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

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ABSTRACT:. 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. Subsequently elevated deformation moduli that attract higher stress must be expected.

1 INTRODUCTION

Hydro-thermo-mechanical HTM modelling of high level nuclear waste disposal scenarios has been actively sought in the last 30 years. In simplified form, the HTM (and chemical) effects of excavation, heating and cooling (with eventual seismic loading from major earthquakes in the very long term), have each to be simulated. The effects of heating and cooling on rock joints likely to exist in the 'geological containment' will be the focus of this paper.

A phenomenon revealed almost 40 years ago, that has proved to have relevance for both HTM field experiments and HTM modelling, concerns *over-closure* of joints. Under ambient conditions we may refer simply to hysteresis effects, but when heat is added, *thermal over-closure* appears to accentuate closure effects in the rock mass. This sounds 'positive' for waste isolation: in fact it may be adverse, due to the subsequent cooling that requires shrinkage in a rock mass that may have *over-closed* rough joint sets that remain closed despite cooling.

Difficulties in obtaining excavation-induced failure of artificial rock slope models, each consisting of 40,000 blocks, reported in Barton, 1971 and 1972, has proved to have an unexpected link to the above concerns. Steep, gravity- and horizontally-stressed slopes with adversely-dipping sets of tension fractures 'would not fail', in relation to slope stability calculations based on strengths obtained from conventional 1:1 direct shear tests.

When loading to 4 or 8 times *higher* normal stress, *prior to unloading and shearing*, successively steeper shear strength envelopes were obtained, as illustrated in Figure 1. The excessively stable slopes (Figure 2) were actually caused by *over-closure* of the rough tension fractures. As observed sometimes in real slope failures, there was evidence in slope-failure debris, of 'over-closed' masses of blocks, which might be interpreted as 'discontinuous jointing' or evidence of 'cohesive strength' in field observations.

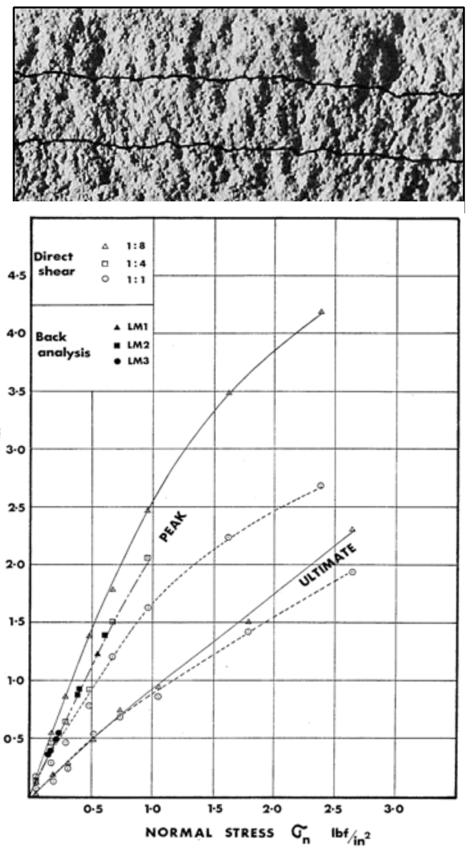

Figure 1. Over-closure (OC) ratios of 8:1, 4:1 and 1:1 (conventional) prior to direct shear testing of rough tension fractures. Barton, 1972. An example of the model tension fractures, and their surface roughness is also shown. 'Back-analysis' refers to the model slope failures.

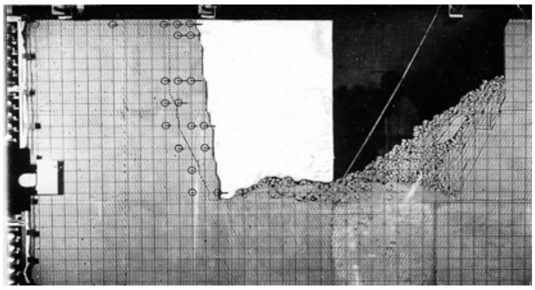

Figure 2. Example of extreme stability (left) and post-failure masses (right) caused by unloading from a higher normal stress when excavating the slopes. Barton, 1971.

These elevated strengths explained the slope-failure difficulties seen in Figure 2, since when excavating a rock slope or open-pit, (as also in these experiments), a reduction in normal stress is usually caused. Many important slope-failures occur in the open-cast mining industry, despite the usual neglect of previously higher loading, when estimating available shear strength. The continued failures might be due to errors in stress-transformation from σ_1 and σ_2 to τ and σ_n on joint surfaces that dilate (Barton, 2006), or for other reasons of structural control including elevated joint water pressure.

Rougher joints seem to have greater closure-related 'benefit', both from ambient and thermo-mechanical loading than smoother, more planar joints. During subsequent cooling, with rougher joints possibly *over-closed*, it is likely to be the more continuous, smoother joints that open to compensate for those that are closed. Reduced shear strength and increased permeability are the possible results, which are clearly effects that should be considered when deciding on the detailed lay-out / location, of high-level nuclear waste disposal.

