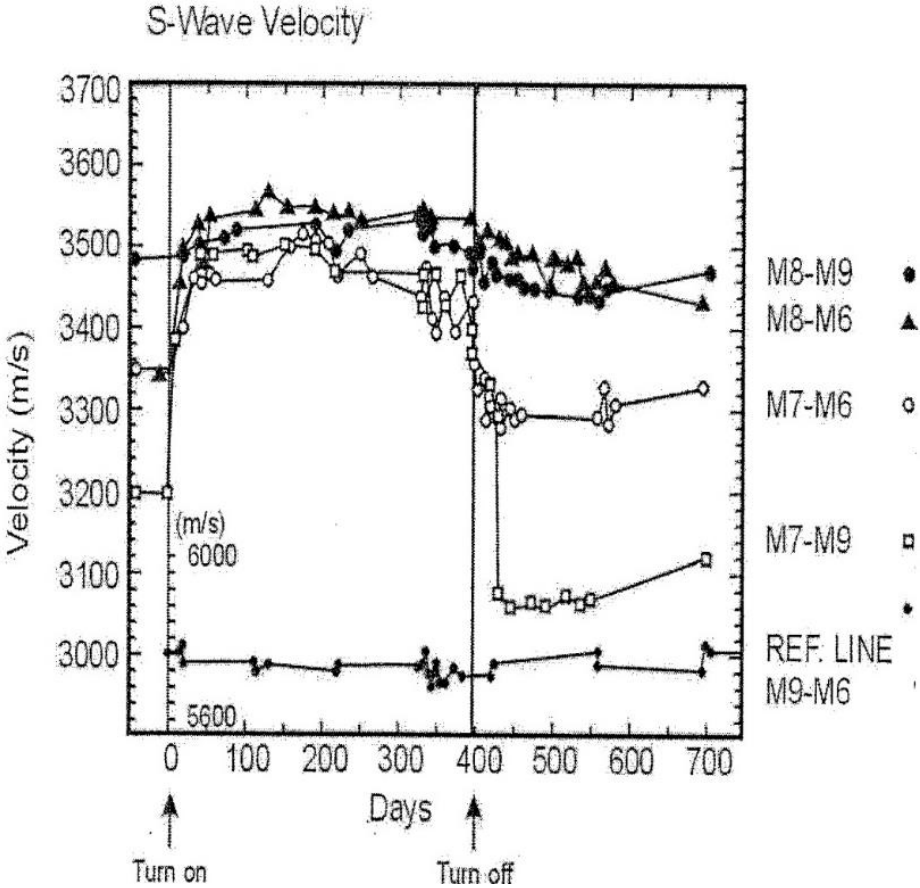






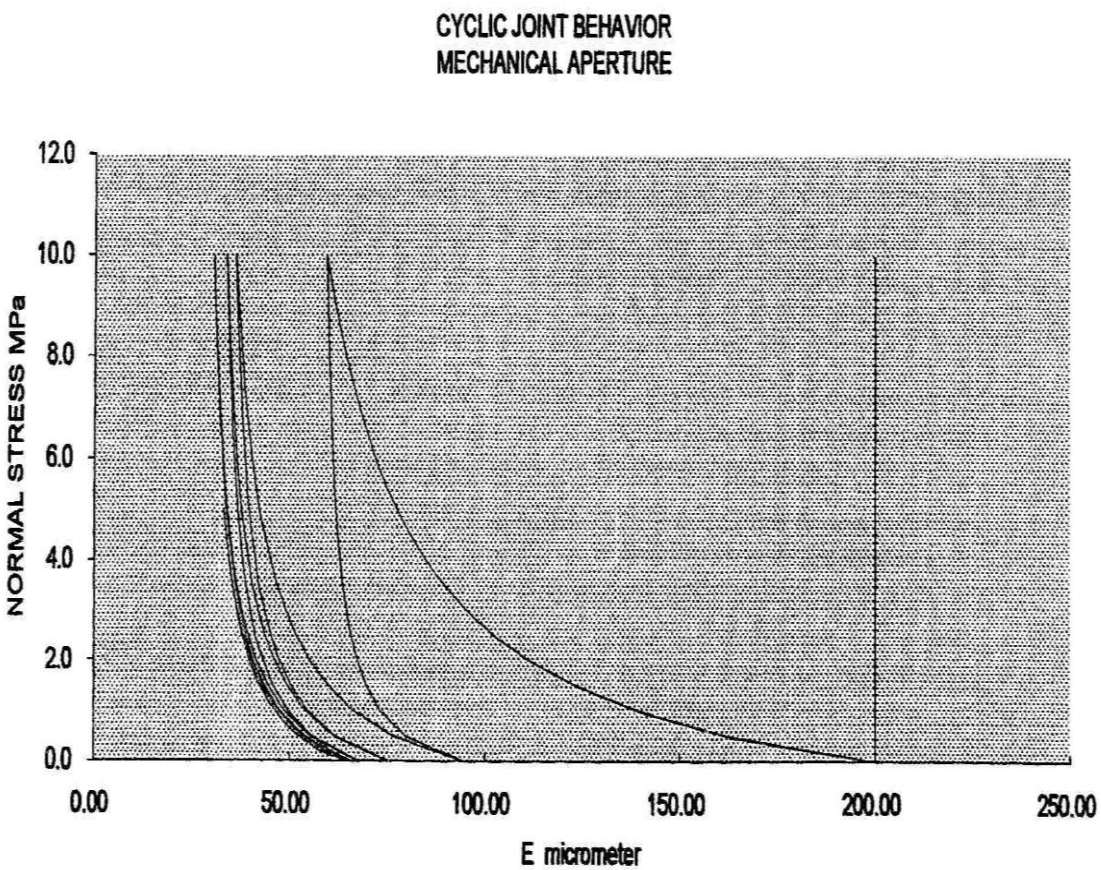
STRIPA BOREHOLE HEATER TEST.....to 750 days, 300 days cooling
(monitoring with cross-hole Vp and Vs : Poulsson et al., 1985)
Note lower velocities at end of cooling (M7-M9, M7-M6) .....
joint opening somewhere??....rough ones *over-closed*??

