Thermal over-closure of rougher joint sets with *potential consequences* for HLW disposal strategies, for geothermal energy injections, and for HTM modelling

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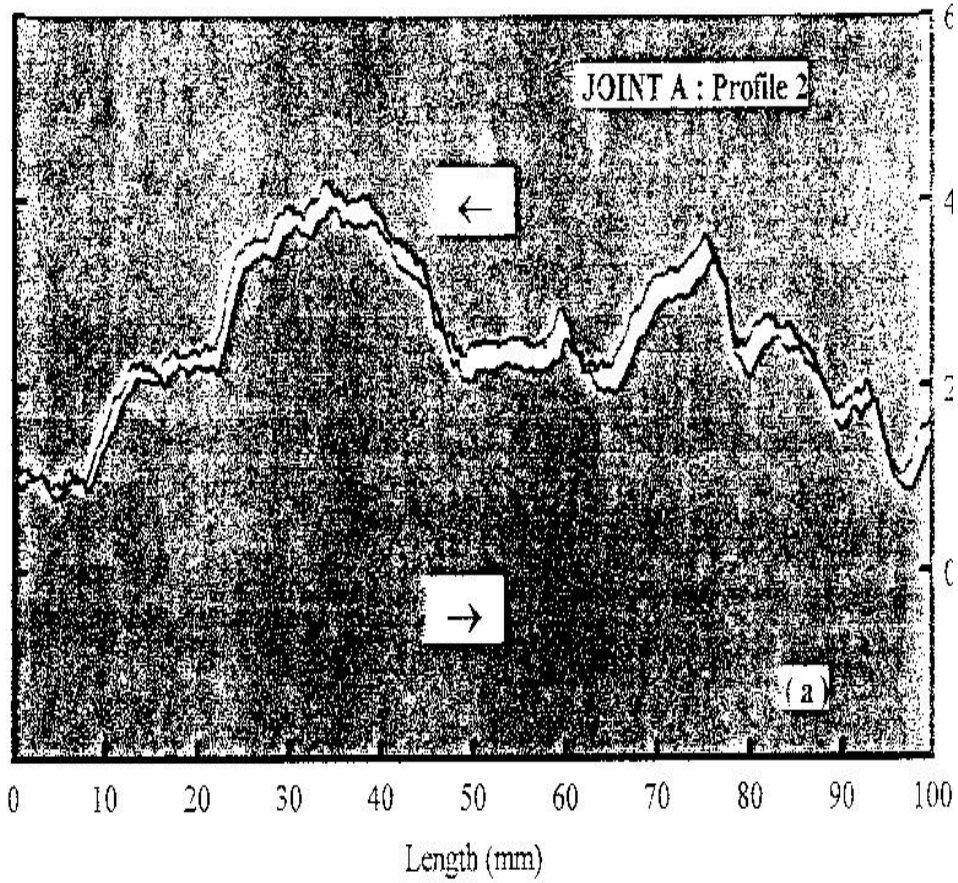
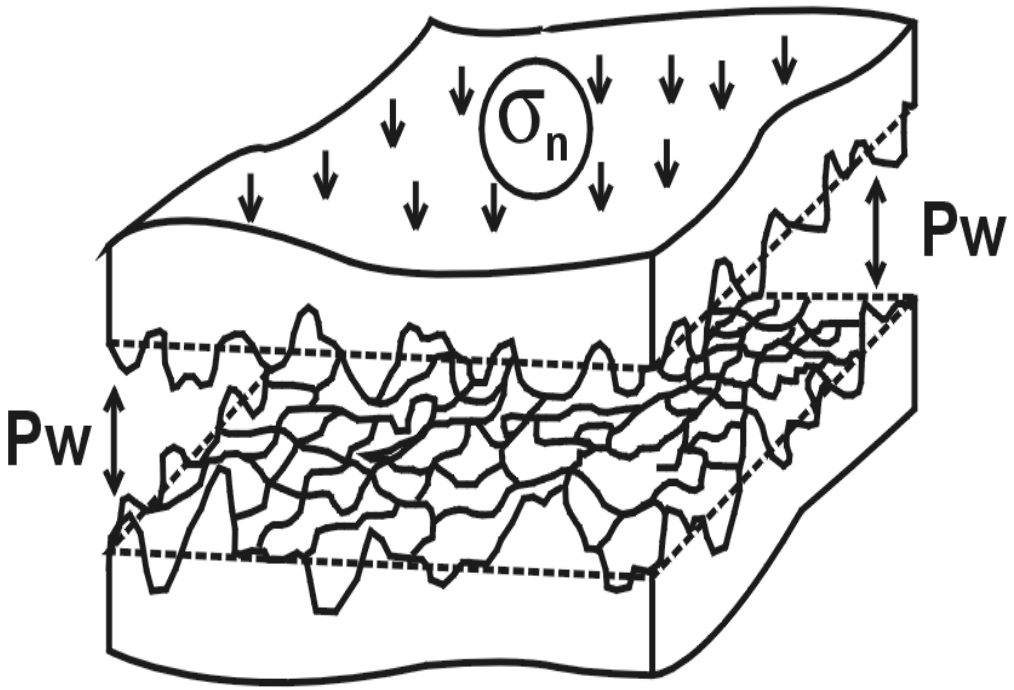
THE MECHANISM OF JOINT CLOSURE IS NOT AS 'SIMPLE' AS WE ASSUME.

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 well fom Kn-studies*

BUT WHAT IF HEATING MAKES THE ROUGHNESS PROFILES FIT TOGETHER BETTER ??

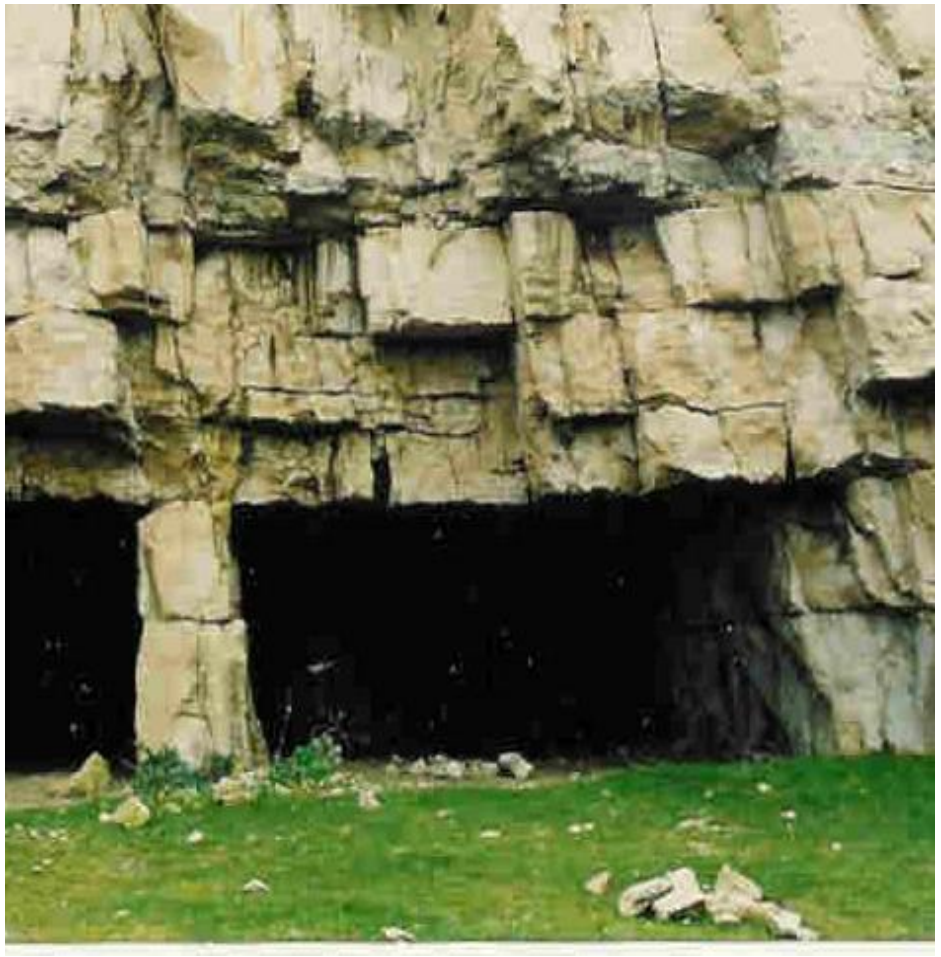


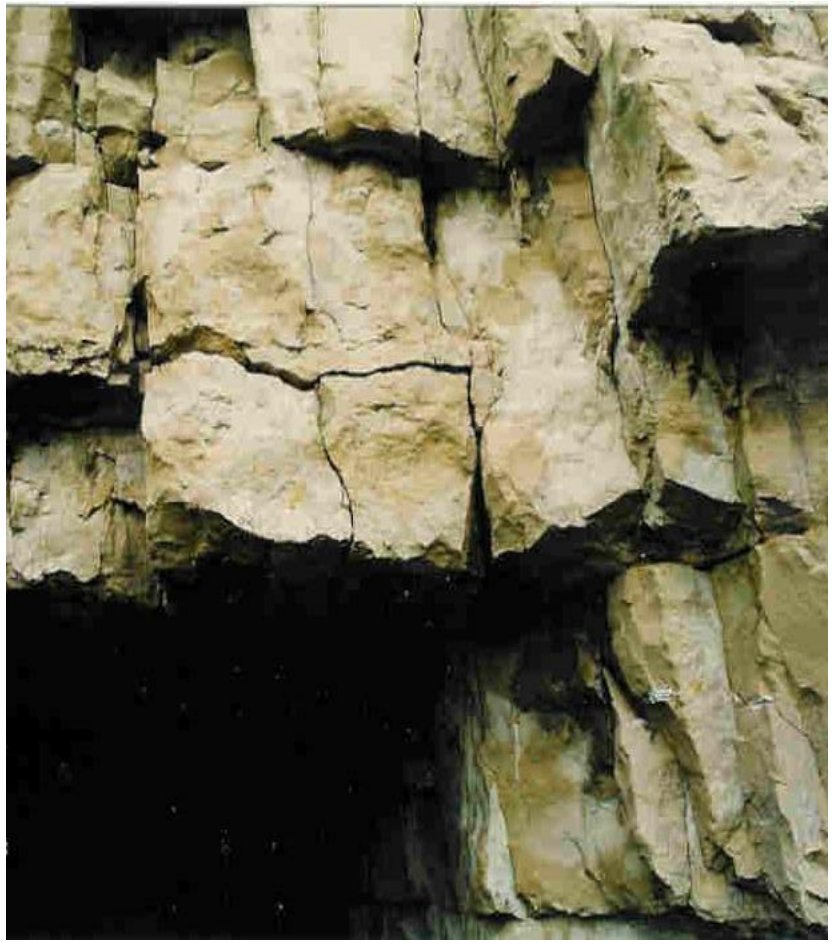


ARE THE JOINTS THAT REMAIN CLOSED EXHIBITING:
CEMENTATION?
OVER-CLOSURE? OR NORMAL - CLOSURE?

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

BUT - SOME MAY NOT HAVE LOST THE O-C EFFECTS, or are N-C due to the increased tangential stress/arching ?





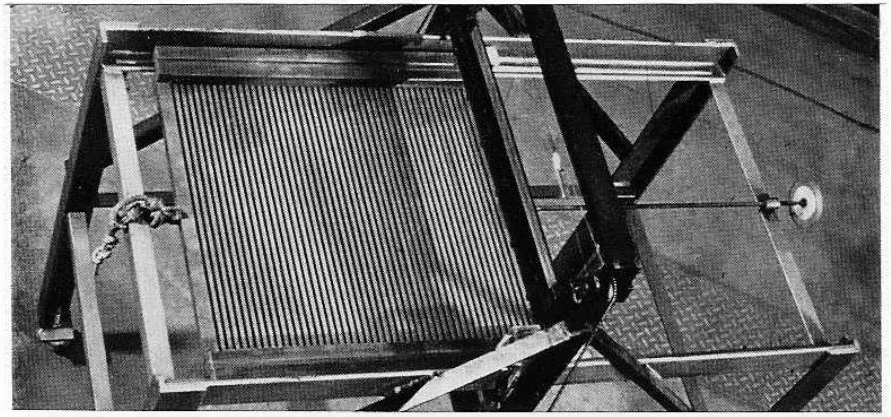
Rough joints can be *over-closed*, and remain over-closed by a previous application of a higher normal stress…IT ALL DEPENDS ON JRC_0.

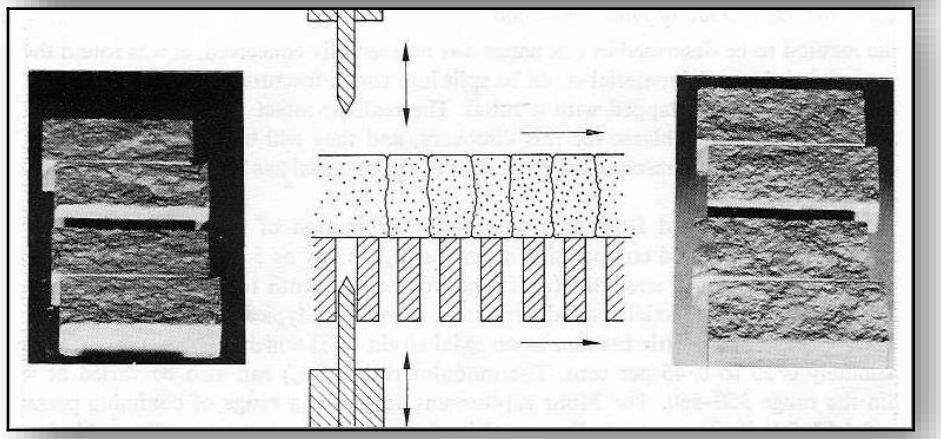
This is an exaggerated form of hysteresis.

BUT: 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.

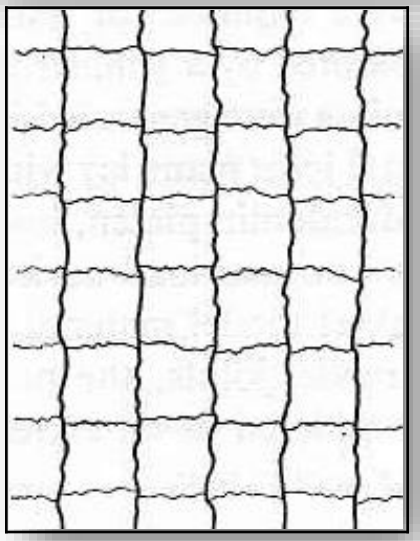
2D JOINTED "ROCK-MASS" – the possible origin of OC interest.

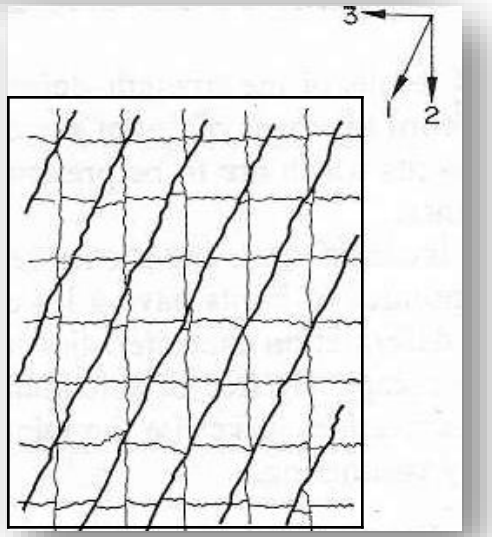


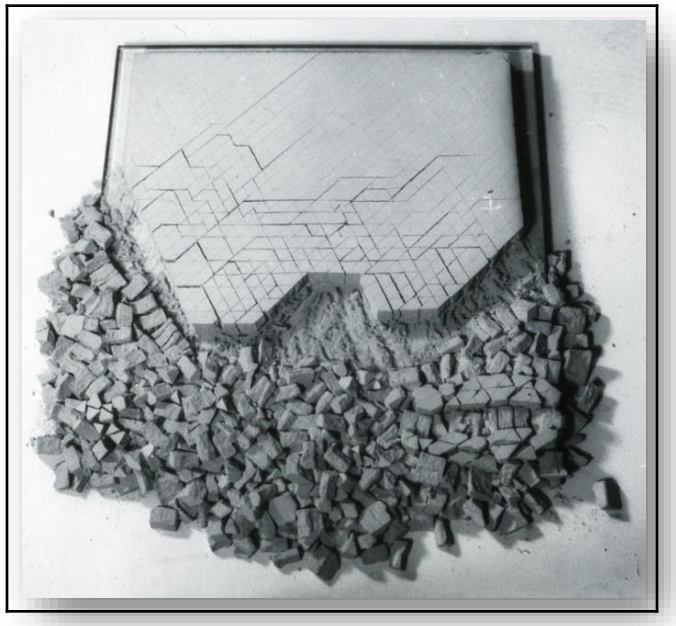


Tension-fracture models used for '*rock slope' studies* (in Ph.D. at Imperial College) 1968-1970. (pre µDEC).