2 AN AMBIENT TEMPERATURE EXAMPLE

Figure 3 shows how *hysteresis* affected the sequential development of deformation when excavating parallel caverns in physical models, using both exaggerated pillar slenderness, and the same *exaggeratedly rough* sets of tension fractures as shown in Figures 1 and 2. The cavern models were excavated in a stressed 'rock mass' consisting of some 20,000 blocks, in the sequence shown. Note how the pillar deformations did not reverse with subsequent excavation, as they would have done, if there had been less severe effects of hysteresis.

3 TEST EVIDENCE FOR 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).

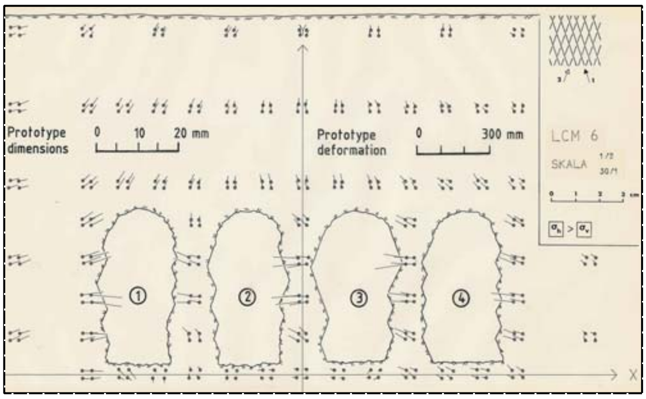

Figure 3. A demonstration of obviously exaggerated hysteresis, due to unloading of *over-closed* tension fractures. Barton and Hansteen, 1979. Deformation vectors were derived from photogrammetric analysis.

- 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.

A selection from the above experiments will be given during the remainder of this paper, to illustrate the different facets of thermal over-closure.

3.1 *Joint aperture decreases due to heating*

Figures 4 and 5 illustrate the loading principles and some key HTM results, from the TerraTek heated block test that was conducted for ONWI in 1980 and 1981. The rock was quartz monzonite, and the rough diagonal joint that was the subject of this particular set of HTM data, had $JRC_o = 13$, and $JCS_o = 90$ MPa. Hydraulic apertures were back-calculated both before and after flatjack-slot drilling, and during the loading, unloading, heating and cooling sequences shown in Figure 5.

The inset tabulation of hydraulic apertures in Figure 5, indicates that ambient loading to 7 MPa (approx.) reduced the hydraulic aperture from about 50 to 30 µm. From this point, thermal loading to 75ºC *at constant normal stress* (achieved by bleeding expanding oil from the flatjacks), caused the hydraulic aperture to reduce successively to 9 µm. During subsequent cooling and partial unloading: *a typical nuclear waste scenario,* the aperture had increased to only 16 µm, in other words the joint was *thermally over-closed.*

Somewhere between a normal stress of 3.5 MPa and full unloading, the hydraulic aperture 'jumped open' to 42µm. A lesson to be learned is that continuum modelling will be inadequate to trace such phenomena, and therefore will tend to miss the most critical events regarding potential 'hydro-geologic' waste isolation.

A feel for the roughness of the diagonal test joint that was the subject of the above heated block permeability tests, is given by the 'reconstructed' tilt tests, and by the photograph

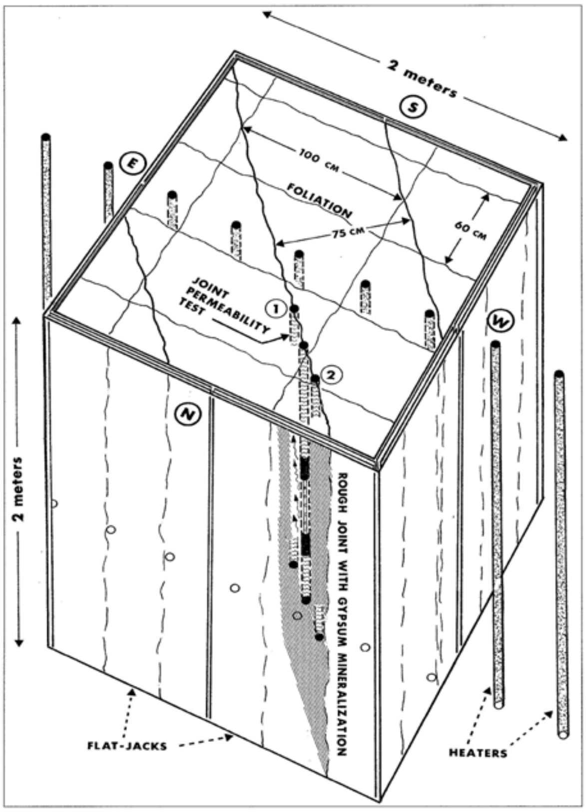

Figure 4. Biaxially-loaded 2x2x2 m heated block test, with HTM measurements along the diagonal (shaded) joint. Hardin et al, 1981. *Average* joint spacings are indicated in this 3D schematic.

