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A review of mechanical over-closure and thermal over-closure of rock joints: Potential consequences for coupled modelling of nuclear waste disposal and geothermal energy development

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ABSTRACT

Rough joints can *over-close* due to a prior higher stress, or due to temperature increase alone. There is better fit of their opposing walls causing increased friction and even tensile strength. 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 likely evidence for this coupled response, which is different from pressure solution. Rock mass deformation moduli, thermal expansion coefficients, hydraulic apertures, shear strength, and seismic velocities can each be affected. In the cooling phase of an HLW repository, and in a geothermal project, rougher joints may be thermally over-closed, and cooling causing contraction effects may be focused where joints are more planar, causing shear and fluid capture.

1. Introduction to over-closure using physical models and rough tension fractures

The writer's first experience of over-closure of rough fractures was during (ambient temperature) research at Imperial College, fifty years ago. Several dry, two-dimensional-slice, model 'rock slopes' excavated in 40,000 block tension-fracture models, with both horizontal and vertical stress, would not fail at the expected slope angles. Fig. 1 illustrates two of these models. The 'proving-ring-and-dial-gauge' loading was applied at both boundaries. It was found that the rough fractures could be *over-closed* and remain over-closed by the previous application of the higher normal stress acting prior to any slope excavation. Direct shear tests on over-closed tension fractures also showed higher strength if *previously loaded* to a higher normal stress than applied in the subsequent direct shear test.

Conventional 1.1, and over-closed 4:1 and 8:1 direct shear tests, with a prior normal stress higher than the normal stress applied in the following DST of the same rough fracture, showed successively steeper shear strength envelopes, and thus explained the reluctance to fail. (Barton, 1971).

Mistaken application of a higher-than-planned normal stress in a direct shear box test of the shear strength of a rock joint in the Engineering Geology department at Imperial College, reportedly resulted in the need to wedge open the joint (pers. comm. Dr. Mike DeFreitas, Imperial College, 1969) as the sample could not be sheared at the correct (lower) normal stress. One may also relate the true story of a tilt test on a tension fracture that we made for a rock mechanics course in a university with poor rock mechanics facilities some 20 years ago. The newly fractured block weighing some 2 kg, with the two halves placed together by self-weight, was slowly rotated by the author, thereby increasing the tilt angle (or dip) of the fracture. Surprisingly, a vertical dip angle was reached – most joint samples slide at 50° to 80° when their JRC value is in the typical range of 5 to 15 (Barton and Choubey, 1977; Barton and Bandis, 2017). This particularly rough tension fracture, with a JRC perhaps even higher than 25, tolerated continued tilting to a dip angle of 180° (i.e. pure over-hang). It now exhibited tensile strength due to presumed *frictional interlock*. This mechanism, repeated at much lower roughness, sets the scene for a new way to look at joint closure. A significant difference to 'asperity shortening' models will be seen.

Some years after the writer had moved from Imperial College to NGI in Oslo, a study for underground nuclear power plants was performed (Barton, 1972, 2019), using the same physical modelling tension fracture technique. This was performed just prior to Peter Cundall's development of the distinct (jointed) element UDEC. A 'demonstration' four-cavern model with 20,000 blocks was also performed at this time, which is illustrated in Fig. 2. Fracture *over-closure* was now demonstrated in more detail. The photogrammetrically recorded deformations across the face of the '2D' model were not reversed in the pillars when successive caverns were excavated. (Barton and Hansteen, 1979). The

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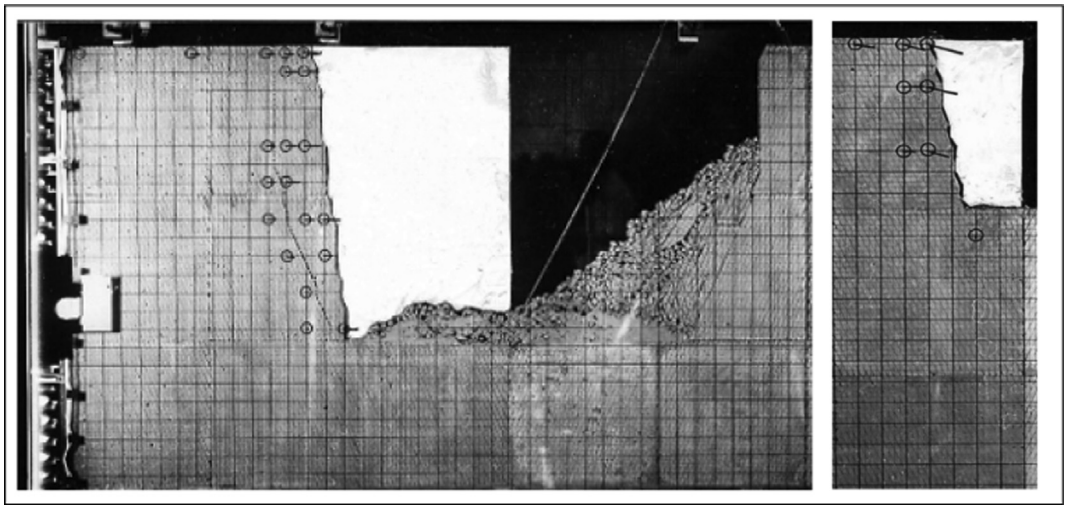

Fig. 1. The left-side photo shows one of the physical slope models of Barton (1971). This model had a high initial horizontal stress. Downward components of deformation are not seen, only horizontal components, as in an 'elastic' unloading. An outline of the final, partially stepped failure is shown by the 'dotted lines'. Slight fracture opening/dilation could be detected along the line of 'dots'. On the right side of the main photograph, the 'debris' following the slope failure shows some multiple-blocks still apparently 'intact' due to O-C (over-closure). Some tensile strength is suggested. The small right-side photo shows the initial stages of a low horizontal stress model, and since with limited 'over-closure' it shows distinctly downward-directed components of deformation, even at half of the final slope height.

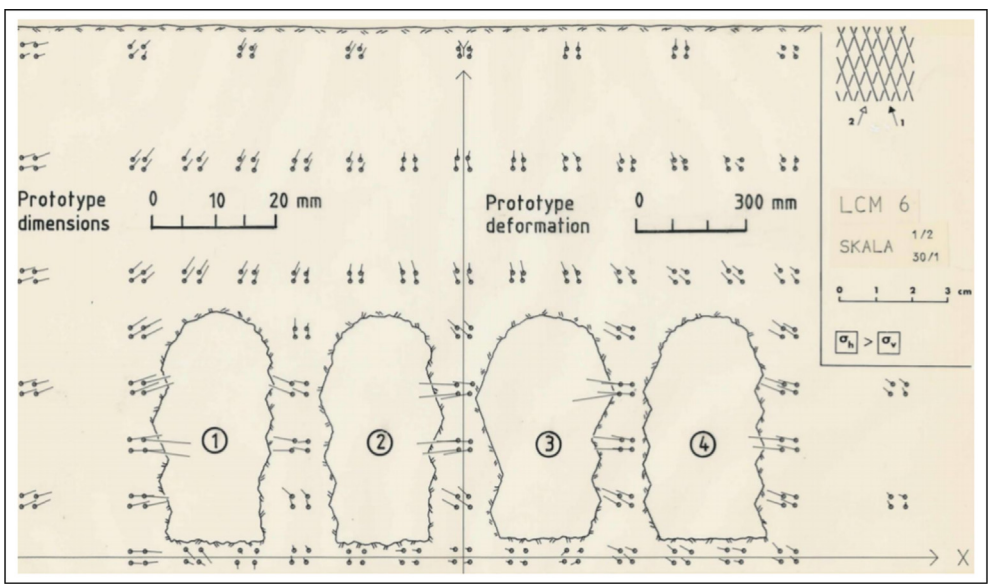

Fig. 2. Caverns in a 20,000-blocks physical model (Barton and Hansteen, 1979) which were excavated in sequence, from left to right: 1 through 4, showed hysteresis, in other words none of the expected reversal of deformation vectors in the pillars as each new cavern was excavated. This was due to over-closure of the rough steeply dipping fractures, which were under higher normal stress prior to excavation. Deformations were recorded by photogrammetry. Loaded boundaries were distant from the caverns. In Fig. 3 (bottom-right), partially failing pillars are seen as a result of a simulated earthquake loading. The orange colour is due to the high density red lead Pb_3O_4 additive to the oven-baked gypsum-sand-ballotini model material. Barton (1971).

rough fracture sets were exhibiting some tensile strength and higher shear strength due to the higher normal stresses that had acted across the steeply-dipping joints, prior to excavation of the parallel caverns. The fractures were mechanically over-closed due to *frictional interlock*. Since this style of physical model seems not to have been utilized by any other researchers in the period either before or after Peter Cundall's Universal Distinct Element Code UDEC became available, and since the models provide a simple visual communication of *over-closure* which will be further illustrated in real rock masses later in this paper, the fracture formation method and their roughness will also be illustrated. Fig. 3 shows a collection of relevant images. Obviously, an immediate conclusion is that the tension fractures are rough: JRC ≈ 18–20.

2. Over-closure of rock joints, ambient or thermal, or pressure solution

Rough joints in igneous and metamorphic rocks, and perhaps also in sedimentary rocks, can *over-close* due to the prior application of a higher normal stress. This has some resemblance to the additional consolidation of over-consolidated clay due to historic deeper burial. However, rough rock joints or fractures exhibit fundamental difference from a clay continuum, because they are discontinuities which can fit together better due to temperature increase alone, apparently because conditions closer to their formation temperature are reached when heating beyond our nominal 20°–25 °C laboratory test temperature. Mineral-constituent thermal expansion (and contraction) coefficients are probably to blame. In other words when formed at some depth and at an elevated temperature, the opposite joint walls would have fit together more tightly than when for instance, a joint sample is intersected by drill-core and is bought to the surface, inevitably disturbed and opened, and (shear or flow) tested in the laboratory at a nominal temperature of 20°–25 °C. The cooled and unloaded joint walls no longer fit together so well, and repeated load-unload-load cycles as performed by Bandis et al. (1983) are needed to approach an assumed *in situ* stiffness and aperture. Typical normal closure-opening cycles as measured on rock joints will be illustrated later. It will be noted that the first closure-opening cycle always displays a big hysteresis, as 'sampling disturbance' is partially removed. Subsequent load-unload cycles

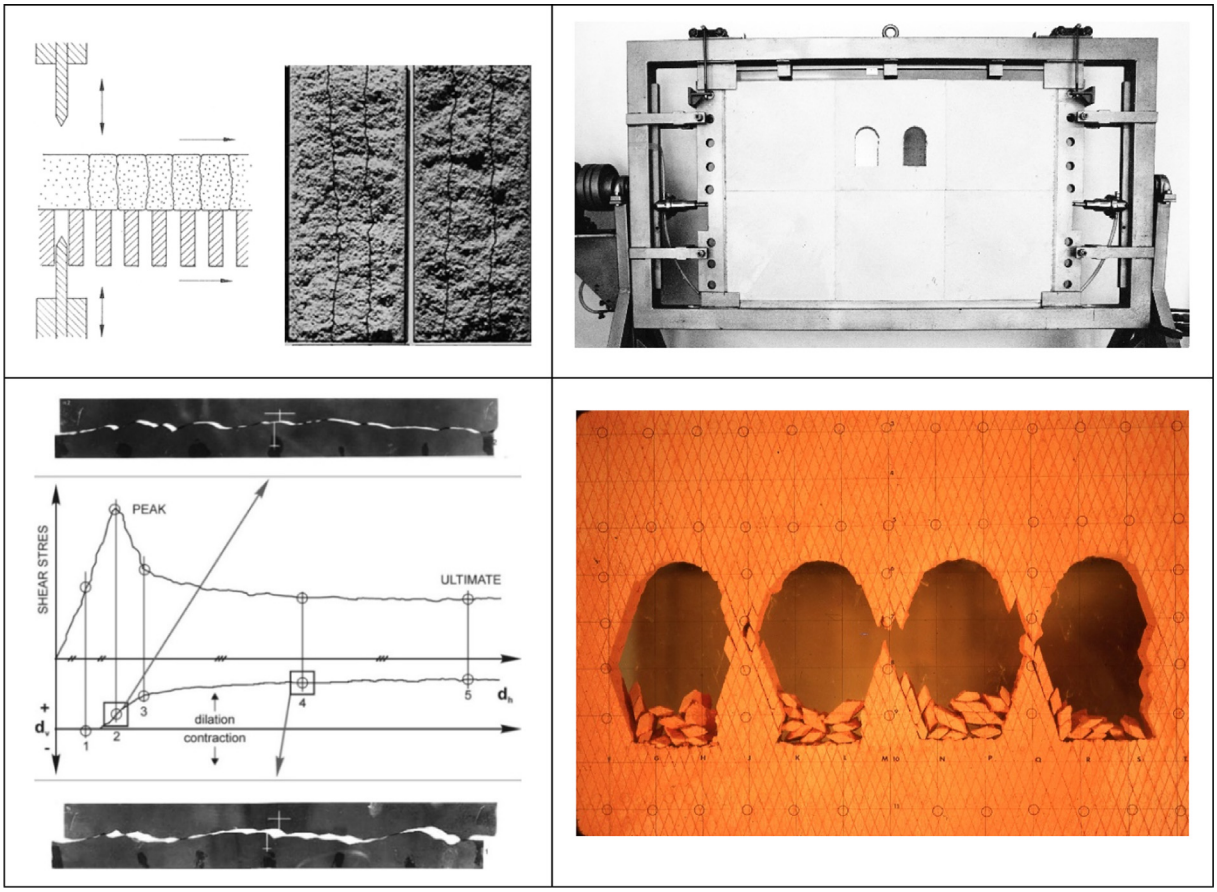

Fig. 3. Details of guillotine method and tension fracture roughness from Barton (1971) with cavern modelling from Barton and Hansteen (1979). Top-left: Double-bladed guillotine and typical fracture roughness. Top-right: Loading rig for applying high (trapezoidal) or lower (triangular) horizontal stress distribution. Bottom-left: Roughness profiles and simulated shear following measured dilation paths. Bottom-right: Photographic demonstration of the 'completeness' of fracture formation, seen from the dynamic loading effect on pillars.

become more similar – almost non-linear elastic. In fact in the UDEC-BB distinct element code the 4th of such 'Bandis-closure' cycles (suitably characterized with relevant joint roughness JRC and joint wall strength JCS) is used to simulate consolidated behavior, prior to e.g. tunnel excavation, unless a particular joint becomes opened, in which case the 1st 'Bandis-closure' cycle is used. Such empirically-based modelling derived from normal closure tests on rock joints from different rock types (Bandis, 1980, Barton and Bandis, 2017) is very different to analyst's 'asperity shortening' models.

The JRC-JCS steered stress-closure concepts will apply to each joint set modelled, very different to analytical 'short-cuts' made for the convenience of pseudo-continuum modelling. The above means that a nominally unstressed joint aperture E_0 (Barton, 1982) of say 0.25 mm (resulting from a self-weight normal stress of e.g. 0.001 MPa from a 4 cm high upper sample) may close down to < 0.1 mm conducting aperture (e), as a result of applying the 4th Bandis closure cycle in the consolidated UDEC-BB model. The consolidated apertures of each joint set influence the modelling of for example, the multiple and anisotropic EDZ effects of tunnel excavation and how this affects coupled MH inflow. Furthermore, physical (E) and hydraulic apertures (e) are differentiated, using small-scale JRC_0, following Barton et al. (1985). This allows some of the details of EDZ phenomena such as stress redistribution in the intact blocks, and shear, opening and closure of joints to be modelled in more detail. The above approach which is used in rock mechanics if continuum modelling is rejected, is presently 'homogenised' using various simplifications, so that very large models of kilometer scale can be more readily performed as pseudo-continuum and isotropic coupled HTM analyses. This need is understood, but possibly can be improved if joint characterization is improved. For example the writer identified three ranges of JRC following contracted reviews of Morrison Knudsen/TRW and BSC Consortium characterization studies at Yucca Mountain from 2000 to 2002: set 1: JRC 2–4, set 2: JRC 4–8, set 3: JRC 12–16. The use of such ranges for thermal test interpretation, and modelling input, also for drift stability, has not been seen.