'Nuclear power plant' *rock cavern* investigations (50m span) (at NGI) 1977-1978 (pre-UDEC)



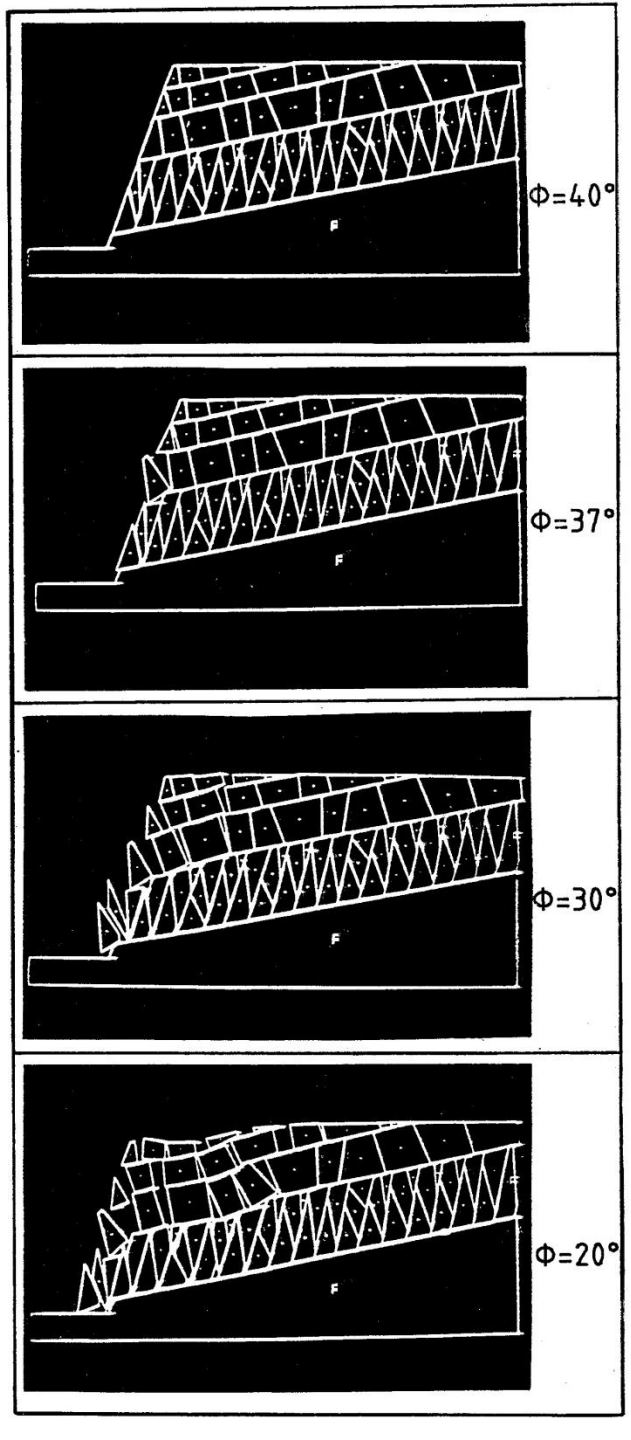




WE HAVE ALL MET THE ‘KTH MAFIA’ – JONNY R., JING L-R: ALL HERE EXCEPT OVE STEPHANSSON

IC mafia, Rio Tinto, field studies, 1967.

Cundall our chief star (ARMA, 2016)

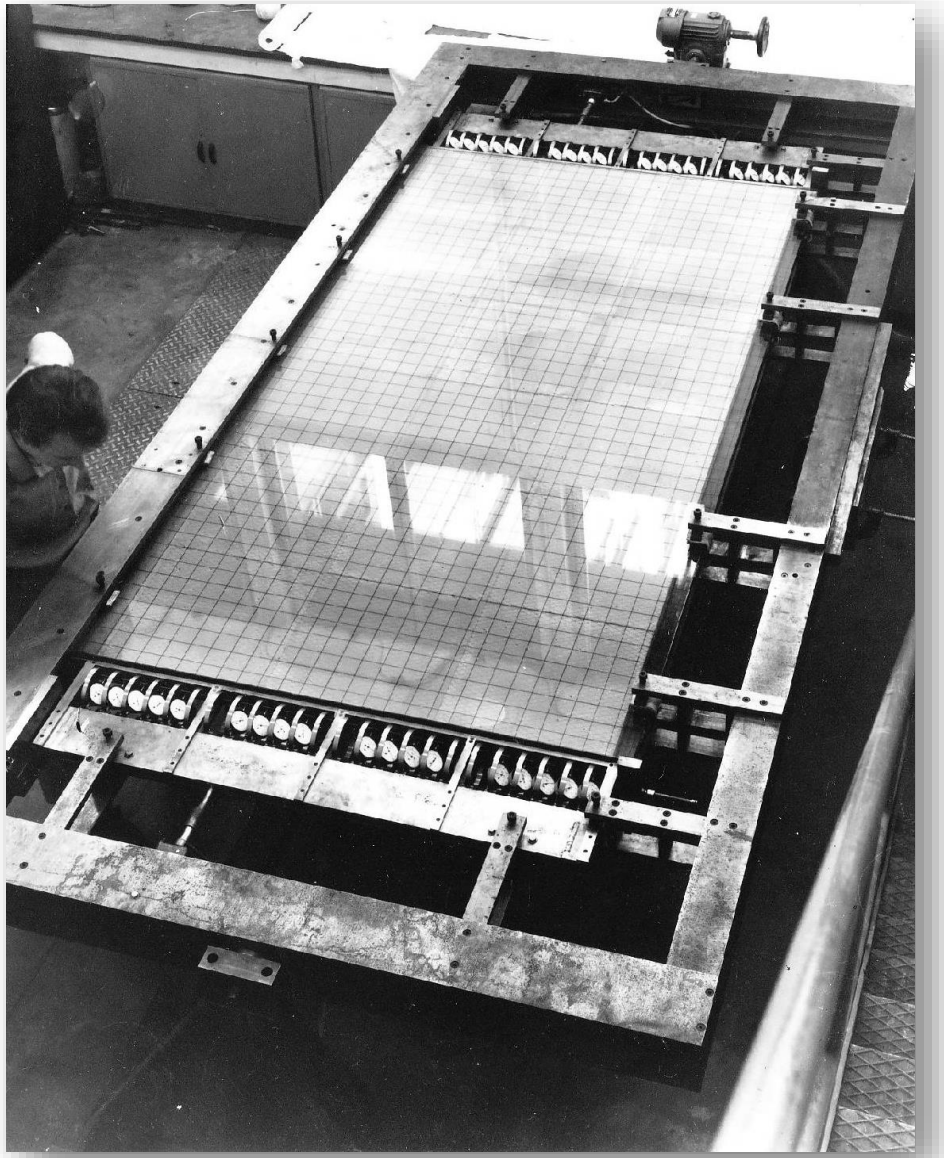


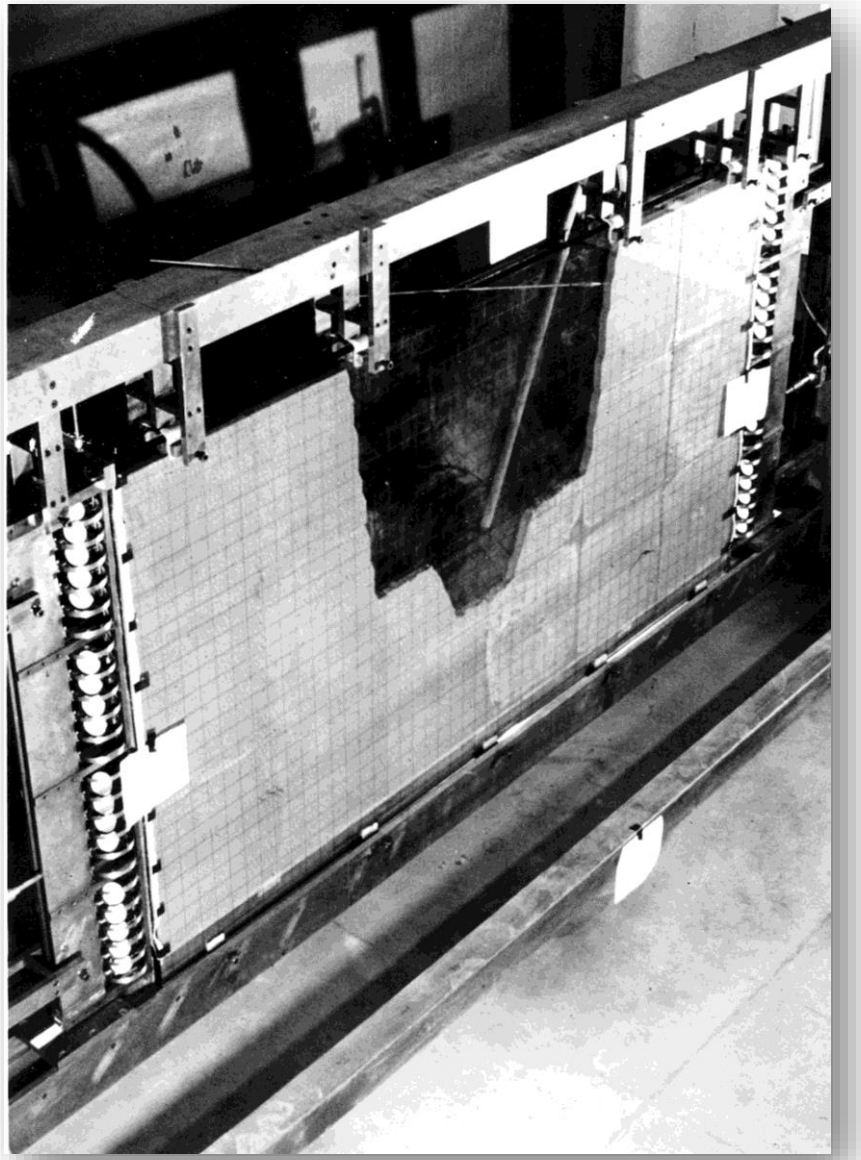
μDEC with rigid blocks 1975

(*Cundall, Voegele and Fairhurst, 1977. US conf. 1975*)

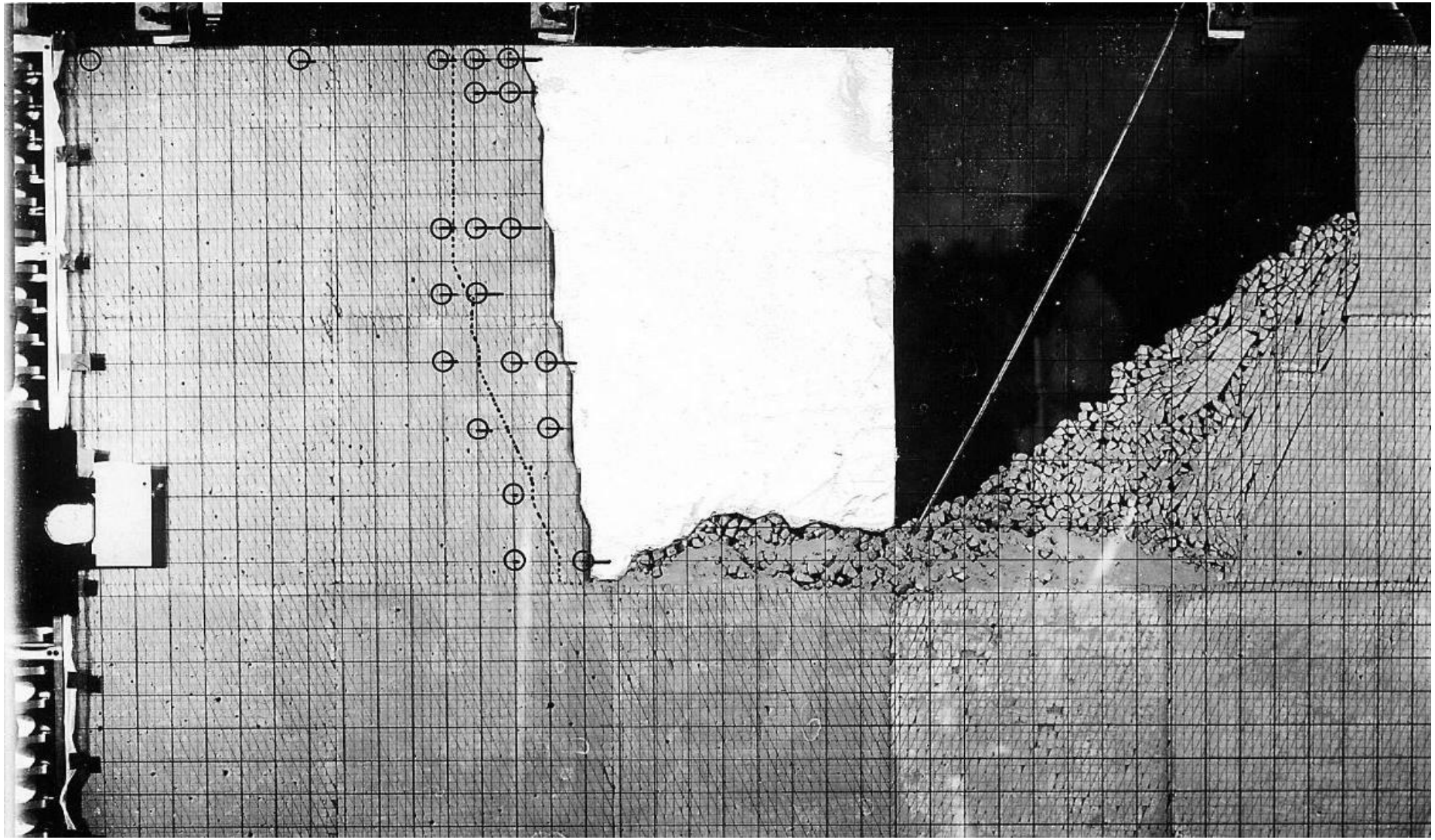
Soon to be followed (in 1980) by UDEC, then UDEC-BB (in 1985)

(Byerlee 'law' μ=0.85 gives 40.2° i.e. not showing enough variability)





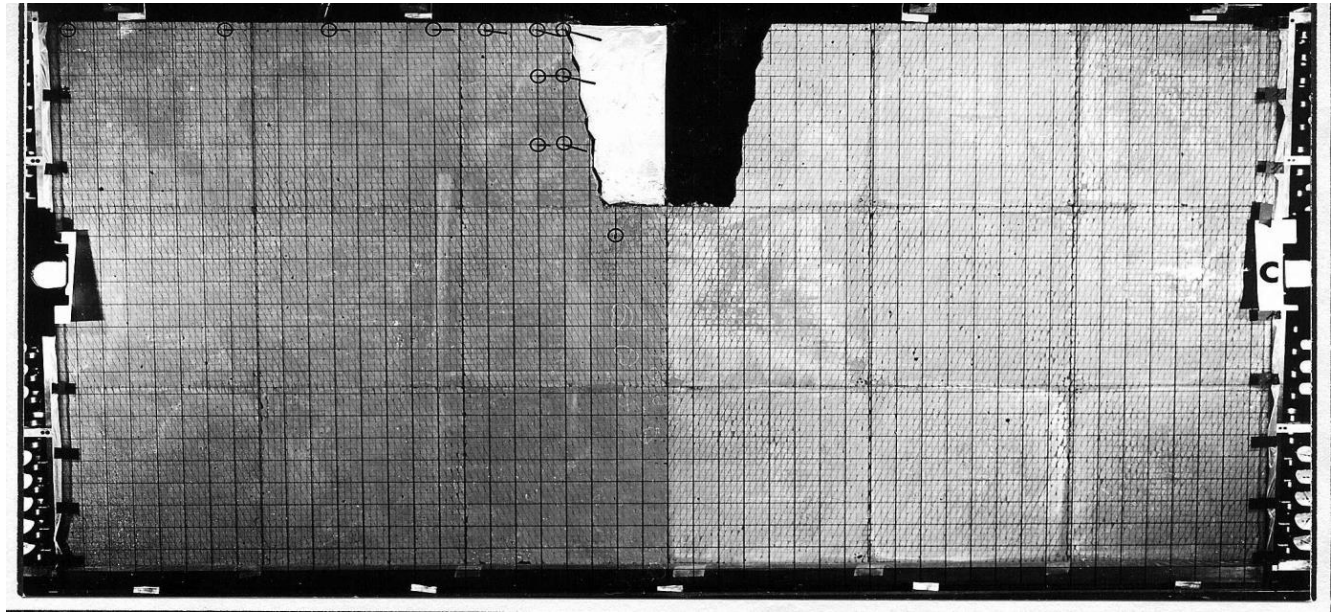
Vertical and horizontal stress cycling to consolidate: gave unexpectedly stable ‘steep excavated rock slopes’ **40,000 blocks, and three ‘joint’ sets**. IC, 1969.



Doctoral thesis problem (1968-1970) 40,000-block tension fracture model ’rock slopes’.

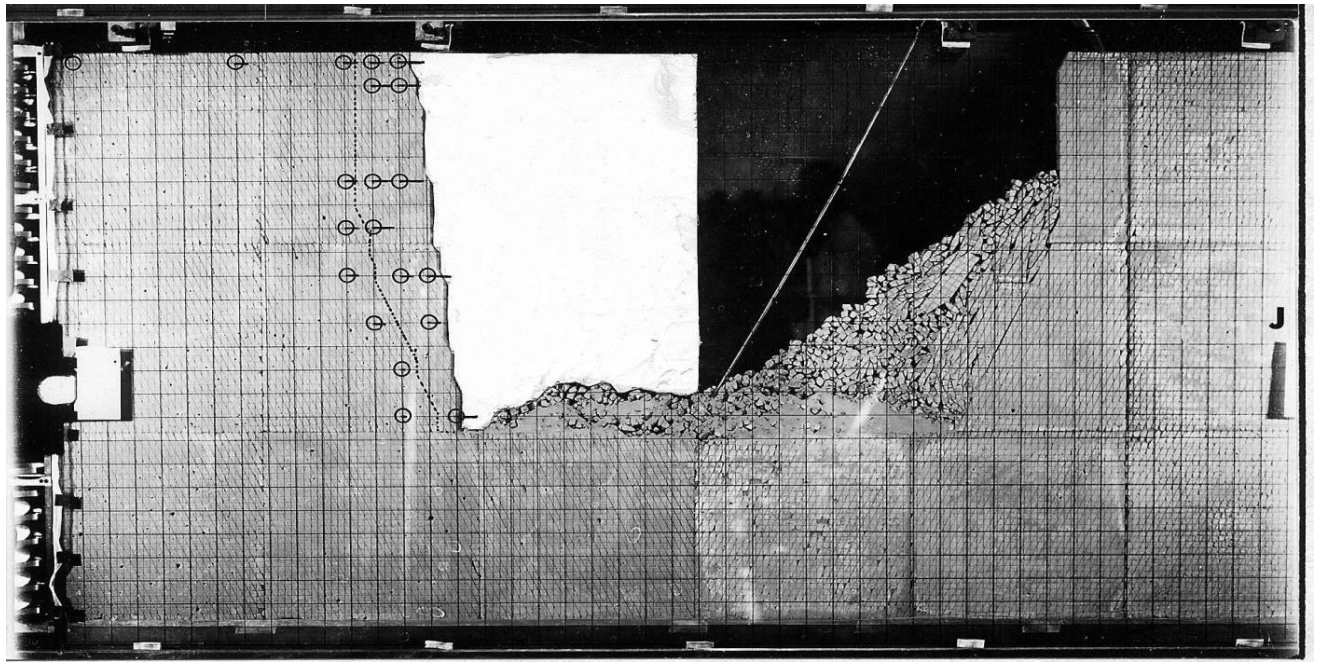
’Steep excavated rock slopes’.....NOT FAILING WHEN EXPECTED!!