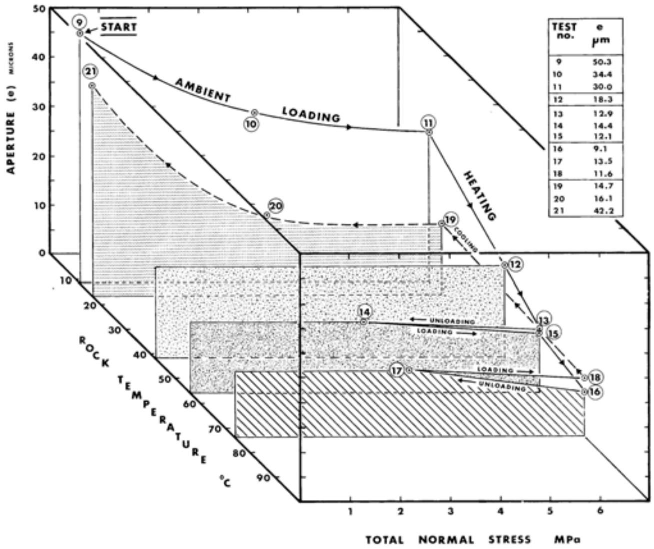

Figure 5. Hydro-thermo-mechanical (HTM) hydraulic aperture, temperature, normal stress behaviour, as back-calculated from the heated block test. Barton, 1982.

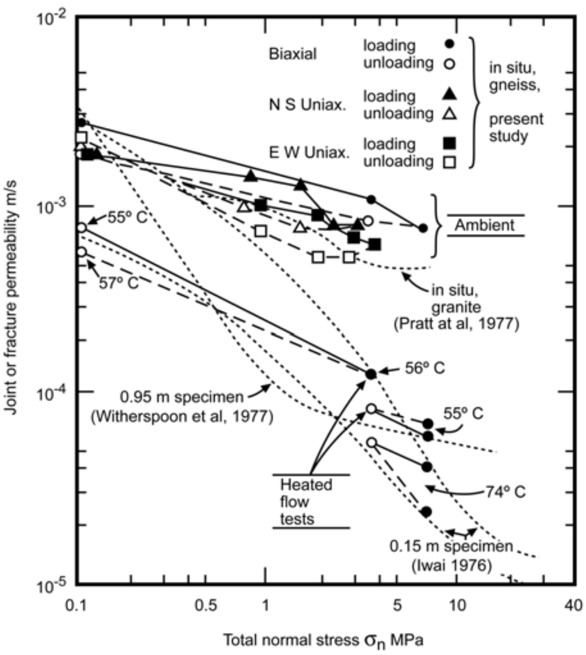

Figure 6. Contrasting stress-permeability behaviour caused by the addition of heat. ***('Present study' refers to Hardin et al. 1981 heated block test referred to initially as gneiss, but as quartz monzonite in subsequent publications).*** Note comparison to some University of Berkeley tests on tension fractures from Iwai, 1976. Barton, 1982.

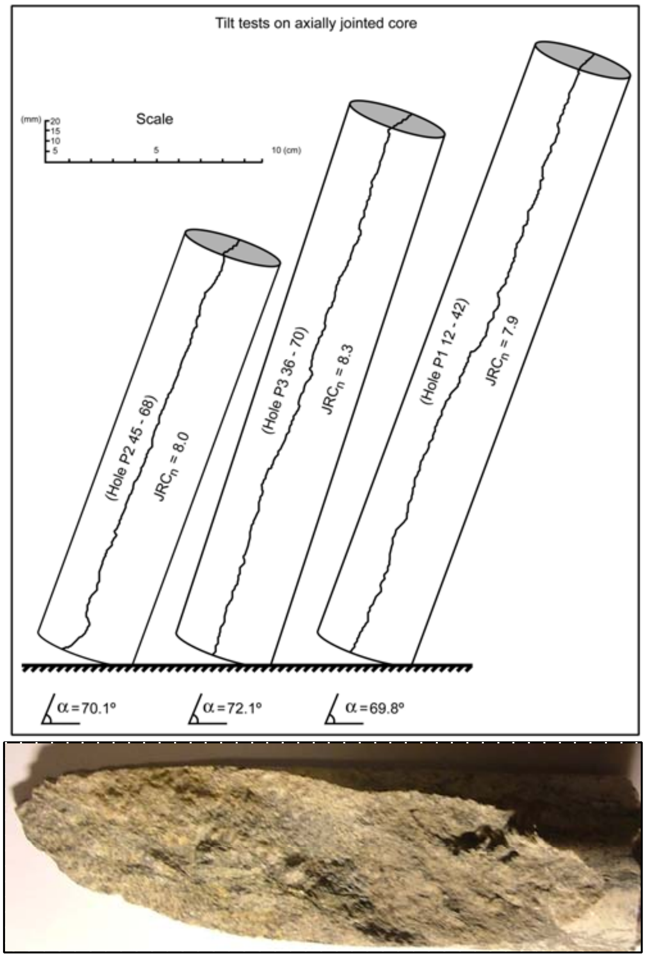

Figure 7. Tilt tests conducted on selected lengths of core drilled *in-plane* with respect to the diagonal test joint. The extended lengths of core gave JRC_n values from 7.9 to 8.3, while JRC_o (with 100 mm reference length) averaged 13.

shown in Figure 7. The JRC_n values obtained from tilt tests of these longer samples are smaller than the nominal 100 mm standard , where JRC_o was 13.