There is a significant school of research, experimentation and analytical modelling that argue strongly, even preferentially, for chemically related pressure-solution mechanisms as a function of time, as the reason for increased joint stiffness, shear strength and reducing joint aperture. Some of these cases are briefly reviewed here. For example, Tenthorey et al. (2003) described cores of Fontainebleau sandstone that were initially loaded to failure in a high-pressure apparatus. The failed specimens were then hydrothermally treated at 927 °C for variable durations under isostatic conditions, and subsequently re-fractured to determine what the authors called the 'inter-seismic' strength recovery. (Their studies were related with faulting mechanisms).

This very high temperature is far beyond the likely range where *mechanical* rather than *chemical* (pressure solution) mechanisms are likely to operate, so will not be considered further in this paper. Another case, suggesting what one may term 'accelerated' pressure solution, or rather acid-enhanced solution, was described by Durham et al. (2001). This would seem like an attempt to obtain an accelerated effect by using both a (mild) acid solution and a potentially soluble rock type (marble). This must therefore be considered an exaggerated example of potential joint permeability reduction through pressure-solution chemical effects, in relation to crystalline rock that is water-

bearing, of course sometimes saline, as in several SKB nuclear waste study locations near the Baltic coast.

A very interesting series of flow experiments in a single rock fracture in granite were described by Yasuhara et al. (2011). The permeability tests were conducted under confining pressures of 5 and 10 MPa, under water pressures ranging from 0.04 to 0.5 MPa, and at temperatures of 20–90 °C. Each experiment lasted several hundred hours. The authors reported that the fracture aperture monotonically decreased with time at room temperature and reached a steady state in relatively short periods (i.e., < 400 h). However, once the temperature was elevated to 90 °C, the aperture resumed decreasing and kept decreasing throughout the rest of the experimental periods. It was first postulated that this flow-interpreted reduction in aperture may result from the removal of the mineral mass from the 'bridging asperities' within the fracture. However, the authors found that the precipitated minerals seemed to have had little influence on the flow characteristics within the fracture, because the precipitation *was limited to quite local and small areas*. The authors assumed that the evolving rates and ultimate magnitudes of the fracture aperture were likely to also be controlled by *the stress exerted over the contacting asperities and the effect of temperature on this mechanism*.

Here we come close to the *thermal over-closure* mechanism proposed by Barton (2007a) and in the present paper, because Yasuhara et al. (2011) observed that it was not possible for them to replicate in their proposed THMC model the abrupt reduction in interpreted hydraulic aperture observed in the early periods of the experiments. They felt this was likely to be due to 'an unaccounted mechanism of more stress-mediated fracture compaction driven by the fracturing of the propping asperities'. Such an assumption seems extreme. In a more recent paper (in Japanese) they show a model with highly stressed asperity peaks. In the opinion of the writer such models that are focussed on 'asperity shortening' is the main reason for the *mechanical over-closure* and *thermal over-closure* mechanisms not yet being generally appreciated by the THMC modellers and analysts, because closure of non-planar rock joints is quite different from the 'shortening asperities' or 'bed-of-nails' type concept. It is actually believed to be asperities sliding past each other and frictionally locking due to the 'perpendicular roughness', or 'JRC at right-angles'. A magnified version of the roughness showing grain or mineral surfaces is all that is needed for visualization of *frictional interlock*. However, when joint roughness or non-planarity is insufficient then the over-closure mechanism (ambient-mechanical or thermal–mechanical) is not activated. The hysteresis and locking mechanisms are then absent. This actually is the danger in our planned use of the deep underground. The frictional interlock mechanism (or its absence) will be illustrated later.

The *thermal over-closure* mechanism may influence high level nuclear waste (HLW) repository cannister disposal lay-outs, and may explain difficulties with the development of geothermal energy projects. It may also influence in a potentially negative way what initially may happen during CO_2 sequestration. This is because of what happens during *local cooling* of a rock mass that may contain one or more joint sets that are *thermally over-closed*. During cooling, the joints belonging to the set or sets with greater roughness will likely remain closed due to sufficient tensile strength resulting from the frictional interlock. They can probably resist the contraction. More planar joints of another set may open to compensate, thereby losing shear strength, and gaining permeability. 'Fluid capture' by joint sets that are not aligned to present-day stress has been seen in several geothermal projects, notably the Cornwall HDR hot dry rock project (Pine and Batchelor, 1984), and Los Alamos' Fenton Hill site (Brown, 2009). This effect may be enhanced by reduced shear strength resulting in minor amounts of shearing, as suspected from micro-seismic monitoring at these projects (see later).

As a result of thermally-induced changes to the *in situ* state of joint-wall inter-lock (which may be minimal before heating) the *rock mass* deformation moduli, the mass thermal expansion coefficients, the seismic velocities, and the physical and hydraulic apertures of individual joint sets may each be affected. In the case of heating or loading a joint sample in the laboratory or in a large *in situ* block test, the initial cause of changed properties is the *initially* lowered normal stiffness of the roughest set of joints due to improved asperity interlock (not asperity shortening) *at the beginning of* their *thermal over-closure*. Aperture(s) both physical (E) and hydraulic (e) which are related by the small-scale JRC_0 roughness value (Barton et al., 1985) are thereby altered, and a hand-full of other properties are thereby affected, as we shall see.

Well-controlled laboratory HTM tests (Makurat et al., 1990), *in situ* HTM block tests (Hardin et al., 1981, Barton, 1982, Cramer and Kim, 1986) and large-scale heated rock mass tests, lasting several years at Stripa (Paulsson et al., 1985), at Climax mine (Zimmerman et al., 1985, Butkovich and Patrick, 1986) and at Yucca Mountain (Yow and Wilder, 1993; Rutqvist and Tsang, 2012 and many other review author combinations) have apparently produced evidence for this *extra* fully-coupled joint response. The four years of heating and cooling effects at the Yucca Mountain Drift Scale Test, using air permeability measurements in the mostly dry jointed non-lithophysal jointed rock, described in detail by Rutqvist et al. (2008) and also in the wide-reaching review of Yucca Mountain *in situ* testing by Rutqvist and Tsang (2012), gave strong evidence of the general closure of joints due to normal stress increase caused by forced heating during four years.

Natural cooling for four years suggested some permanent closure, with some local permeability increases, some of which might have been shearing induced. As pointed out by these authors the reduction of permeability interpreted as the reduction of conducting apertures can be a combined mechanical effect and a chemical effect. It is presently difficult to isolate HMT and HMTC effects, so models that fit data trends may or may not have appropriate weightings for the thermal over-closure and the pressure-solution components.

The writer has previously expressed the opinion (Barton, 2007a) that the coupled *thermal-OC* effect in HTM numerical modelling will require thermal expansion coefficients that *include* rather than *exclude* relevant joint sets, if these have marked roughness and if they originated at elevated temperature. This is a 'logical' conclusion from what we know of the different joint stiffness contributions from joint sets with different JRC and JCS character. However, further study of the phenomena with the help of the significant review by Rutqvist (2015), have convinced the writer that the thermal over-closure phenomenon does have a 'reducing effect' on the apertures, which all tend to close to a greater degree when heated.

Nevertheless, the writer doubts that it is possible to measure the thermal expansion coefficient as a temperature dependent variable, *without the need to include the jointing*. This would be illogical but does become 'partially logical' due to the relatively strong closure of the rougher joints during heated *in situ* tests. It is claimed that intact samples can be used for (almost?) satisfactory measurement of the temperature dependent thermal expansion coefficients, perhaps because of the 'unifying/reducing' nature of the thermal over-closure mechanism.

However, concerning the thermally loaded *in situ* tests, elevated deformation moduli that attract higher stress must be expected, as a result of the initial easier *frictional interlock* closure of the rougher joints when heated. At least a 2:1 mismatch of rock mass deformation moduli occurred in the Climax quartz monzonite in a so-called heated 'mine-by' experiment in the late 1970s. Also, as we shall see later, as a result of the large-scale heater experiment in the jointed non-lithophysal tuff at Yucca Mountain, deformation moduli were more than twice as high on the heated side of a drift with apparently similar rock quality Q-values as compared to the ambient temperature side.

3. Terra Tek/CSM heated block test

In 1980–1984 the author was working at Terra Tek in Salt Lake City, and was able to take part in their unique 1979–1981 HTM (hydro-

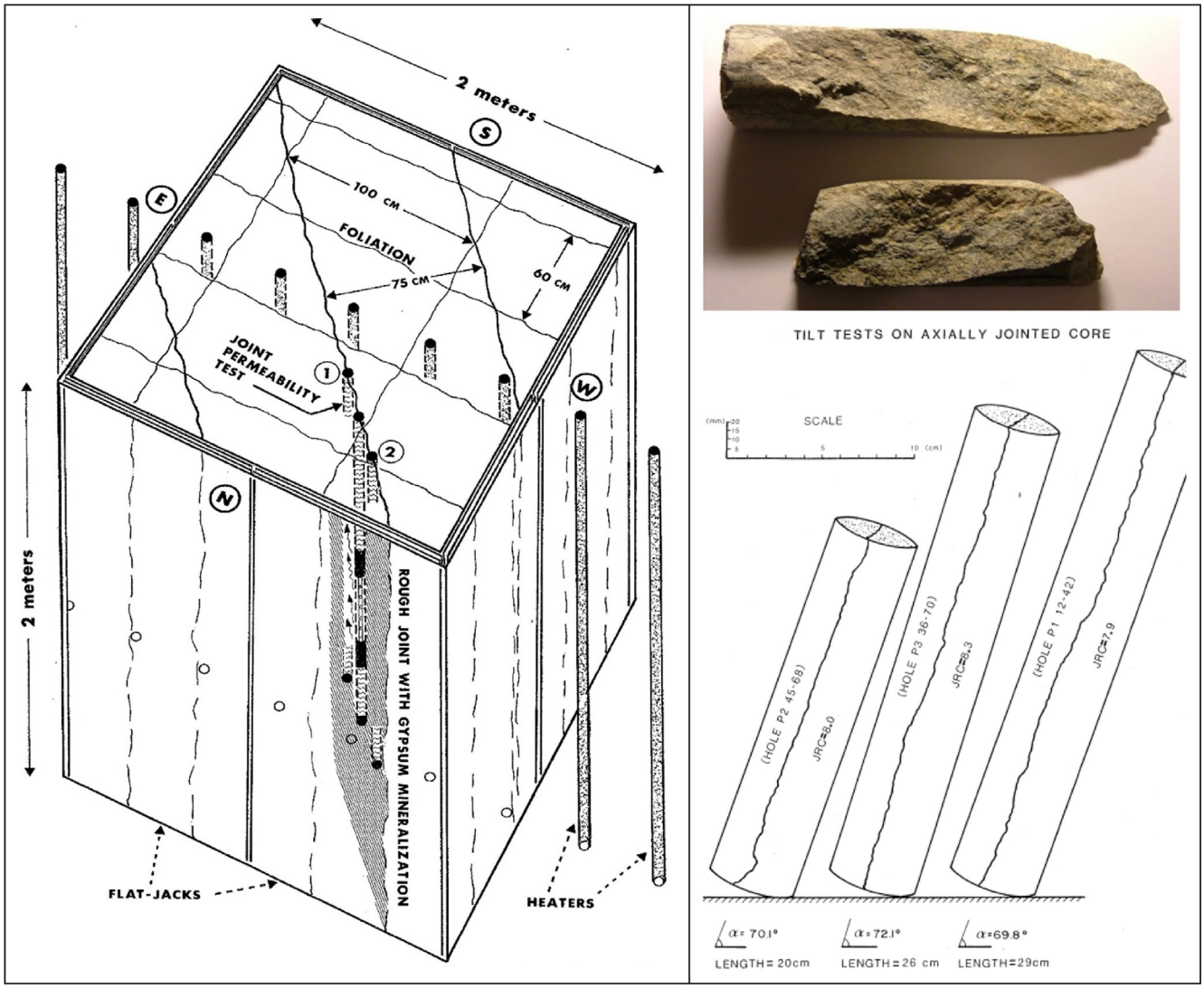

Fig. 4. Schematic of the Terra Tek/CSM *in situ* 2 × 2 × 2 m HTM block test showing mean joint spacings and borehole heaters. The permeability test joint is nearly a diagonal. It could be loaded up to 6.9 MPa normal stress. A moderate shear stress could be applied when loading with only one opposite pair of flat-jacks. Joint character and tilt test results from core in three holes are as indicated ($JRC_n \approx 8$, for 20–30 cm long samples). Hardin et al. (1981), Barton (1982), Bandis et al. (1981).

thermo-mechanical) heated block test, and assist in measurements and test data analysis, especially that related to elevated-temperature permeability testing. The block test was conducted in the Colorado School of Mines underground facility, in Colorado Springs, in very high strength *quartz monzonite* (incorrectly referred to as granitic gneiss in some publications). Extremely arduous vertical line-drilling to make space for twin pairs of stainless-steel and lubricated flat jacks, totaling 4 m^2 on each side was the forerunner to the installation of many types of instruments within and above the 8 m^3 block. (For details see Hardin et al., 1981).

The block was attached to the rock mass at its base, 2 m below the test adit floor. It could be heated using a line of borehole heaters. There was a nearly diagonal joint that was used for between-straddle-packer hole-to-hole (source/sink) permeability testing. A schematic drawing representing the average spacing of three sub-vertical joint sets is shown in Fig. 4. Tilt-test results with joint roughness JRC_n are also shown, with tilt angles, sample lengths and roughness profiles as recorded (Barton, 1982). The rough diagonal joint that was the subject of this particular set of HTM data (Fig. 4) had small-scale (nominal 100 mm length) $JRC_o = 13$, and $JCS_o = 90$ MPa. Hydraulic apertures were back-calculated before and after flat-jack-slot drilling, and during the loading, unloading, heating and cooling sequences shown in Fig. 5. The inset tabulation of hydraulic apertures in Fig. 5, indicates that ambient loading to 6.9 MPa (approx.) reduced the hydraulic aperture from about 50 to 30 μm. From this point, thermal loading to 74 °C *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 42 μm. There was a consistent mismatch of measured physical aperture change (ΔE) and the interpreted and smaller hydraulic aperture change (Δe) with assumed intrinsic permeability $k = e^2/12$. The approximation $e \approx E^2/JRC^{2.5}$ was suggested in Barton (1982), but slightly more sophistication was derived by Olsson and Barton (2001), who separately incorporated the effect of shearing and gouge. The mismatch of apertures e and E, principally for the case of joint closure as opposed to shear, is illustrated in Fig. 6.