Reason: Mechanical ***over-closure*** due to higher original normal stress prior to slope excavation.



Model M2: medium horizontal stress

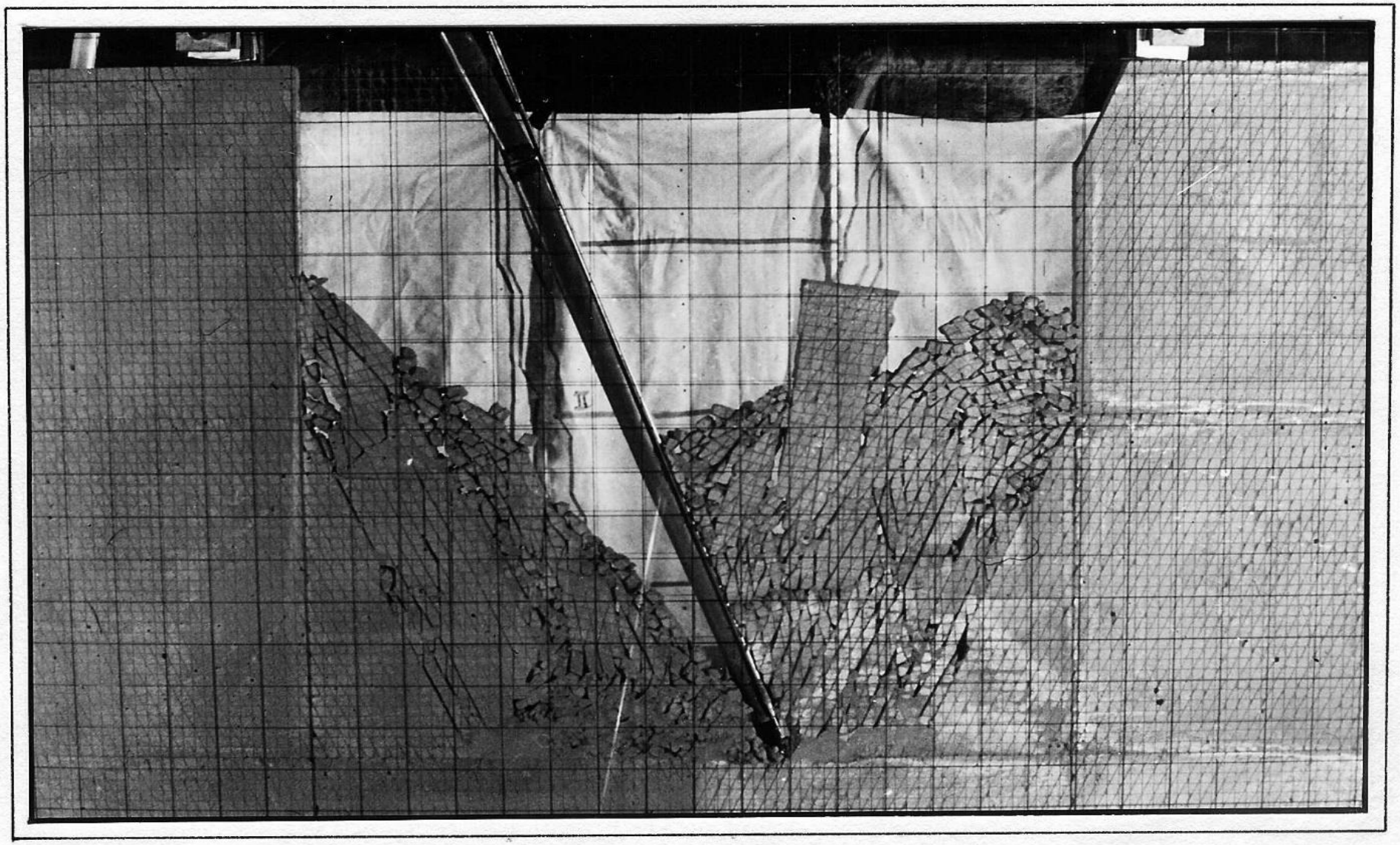
(Shows some logic in the ***downward direction*** of deformation vectors, prior to slope failure)



Model M3: high horizontal stress

(Shows 'no logic': behaviour is partially elastic, with no downwards component)

(40,000 blocks in each model)



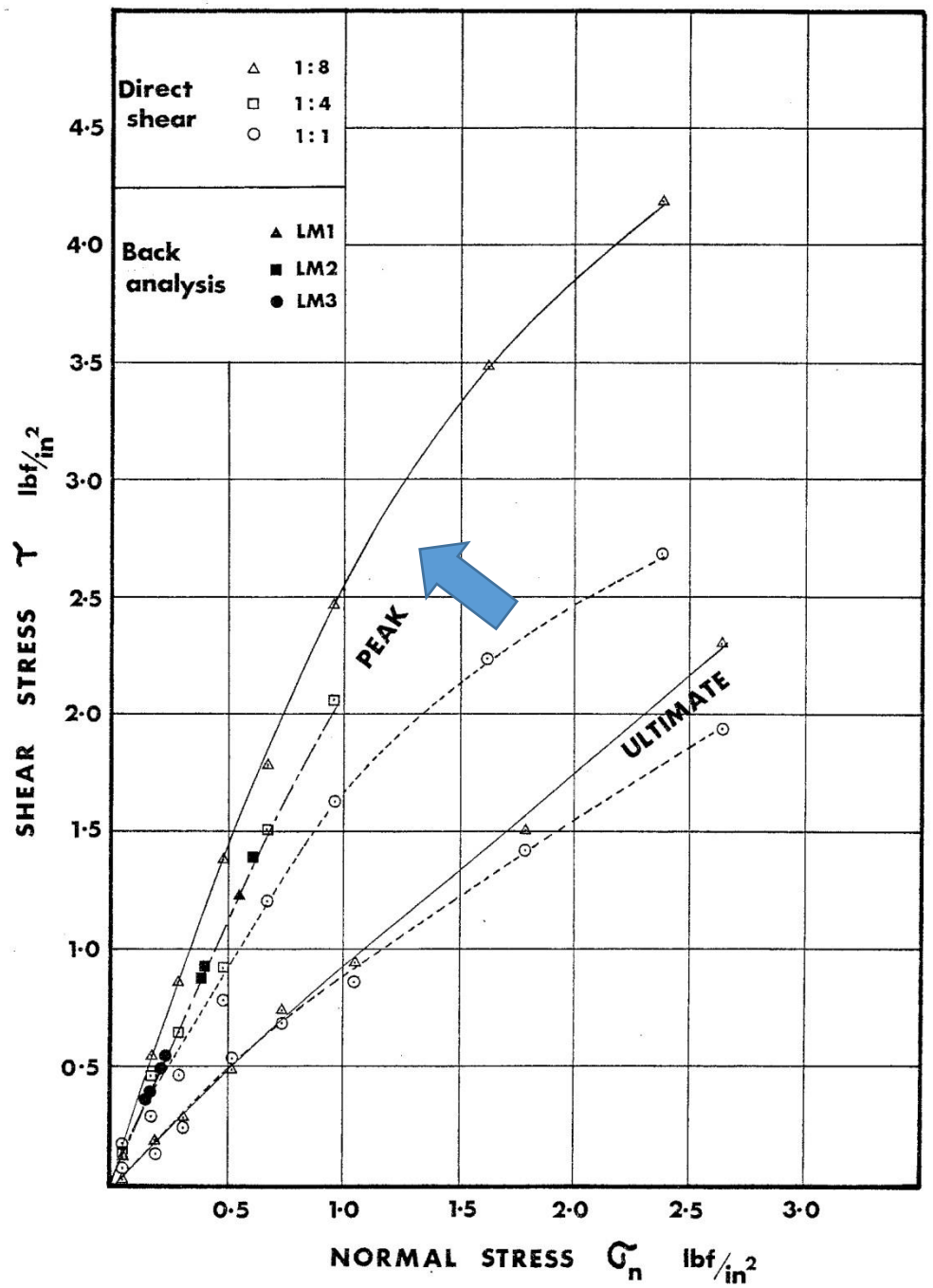
Note 'intact' multi-fractured blocks, due to Mechanical *over-closure*

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

- *Conventional* means normal stress σ_n application of the same magnitude as that acting beneath the slope (when slope already exists)

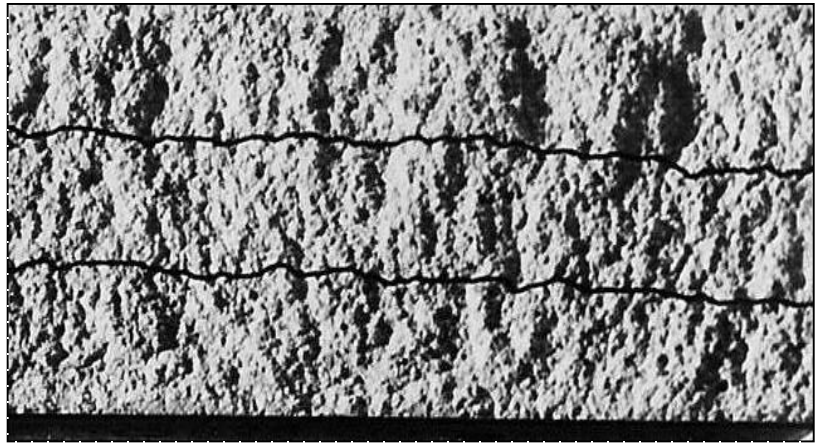
- What about the normal stress level acting ***before*** the slopes were constructed?

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



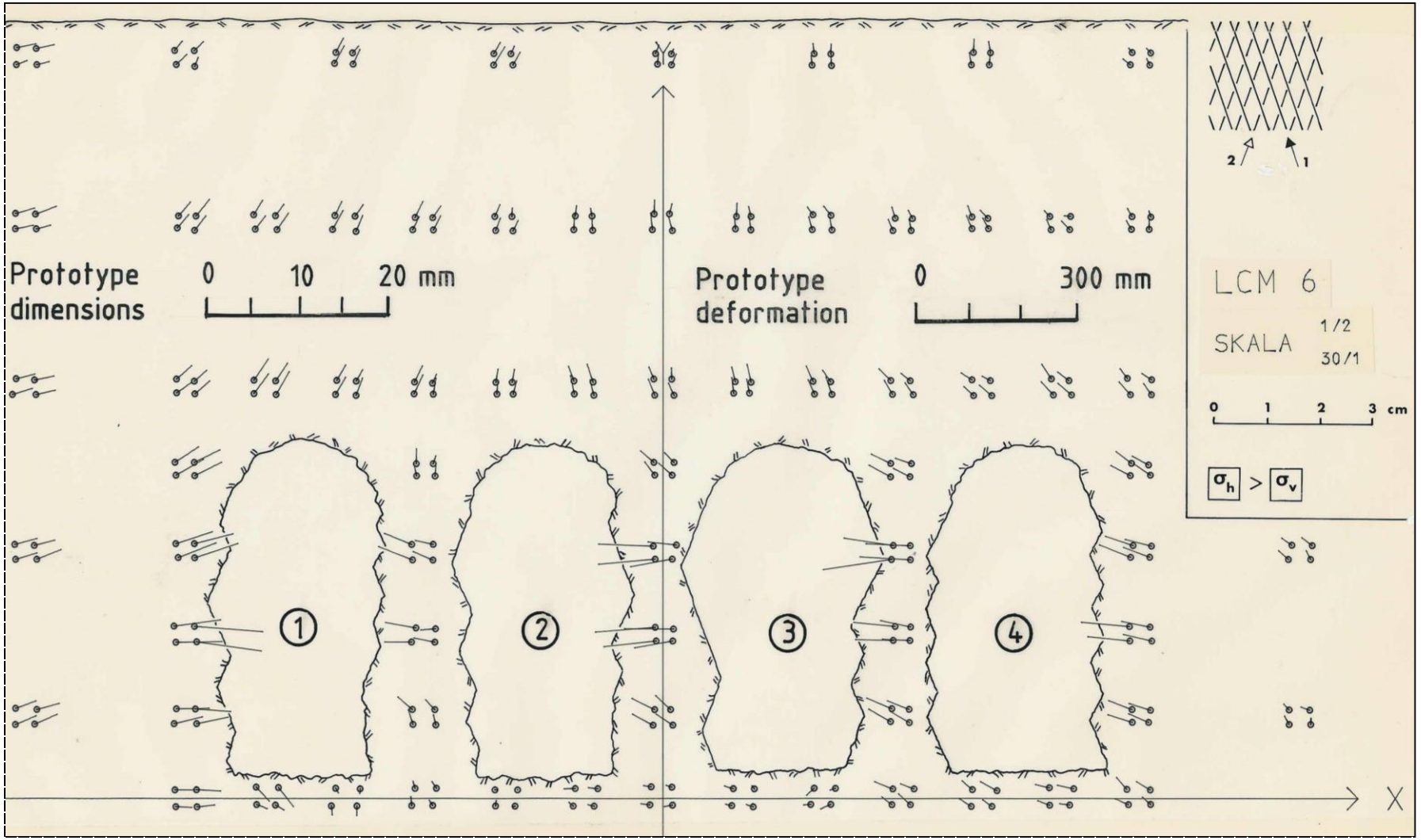
Conventional (1:1) and pre-closed, therefore *'over-closed' 4:1 and 8:1* direct shear tests.

(Barton, 1971)



Rock bridges of course.

Perhaps also *over-closed* where jointed ???



20,000-block models of 'rock caverns'.

(Barton and Hansteen, 1979)

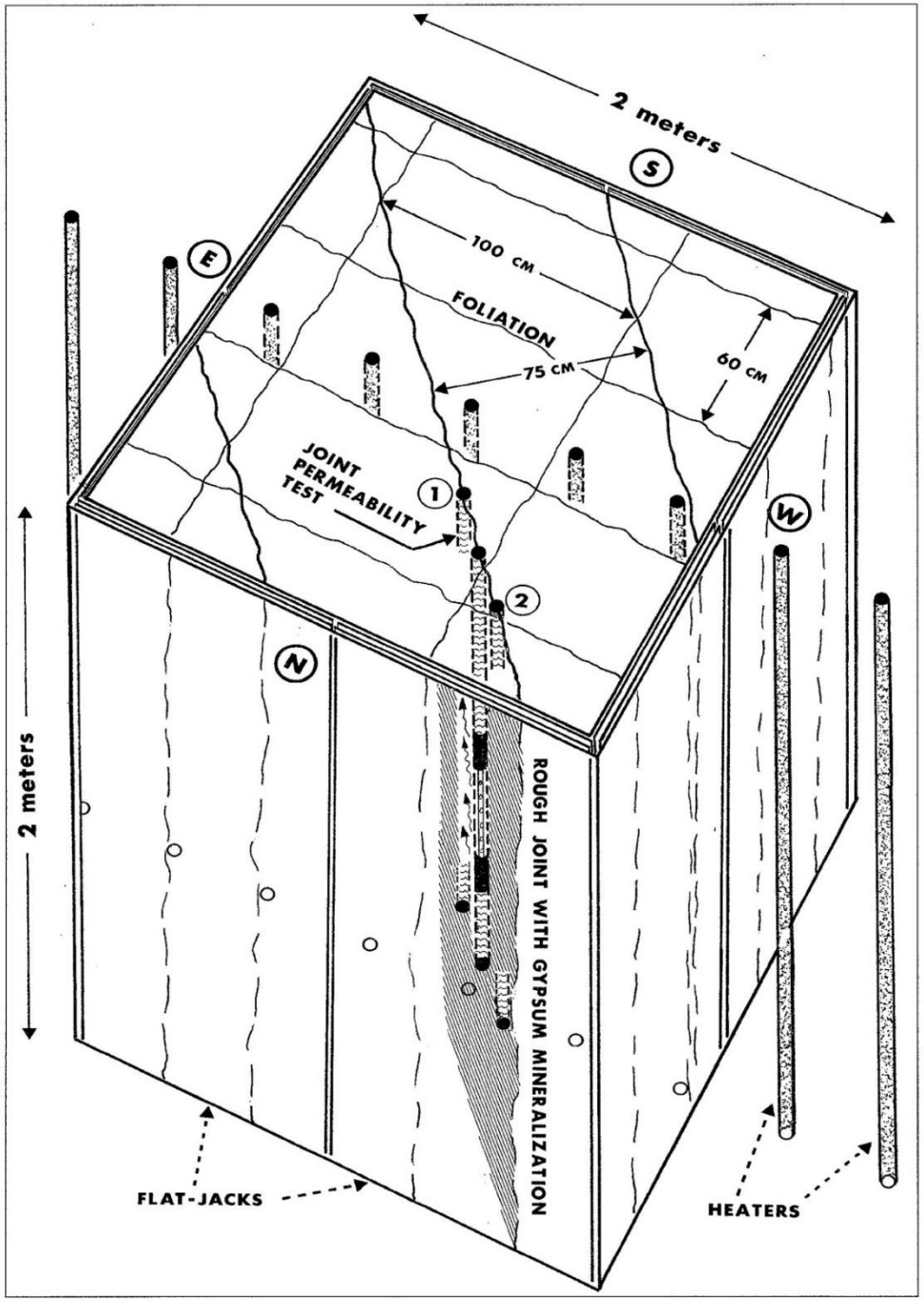
Extreme hysteresis (= ***over-closure***) was again experienced