3.2 *Coupled stress flow CSFT laboratory tests*

CSFT test methods described by Makurat et al. 1990, using the apparatus depicted in Figure 8, showed *physical aperture reductions* when heating joints (Figure 9), that were in excess of those expected due to application of higher normal stress. Three tests on joints in granite from URL in Canada, were loaded up to 14, 19 and 26 MPa, and on the 4th load cycle of each test, suffered joint closures (ΔE) at the respective test temperatures of 20ºC, 60ºC and 80ºC of 24μm, 54μm and 151μm, that were out of all proportion in relation to the moderate stress increases. These reductions of physical aperture (ΔE) lead of course to smaller reductions of conducting aperture (Δe), due to roughness effects, from $e \approx E^2/JRC_o^{2.5}$. (Barton et al. 1985). An increase of 40ºC was shown to decrease Δe by 39% in Test 2. The highest temperature cracked Test 3 sample, so Δe was unreliable.

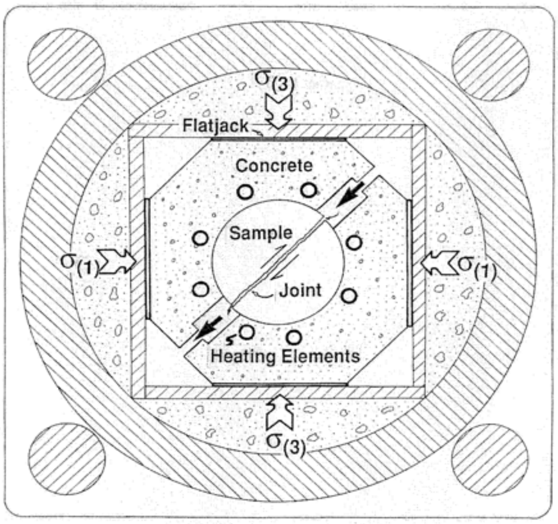

Figure 8. The CSFT apparatus used for MHT coupled-process joint tests in NGI's nuclear waste related projects for the Stripa SCV/SKB, Sellafield/UK Nirex Ltd, and URL/AECL studies. Makurat et al. 1990.

3.3 *Heated block test in G-Tunnel, Nevada*

A second heated block test in the USA was conducted in G-Tunnel at the Nevada Test Site, by SAIC engineers, for Sandia National Laboratories. This is shown in diagrammatic form in Figure 10, and the detailed jointing and permeability test joint are shown in Figure 11.

This 2x2x2m block test was also instrumented extensively, in order that deformation moduli, mass 'Poisson's ratio' (that reached 0.6), thermal expansion coefficients and joint permeability could be monitored through a range of load cycles (0 to 10.6 MPa) and temperature cycles (48°, 69°, 94°C at block centre).

Hydraulic apertures reduced from approximately 60 to 35 μm along the diagonal test joint, due to the effect of this heating. (Zimmerman et al. 1985). The measured joint roughness JRC_o for the NW-SE joint set that was showing this thermal over-closure averaged 9.0 (TerraTek, 1983) with a range from 6 to 11. Joint profiling was conducted in the drift walls in the immediate proximity of the block test.

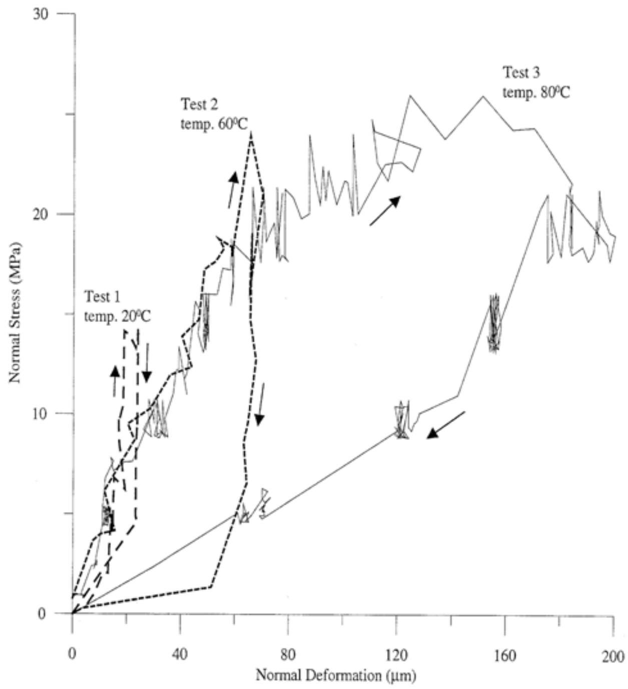

Figure 9. CSFT tests on URL granite joints, showing the effect of increased temperature on the 4th cycle of loading of Tests 1, 2 and 3. For methodology, see Makurat et al. 1990.