Min et al. (2009) made alternative analytical interpretations of the above heated block test, using numerous assumptions and quite complex equations, and produced a model that could 'explain' the measured

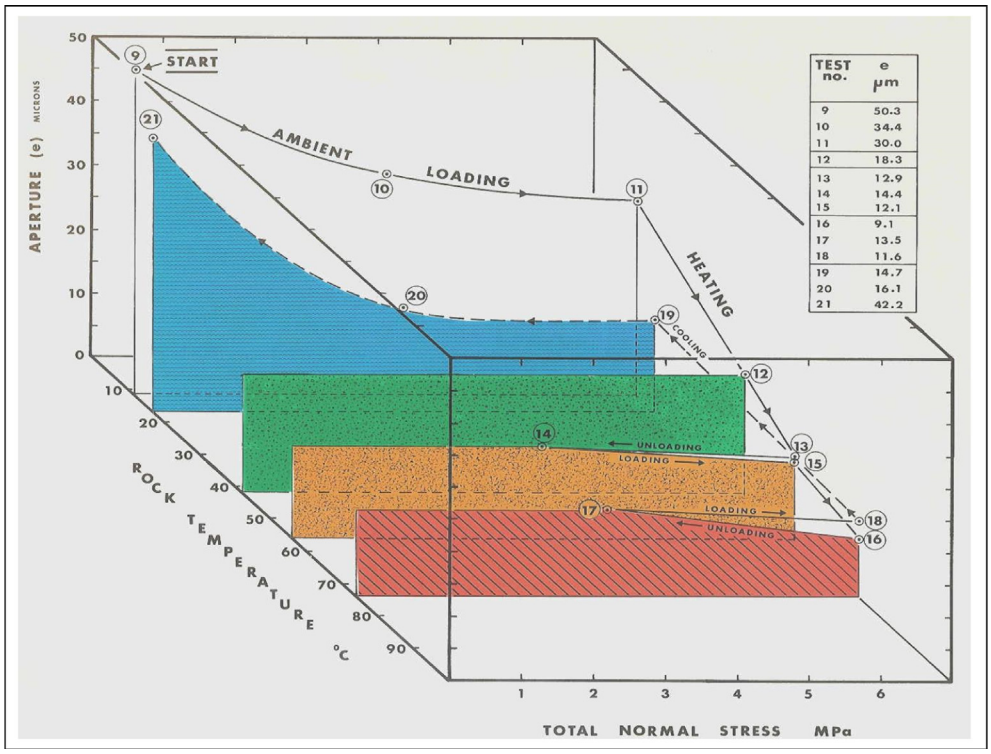

Fig. 5. Permeability tests showing both ambient and heated HTM stress-aperture behavior. The tabulated apertures are the back-calculated hydraulic apertures (e). The load-unload and heating cycles included biaxial 0–6.9–0 MPa at ambient temperature (12 °C) and heating to 41°, 56° and 74 °C while under a constant biaxial load of 6.9 MPa (i.e. 1000psi). Partial unload-load cycles and final cooling are also shown.

reduction in conducting aperture by means of a combined mechanical closure and 'dissolution-like' pressure-solution explanation. However, the model depends on calibration with test results, and some questionable 'residual aperture' assumptions (e.g. 6 µm under 'mechanical stress alone', and 6 µm 'under chemical solution') for which there are no supporting data. Nevertheless, many of the loading and heating stages of conducting aperture evolution are followed closely with their proposed dual-process model, However, the unloading effect at ambient temperature (points 19, 20 and 21 in Fig. 5) is not followed by the proposed model, which perhaps suggests that the 'chemical'

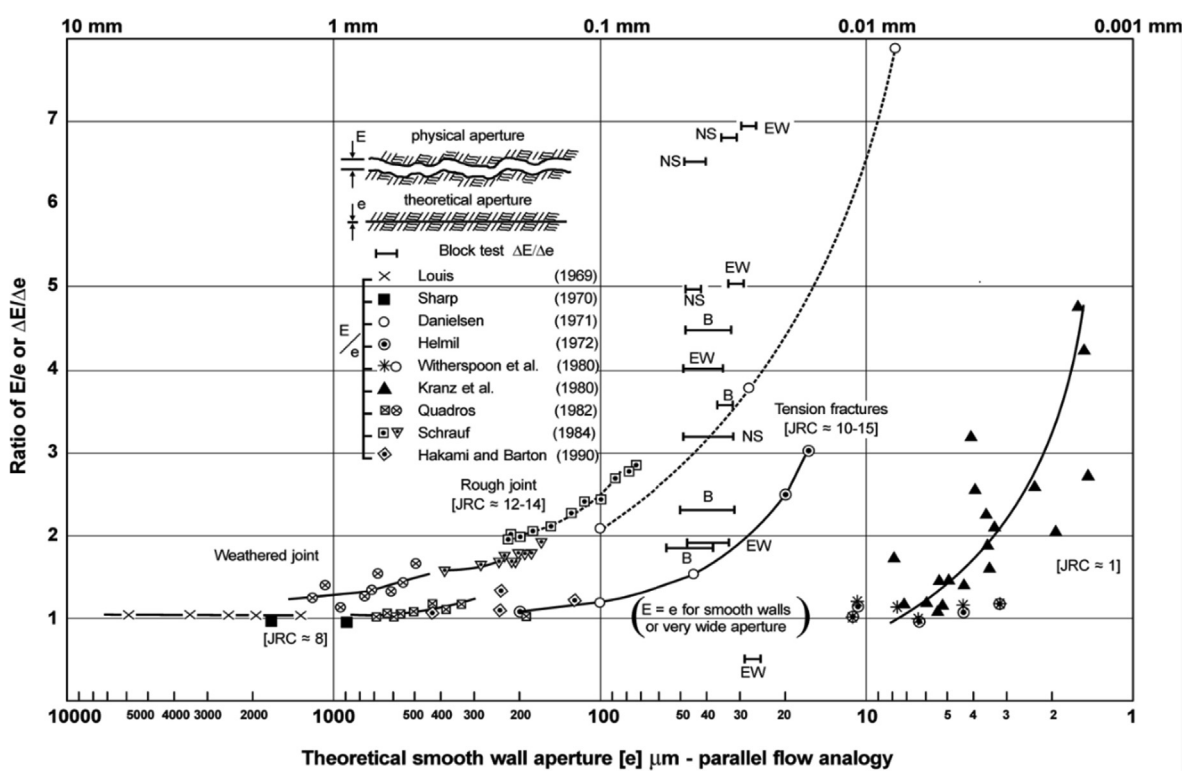

Fig. 6. Updated experimental data for differentiating apertures e and E and changes due to loading (Δe and ΔE) from Barton et al. (1985). All references appearing in the inset are given by Barton and Quadros (1997). Note that the 'vertical column' of bars is the data from the heated block test (Figs. 4 and 5): B = biaxial (normal stress), NS and EW represent slight shearing of the diagonal joint using opposed pairs of the 4 m^2 lubricated-sandwich of stainless-steel flatjacks.

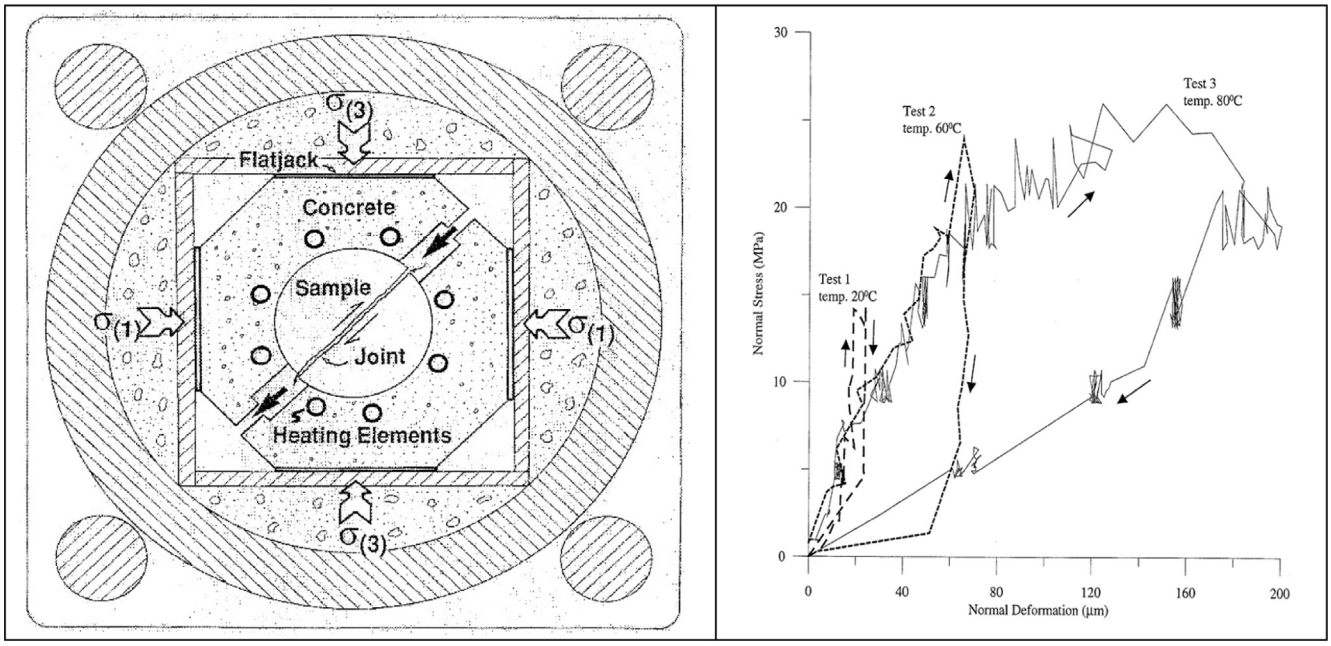

Fig. 7. Left: the CSFT (coupled shear flow test) apparatus used for MHT coupled-process joint tests in NGI in the mid nineteen-eighties and nineteen-nineties. Makurat et al. (1990). Right: URL joints in granite that were cyclically normal loaded and then heated during the 4th load cycle. Physical aperture changes (ΔE) were out of proportion to the normal loading, so thermal over-closure was suspected.

assumptions are more dominant than the mechanical assumptions concerning joint closure and opening. The conceptual model of asperity shortening and resulting aperture reduction used by these authors will be referred to later in this paper, and will be contrasted to the *frictional interlock* concept favoured by the writer.

4. Coupled stress flow CSFT laboratory tests

CSFT test methods described by Makurat et al. (1990), using the apparatus depicted in Fig. 7, showed *physical aperture reductions* when heating the joints, 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 20 °C, 60 °C and 80 °C of 24 μm, 54 μm and 151 μm, that were out of all proportion in relation to the moderate stress increases, and presumably with no possibility of pressure-solution in the short duration of the tests.

These reductions of physical aperture (ΔE) lead to smaller reductions of conducting aperture (Δe), due to roughness effects, according to the empirical conversion $e \approx E^2/JRC_o^{2.5}$ (Barton et al., 1985). An increase of 40 °C caused Δe to reduce by 39% in Test 2. The highest temperature cracked the Test 3 sample, so Δe was unreliable. This test method was utilized in several of NGI's nuclear waste related projects in this period: in the Stripa SCV (for SKB: Barton et al., 1992a), and at Sellafield (for UK Nirex: Barton et al., 1992b), and at URL (as Fig. 7) for AECL.

5. 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 Science Applications Int. Corp. engineers, for Sandia National Laboratories. This is shown in diagrammatic form in Fig. 8a, and the detailed jointing and permeability test joint are shown in Fig. 8b. 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 (0–10.6 MPa) and temperature cycles (48°, 69°, 94 °C measured at block centre).

Hydraulic apertures reduced from approximately 80 μm to a minimum of 50 μm along the diagonal test joint, in the first ambient temperature loading, showing little tendency to close further when the normal stress was increased beyond 5 MPa. But as a result of the heating, the interpreted hydraulic aperture reduced to approx. 35–40 μm (several measurements) but showed remarkably little tendency to respond to normal stress increase from 0 through 10 MPa. The thermal loading alone caused a mean closure of approx. 40 μm at zero normal stress, and a mean closure of no more than 20 μm as normal stress was raised to 10 MPa. (Zimmerman et al., 1985, Rutqvist and Tsang, 2012).

The measured joint roughness JRC_o for the NW-SE joint set that was showing this apparent *thermal over-closure* averaged 9.0 (range approx. 6–11). Representative roughness profiles measured on adjacent G-Tunnel walls are shown in Fig. 8c and the typical appearance of the joints is seen in Fig. 8d.

6. Plate jacking tests at Yucca Mountain

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 29.5 GPa respectively, based on the widely different load-deformation responses shown in Fig. 9. 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). Site observation by the writer confirmed this opinion.

This test suggests that the joints in the welded tuff, which were presumably formed at a temperature (and depth) different from that exposed 'in the nineteen nineties' were able to fit together better at the higher temperature side of the test. If this is the correct mechanism then there would be a temporarily reduced normal stiffness and therefore a

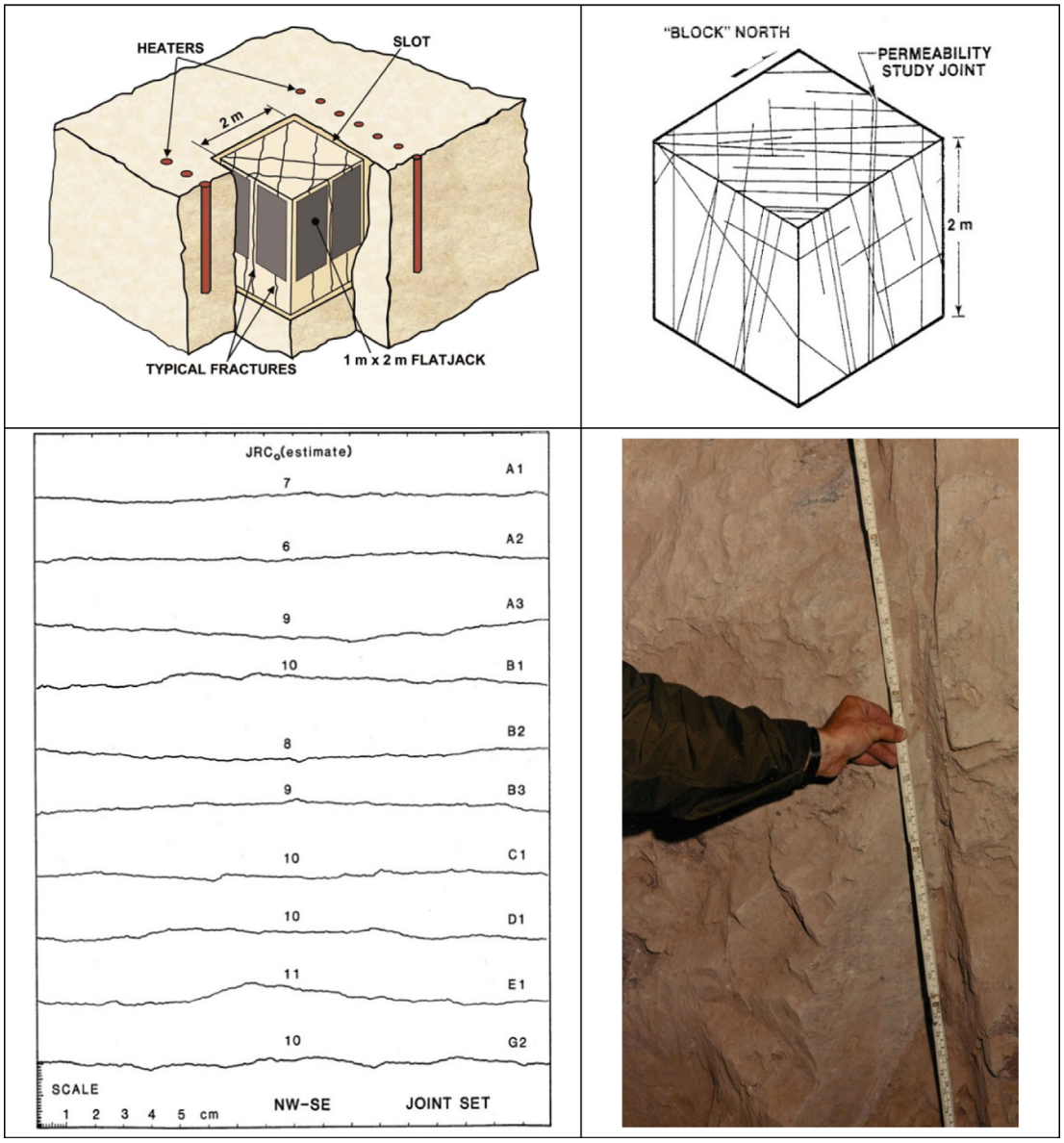

Fig. 8. HMT block test performed in welded tuff, in G-tunnel, Nevada Test Site. Zimmermann et al. (1985). The roughness profiles and JRC estimates were recorded by the writer. The top-left block diagram was reproduced from the comprehensive Yucca Mountain *in situ* test review by Rutqvist and Tsang, 2012.

temporarily reduced thermal expansion coefficient (for the rock mass, not for the intact rock). Parallel effects would be reduced joint apertures and increased seismic velocities. As we have discussed earlier, it is perhaps the 'homogenising' effect of thermal over-closure of the joints (rough joints would not normally close 'so easily') that actually brings the heated rock mass to behave *closer to* the way that heated intact rock behaves, but in the opinion of the writer, not quite equal to the intact rock, as that would defy rock mechanics logic.