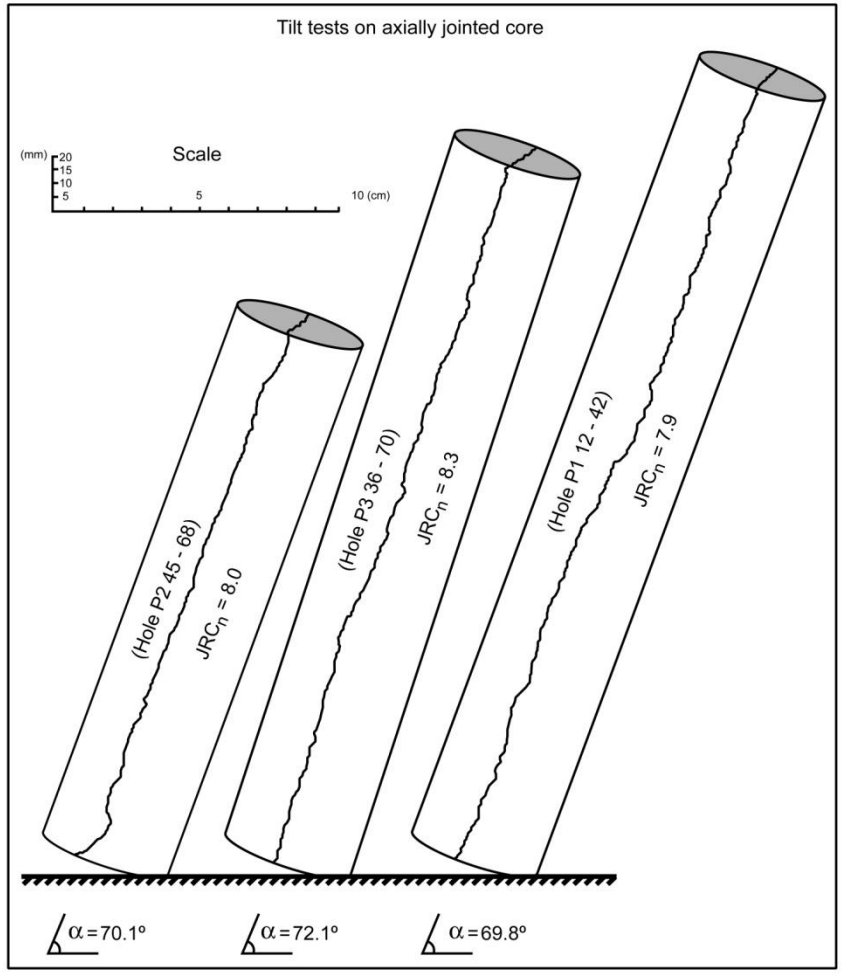
(DEFORMATIONS DIRECTED ONLY TOWARDS THE LAST EXCAVATION)

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

MANY EXAMPLES OF THERMAL OVER-CLOSURE

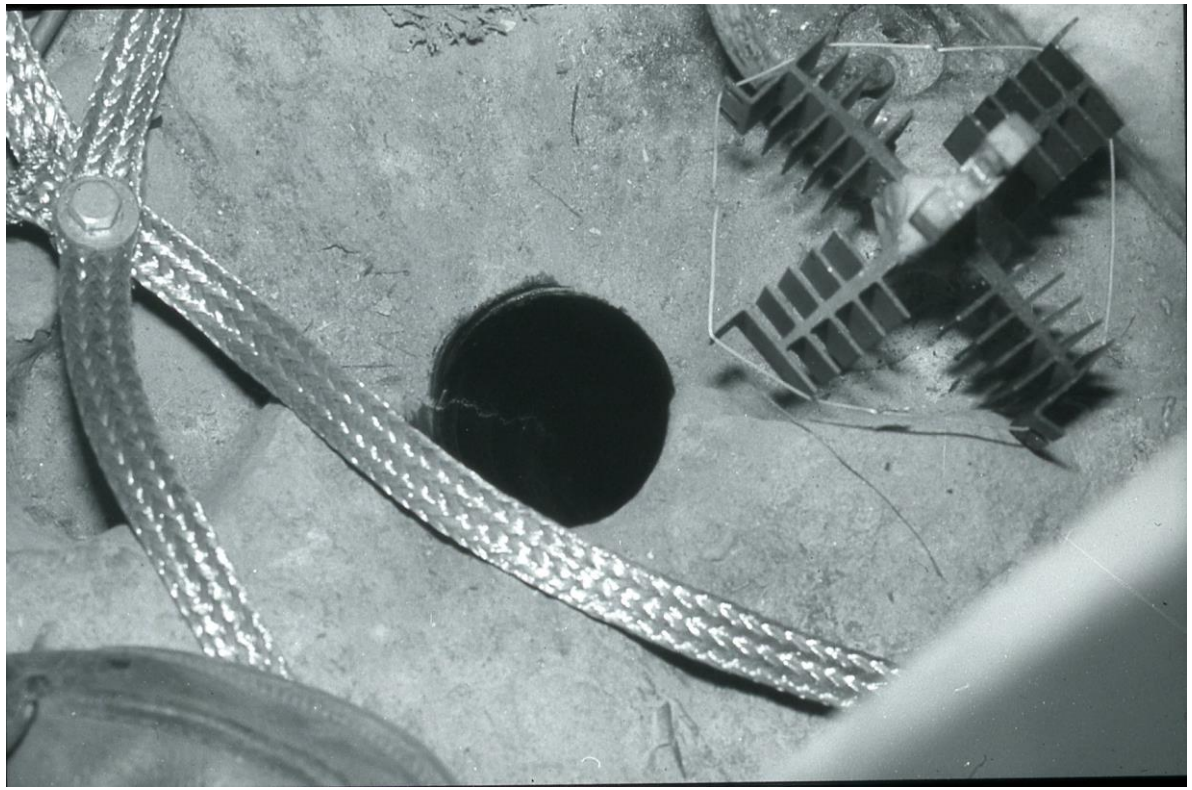
First a summary of effects of TOC, then some figures, then some brief project summaries



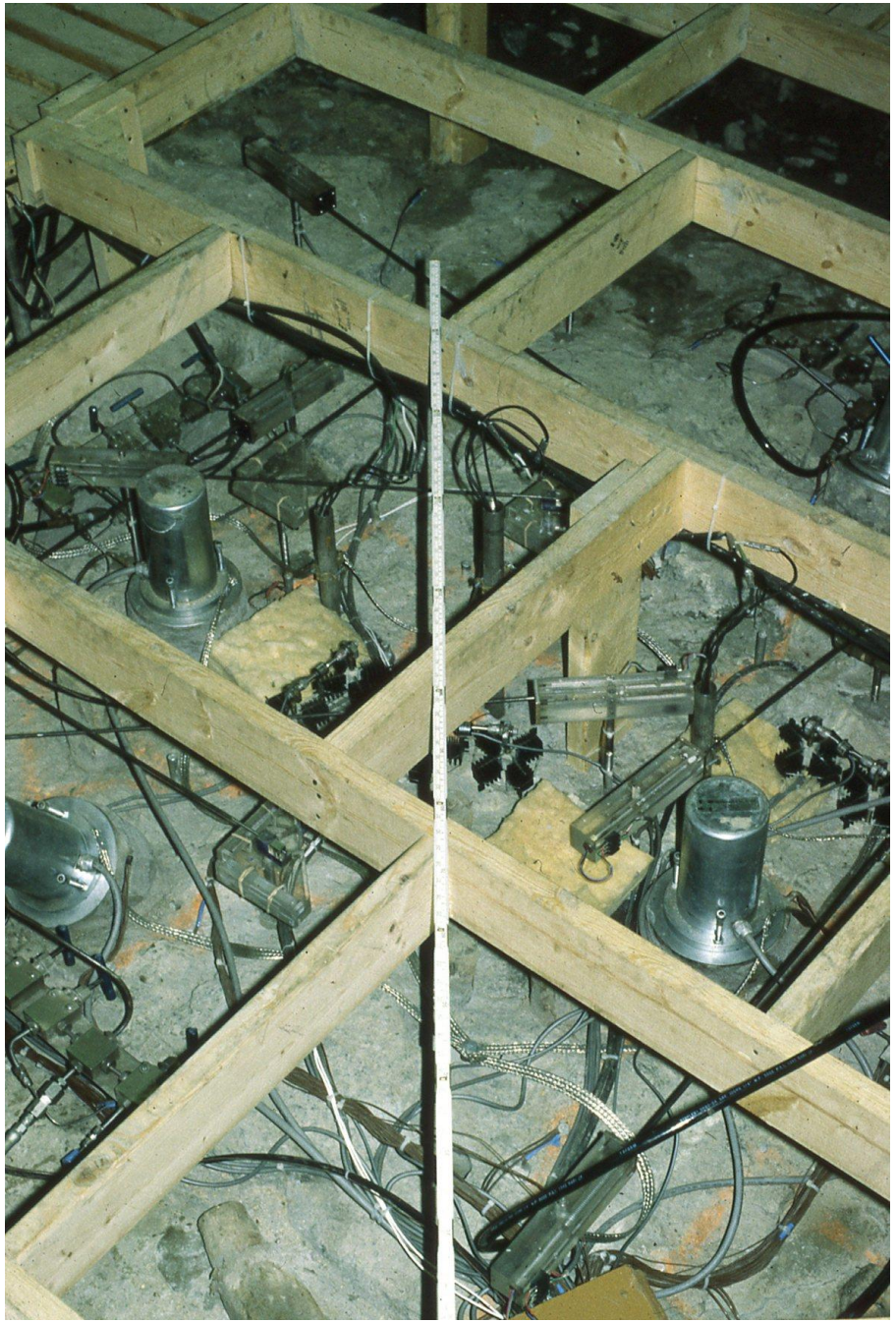


TerraTek/CSM Heated Block Test

Hardin et al. 1981, Barton, 1982



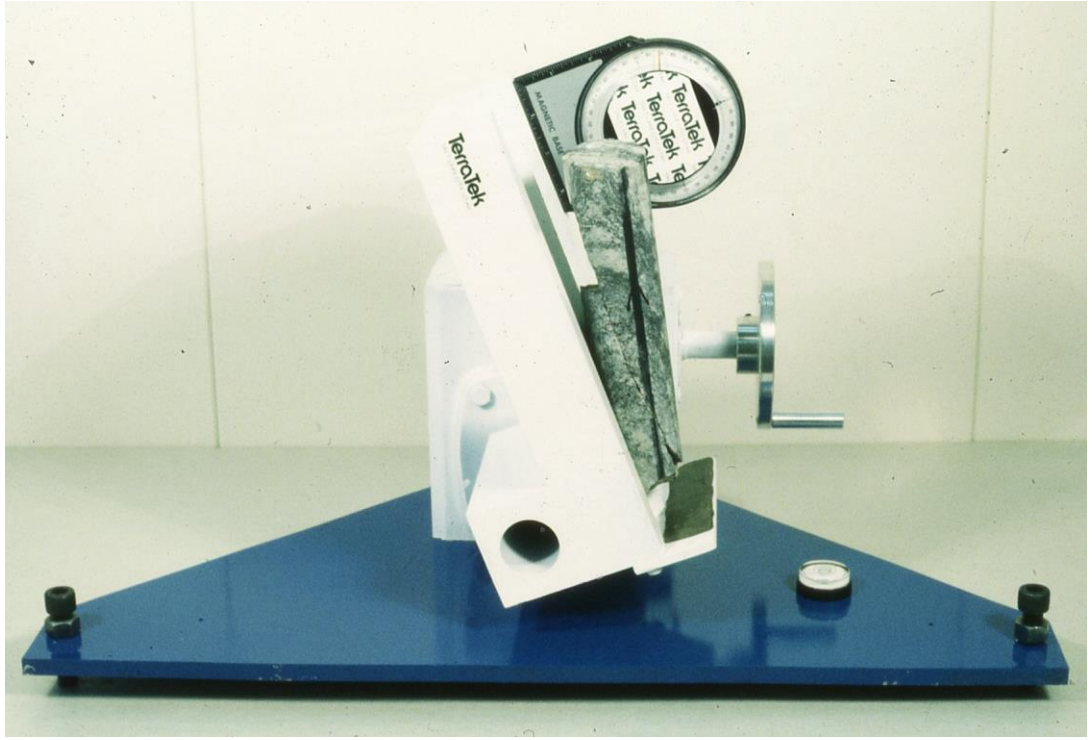
Permeability test, diagonal joint

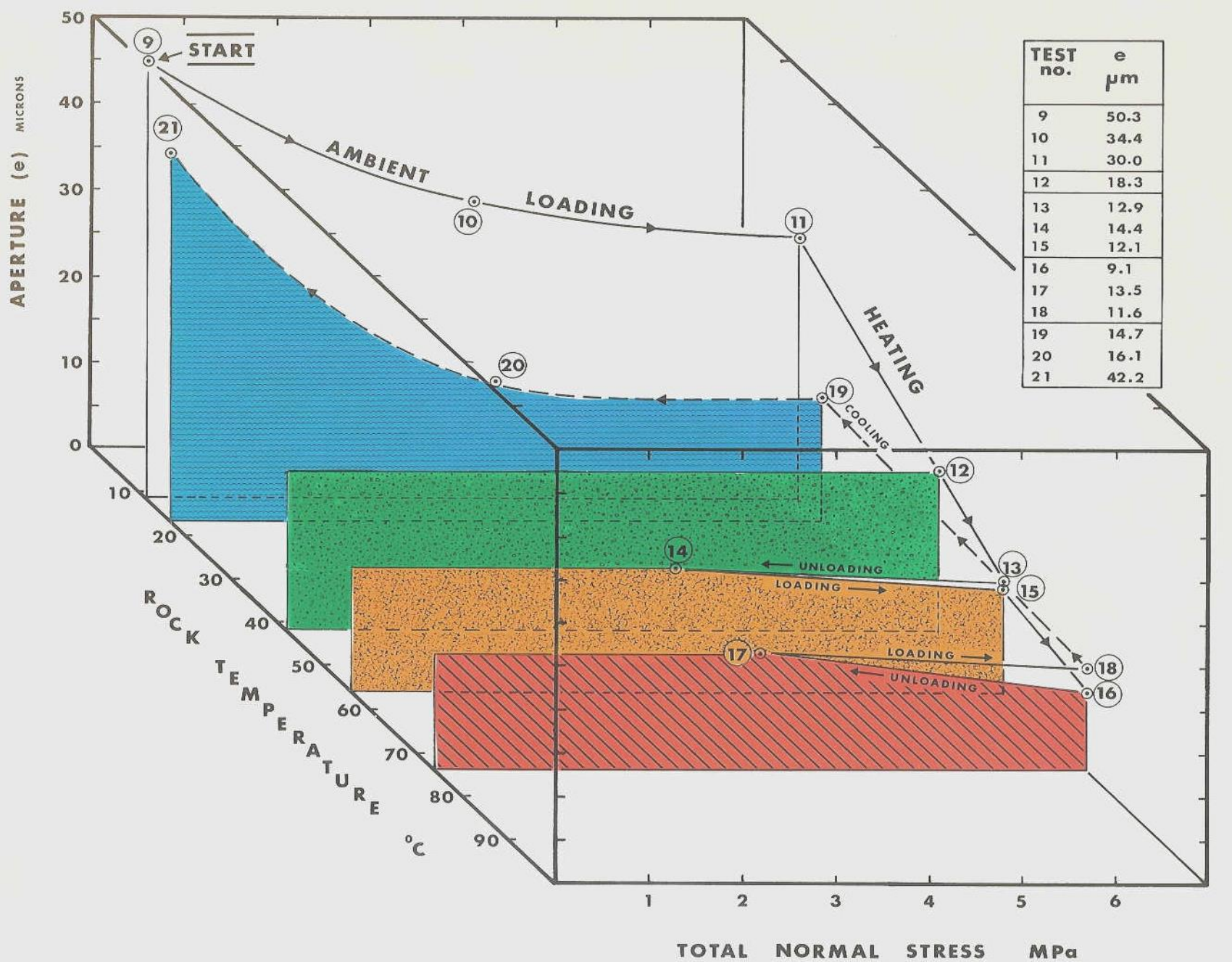


ONWI HEATED BLOCK TEST INSTRUMENTATION

(partial view: 8% of volume was boreholes).

Tilt tests for JRC_0 of permeability-test cores.