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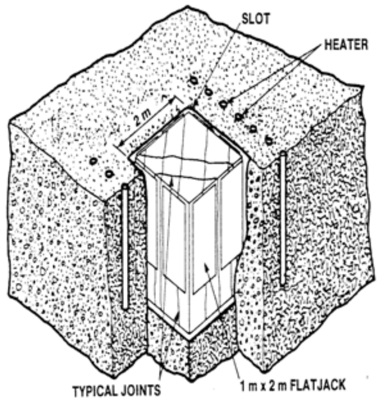

Figure 10. HMT block test performed by SAIC, for Sandia in welded tuff, in G-tunnel (Nevada Test Site). Zimmermann et al. 1985.

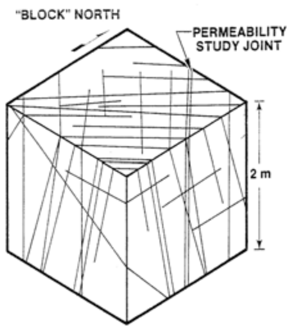

Figure 11. Details of jointing in the G-Tunnel test block. Zimmermann et al. 1985.

3.4 *Plate Jacking tests at Yucca Mountain ESF*

Sandia National Laboratories conducted plate jacking tests across a small drift at the Yucca Mountain ESF (Exploratory Studies Facility). The jointed, welded tuff yielded two different values of deformation modulus, depending upon whether the walls of the drift were heated due to proximity to a large scale heater experiment. One side of the plate-loaded drift was heated to ≥ 100°C, the other side was at near ambient temperature.

The authors, George et al. 1999 calculated ambient and thermal rock mass deformation moduli of 11.4 GPa and 24.5 GPa respectively, based on the widely different load-deformation responses shown in Figure 12. They surmised that the rock mass quality might be more heterogeneous than previously thought, but were unable to conclude that the heated side had higher quality (i.e. higher RMR or Q-values). Observation by this author confirms this opinion.

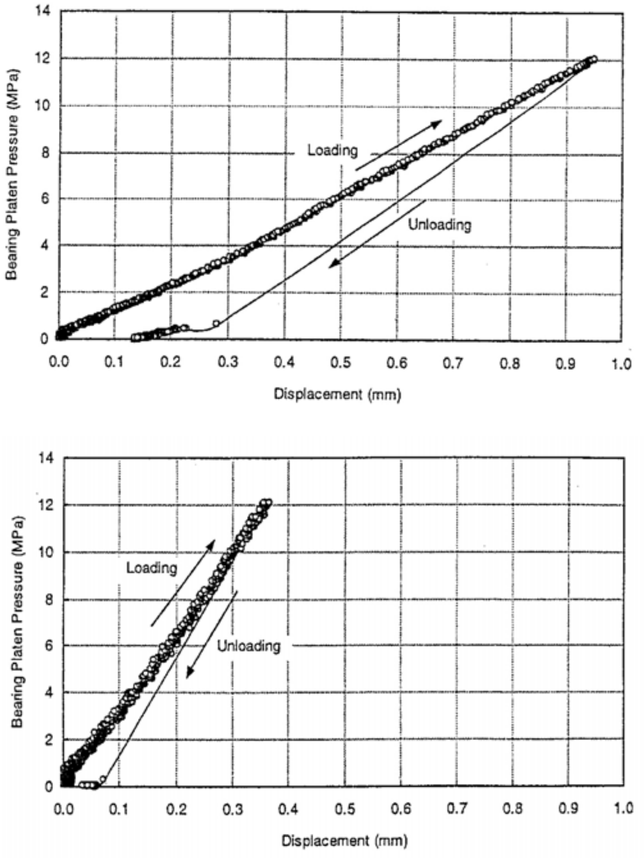

Figure 12 a, b. Yucca Mountain plate-load test performed in an adit with one side heated. E_{mass} (ambient) = 11.4 GPa, E_{mass} (heated) = 24.5 GPa. George et al.,1999.

3.5 *Near-Surface Test Facility in Hanford basalt*

At the Near-Surface Test Facility, at Hanford, another well-instrumented 2.3 x 2.3 m block was flat-jack loaded and heated in the wall of a drift in the Colombia River basalt formation. Although this heated block test did not give *direct* measurement of thermally induced joint closure (or over-closure), there was enough circumstantial evidence to suggest that such was occurring. Cramer and Kim, 1986.

The thermal expansion coefficient *of the rock mass* in three dimensions, showed a maximum reduction from 6.34×10^{-6} $°C^{-1}$ (over the range 18° to 60°C) to 2.59×10^{-6} $°C^{-1}$ (over the range 60° to 100°C).

At 100°C, Cramer and Kim (1986) reported a related 30% increase in deformation modulus, while at 200°C there was a 135 to 190% increase. All in situ moduli, even those at elevated temperature, were of course significantly lower than the intact rock value that averaged 86 GPa.

The increased temperature testing of the heated block of columnar basalt reportedly reduced the degree of inelastic and *continuously yielding* deformational behaviour. Translation and rotational movements of the columnar structures inferred from numerical modelling, were assumed to have been reduced by the thermally induced "lock-up" of interacting rock block structures. This case of course had joints formed at very high temperature when the basalt was sufficiently brittle.