7. Seismic velocity and permeability response to stress or depth increase

Without obviously claiming any thermal over-closure mechanism in the case of the shallow Norwegian Gjøvik cavern cross-hole velocity result shown in Fig. 10, it is nevertheless interesting that, despite no systematic increase in RQD with depth, nor any reduction in joint spacing, nor any improvement in the Q-value with depth, there was a 2 km/s increase in V_P over the depth interval of 10–60 m. This was presumably due to more tightly closed joints as a result of favourably high horizontal stress: it increased from about 2 to 5 MPa in the first 60 m depth. An equivalent result is expected if heating was to cause over-closure, as we presumably see in a later example from the Climax heated mine-by test, which had a reported 15 million instrumentation data points, but nevertheless difficulties in understanding the discrepancies between the modelling and the reality.

The result of velocity increase with depth, together with deformation modulus increase with depth, was extensively documented in Barton (2006). Principal results of this depth dependence are illustrated in Figs. 11 and 12. As an illustration, in the numerical modelling with UDEC-BB that was performed for the Gjøvik cavern, which is detailed in Barton et al. (1994), we already utilized moduli of 20, 30 and 40 GPa with increasing depth, and obtained a virtually 1:1 match of predicted deformation (7–8 mm) to measured deformation (7–9 mm) using UDEC-BB.

An increase of modulus with depth, which seems to be important, has apparently been ignored by the large number of people using RocScience and Hoek-Brown GSI based methods of numerical modelling. The 'standard' modulus estimate used in RocScience software, based on Hoek and Diederichs (2006) does not have the adjustment for depth, only a 'D' value (from 0 to 1) to make allowance for a reduced

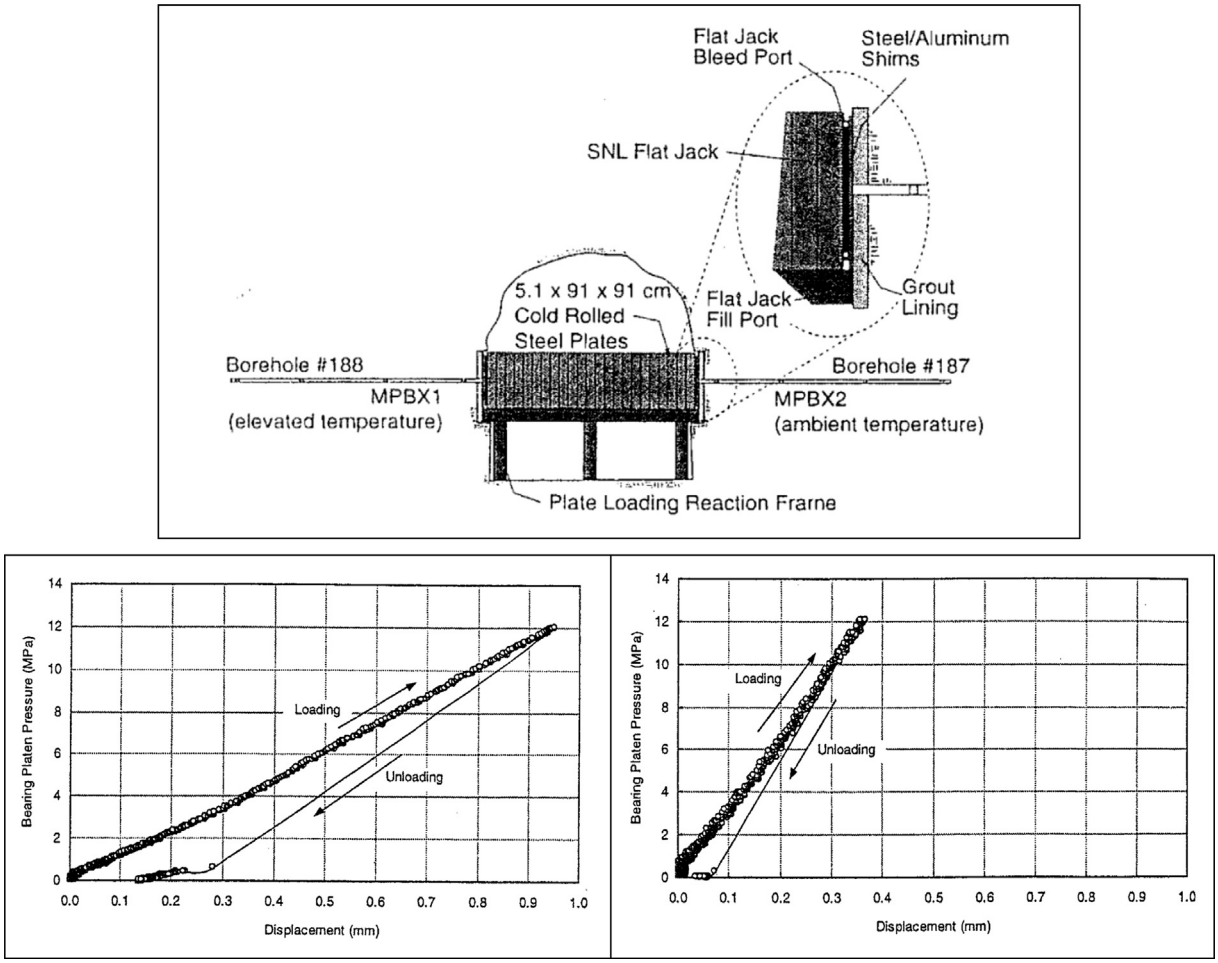

Fig. 9. An unusual, perhaps unique 'hot-and-cold' deformation modulus measurement in a test adit in welded (non-lithophysal) jointed tuff at the Yucca Mountain ESF Experimental Studies Facility. The measured E_{mass} (ambient, left) was 11.4 GPa, while E_{mass} (heated, right) was 29.5 GPa. George et al. (1999).

modulus for the EDZ, as described by Hoek and Brown (2019).

In reality deformation modulus data plotted versus the visual recognition method GSI (the 'geologic strength index') exhibits large scatter, and this can hardly be justified or adequately corrected, by invoking a 'disturbance factor' D of 0 to 1. Reviews of up to twenty models for predicting rock mass deformation modulus, many of them semi-empirical, are seen quite often in rock mechanics literature, for comparison with measured plate-load test results at specific dam sites. The predictive methods have almost without exception, *no adjustment for stress-level or depth*. This is surprising.

Fig. 11 shows an approximate empirical scheme that allows the user to adjust the deformation modulus (and seismic velocity) for increased depth, in other words allowing for the likely effect of ambient-temperature joint closure, and perhaps over-closure in the case of any rough-surfaced joint sets. As can be noticed, increased depth increases the velocity estimates. Many of the deeper P-wave velocity trends represented by the less inclined lines in the figure were based on deep cross-hole tomography performed at the UK Nirex Sellafield site, where NGI were responsible for some 10 km of core logging and selected joint index and laboratory shear and coupled flow tests (Barton et al., 1992b).

Rock mass quality and P-wave velocity have an important role in estimation/explanation of permeability variation both near-surface and at depth. For some reason, perhaps because rock mass quality Q is less familiar outside rock mechanics and tunneling circles, the variability of permeability with depth does not seem to have been related also to rock mass quality variation. The likelihood is illustrated in Fig. 12a, b, and c. (See Barton, 2006 for further details of the simple logic behind these potential Q-V_P -K linkages)

The 'central diagonal' line in Fig. 11 represents shallow refraction seismic results (nominal 25 m depth and nominal porosity 1%) which need adjusting for depth (+ve) or porosity (−ve). Note that deformation modulus (in GPa) as a function of depth can be linked to the increased P-wave velocity (in km/s) at depth, using the following equation: E_{mass} (or M) $\approx 10^{(Vp\ -2.5+\log \sigma c)/3}$, where σ_c or UCS is in MPa. Examples: If V_P = 3.5 km/s, and σ_c = 100 MPa, M = 10GPa. If V_P = 6.5 km/s, and σ_c = 100 MPa, M = 100 GPa. (Barton, 1995, 2007c).

The Q_c 'iso-curves' shown in reverse in Fig. 12b, indicate from the left: Q_c = 0.001, 0.01, 0.1, 1, 10, 100, and these values can, on the basis of the above approximation, be approximated by intrinsic permeability estimates of 10^{-11}, 10^{-12}, 10^{-13}, $10^{-14}m^2$ (≈1 Lugeon ≈10^{-7}m/s), 10^{-15}, 10^{-16} – and 10^{-17} m^2, if we extend the Q_c 'iso-curves' to the almost unjointed character of e.g. Rio de Janeiro's 'Sugar Loaf', i.e. an unjointed monolith with Q ≈ 1000 and σ_c ≈ 100 MPa for the moderately hard, massive granitic-gneiss.

Fig. 12c is reproduced from Rutqvist, 2015 who was reproducing, with the improved clarity of colour, the extensive permeability-depth data assembled by Juhlin et al. 1998 from SKB. Note that the opinions expressed in the diagonal inset are from Rutqvist. *Thermal over-closure and increasing pressure solution with depth* would have been suggested by the present writer, not 'void collapse. The missing link in these assemblages of permeability data seems to be the rock mass quality which varies widely, also down 1000 m deep boreholes in the same granite. Core from several such 1000 m deep holes have been Q-histogram logged by the writer, for SKB. (e.g. Barton, 2003 for the case of

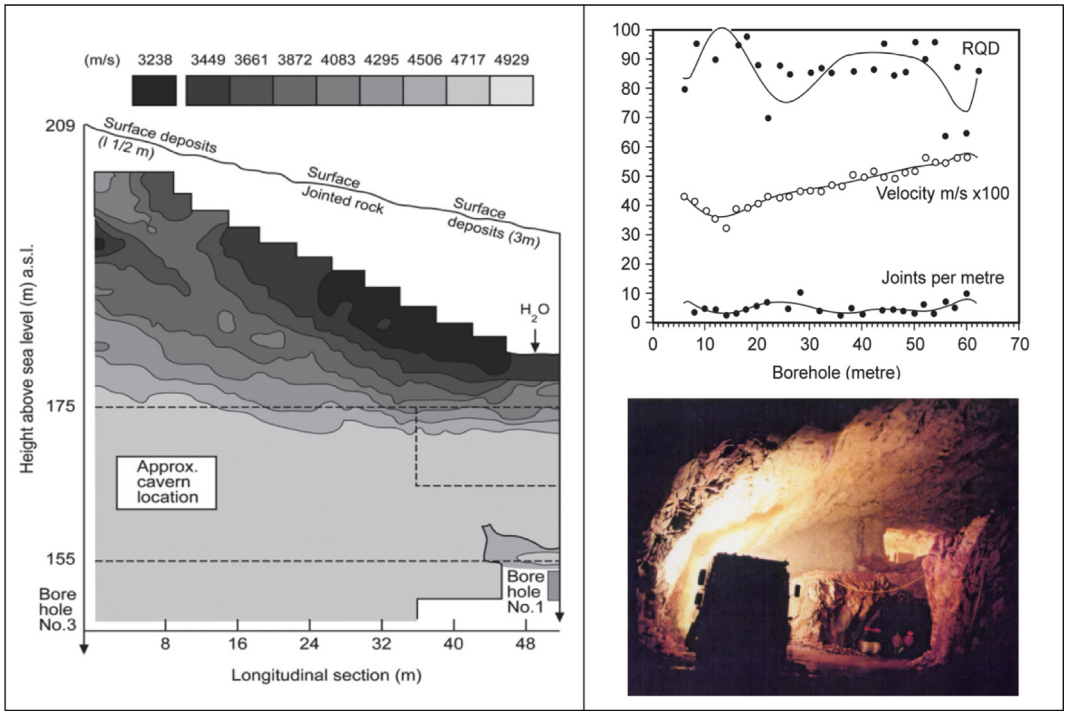

Fig. 10. Cross-hole seismic tomography velocity measurements between the four exploratory boreholes used for core recovery and stress measurements at the site of the Gjøvik cavern, indicated that there was a strong increase in P-wave velocity with depth. This was despite no systematic trends for increases with depth, for RQD, for joints/m, or for the Q-value, which averaged about 10. Barton et al. (1994).

Forsmark, hole KFM 01A).

8. 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 plan and cross-section showing the extensive instrumentation is shown in Fig. 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

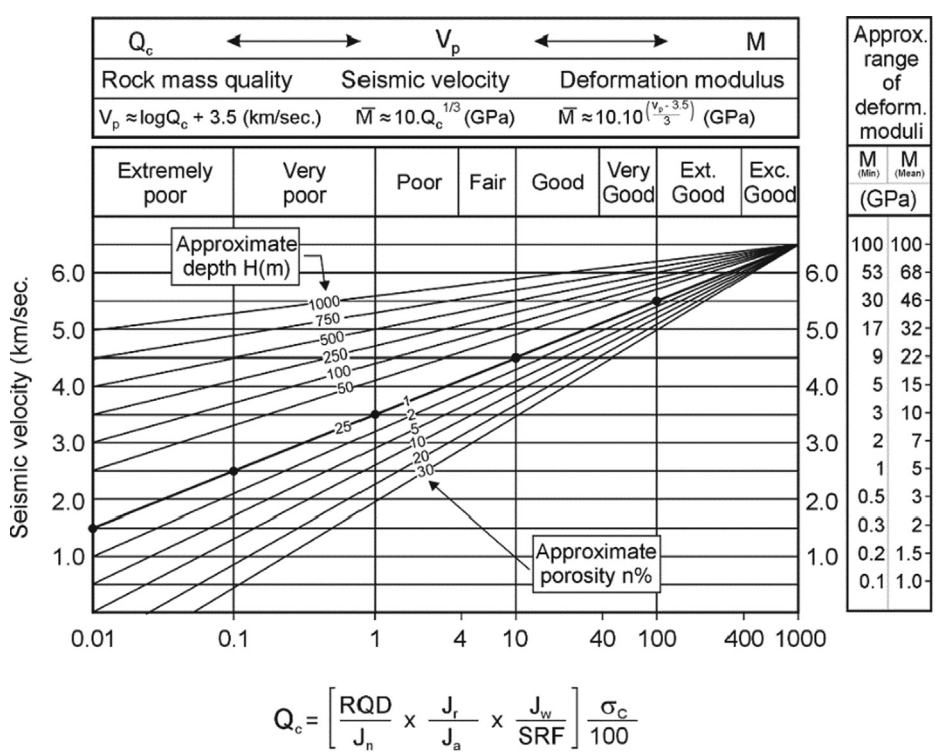

Fig. 11. The linkage between Q-value normalized by uniaxial compression strength and the P-wave velocity V_P. M is the estimated rock mass deformation modulus, also depth dependent. Barton (1995) and Barton (2002).