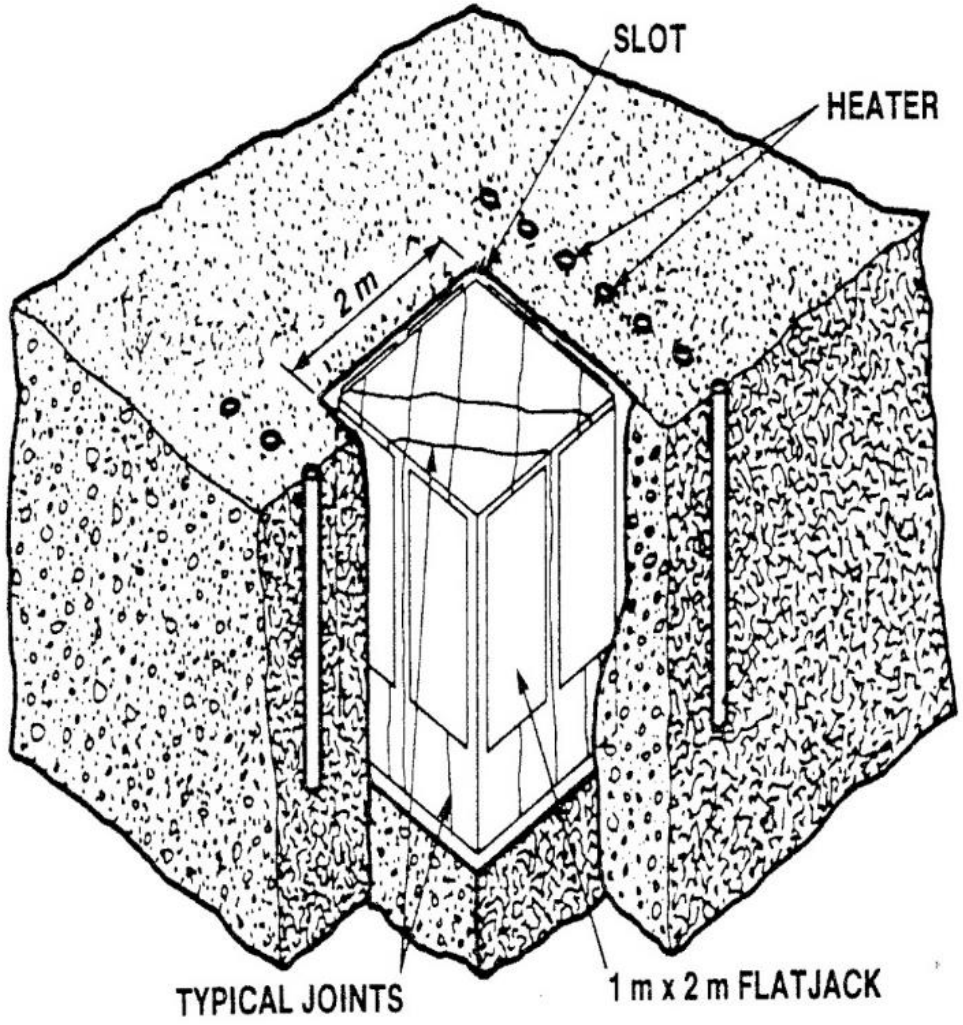


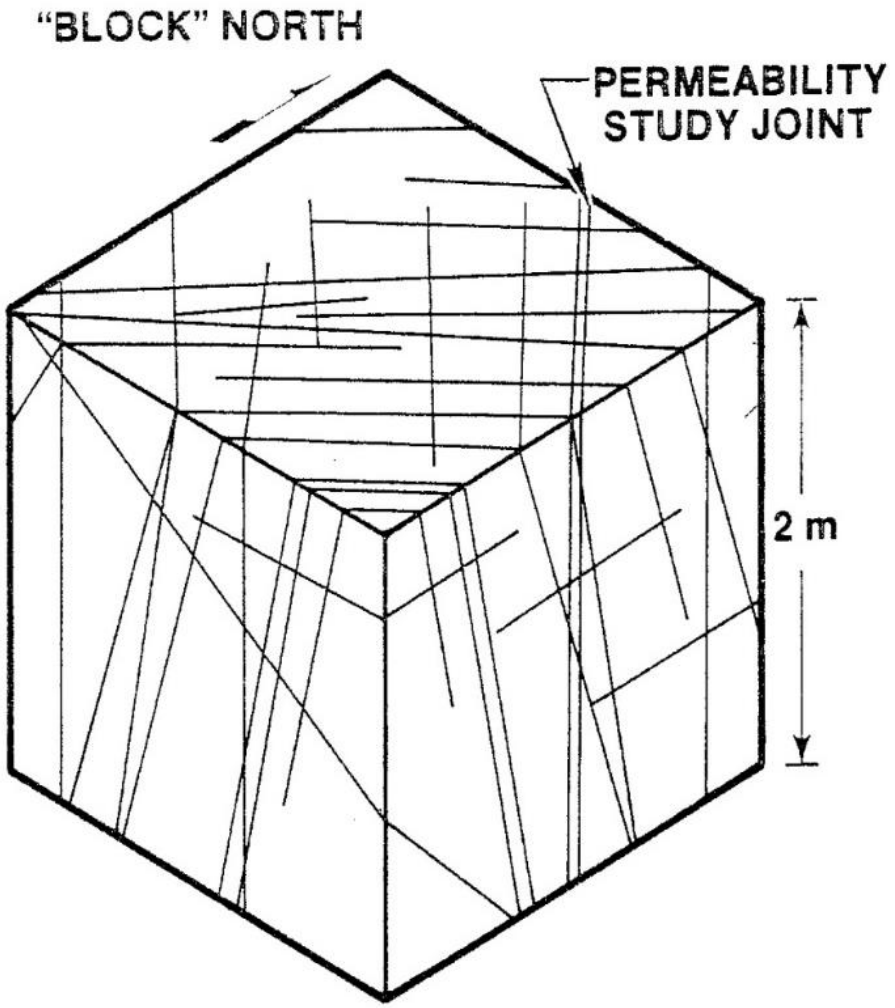


Note conducting aperture **reduction with temperature alone**

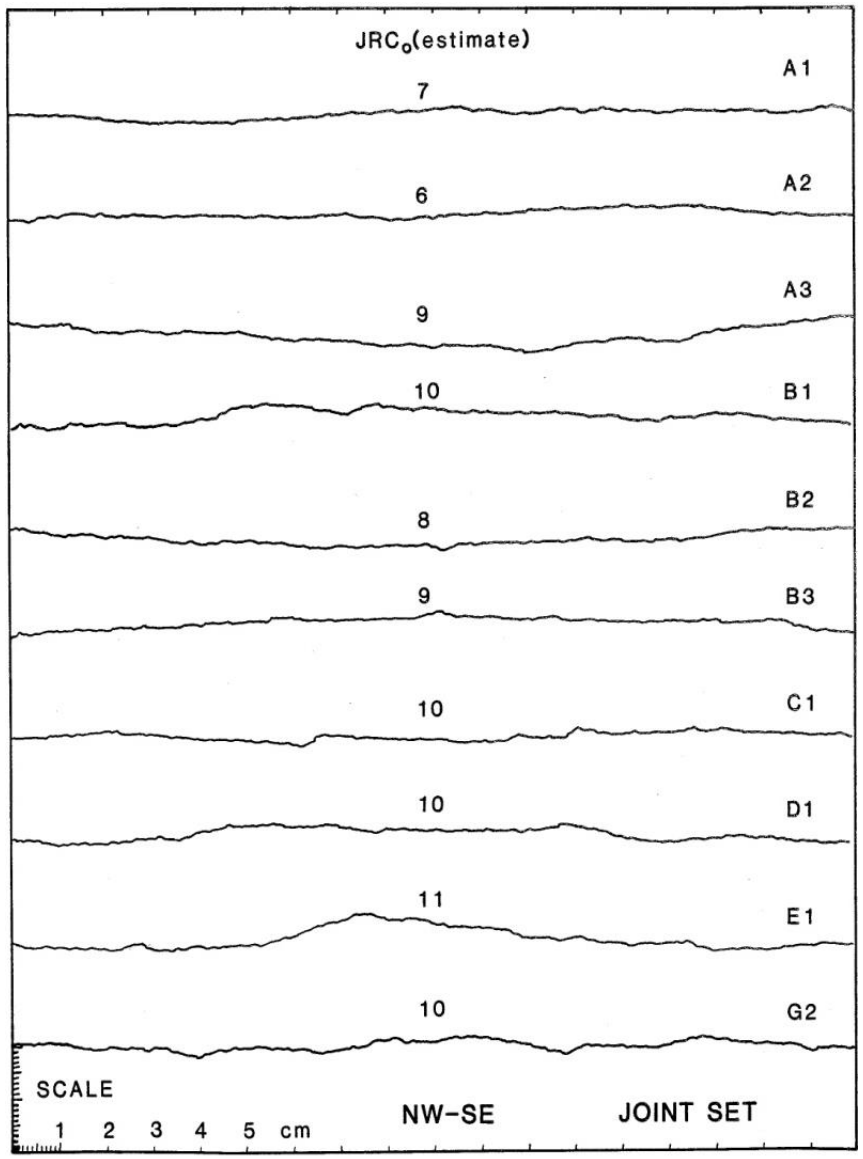
(near-maintenance of aperture (at first)when unloaded or cooled)

G-tunnel (NTS) HMT block test (SAIC, for Sandia). *(Hydraulic apertures reduced due to heating: 60µm to 35µm).* Zimmerman et al. 1986.





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



ONE MAY *ONLY* NEED TEMPERATURE RISE FOR THE *O-C* EFFECT TO OCCUR (note: controlled flat-jack pressures during heating)

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

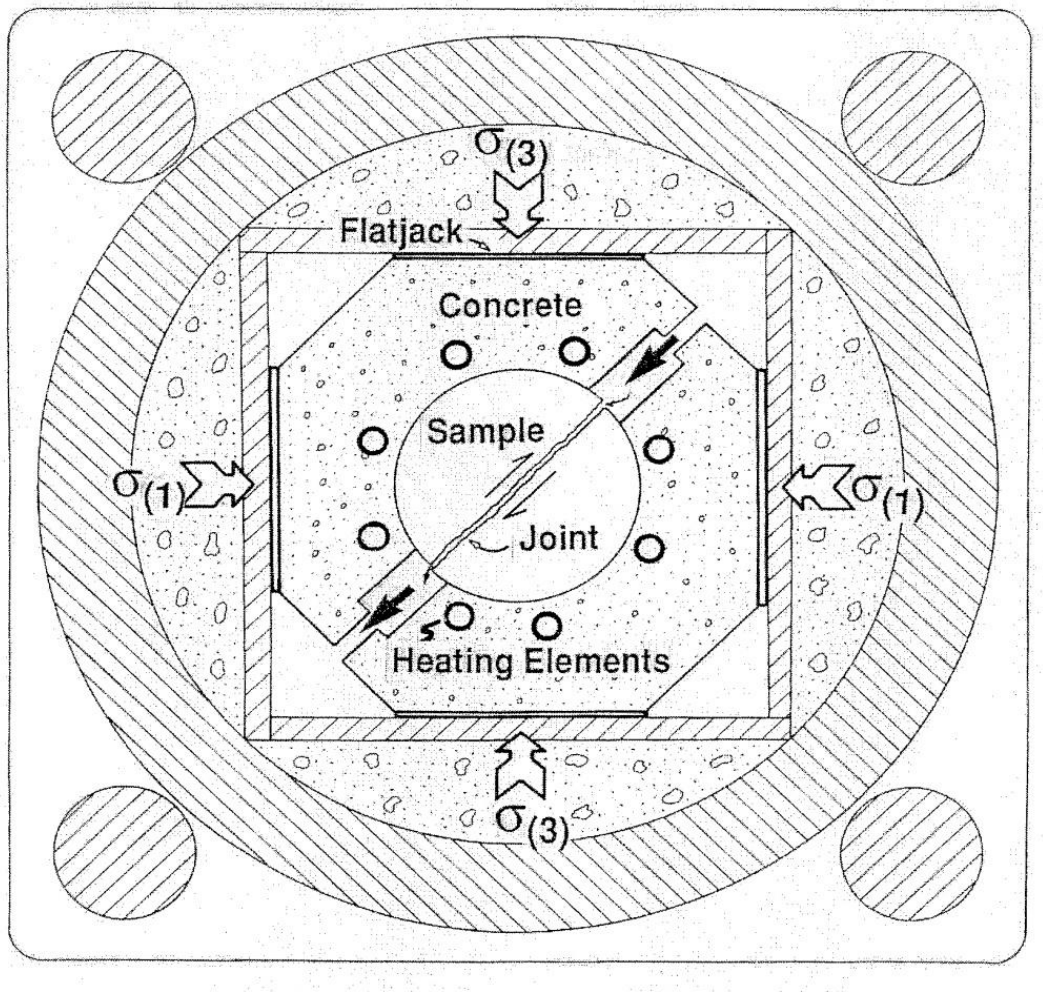
- Why better fit?...Anisotropic thermal expansion/contraction of constituent minerals in opposing joint walls....*the joint's memory of warmer conditions at it's birth*?... a primeval 'finger-print' (joint-print) of 3D-roughness.

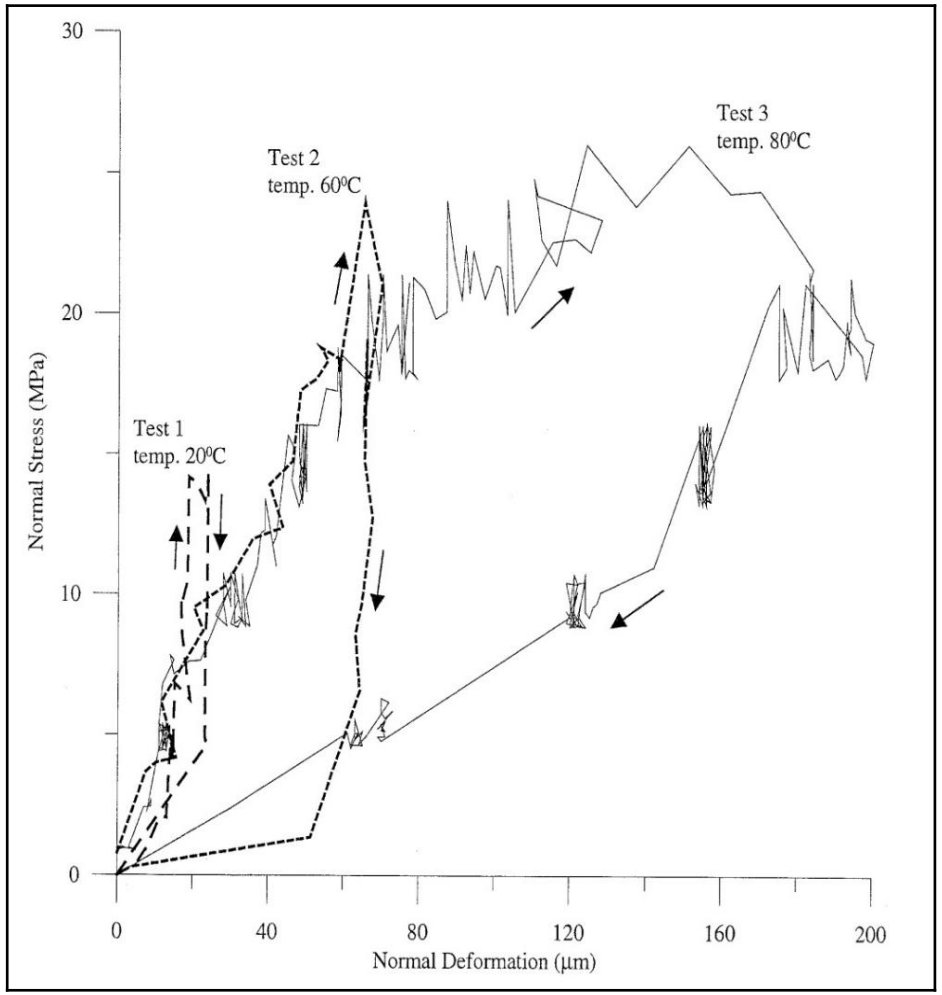
- The *3D roughness finger-print* in 'today's laboratory environment' though very recognizable, would be subtly altered in its finer details by today's cooler conditions.

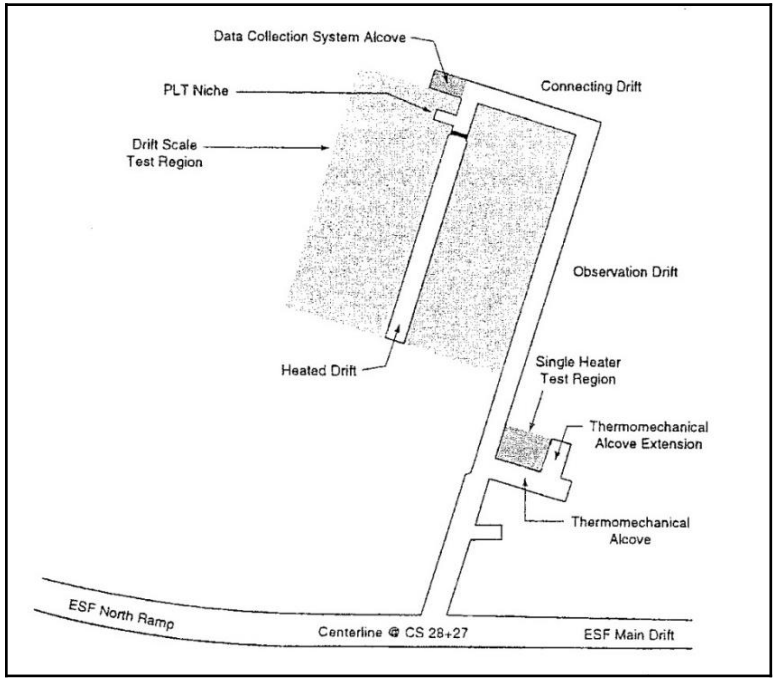
- **(So: Need 3D laser scans when joints are 'hot' ? Need tilt tests when joints are 'hot'?)**

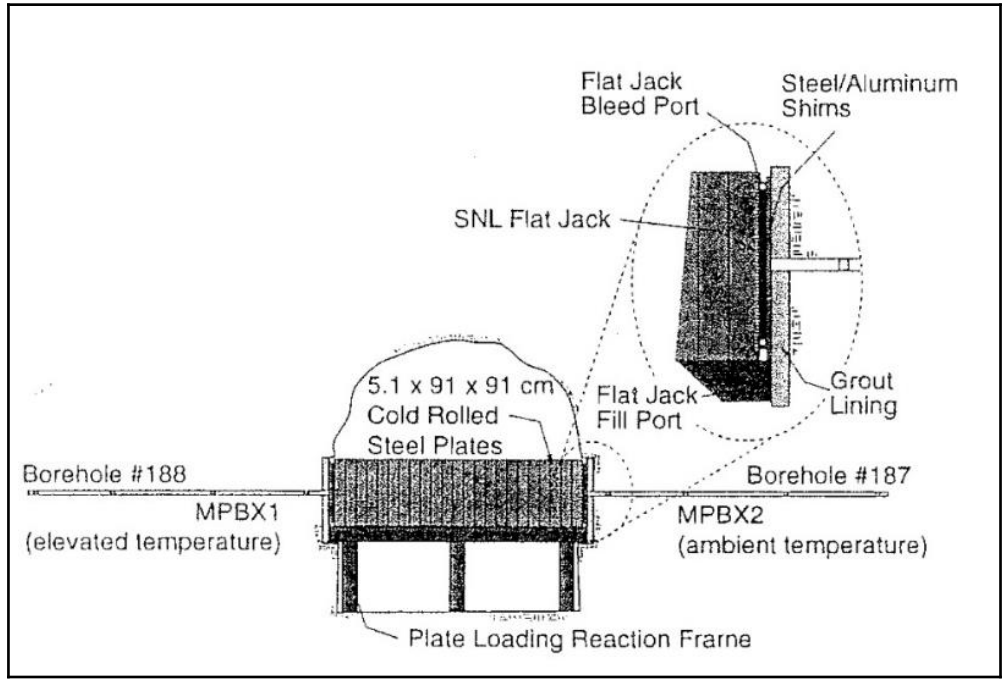
Three tests on joints in granite from AECL Manitoba URL in Canada, loaded to 14, 19 and 26 MPa in NGI's CSFT apparatus (Makurat, 1985, 1989)