3.6 *The Spent Fuel Test (SFT) at Climax Mine*

A large scale mine-by and spent fuel heater test was conducted by Lawrence Livermore National Laboratory in the early eighties. A cross-section showing the extensive instrumentation is shown in Figure 13. The three parallel drifts of about 10 and 15 m span, were excavated at 430 m depth in jointed quartz monzonite. The test location was about 150 m above the water table, i.e. it was unsaturated but not dry. Joint frequencies were about 0.9 to 2.2 per meter in the test area, and there were reportedly four dominant joint sets. (Yow and Wilder, 1993).

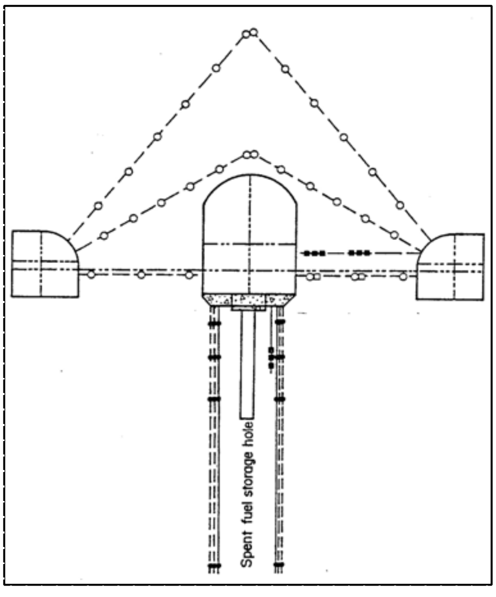

Figure 13. A heated mine-by experiment in the Climax Mine, in quartz monzonite. Spent Fuel Test, Yow and Wilder, 1993.

The extensive instrumentation was designed to measure the bulk response of a jointed rock mass, to excavation of the central tunnel (the mine-by), followed by a 3-year period of heating, and 6 months of cooling. Unfortunately monitoring beyond this 6 months was not reported, presumably due to project termination.

Extensive finite element (ADINA) calculations were performed to compare predicted performance with measured performance. In this code, isotropic thermoelastic behaviour was assumed, with temperature dependent thermal expansion coefficients (Butkovich and Patrick, 1986). Numerous scales of deformation moduli were tested. As in the case of the smaller scale Stripa heater tests discussed next, there was significant discrepancy between measured thermally induced displacements in the canister drift, which were about ¼ to ½ of those calculated, both in the horizontal and vertical directions. Instrument error was first suspected, but was eliminated by thermal calibration.

Yow and Wilder (1993) interpreted these discrepancies as evidence for a *thermally increased rock mass modulus*, citing possible thermal closure of joints as described by Barton et al., 1985, as the reason for increased rock mass stiffness.

At the end of the monitored 6 months of cooling, joints that had closed during heating had not yet unloaded enough for one to determine whether or not all of the heating-phase deformation would be recovered (Yow and Wielder, 1993). *Obviously non-recoverable*, thermally induced shear displacements were also reported.

Thermally induced hysteresis, and deformation moduli and expansion coefficients different from what was expected seem to be a general pattern of behaviour for these heater experiments. Constitutive modeling needs to allow for these *extra fully-coupled* phenomena, i.e. thermal over-closure.

3.7 *Stripa borehole heater effects on velocities*

The Stripa heater experiment has been described by numerous authors. The full duration of the test was eventually 750 days, with 398 days of heating. The simple basic layout of the test is shown in Figure 14. The long period of cooling generally returned seismic velocities to values *lower* than before the heating, suggesting permanent changes, such as local excessive joint opening as hypothesised elsewhere in this paper.

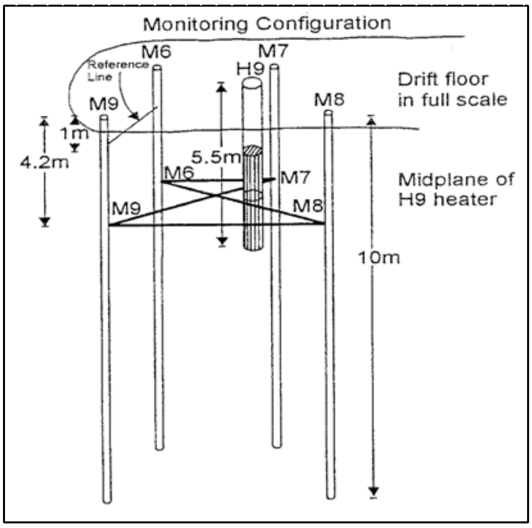

Figure 14. The Stripa borehole heater experiment. Paulsson et al. 1985.

The non-linear, thermally induced strains were about half those expected from linear thermo-elastic analyses, using laboratory tests of $\alpha°C^{-1}$ on intact samples. These important effects were discussed by Cook (1983). The discrepancy, as at Climax, was due to thermally-induced joint closure and hysteresis, what we now call *thermal over-closure*. A significant quantity of water expelled during the heating signified the general closing of the joints. Temperatures were over 100°C in only a small region around the heater, and water was expelled also from distant boreholes where perhaps the low initial permeability was less reduced.