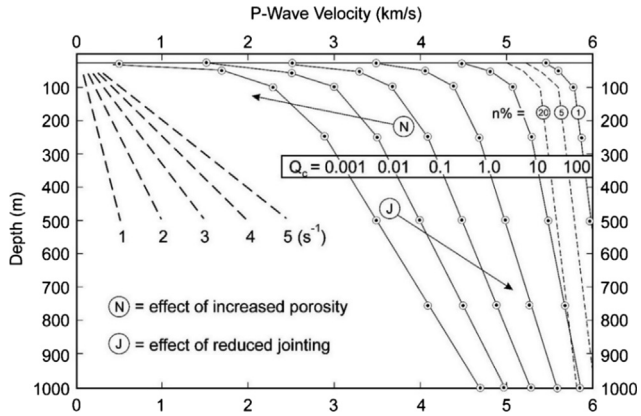

Fig. 12a. This figure illustrates an alternative plotting routine: velocity-depth-Q_c so that velocity-depth gradients can be estimated. Barton (2006). This textbook contains a chapter (Ch. 9) arguing for the theoretical similarity of Lugeon ($k \approx 10^{-7}$m/s) and the inverse of Q_c for the case of clay-free rock masses i.e. $L \approx 1/Qc$. (A parameter Q_{H2O} is used when clay-filled joints are present i.e. in the weathered near-surface, and it then provides a depth-dependent and rock mass quality dependent permeability estimate: Barton, 2007b).

dry. Joint frequencies were about 0.9–2.2 per meter in the test area, and there were reportedly four dominant joint sets (Yow and Wilder, 1993). The extensive instrumentation was designed to measure the bulk response of a jointed rock mass, to excavation of the central cannister drift 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 and partially jointed JPLAXD) calculations were performed to compare predicted performance with measured performance. In ADINA, 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. As a result of the Mine-By Experiment there was an unexpected reduction of vertical stress and a horizontal contraction in the pillars. Finite element modeling predicted the reverse, i.e. that load in the pillars would increase when the canister drift was mined. Instrument error was first suspected, but was eliminated by thermal calibration, i.e. calibrating instruments against alternative deformation and strain measurements, each as a function of temperature. (Hardin, 1992). This instrument calibration work at elevated temperatures was central in the CSM heated block test (Hardin et al., 1981).

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 Wilder, 1993). *Obviously non-recoverable*, thermally induced shear displacements were also reported. Thermally induced hysteresis, and deformation moduli and thermal 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, since we are quite likely to involve them in geothermal and (planned) waste disposal projects.

9. Characterizing columnar basalt – An obvious candidate for thermal over-closure

Some sophisticated characterization of columnar basalt was also made in the 1980s in the USA, in the hope of finding a suitable nuclear waste disposal geology. One of the USA's nuclear waste disposal candidates of the early and mid-eighties was the 900 m deep Cohasset flow, seen at the surface at the extensive Colombia River basalt exposures. Basalt was also found at a more convenient *shallow* depth for preliminary but extensive characterization studies, at the Near Surface Test Facility (NSTF) where it was the shallow Pamona basalt flow. Some interesting joint deformation effects were caused by the low horizontal stress levels at this obviously too shallow location, as revealed in an *in situ* heated block test, and at larger scale, in some cross-hole seismic measurements in a tunnel wall, which showed strong EDZ effects.

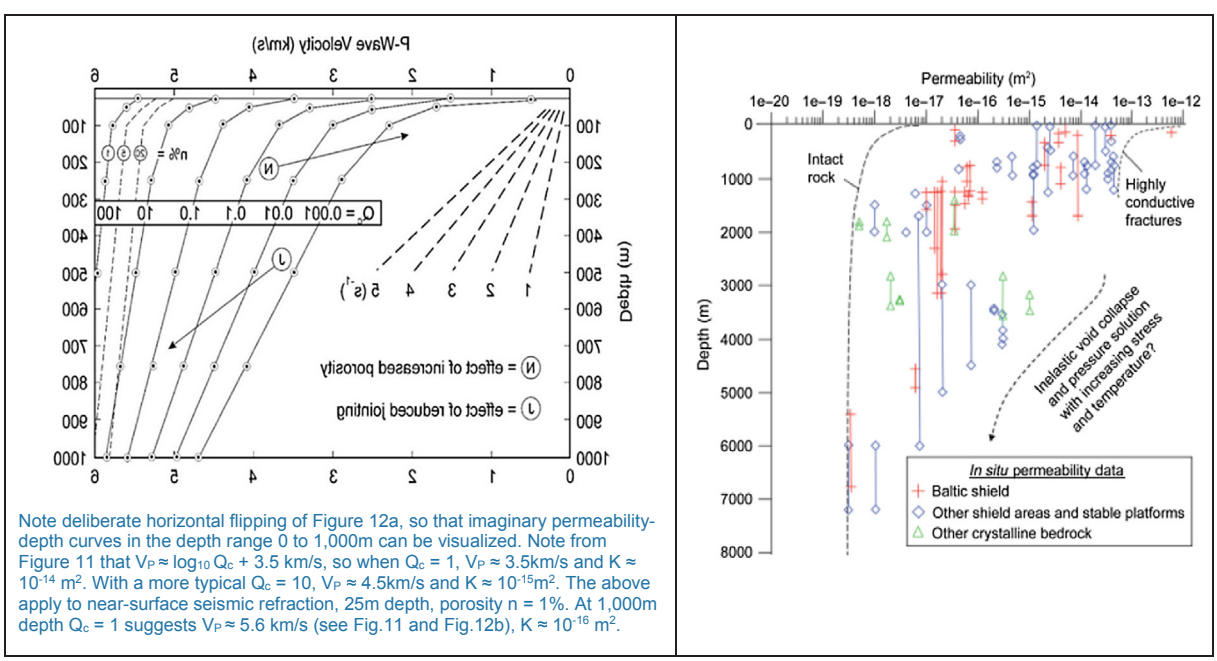

Fig. 12b and 12c. Since at 20 °C intrinsic permeability K of magnitude 10^{-14} m^2 can be approximately related to k of magnitude 10^{-7} m/s, we see that $K = 10^{-14}$ $m^2 \approx 1$ Lugeon $\approx 1/Q_c$. This allows us to make a tentative linkage between Q, UCS, V_P, k m/s (at 20 °C), and K m^2.

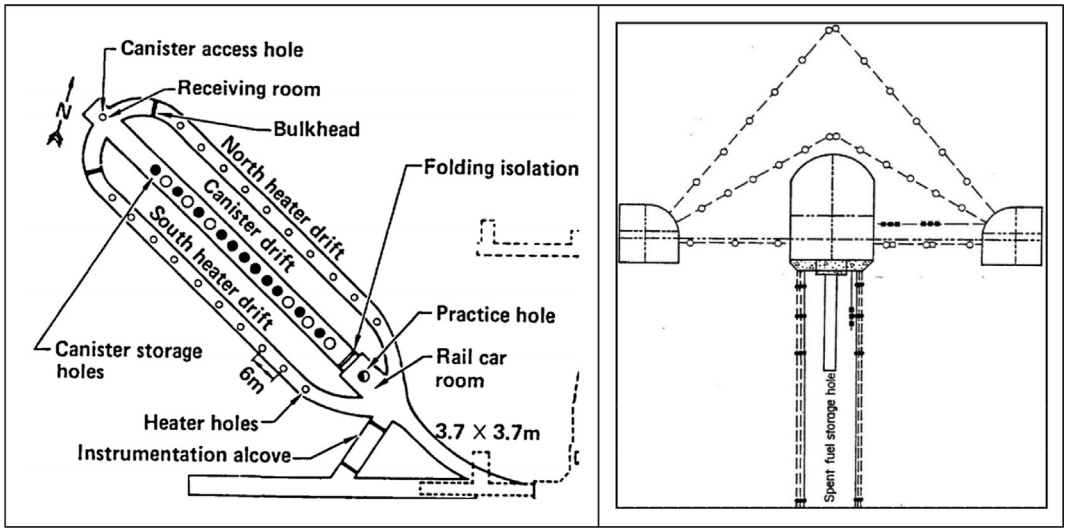

Fig. 13. Heated mine-by experiment in the Climax Mine Spent Fuel Test, in quartz monzonite. (Yow and Wilder, 1993). Counting instrumentation and heater holes, a total of 1570 m of core were obtained and analyzed at this mine-by experiment (Patrick, 1985). Strongly over-estimated deformations using ANDINA (2:1 and even 4:1) were the result of the thermal over-closure TOC phenomena. Butkovich and Patrick (1986).

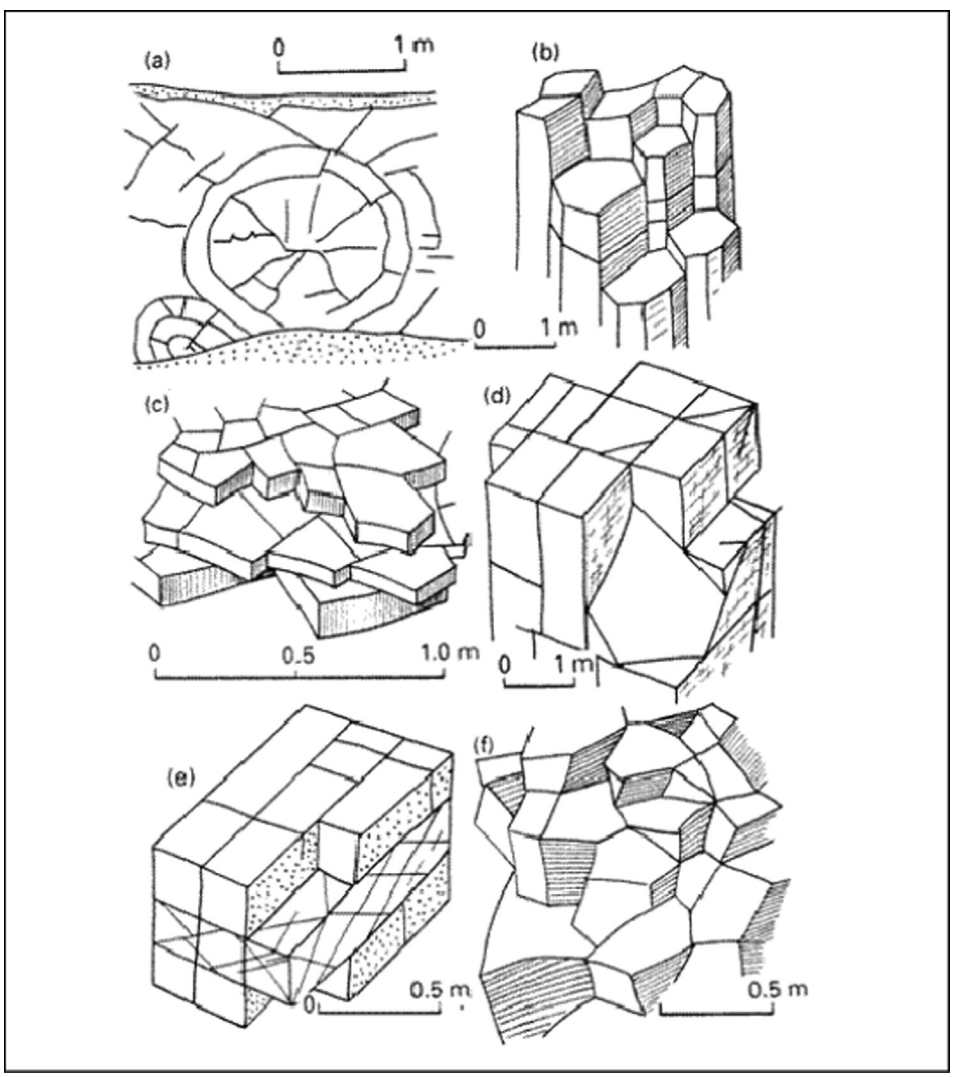

Fig. 14. Basalt forms blocks of many shapes and forms. (Source of figure unknown).

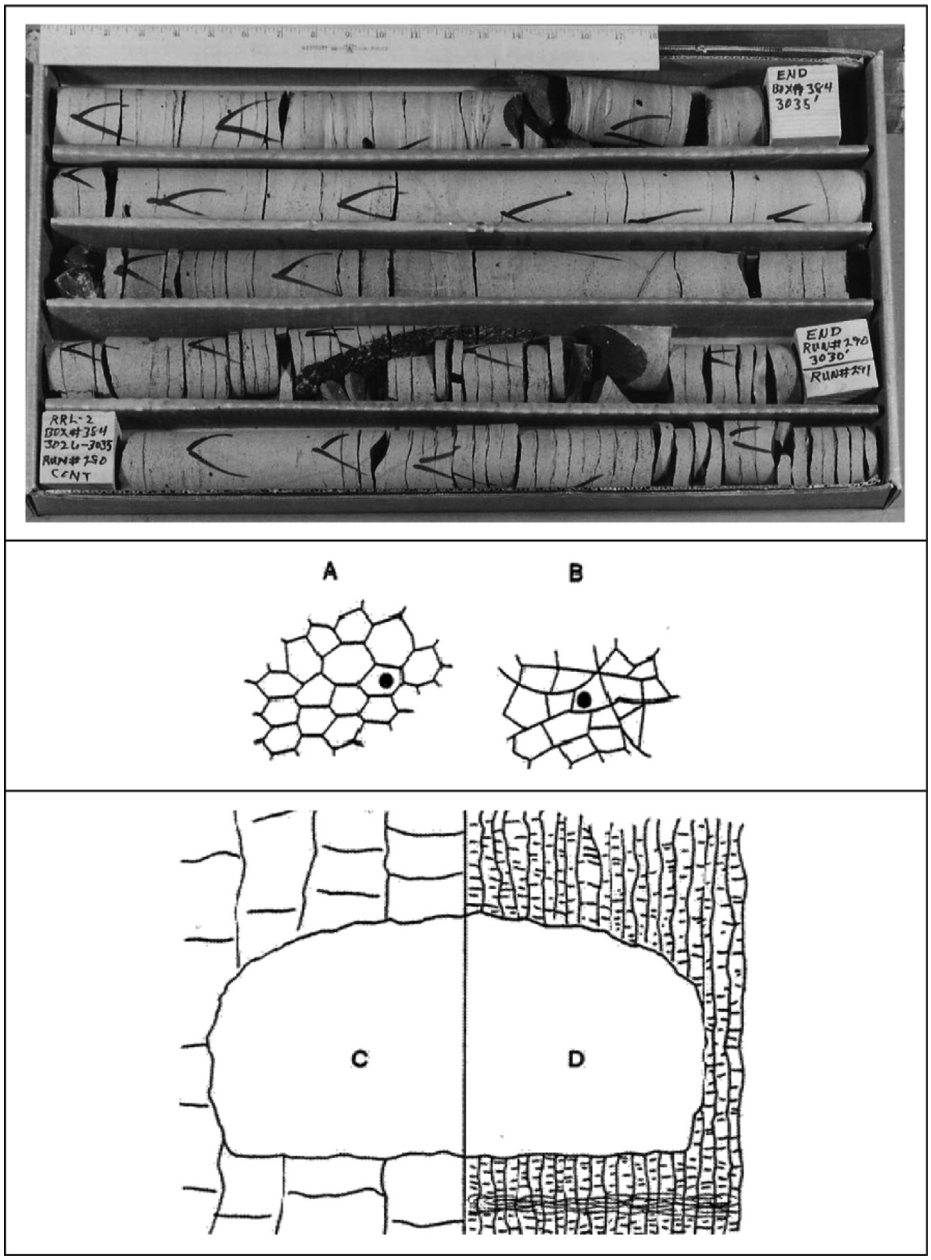

Fig. 15. Top: core-discing at more than 3000 feet depth. Comparative scales of boreholes in 'massive' rock and tunnels in jointed rock: either columnar or entablature. Stress-fracturing (core-disking or rock-bursting) in cases A, B, and (perhaps) C, but not in case D, due to a more dispersed tangential stress and greater deformation. (Barton, 1983. Unpublished TerraTek contract report).