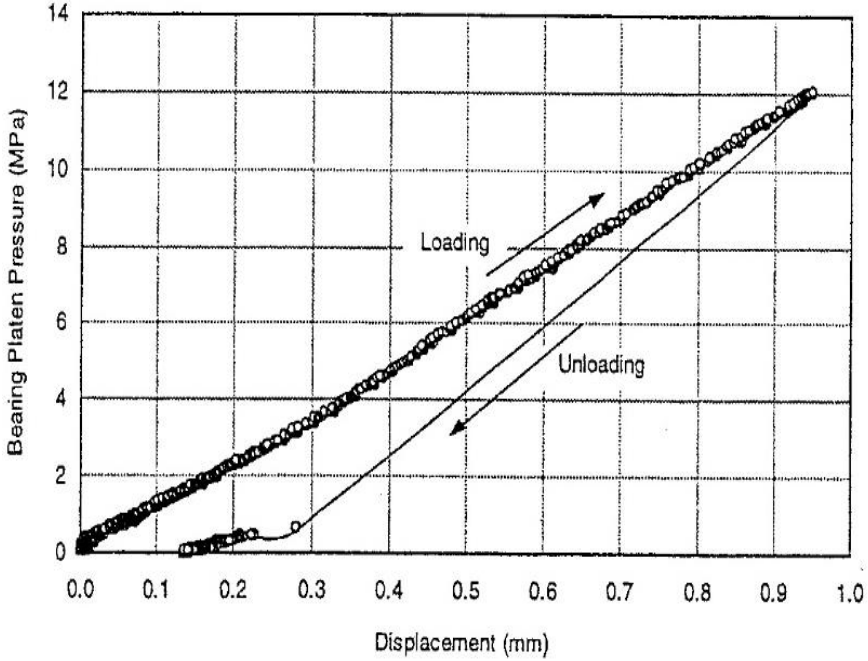
On the 4th load cycle of each test, joint closures (ΔE) = 24µm, 54µm and 151µm recorded at 20ºC, 60ºC and 80ºC (i.e. increases out of proportion to stress increases….when stiffening)

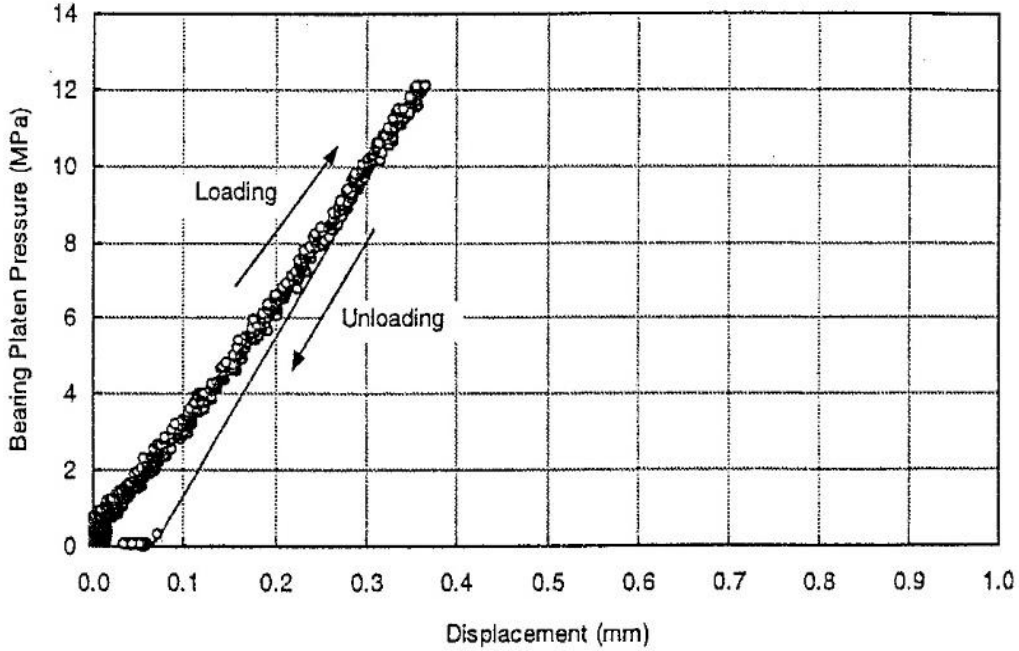












YUCCA MOUNTAIN ESF plate-load test.

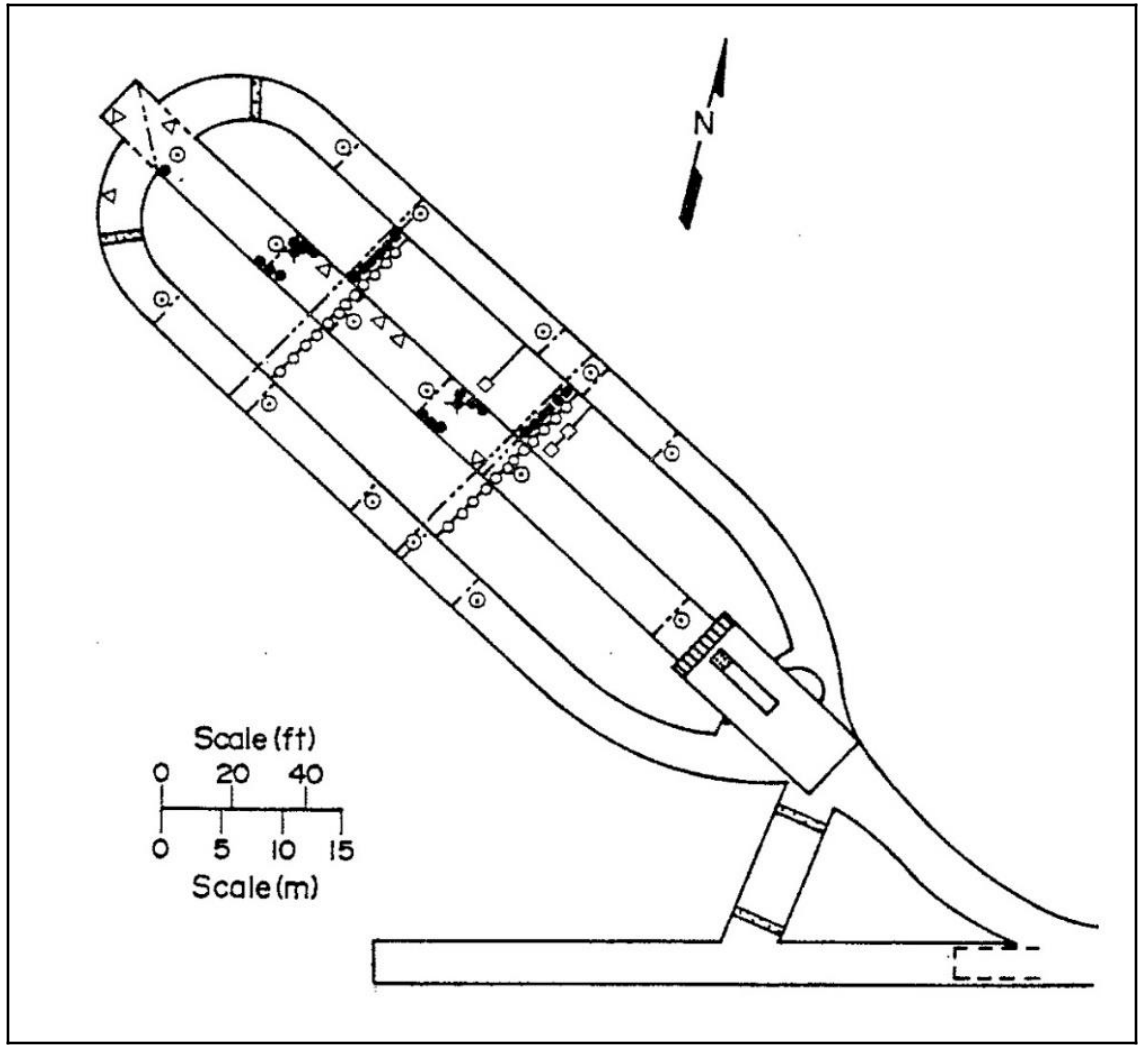
E_{mass} (ambient) = 11.4 GPa,

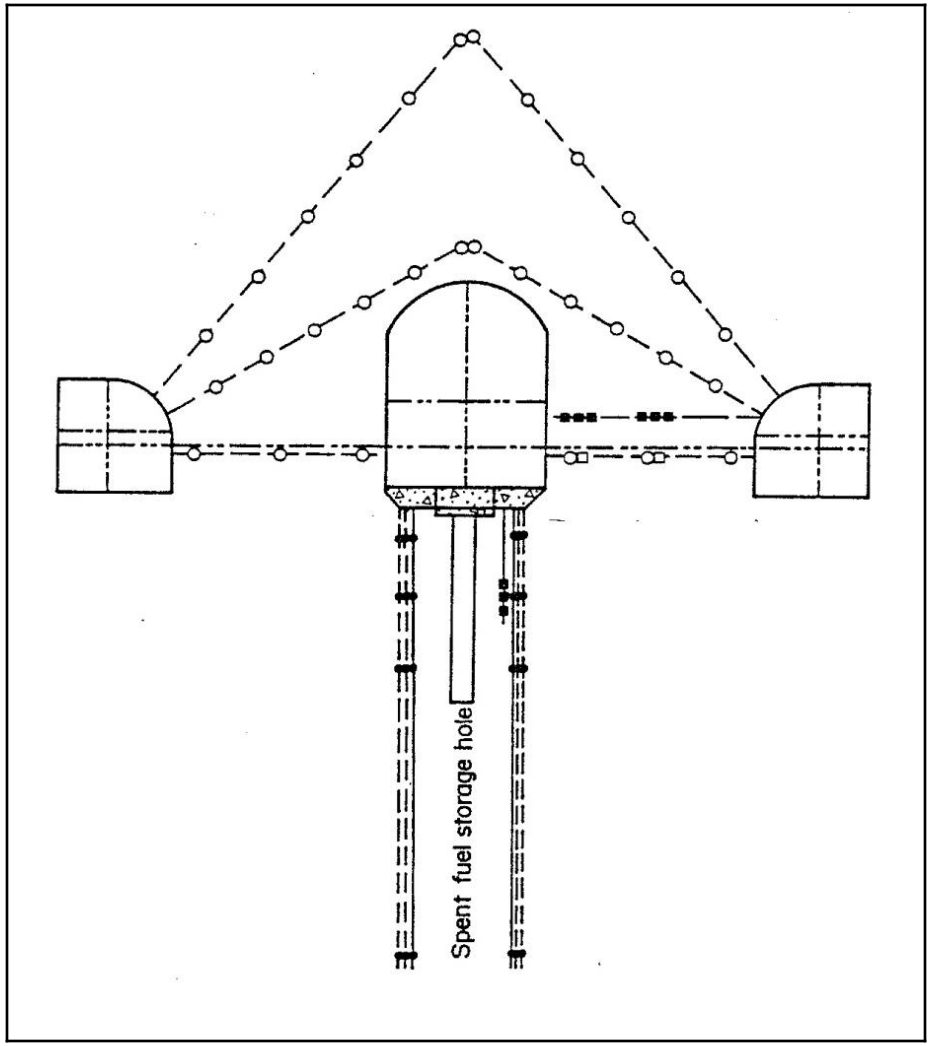
E_{mass} (heated) = 24.5 GPa

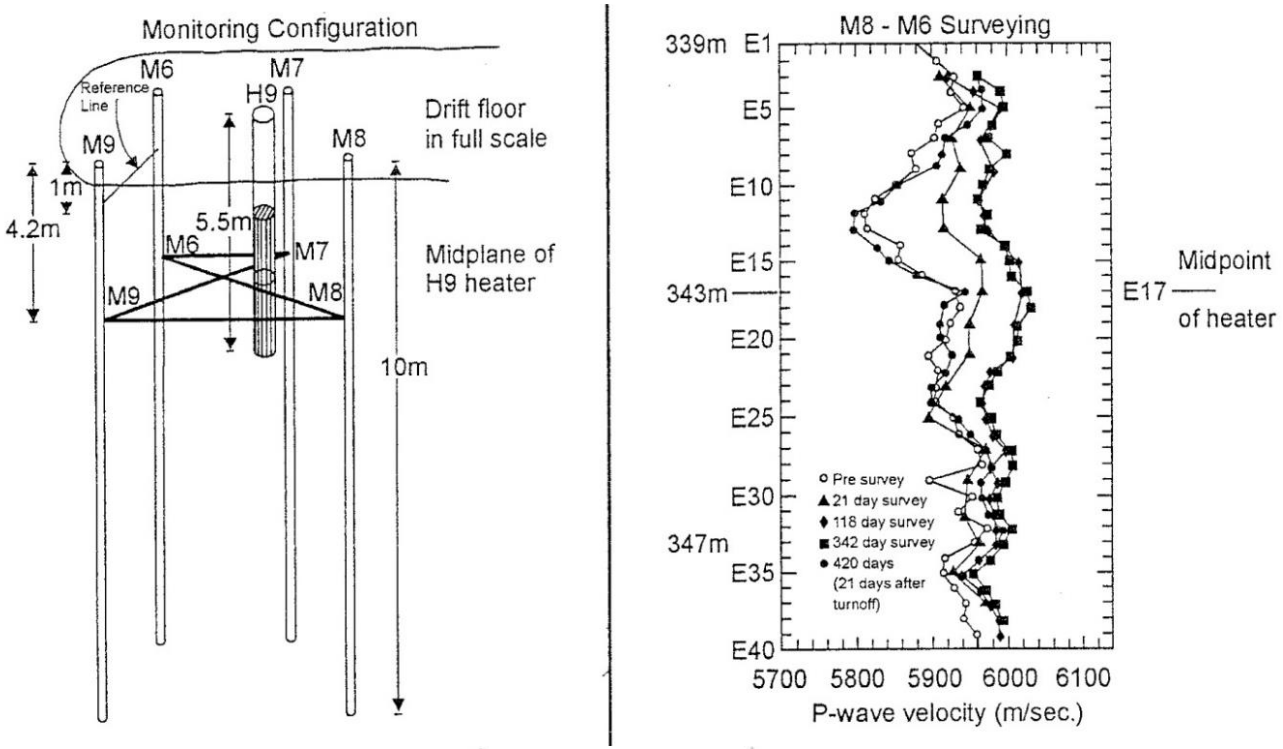
(George et al. 1999)

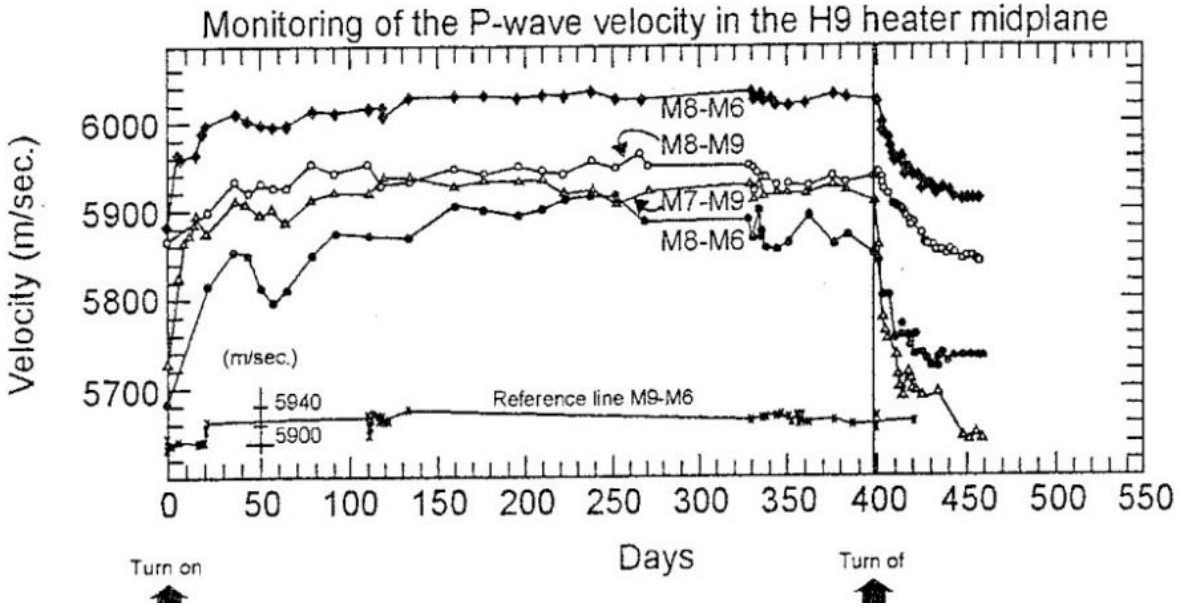
CLIMAX MINE (quartz monzonite) HEATED MINE-BY at 400 m depth, as part of the late 1970's SPENT FUEL TEST (Yow and Wilder, 1993)