The *initial increase* in velocity with temperature was linear and varied from 2 to 4 m/s/°C. The average joint frequency in the test area, analysed from 224 m of core, was 8.3/m. The largest velocity changes caused by the heating, amounting to 0.2-0.3 km/s, were interpreted as occurring in the direction of the minimum horizontal stress, which is logical since the *calculated* thermal stress was as much as 55 MPa in, presumably, the direction of maximum horizontal stress.

An elastic continuum analysis conducted prior to the test had indicated larger stresses and local displacements than were actually measured presumably due to the *thermal compliance* of all these joints. The full record of P-wave and S-wave velocities over the 750 days duration of the test is shown in Figure 15.

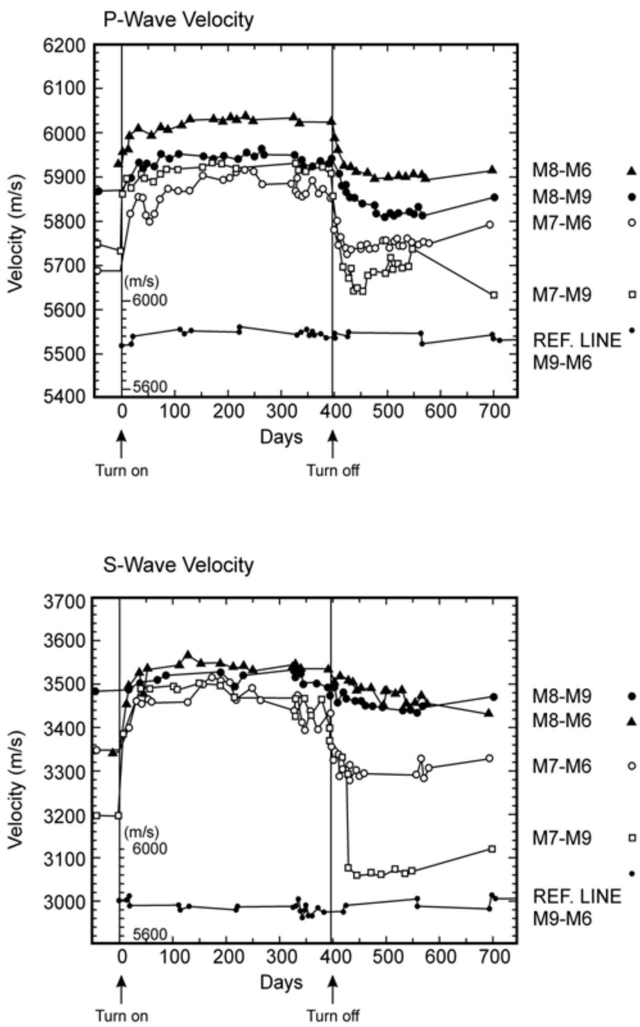

Figure 15 a and b. Stripa borehole heater test: effects of prolonged heating and cooling on V_P and V_S. Paulsson et al. 1985.

4 DISCUSSION

The explanation for the phenomenon of *thermal over-closure* is assumed to be quite simple (Barton, 1982, Barton, 2006). Namely that the joints in question, and perhaps the huge majority of joints developed in the crust, were formed at variously elevated temperatures compared to 'ambient'. They were thereby given a primeval 'finger-print' of 3D-roughness that reflected the warmer conditions at their birth. The details of this 'finger-print' would clearly be influenced by the diverse properties of all the minerals (or grains) forming the joint walls, and their mechanical resistance to joint formation, whether in tension or shear or by cooling,

Today's rock joints as sampled at the surface or near surface (1 km is also 'near-surface') have probably cooled by many tens if not several hundreds of degrees, in relation to their formation, often nearer the brittle-ductile transition, or when deeply buried in a typical geothermal gradient. When cooled, the 3D roughness *finger-print*, though very recognizable in relation to the original, would be subtly altered in its finer details.

If (or because) the constituent minerals have unequal thermal expansion coefficients (for example a log normal distribution of values from 1 to 20 × 10^{-6} °C^{-1}, giving a mean (measured) value for the whole rock of *say* 10 × 10^{-6} °C^{-1}, then it is reasonable to expect a degree of micro-mismatch across the joint walls, assuming that several different minerals usually form the joint walls. (At the heated block test described by Hardin et al. 1981, the thermal expansion coefficient was ½ to 1/3 parallel to foliation, compared to perpendicular to foliation).

The variable quantities of constituent minerals in igneous rocks, and in addition the important *differences in* α *°*C^{-1} *when heating or cooling,* quoted from Skinner (Section 6 of Clark, 1966), suggest that micro-mismatch is inevitable when joints are tested colder than at their formation. This is surely one reason for the variously hyperbolic shape of (ambient) normal closure tests, as described in great numbers by Bandis et al. 1983, for a wide range of JRC_o and JCS_o values.