At each scale, behavior was affected in special ways by the anisotropic joint properties and by anisotropic stress levels, particularly the low horizontal stress. However, the latter could be controlled in the block test, and thermal loading logically caused joint closure: i.e. closer to the original state just after the cooling joints were formed. An unexpected and quite unusual linear stress-deformation behaviour was measured in the block test, apparently due to the contribution of both shear and normal components of joint deformation (Barton, 1986). This mechanism will be illustrated and UDEC-BB modelled later.

Some site characterization was performed by the writer, along exposures of the candidate Cohasset Flow which formed impressive cliffs along the distant Colombia River. Several of the characteristics of jointed basalt that are illustrated in Fig. 14 were on display along this major exposure. Both joint properties and rock mass properties were described, in an attempt to evaluate their potential effect on disposal tunnels planned for 900 m depth at the candidate site, including possible tunnel support quantities. Deep drilling and stress measurements had indicated strongly anisotropic stresses of approximately 60, 40 and 30 MPa, and some cores, presumably drilled in the midst of large basalt columns, displayed strong core disking as illustrated in Fig. 15. The likely performance of the planned disposal tunnels at the same depth, was therefore of some concern. In retrospect, now knowing of the thermal over-closure phenomenon, some special effects could have been experienced at depth, such as higher than expected deformation moduli, as indeed suggested by the block test due to thermal over-closure of the columnar joints.

A conceptual image of joint-spacing induced 'scale effects' is shown in Fig. 15, to illustrate the likely relative effects of massive columnar basalt and the more jointed and irregular entablature, on the performance to be expected in planned disposal tunnels. We can estimate a possible maximum tangential stress of $\sigma_{\theta\ max} \approx 140$ MPa at 900 m depth if joint spacing is large (massive columns assumed), with failure

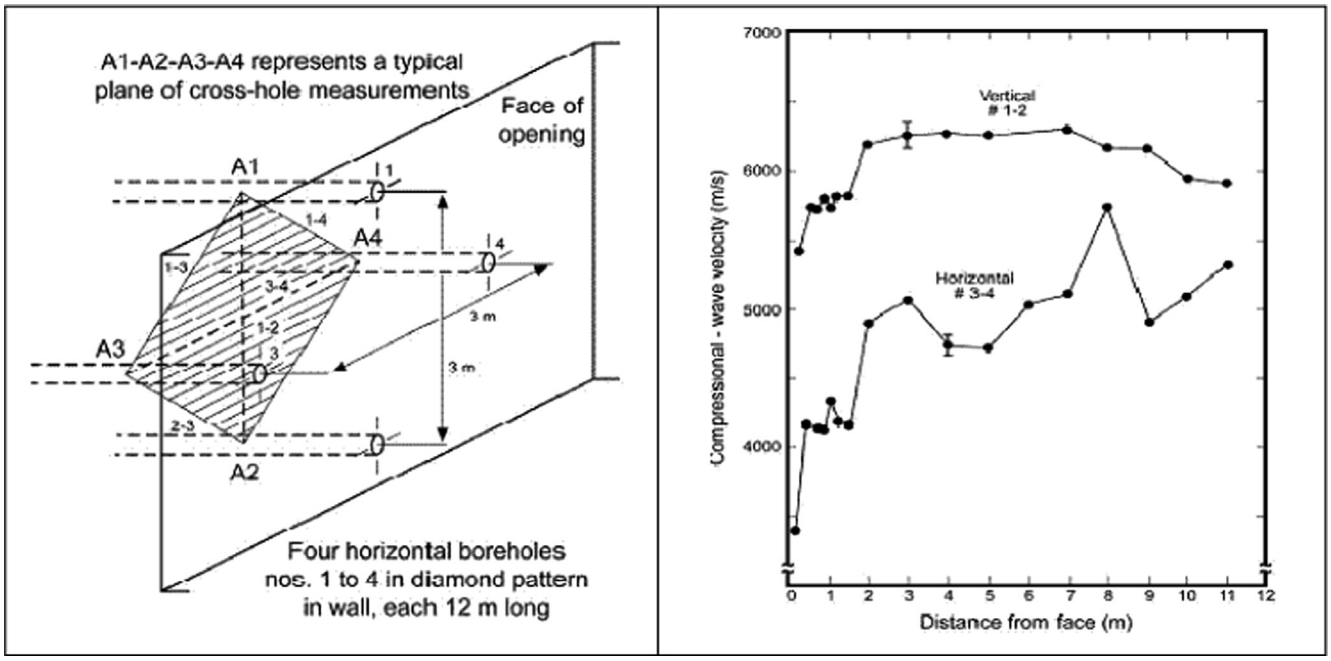

Fig. 16. The borehole layout for cross-hole seismic measurements in the wall of a drill-and-blasted experimental tunnel in principally columnar basalt. The vertical and horizontal ray-paths showed great contrast due to the low stress acting across the columnar cooling joints. The two diagonal seismic-ray paths #1–4 and #2–4 showed, in contrast, almost identical seismic velocities, with a plateau at about 5–5.5 km/s, and reduction to about 3.6–4.4 km/s in the outer 2–3 m. King et al. (1986).

initiation at about 0.4–0.5 × UCS (Barton, 1986). Today we know that the critical tangential stress (approx. 0.4 ± 0.1 × $\sigma_{\theta\ max}$) for explaining fracture (and AE initiation) can be replaced by the more relevant ratio of tensile strength and Poisson's ratio (σ_t/ν): see Shen and Barton (2018).

To further introduce the subject of cross-hole seismic measurements, because these will be the subject of *thermal over-closure* apparently experienced in the Stripa (Swedish/USA) nuclear waste related work, the following ambient cross-hole studies of King et al. (1986), will be related first. These researchers performed shallow depth cross-hole seismic in a part flow-entablature part columnar basaltic rock mass, in the NSTF. See Fig. 16. The basalt columns were regular but sinuous, 0.15–0.36 m in thickness, dipping 70–90°, with frequent low angle, discontinuous cross-jointing. The measurements were made between four horizontal boreholes drilled 12 m into the wall of a drill-and-blasted underground opening, at 46 m depth. The objective was to investigate the effect of blast damage and the inevitable stress re-distribution, i.e., two of the assumed chief components of the EDZ or excavation damage and disturbed zone.

The large contrasts in V_P values for the vertical path (#1–#2) and for the horizontal path (#3–#4) close to the opening (1.5–2.0 km/s difference) are a clear indication of the easily disturbed columnar jointing. There is also some indication of a tangential stress concentration effect: the background (far-field) velocity of about 5.4–5.8 km/s appears to be elevated by about 0.5 m/s from about 4 to 8 m depth in the wall, with a lower background velocity.

The sophisticated heated block test was one of the main components of the *in situ* testing at BWIP. Flat jacks were used to load four sides of the large jointed block and confinement on a fifth side was available too, by using cable anchors embedded deep inside the tunnel walls. (See next section for description of this block test). Unusually for jointed rock masses, neither concave nor convex load-deformation curves were produced: rather the load-deformation was *linear* when performed across the part-columnar part entablature jointing. Fig. 17 suggests how this 'linearity' may have been due to the combination of joint closure phenomena (concave) and joint shearing tendencies (convex). UDEC-BB models of these joint configurations also showed such trends. (Barton, 1993). However, there is no thermal closure or thermal over-closure modelling in UDEC-BB at present.

Note that in the case of simply *heating* the basalt columns, it would not be necessary to apply either biaxial or uniaxial loading (as here) because better fit of the columnar basalt is an obvious likelihood. How close to the surface one could experience thermal over-closure, in other words basalt columns with rough enough hexagonal joints that have remained closed is something to consider further. Perhaps over-closed 'columnar assemblies' (as for the slope-failed 'assembled blocks' in Fig. 1) would need to be compensated by opened-and-loosened columns nearby, so as to spread the contraction effect of early cooling more uniformly on a large scale.

10. Near-surface test facility in Hanford basalt

At the Near-Surface Test Facility, at Hanford, the third US flat-jack loaded and well-instrumented heated block test was performed in the USA. This was a 2.0 × 2.0 m cross-section block which was loaded and heated in the wall of a drift in the shallow Pamona basalt formation. Load in the third dimension was provided by cable anchors as indicated in Fig. 18. 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°–60 °C) to 2.59 × 10^{-6} °C^{-1} (over the range 60°–100 °C). At 100 °C, Cramer and Kim, 1985 reported a related 30% increase in deformation modulus, while at 200 °C there was a 135–190% increase in deformation modulus. All *in situ* moduli, even those at elevated temperature, were nevertheless significantly lower (at 20–48 GPa) compared to the intact rock value that averaged 86 GPa. 'An improved fit between originally mated joint walls at elevated temperature' is one of the familiar conclusions as the possible reason for increased moduli.

The increased temperature testing of the heated block of columnar basalt reportedly reduced the degree of inelastic and *continuously yielding* deformational behaviour. Translational 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 that formed at very high temperature, but not before the basalt was

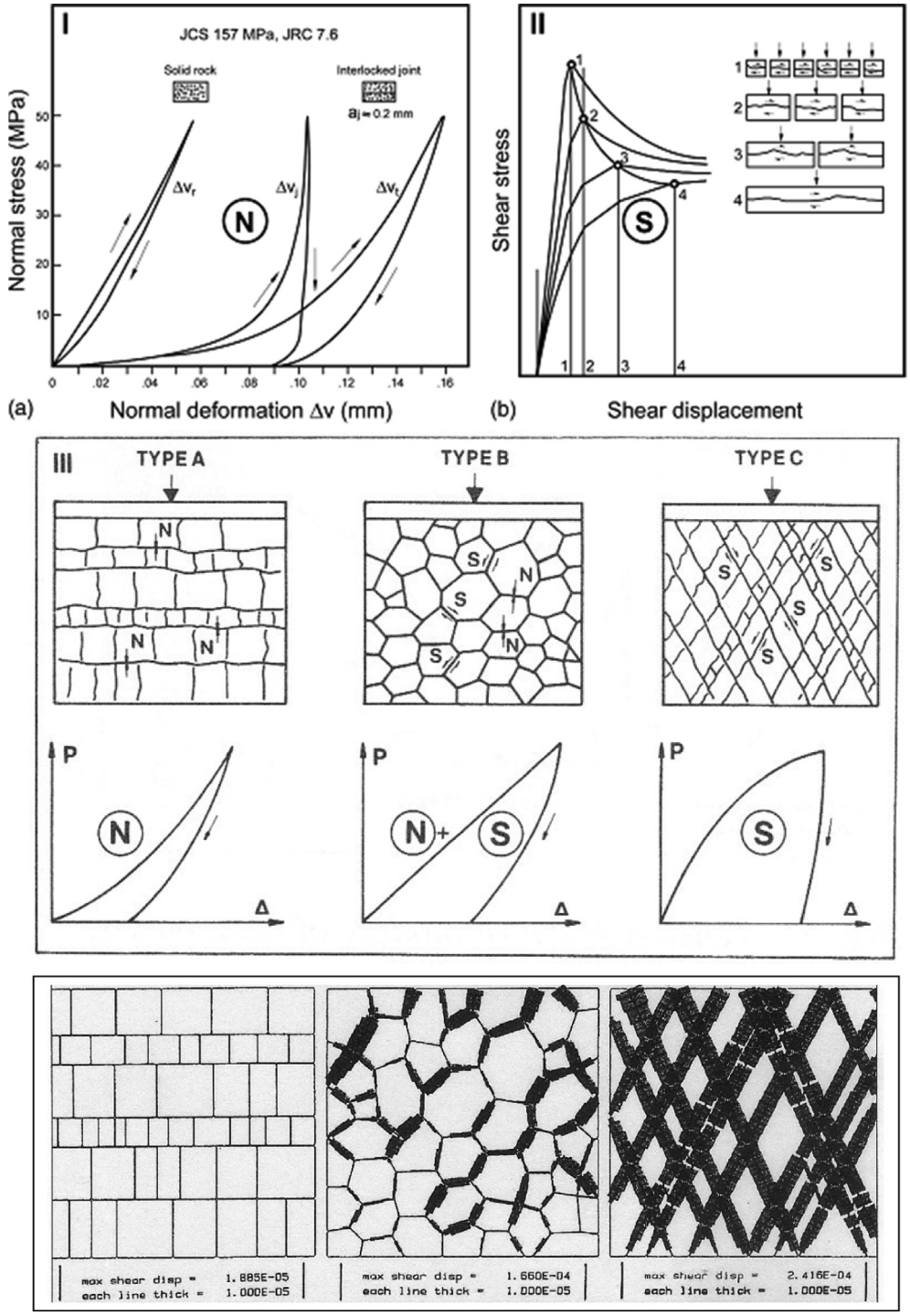

Fig. 17. Conceptual explanation of linearity and non-linearity, using the illustrated N and S joint deformation components, i.e. concave, linear and convex load-deformation curves, as also seen when performing *in situ* testing with specific jointing. Bottom: UDEC-BB modelling result obtained by Chryssanthakis (NGI) showing relative magnitudes of joint shearing (in black). Barton (1986, 1993).

sufficiently cooled and brittle to fracture. It is significant that values of the *coefficient of thermal expansion* measured *in situ*, at elevated temperature, were generally lower than laboratory generated values, which seems to be contrary to conclusions drawn from Yucca Mountain analyses, that laboratory values were adequate. This would be one of the results of joint closure with the rise of temperature – a process that in fact does not require normal stress increase.

11. Stripa borehole heater test effects on seismic 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 Fig. 19. The granitic rock mass was fractured and saturated. 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 to compensate for joints that were presumably *thermally over-closed*.