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







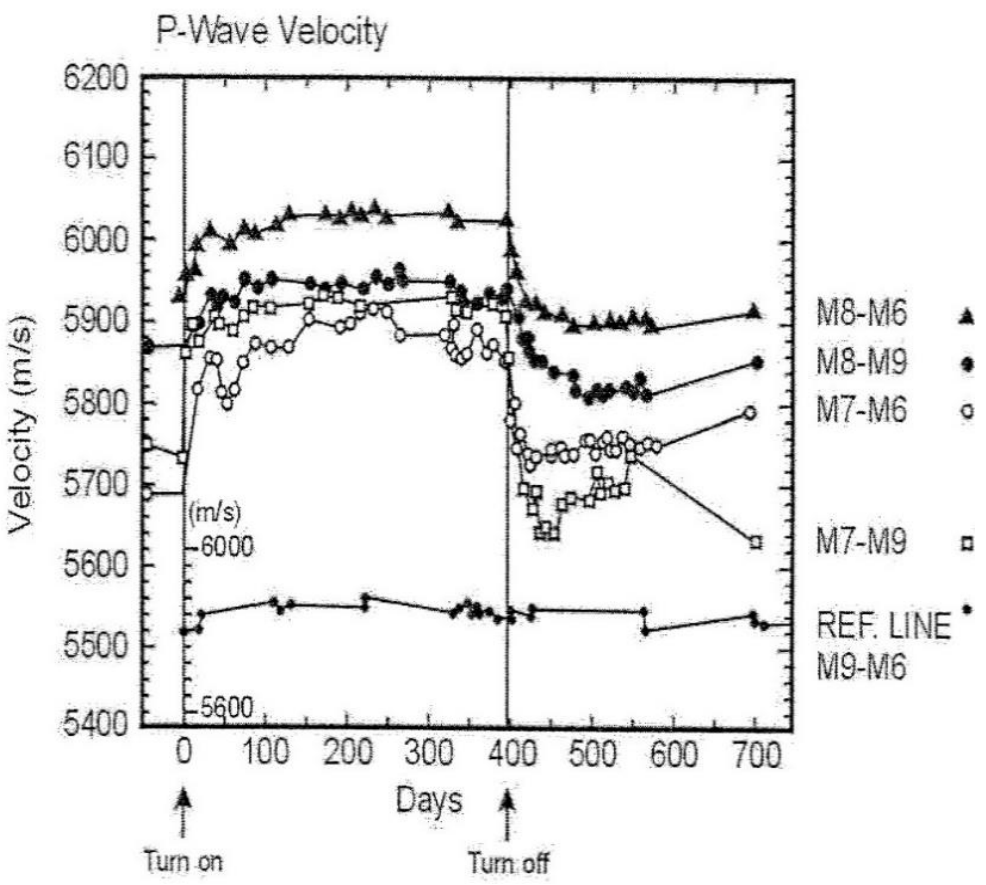


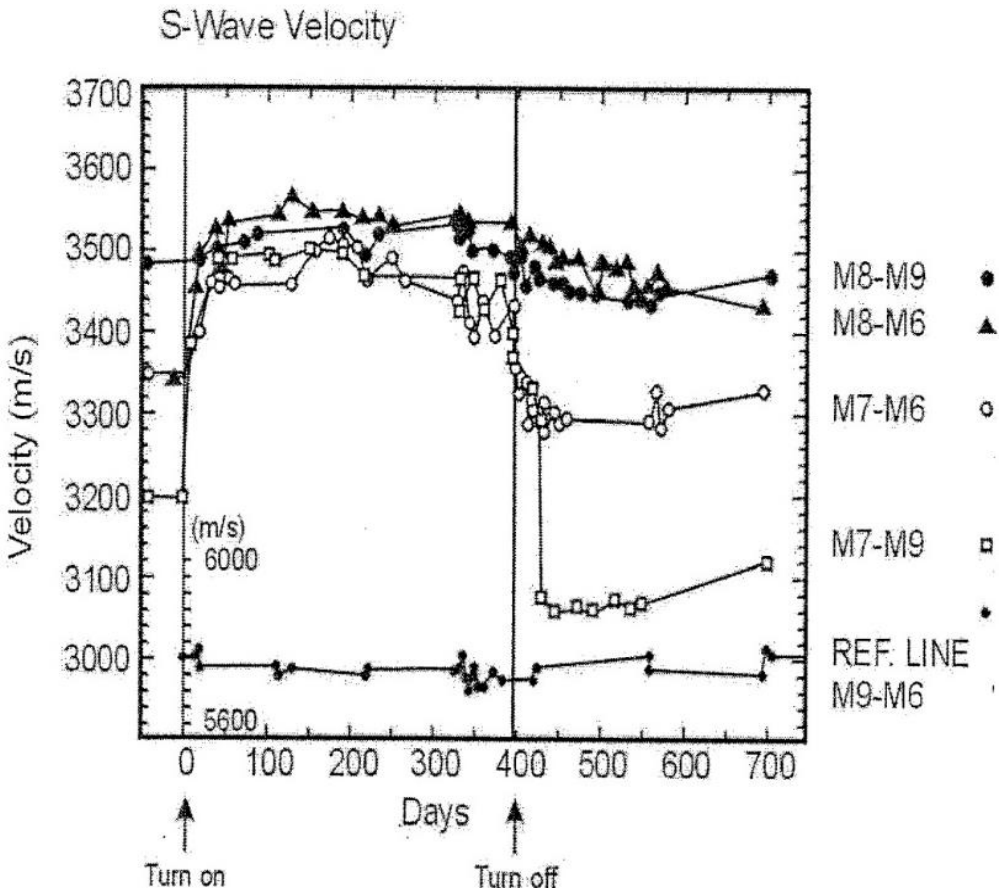
BOREHOLE HEATER TEST AT STRIPA

1st 400 days heating

(monotored by cross-hole seismic)

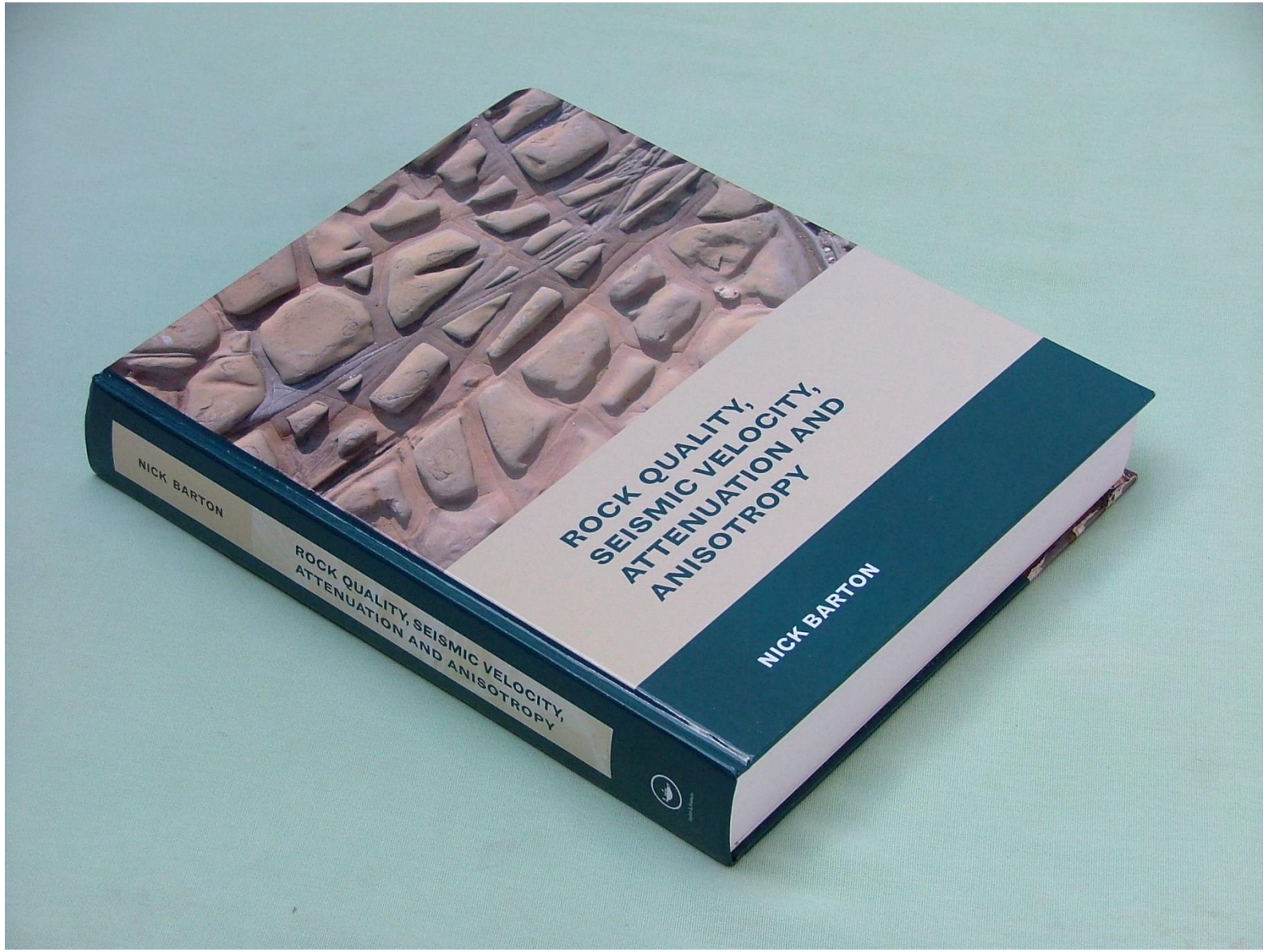
Paulsson and King, 1980





STRIPA BOREHOLE HEATER TEST.....0 to 750 days, 300 days cooling
(monitoring with cross-hole Vp and Vs : (Poulsson et al., 1985)

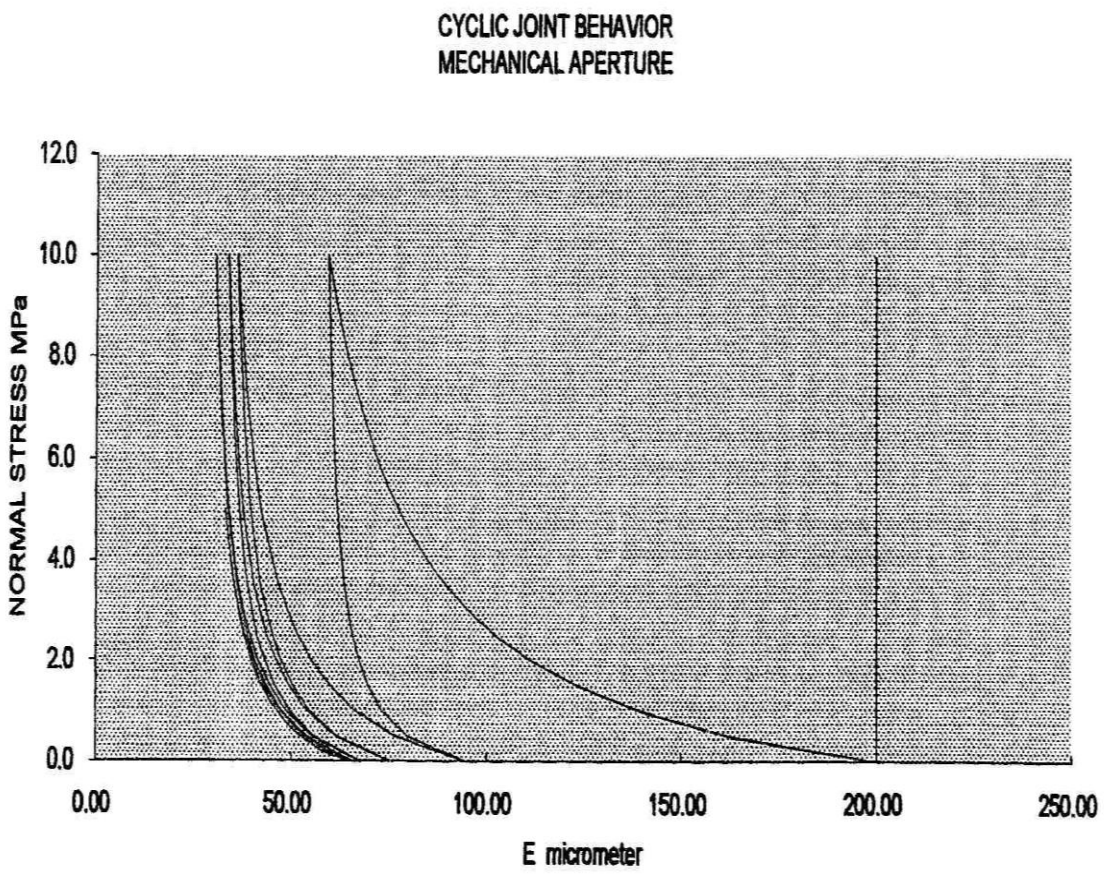
Note lower velocities at end of cooling (M7-M9, M7-M6) .....
joint opening somewhere??....rough ones *thermally over-closed*??

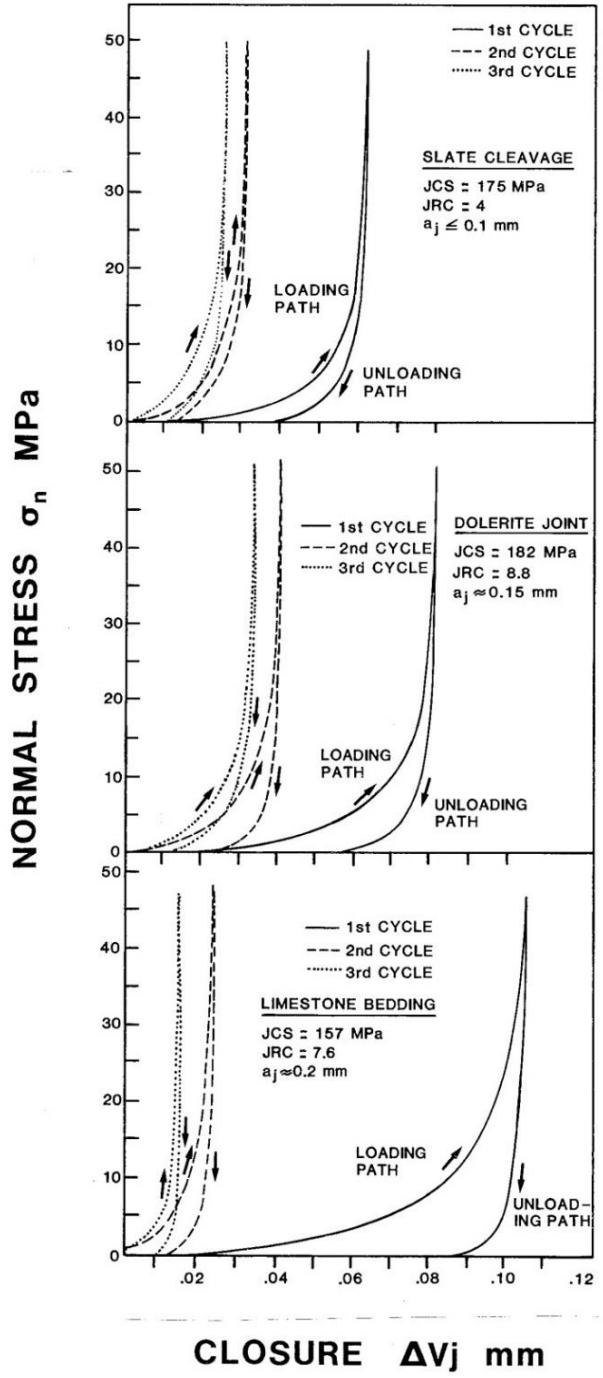


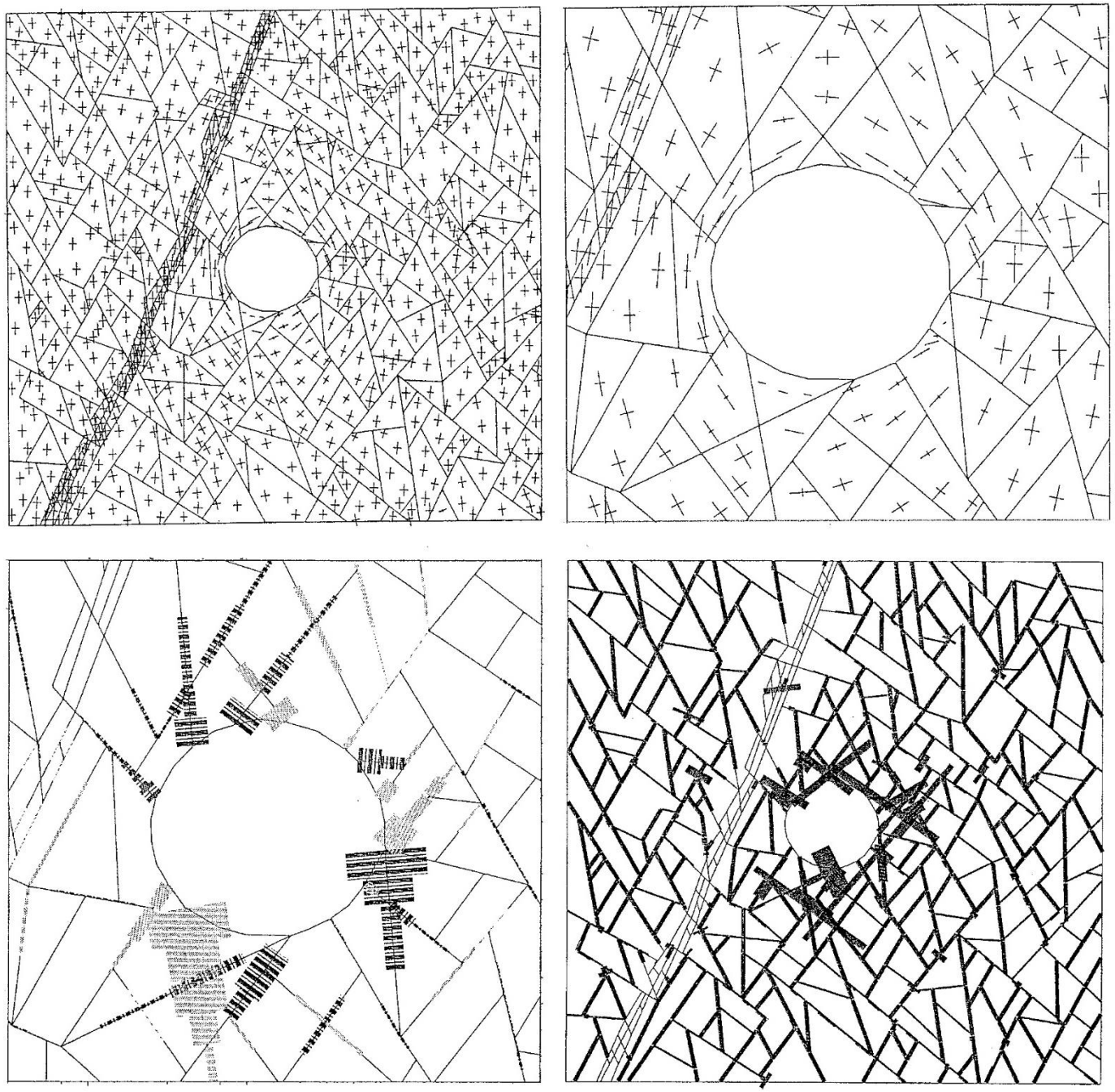
CASES INVOLVING SEISMIC VELOCITY PHENOMENA ARE DESCRIBED IN THIS 800-references VOLUME

Bandis normal closure tests (Bandis 1980, 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 (or 1st if opened) non-linearity and hysteresis* ***is*** *modelled (in UDEC-BB). (E and e apertures tracked).*







UDEC-BB MODELS OF a UK Nirex planned TBM access spiral.