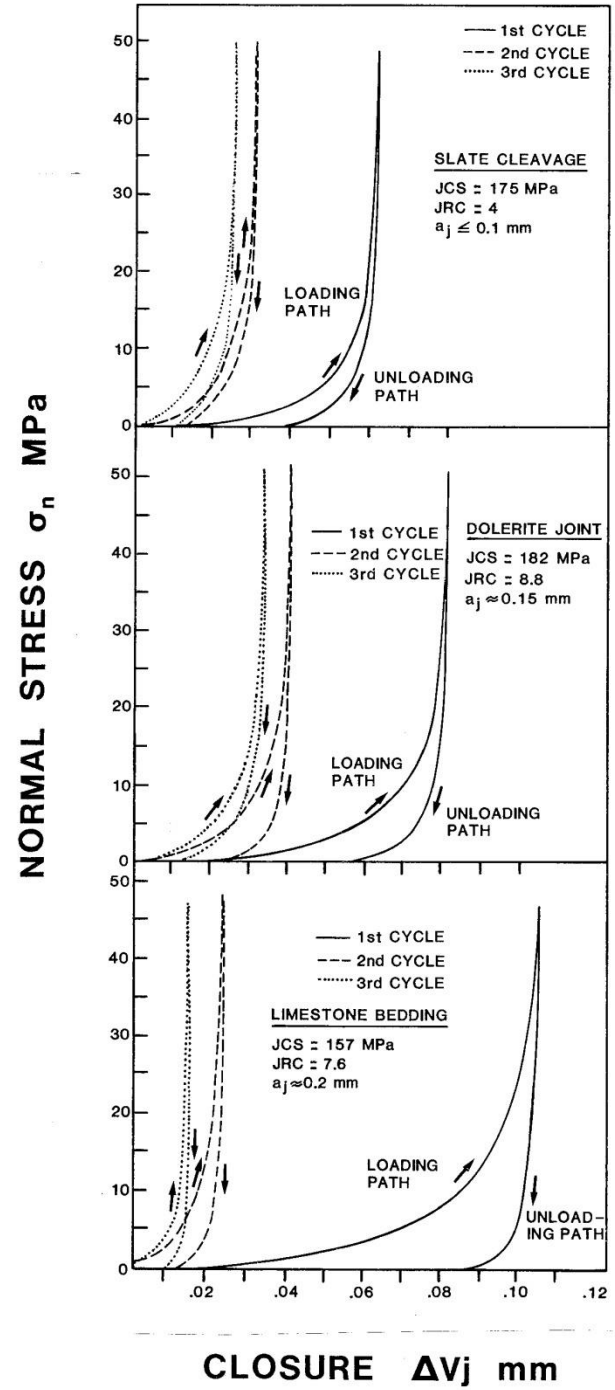




Bandis normal closure tests (Bandis et al.1983) show over-closure (i.e. hysteresis) when the roughness is significant.

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





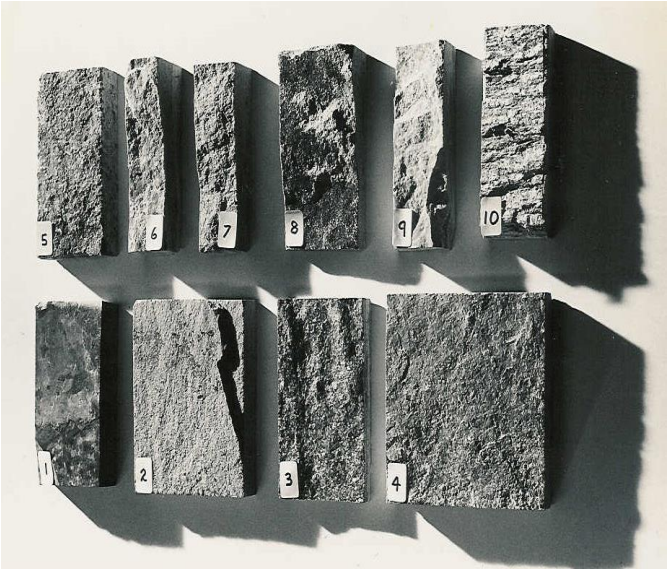
JRC_O (small-scale)