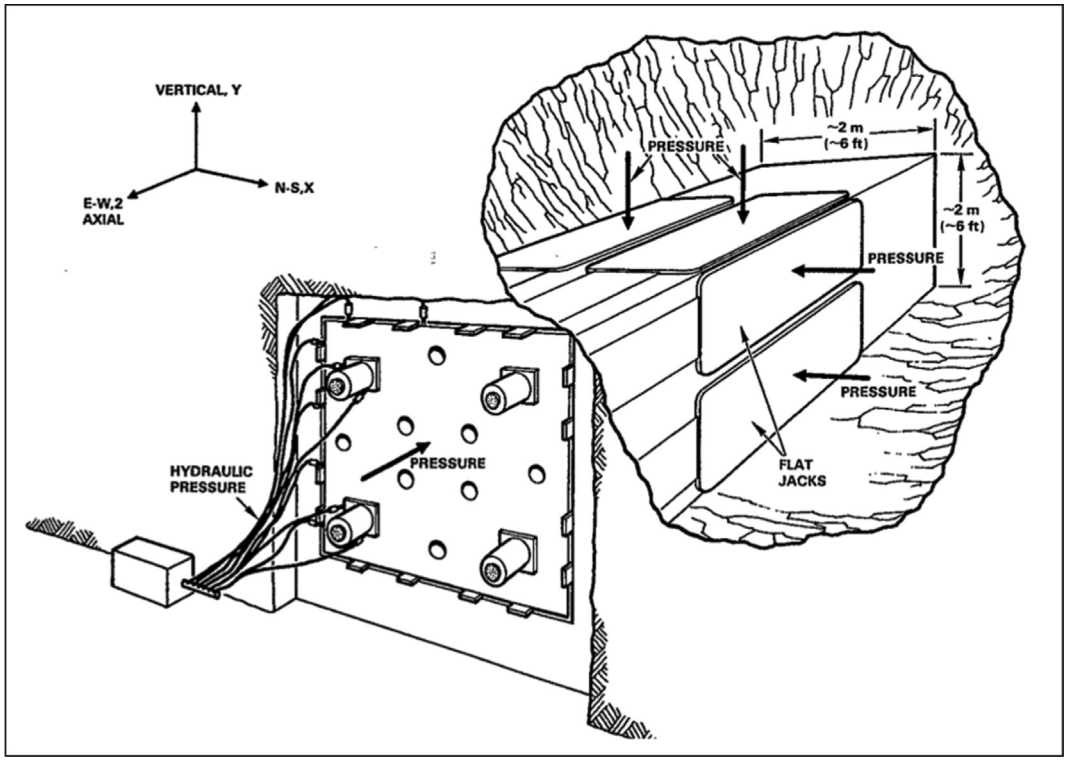

Fig. 18. Testing the thermo-mechanical behavior of a basalt flow (the Pomona basalt) at the Near Surface Test Facility, Hanford area, Washington by means of a 3D-loaded heated block test. Cramer and Kim (1986).

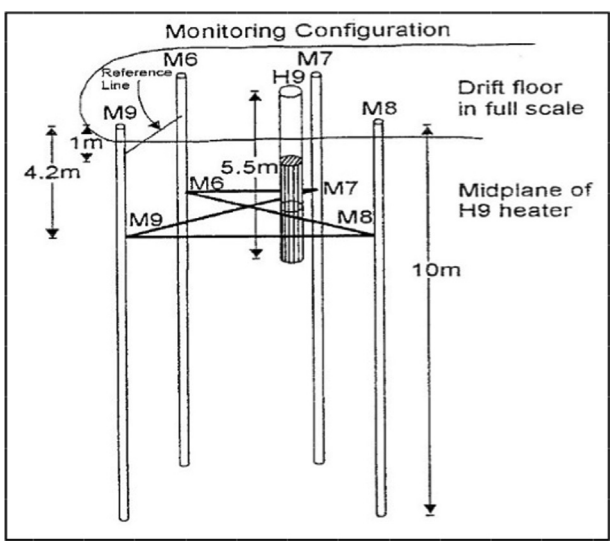

Fig. 19. The Stripa borehole heater experiment. Paulsson et al. (1985).

Rock deformation was less than expected and nonlinear during the first weeks of heating, and measured displacements were much less than predicted by linear thermo-elasticity (Hood, 1979). Later in the tests the displacements increased uniformly but in fixed proportion to predicted levels. A logical explanation is closing of fractures in response to thermal expansion. Fracture closure was confirmed by observation of water inflow into the heater holes and instrument boreholes (Nelson et al., 1981), and by increases in ultrasonic velocity during heating (King and Paulsson, 1981).

The non-linear, thermally induced strains were about half those expected from linear thermo-elastic analyses, using laboratory tests of the thermal expansion coefficient $\alpha^{\circ}C^{-1}$ on intact samples. These important effects were discussed by Cook (1983). The discrepancy, as at Climax, was likely due to *thermally-induced joint closure and hysteresis*, what we should be referring to as *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 per 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 initial *thermal compliance* of the joints. The full record of P-wave and S-wave velocities over the 750 days duration of the test is shown in Fig. 20.

12. Summary of TOC effects

TOC (*'thermal over-closure'*) effects in rock joints and/or rock masses have been measured or interpreted in the case of the following:

1. initial reduction in normal stiffness of the rougher joints ($-\Delta kn$)
2. thermal expansion coefficient reduction (because joints initially close easier)
3. subsequent deformation modulus, normal stiffness increase ($+\Delta E_{mass}$, $+\Delta kn$)
4. shear strength increase (due to joint closure) ($+\Delta JRC$, $+\Delta\varphi^{\circ}$)
5. rock joint physical and conducting aperture decrease ($-\Delta E$, $-\Delta e$)
6. rock joint and rock mass permeability reduction (until cooling) ($-\Delta k_j$, $-\Delta k_m$)
7. seismic velocity increase (until cooling, *then net reduction: because some joints open, rougher joints stay closed)* ($+$*then* $-\Delta Vp$)

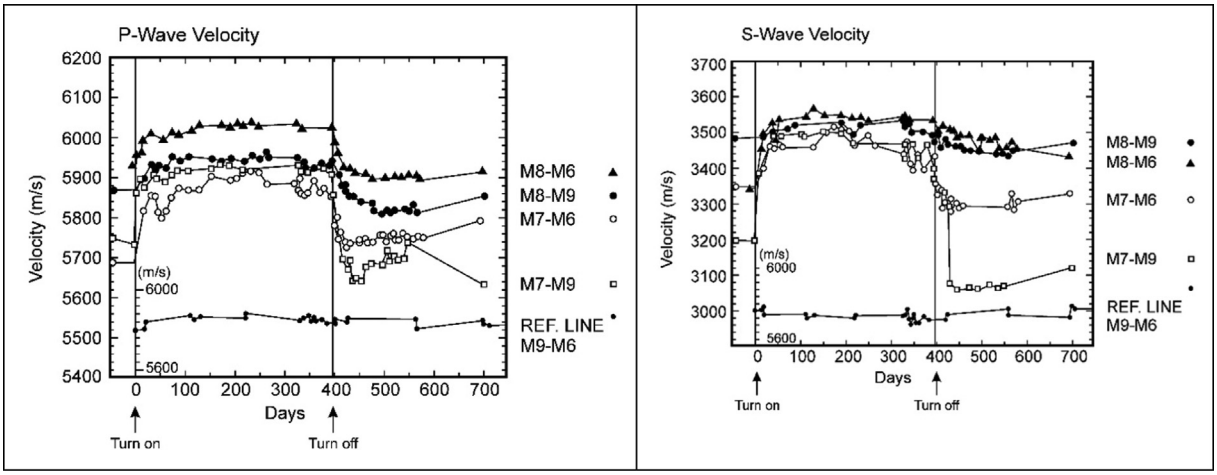

Fig. 20. Stripa borehole heater test, and the effects of prolonged heating and cooling on V_P and V_S. Paulsson et al. (1985). Re-drawn for greater clarity in Barton (2006).

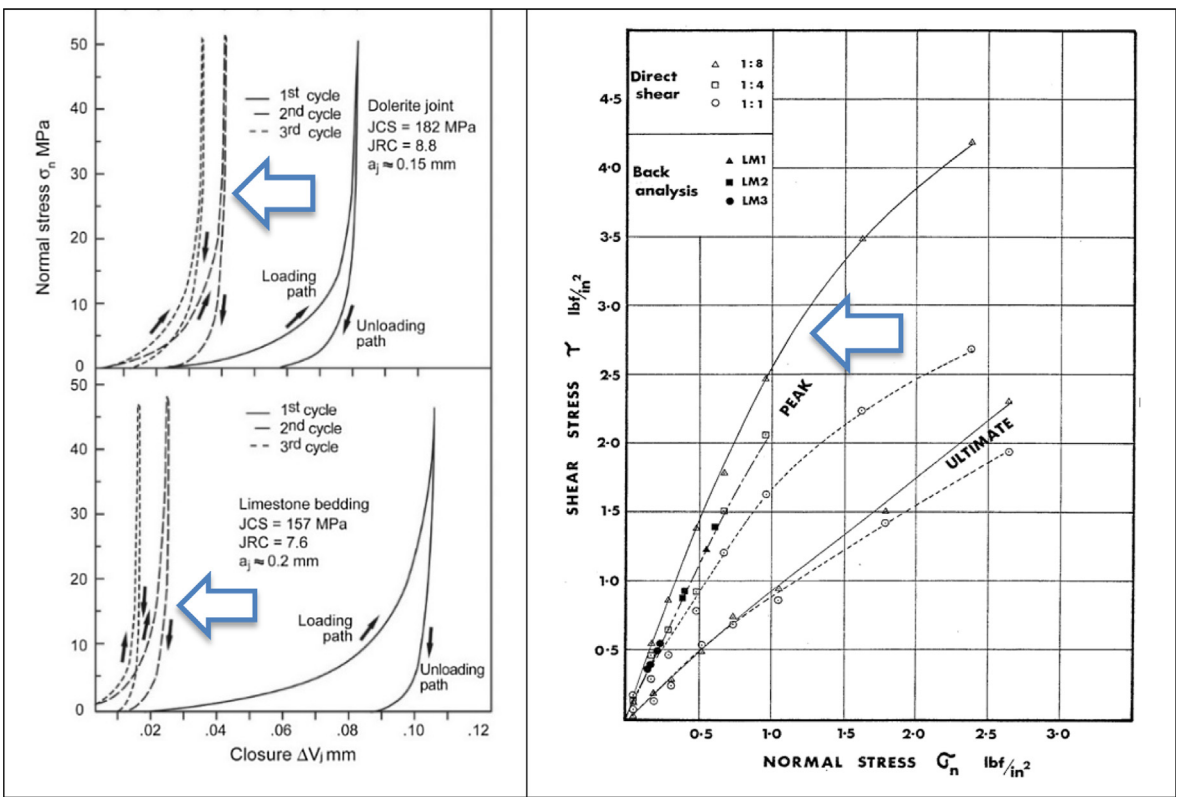

Fig. 21. Over-closure effects shown with arrows: assumed or measured. Left: Two examples of Bandis (1980) and Bandis et al. (1983) normal closure cycles on natural joints, as obtained from 'ambient temperature' load-unload cycling. The strong hysteresis and marked closure on the first cycle is due to 'sampling disturbance'. The arrows indicate what would happen if tested at higher temperature. Right: Three peak shear strength envelopes that were obtained with over-closure (OC) ratios of 8:1, 4:1 (i.e. ratios of prior normal stress to normal stress when shear tested) and 1:1 (conventional) prior to direct shear testing of the rough tension fractures. (Barton, 1971, 1972). Solid symbols show the result of back-analysis of the model slope failures, three of which (two prior to failure) were shown in Fig. 1. The six major slope failures recorded had a steeply inclined set of fractures with peak shear strengths corresponding (approximately) to an O-C ratio of 4:1.

8. numerical model prediction difficulties e.g. with a continuum FEM ADINA code, compared to HMT rock *mass* measurements: Discrepancy factor of 1:2 or worse: even deformations in opposite direction to what was modelled in pillar (Climax mine-by).

13. Discussion of over-closure mechanism and its possible wider consequences

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 our concept of 'ambient' temperature. 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/extension such as when a basalt cools, or

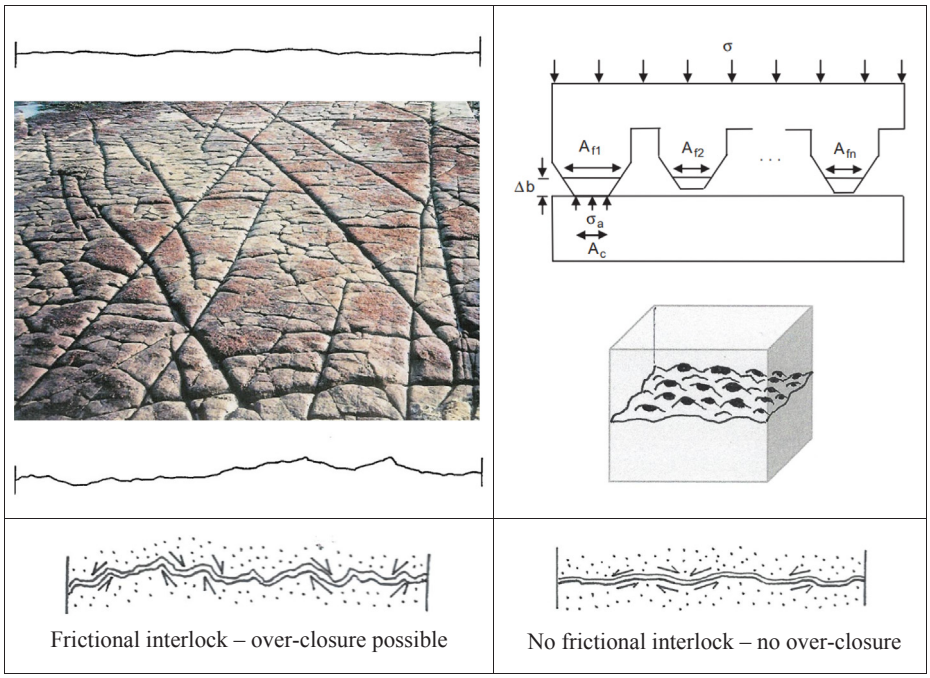

Fig. 22. Photo: Joints with variable roughness in a dolomite wave-cut platform, Kimmeridge Bay, Dorset, UK. Above and below the photograph are two of the Barton and Choubey (1977) roughness profiles for JRC = 4–6, and 16–18. Right: The 'asperity shortening' joint aperture model utilized by Min et al. (2009), and the 3D image of loaded asperity peaks, after Ogata et al. (2018) are given to emphasize their contrast to 'frictional interlock' (lower diagrams) which is the model of joint (over-) closure that can best explain the phenomena described in this paper: easier closure when heated, possible tensile strength when over-closed.

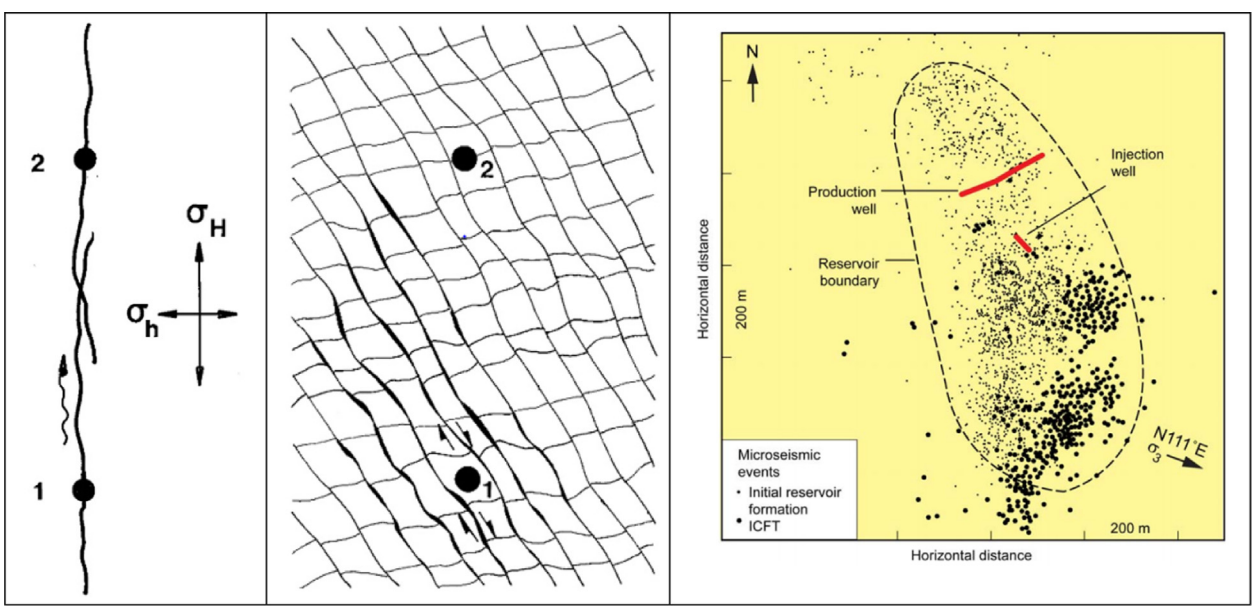

Fig. 23. Left: The idealized hydraulic fracture connection between a pair of wells drilled parallel to the HFRAC-measured major horizontal principle stress direction resembles a 1974 Los Alamos patent. In practice this idealized hydraulic connection proves almost impossible as the rock involved needs to be virtually unjointed. Centre: the additional sketch from Barton (1986) illustrates, in just two dimensions, the presumed difficulties experienced (in three dimensions) by several geothermal projects, with water hardly reaching the production well (#2). Right: Micro-seismic at Fenton Hill (Brown, 2009) during an MHF test showing the presumed capture of injected water into the jointed rock so that the 'reservoir' extended at about 45° compared to the minimum stress (direction N 111°E) and maximum principal stress directions. Different joint opening pressures were noted for different joint sets, and the highest pressure was needed for the set that was most closed. Could this be a sign of thermal over-closure, and the additional effect of chemical deposition in conveniently tight joints?

sometimes under shear stress in the case of tectonically-induced fracturing.