The *mechanical over-closure* and the *thermal over-closure* referred to in this brief review of test data, suggests that it is time to perform a more comprehensive series of tests on rock joints in rock mechanics laboratories. For example, we do not usually (ever?) load rock joints to normal stress levels appropriate to existing stress levels, *followed by* unloading to the post-excavation stress levels, *prior to shearing* in direct shear testing. The addition of heating is seldom considered.

Concerning 'geologic' disposal of nuclear waste with subsequent thermal loading and unloading, it is clearly necessary to perform permeability tests on rock joints in the heated state. Specifically, the effect of increasing temperature *combined* with increased normal stress needs to be investigated, and most importantly the effect of reducing temperature and reducing stress, all as a function of roughness JRC_o. Just the measurement of shear strength changes as a result of heating, for a range of JRC_o , would also be informative.

Under ambient conditions, maximum joint closure was aided by lower JCS_o and lower JRC_o for the medium to hard jointed rocks tested by Bandis. However, when *thermally over-closed*, joints will display higher stiffness and higher strength, as though both JCS_o and JRC_o have been increased by the process of intimate interlock. This is the dilemma that we face in constitutive modelling, and unloading may or may not reverse the above process.

Consider the jointed pavement (in a prominent dolomite bed) at Kimmeridge Bay in southern England, which is depicted in Figure 16. The rougher, less continuous joints that occur between the two (or three) major sets, contribute to an initially reduced deformation modulus through the reduced RQD and reduced Q-value. The 'ambient' deformation modulus would depend on Q and Q_c (= Q x σ_c /100) and on the depth or stress level (Barton, 2002, 2006).

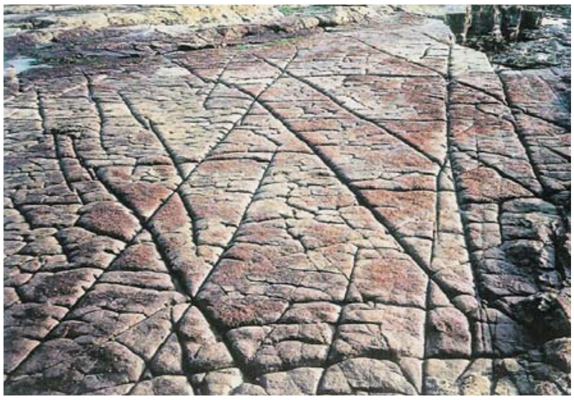

Figure 16. Dolomite pavement which can be used to illustrate some important aspects of HTM modeling.

If this rock mass became heated, it would be these short, rough joints that closed most efficiently, causing an increased deformation modulus at higher temperature. Upon cooling these same joints would tend to remain with small aperture, thereby requiring opening of the more continuous joints. It is these more continuous joints that would usually be discretely modeled in a numerical model such as UDEC-BB or 3DEC-MC.

An adjustment to the input data for such a model would be the requirement of thermal expansion coefficients that *included* the thermally compliant rough jointing. Some of the thermal expansion would thereby be absorbed, but the negative factor might be that the reduced apertures would remain 'closed' during subsequent cooling, thereby potentially activating the major joints.

Figure 17. Two contrasting joints with JRC_o values of about 1 and 16 according to back-analysed direct shear tests.

The rougher of the two joints shown in Figure 17, must be expected to suffer thermal over-closure, while the planar discontinuity, possibly a minor fault, might be opened during cooling, if in the same neighbourhood, to compensate for this closure. The fourth component of coupled behaviour; the chemical changes incorporated in HTMC modeling, would logically include the increased likelihood of chemical deposition in the low-permeability *thermally over-closed* joints, as actually appears to have occurred already in Figure 17.

5 CONCLUSIONS

1. Numerous HTM *in situ* experiments, some of them heated block tests, others consisting of larger scale heating of the rock mass, have demonstrated a consistent phenomenon of changed properties caused by joint closure during heating. This is something *additional* to the expectation of higher thermally-induced stresses causing joint closure.

2. During the heating of jointed rock in the immediate surroundings of an HLW repository, the thermal over-closure mechanism that appears to affect non-planar joints, will tend to cause a marked reduction in joint permeability, an increase in seismic velocity, and a final increase in deformation moduli, due to the transient reduction of the thermal expansion coefficients. The latter is due to transient 'softening' of joint normal stiffnesses with heating, due to *thermal compliance* causing *thermal over-closure.*

3. During the subsequent cooling phase of an HLW repository, one may experience rougher joints that have been thermally over-closed, and that may not open during cooling. These joints have increased cohesive and frictional strength and reduced aperture. They may also be preferentially involved in chemical deposition and sealing.

4. Smoother, planar, and probably more continuous features will tend to open to compensate for those that may remain closed during the cooling, thereby potentially losing strength and gaining permeability. This should alert designers and constructors to avoid the continuous planar features in their disposal canister deployments.

5. Thermal over-closure phenomena seem to have been almost ignored in more recent rock mechanics testing and engineering design work. The numerical modelling of over-closure in repository scenarios, including both mechanical and subsequent thermal effects, is therefore needed, once the necessary thermal data base is developed.

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