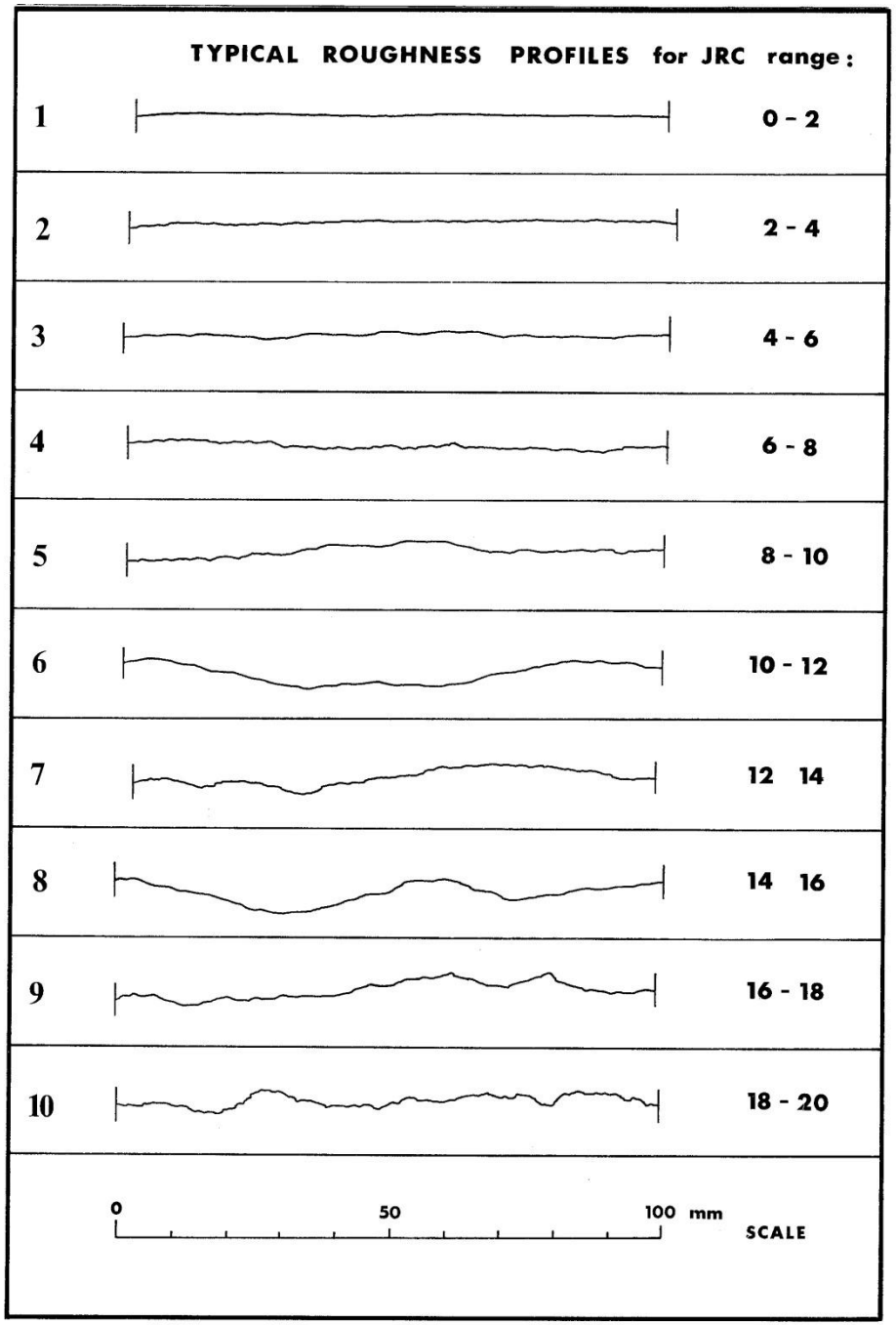
- Joint roughness is going to be the all-important discriminator in this interlock mechanism, which resembles the effect of a ‘perpendicular-JRC’.

- The influence of this perpendicular roughness is easy to see when tilt testing.

- With sufficient roughness ’tensile strength’ is exhibited. *Very rough* joints give 180º tilt angles.

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





EXAMPLES OF A PLANAR JOINT (?minor fault?) AND A ROUGH JOINT, WITH RESPECTIVELY ZERO, AND A HIGH PROBABILITY OF OVER-CLOSURE PHENOMENA

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

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.

- The need to address these effect is clear

CONCLUSIONS

- 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 (Note: JRC_o and JCS_o may both increase)

- NEW CONSTITUTIVE MODEL SUB-ROUTINES WILL THEN BE REQUIRED – ALSO FOR THE BB-MODEL

- 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)