NGI, 1991 (Chryssanthakis, Hansteen).
Barton, 2000. TBM book.

Note: No thermal over-closure routine in BB in last 30 years, since 1985 initiation in UDEC.

Test evidence for thermal over-closure: summary listing

Joint closures in laboratory HTM coupled stress flow tests (CSFT) (Makurat, NGI for AECL/URL): Increased joint closure at 60° C compared to 20°C, with further increase at 80°C. [3].

Conducting aperture (e) decreases due to temperature increase in the Terra Tek / CSM 2 x 2 x 2m HTM in situ block test (for ONWI). Also consistent evidence of ΔE > Δe. The reduced apertures occurred despite control of boundary flat-jack pressures during the heating. Partial recovery of apertures when cool. [4], [5].

Reduced thermal expansion coefficients at NSTF Hanford (for Rockwell-Hanford). The thermal expansion coefficients of the approx. 8m^3 columnar basalt block which was loaded in three dimensions, showed a maximum reduction from *6.34×10^{-6} °C^{-1}* to *2.59×10^{-6} °C^{-1}* over the two temperature ranges of 18° to 60°C, and 60° to 100°C [6].

Conducting aperture reductions from 60 to 35µm during temperature increases through 48°, 68° to 94°C in 2 x 2 x 2m HTM in situ block test in G-Tunnel (for Sandia National Laboratory). The mean JRC_0 of the same joint set in the surrounding drift was 9 [7].

Continued:

Reduced Vp and Vs after long-term (several years) heated-then-cooled cross-hole borehole tests at Stripa (LBL/SKB). There was remarkably poor numerical model prediction of displacements, due to thermal joint over-closure and therefore changed deformation moduli [8].

Heated mine-by (Spent Fuel Test) at Climax (Lawrence Livermore). Poor model prediction (2:1 and even up to 4:1 errors in displacement prediction) due to higher final moduli caused by lower thermal expansion coefficients, due to thermal-over-closure (TOC) of the joints [9], [10].

Increased cohesive and frictional strength of joints in welded tuff that have been heated. (Sandia National Laboratories).

Heated and ambient sides of plate load test at Yucca Mountain, during the large-scale heater tests (DoE/Sandia). Widely different moduli were measured in the ambient and heated sides of the same drift [11].

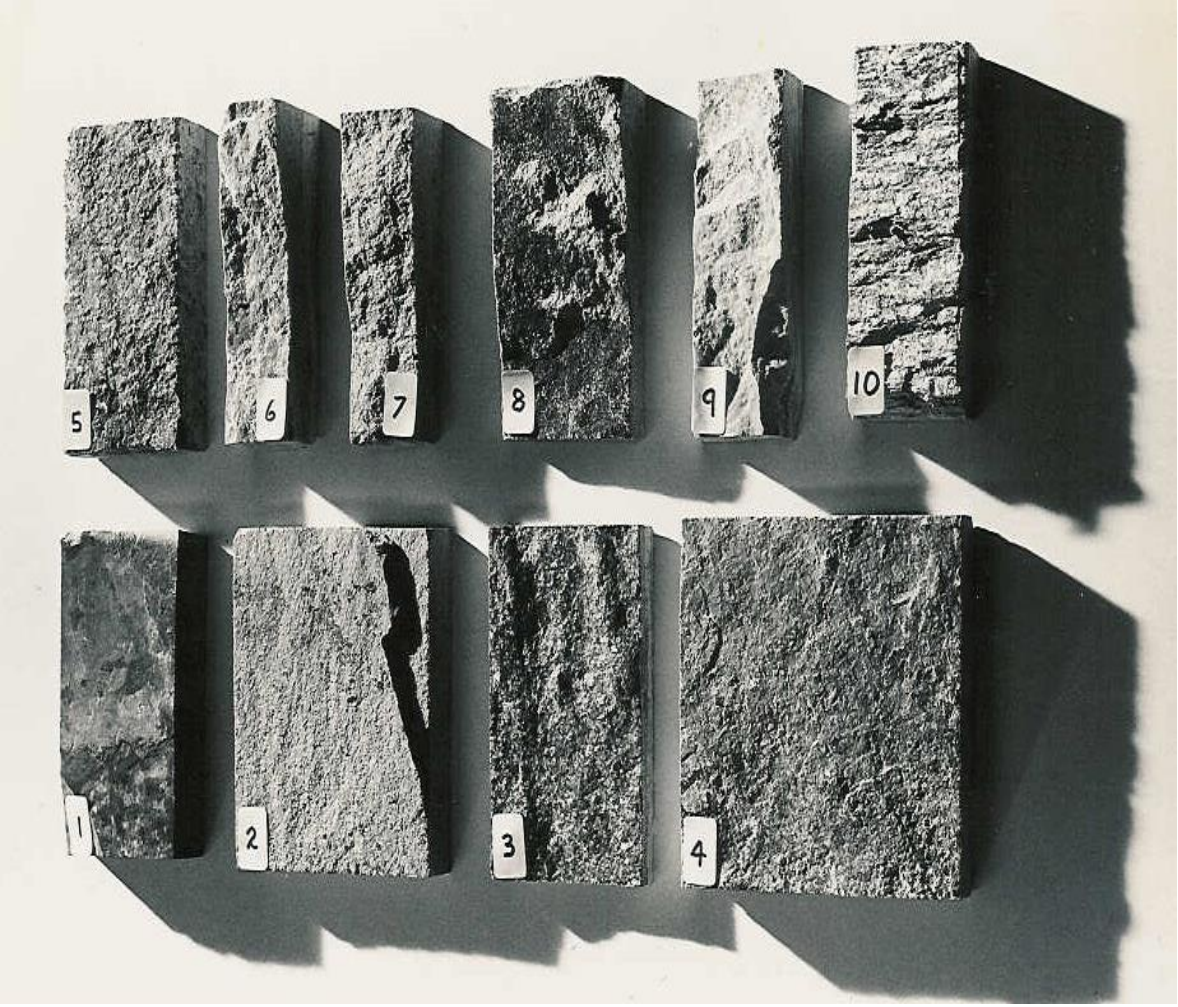
JRC_O (small-scale)

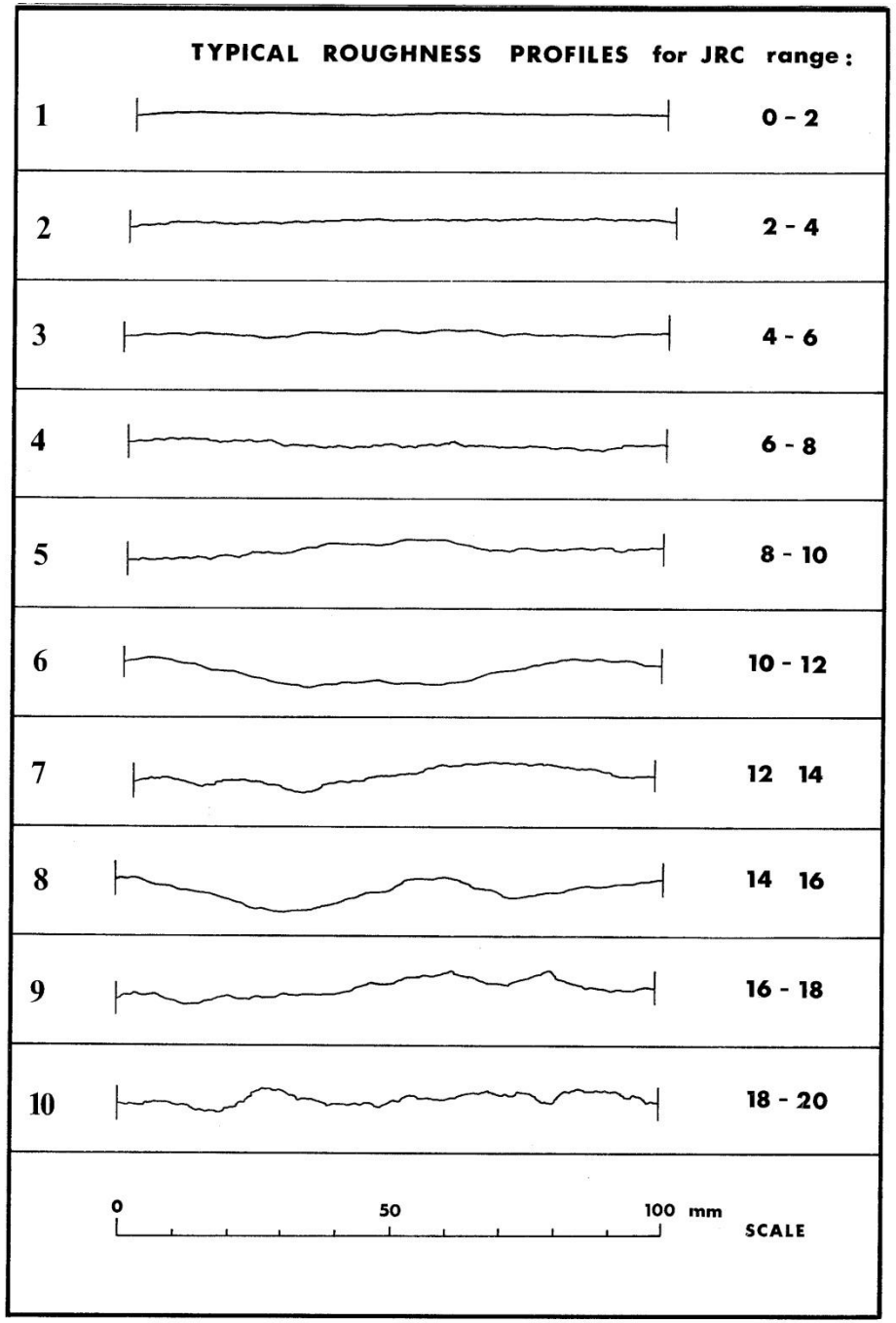
- Joint roughness is going to be the all-important discriminator in this interlock mechanism, which resembles the effect of a ‘perpendicular-JRC’.

- 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 (!)

O-C beyond JRC = 8 to 10?





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

(JRC = 1 and 15)

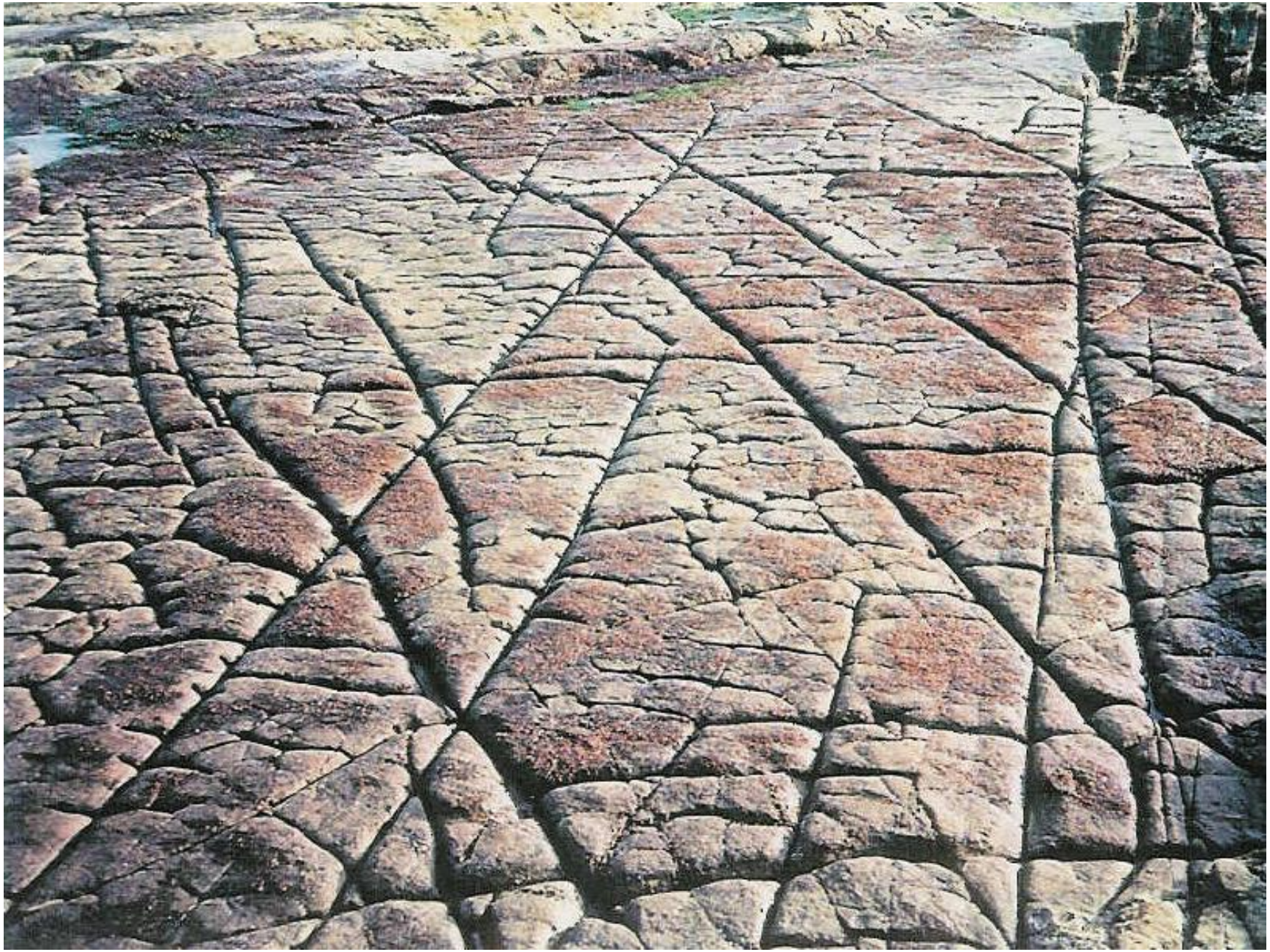
Back-calculated from DoE Yucca Mountain DST (Denver lab).

(Non-lithophysal welded tuff)

TOC (*'thermal over-closure'*) effects in rock joints:

1. INITIAL REDUCTION IN NORMAL STIFFNESS OF THE ROUGHER JOINTS (-Δ Kn)
2. THERMAL EXPANSION COEFFICIENT REDUCTION (BECAUSE JOINTS CLOSE EASIER)
3. RESULTANT DEFORMATION MODULUS, NORMAL STIFFNESS INCREASE (+ΔE mass, + ΔKn)
4. SHEAR STRENGTH INCREASE (DUE TO JOINT CLOSURE) (+ΔJRC, +Δ'c', +Δφ°)
5. ROCK JOINT PHYSICAL AND CONDUCTING APERTURE DECREASE (-ΔE, -Δe)
6. ROCK JOINT AND ROCK MASS PERMEABILITY REDUCTION (UNTIL COOLING) (-Δ kj , -Δkm)
7. SEISMIC VELOCITY INCREASE (UNTIL COOLING, *THEN NET REDUCTION: BECAUSE SOME JOINTS OPEN, WHEN SOME STAY CLOSED)* (+ΔVp, then – ΔVp……..maybe)
8. NUMERICAL MODEL PREDICTIONS E.G. ADINA CODE, COMPARED TO HMT ROCK *MASS* MEASUREMENTS. DISCREPANCY FACTOR OF 2/1 OR WORSE (4/1)

Few seem to have reckognised , acknowledged, modelled (??) or identified the cause of these phenomena



IF ROUGH SHORTER JOINTS REMAIN OVER-CLOSED DURING (HLW) COOLING, WHERE WOULD CONTRACTION BE CONCENTRATED?

IN THE CASE OF GEOTHERMAL RESERVOIRS, THE POSSIBILITY OF 'CAPTURE' OF THE INJECTED COLD WATER BY THE MOST PERMEABLE JOINT SET IS ACCENTUATED BY **TOC** – *IF ROUGHER SET(S) REMAIN CLOSED DUE TO **TOC.***

Long term implications for HLW repositories

- In the cooling phase of an HLW repository, one may experience rougher joints that are now 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 effects (by avoiding cannister locations near jointing) is clear – and now *extra obvious.*

- Consequence: more ‘tunnel-acres’ required at e.g. 500-700m depth.

CONCLUSIONS

- OVER-CLOSURE (of joints) DOES NOT YET APPEAR IN THE ROCK MECHANICS VOCABULARY – AFTER 40 YEARS OF APPARENT NEGLECT (??) BY THE **THM(C)** COMMUNITY. (Please correct speaker if incorrect!)

- HMT LABORATORY TESTING OF JOINTS IS NEEDED - OUR DATA IS VERY LIMITED. MUST TEST JOINTS WITH A WIDE RANGE OF JRC_0 and TEMPERATURE.

- NEW CONSTITUTIVE MODEL SUB-ROUTINES WILL THEN BE REQUIRED – ALSO FOR THE BB-MODEL – WITH JRC_0 AS ONE OF THE DESCRIMINATORS ***(? $10 \leq JRC_0 \leq 20$?)***

- 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 IN MAJOR AND EXPENSIVE PROJECTS (e.g. Stripa, Climax)

- **TO-C** MIGHT EXPLAIN GEOTHERMAL DIFFICULTIES: ***'DEVIOUS-CAPTURE'*** OF INJECTED WATER BY MORE CONTINUOUS PLANAR JOINTING/FAULTING BECAUSE ROUGHER SETS REMAIN CLOSED WHEN COOLED.

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