Today's rock joints sampled at the surface or near surface (1 km is also 'near-surface') have probably cooled by many tens if not several hundreds of °C, in relation to their formation temperature, perhaps near the brittle-ductile transition, or when deeply buried in a typical geothermal gradient. When cooled, the 3D roughness *fingerprint*, though very recognizable in relation to the original, would be subtly altered in its finer details. The tilt-test (or DST) back-calculated JRC values measured at ambient temperature on a recovered and unloaded joint sample, is likely to be too low (i.e. conservative) in relation to the undisturbed and probable thermally over-closed state, in the specific cases of joints with significant roughness.

The variable quantities of constituent minerals in igneous and metamorphic rocks, and in addition the important *differences in thermal expansion and contraction coefficients when heating or cooling* (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 shapes of (ambient) normal closure tests, as described in considerable number by Bandis (1980) and Bandis et al.

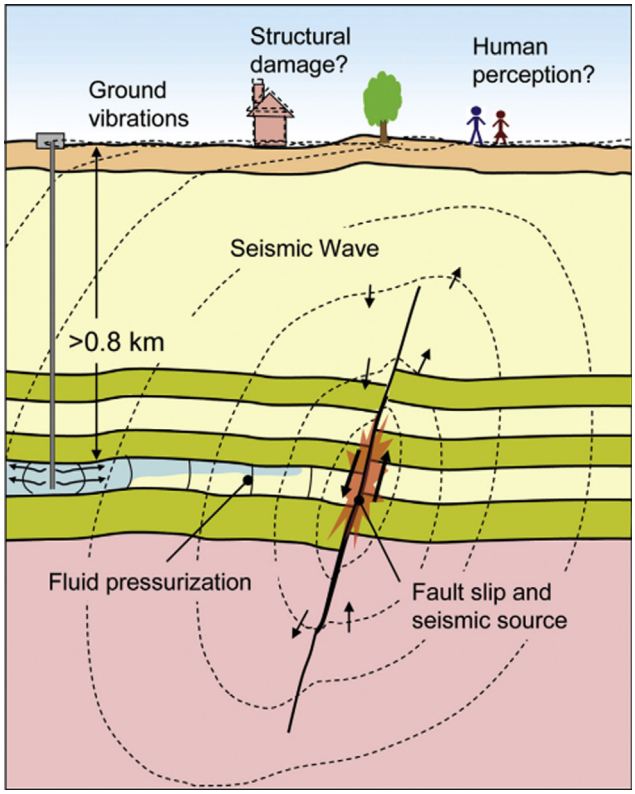

Fig. 24. Conceptualization of the risk of seismic triggering of fault slip by CO_2injection. Reproduced from Rutqvist et al. (2014). In the context of potential thermal over-closure, the blue-coloured fluid pressurization might cause a strongly anisotropic enhancement of rock mass permeability, thereby accelerating, or decreasing, the likelihood of a near or distant fault triggering.

(1983), for a wide range of JRC_o and JCS_o values. Some examples are shown in Fig. 21. (More examples are shown in Barton and Bandis, 2017). Heating the joint samples represented by these two examples of normal closure cycles, both for these two rock types, and for many, many others, would be expected to 'tighten' the load-deformation behavior considerably, which would be particularly noticeable in the first load cycle, as closure would become much easier with the better 'thermal fit'.

This is the reason that the normal stiffness initially reduces. Such a mechanism cannot be understood with 'asperity-shortening' logic because closure of mating joints is unlikely to be due to asperity shortening. The first load-unload cycle would move close to cycles 2 and 3, and these would also 'tighten' due to the better fit, thereby giving reduced physical aperture (E) and therefore an even smaller conducting aperture (e). The difference between these two apertures has been documented for the last 50 years so needs to be accounted for in modelling.

The large closure and hysteresis on the first load-unload cycle (Fig. 21a) is because of the relative 'lack-of-fit' that one has caused by testing at ambient laboratory temperature (usually 20–25 °C) i.e. not testing at the *in situ* undisturbed temperature, nor of course at the temperature of structural-geologic-origin, if this could ever be known with any certainty.

The *mechanical over-closure* and the *thermal over-closure* referred to in this 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 load rock joints to normal stress levels appropriate to pre-existing stress levels, *followed by* unloading to the presently relevant stress levels, *prior to shearing* in direct shear testing. This was done in Barton (1971) of necessity (see Fig. 21b) for the special reasons outlined in Fig. 1, and the over-closure mechanism was also confirmed later by Bandis (1980).

Under ambient conditions, maximum joint closure is aided by lower JCS_o (meaning weaker rock types) and lower JRC_o. However, when *thermally over-closed*, joints will have displayed an initially 'softer' normal stiffness aiding the thermally assisted closure, followed by higher stiffness and higher strength when the joints are more over-closed. In effect JRC_o will have been increased by the improved intimate interlock. This is believed to be a process of initially reduced friction in the *perpendicular* (closure) direction. This frictional resistance to closure (imagined more easily when magnifying the grain and crystal sizes) is higher for rough joints and lower for smoother joints, for the reasons sketched in Fig. 22. The inclined direction of the frictional resistance components becomes less steep as roughness reduces, so the perpendicular component resisting closure reduces. This is a different mechanism to *asperity shortening* which may apply to non-matching roughness, following shear, but then with some damaged asperity sides and perhaps sheared asperity peaks.

The $JRC_{mobilized}$ model of Barton et al. (1985) takes care of the shearing induced pre-peak and post peak changes of JRC, and the modelling of shear-displacement dependent dilation. Each are block-size dependent. Barton and Bandis (1982, 1990, 2017) give simple scaling rules, which are based on the mean spacing of cross-joints: those intersecting the joint set being modelled. In a realistic UDEC-BB model (see later), specific JRC-JCS combinations for the different sets of joints may have a variety of mean block sizes for scaling, i.e. L_n = 1.5 m, in relation to the nominal laboratory (core-sample based) length of sample L_0 = 0.1 m.

The jointed dolomite pavement illustrated in Fig. 22 can be used to illustrate some important aspects of thermal over-closure modeling. The longer more continuous joints have lower JRC, while the less continuous joints that occur between the major sets can be seen to have higher roughness. Imagine that this was a representation of a rock mass at depth. It would naturally be under stress and have a significantly higher temperature. However, if it was locally cooled by colder fluid in a geothermal or CO_2 injection, or when an HLW repository was finally cooling, the rougher shorter joints would likely remain (over-) closed while one or two of the smoother sets which were not over-closed would open easily, thereby allowing for the necessary thermal contraction. The results would be aperture increase, increased permeability, reduced shear strength, and possible 'capture' in the case of injected fluid. One can assume that this may have occurred in the Cornwall HDR and at Los Alamos' Fenton Hill. (See Fig. 23).

Conceptually representative roughness profiles with JRC_{100} = 4–6 and 16–18 have been utilized in Fig. 22 to represent the *frictional interlock* resulting in over-closure. In the opinion of the writer the asperity shortening models that are also illustrated only apply when the joints are mismatched, in which case there may already be damage to shear-opposed asperity slopes and possible sheared asperity peaks.

If the rock mass depicted in Fig. 22 became heated, these short, rougher joints could also close more efficiently due to better frictional interlock, and resist opening due to reversal of the small arrows. An increased deformation modulus at higher temperature is one of the fundamental results – also reduced permeability. Upon cooling these same joints would tend to remain locked with small aperture, thereby requiring opening of the more continuous joints to compensate for the thermal contraction. It is these more continuous joints that would usually be discretely modeled in a numerical model such as UDEC-BB or 3DEC-MC. However, because the (heated) deformation modulus of the rock mass as a whole will now actually be higher than expected (as suspected at Climax Mine-By) due to the heating initially reducing the thermal expansion coefficient, a correct modelling result is seriously prejudiced, as also demonstrated at Stripa in prior discussion.

An adjustment to the input data for such a model would be the requirement of thermal expansion coefficients that *included* thermally compliant rough jointing, if present. Some of the thermal expansion would thereby be absorbed. The negative factor might be that the

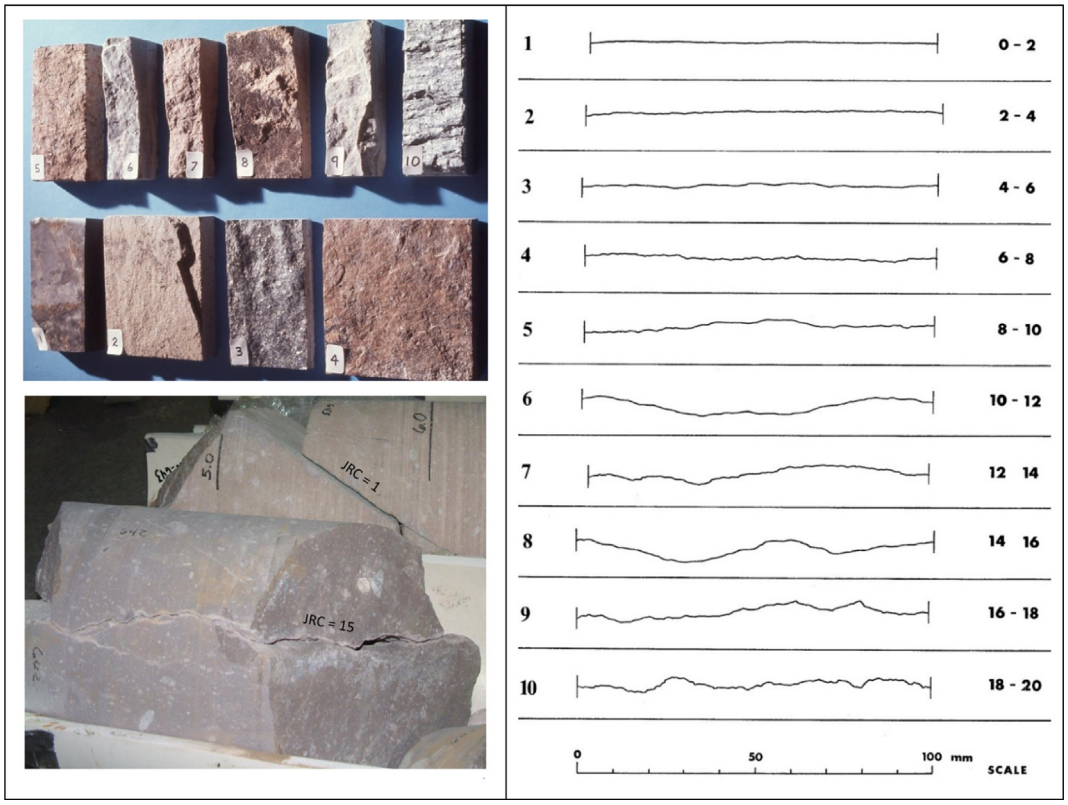

Fig. 25. The 'standard' ten JRC profiles (and the relevant samples) from Barton and Choubey (1977). Two contrasting joints recovered with large-diameter coring from Yucca Mountain are also shown. They have JRC_o values of approx. 1 and 15 according to the writer's back-analysis of DoE's direct shear tests. The rougher of the two joints must be expected to suffer thermal over-closure, while the planar joint, representing a different joint set, would clearly be opened during cooling, if in the same neighbourhood, to compensate for this over-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 in the case illustrated. There are traces of mineralization in the rough joint with JRC = 15.

reduced apertures would remain 'closed' during subsequent cooling, thereby potentially activating the major and likely more planar joints, giving lower shear strength and higher permeability. The writer frankly doubts that the thermal expansion coefficient of intact rock is generally sufficient, without the need to incorporate the thermally dependent closure of the jointing, as has been claimed in Yucca Mountain modelling. Such a conclusion seems to lack logic, so may perhaps be the result of instrumentation error in the case of the *in situ* testing.

The potentially adverse effects of *thermal over-closure* on nuclear waste cannister lay-outs, if using the SKB (Swedish) KBS-3 concept with copper cannisters in large diameter boreholes 'equally-spaced' along the floor of the disposal tunnels, is the following. Where there are more planar rock joints, cannister placement would be ill-advised, due to the enhanced risk of shear displacements on such geologic features. During the repository cooling phase the rougher joint sets would likely be suffering from *thermal over-closure,* thereby concentrating cooling/contraction effects in adverse locations, i.e. along the more planar joints, which are often more continuous.

This brings discussion to other injection/disposal scenarios such as geothermal energy projects and CO_2 sequestration. It appears from results so far that it is more difficult than expected to extract thermal energy by injecting cold water and producing geothermally heated water (or steam) from initial pairs of deep wells. Engineered (or enhanced) geothermal systems (EGS) seem to encounter a common problem that has been experienced by now on several occasions. The injected fluid often cannot be fully recovered from the planned producing well. In some cases as little 10%, even as little as 0.1% is recovered, due to apparent 'capture' of the injected water by specific joint sets. This has been experienced in projects in the USA, UK, Japan and France among others.

Interestingly and significantly, the early geothermal reservoir development at Fenton Hill in the USA saw 'extension' of the reservoir at approx. 45° to the direction of the major horizontal stress, as a result of MHF (massive hydraulic fracturing), signifying the greater influence of the jointing than the major principal stress. This is indicated in Fig. 23. Those concerned with the shearing strength of rock joints would probably tend to have expected such a potential result, when injecting cold water into a rock mass with one or more joint sets that may be under some magnitude of shear stress. It may be reasonable to observe that the thermal over-closure phenomenon explored here could increase potential 'capture-by-joint-set' geothermal production problems, since the cooling/contraction effect of regular cold-water injection and especially of MHF, would enhance the likelihood of permeability increase (and potential shearing) along a *more planar joint set* or along an individual planar feature such as a fault plane (if present).

To quote Brown (2009) concerning the development of a geothermal reservoir: *The major finding of the work at Fenton Hill is that an HDR reservoir should first be created from the initial borehole, and then accessed by two production boreholes. It is almost impossible to create an effective system by drilling the boreholes first and then trying to connect them by hydraulic pressurization.* With the benefit of hindsight this is easy to comprehend. It is interesting to note that at Fenton Hill different joint opening pressures were registered for different joint sets, and this reservoir, unlike some others, was not losing water out from its boundaries due to the tight, presumably thermally over-closed, and therefore perhaps partly mineralized joints.

The process of geothermal reservoir development starts with the injection of a fluid that is colder than the ambient conditions. Since fluid pressurization when desiring to store CO_2 also has points in common, we may expect that unexpected effects may also occur in the

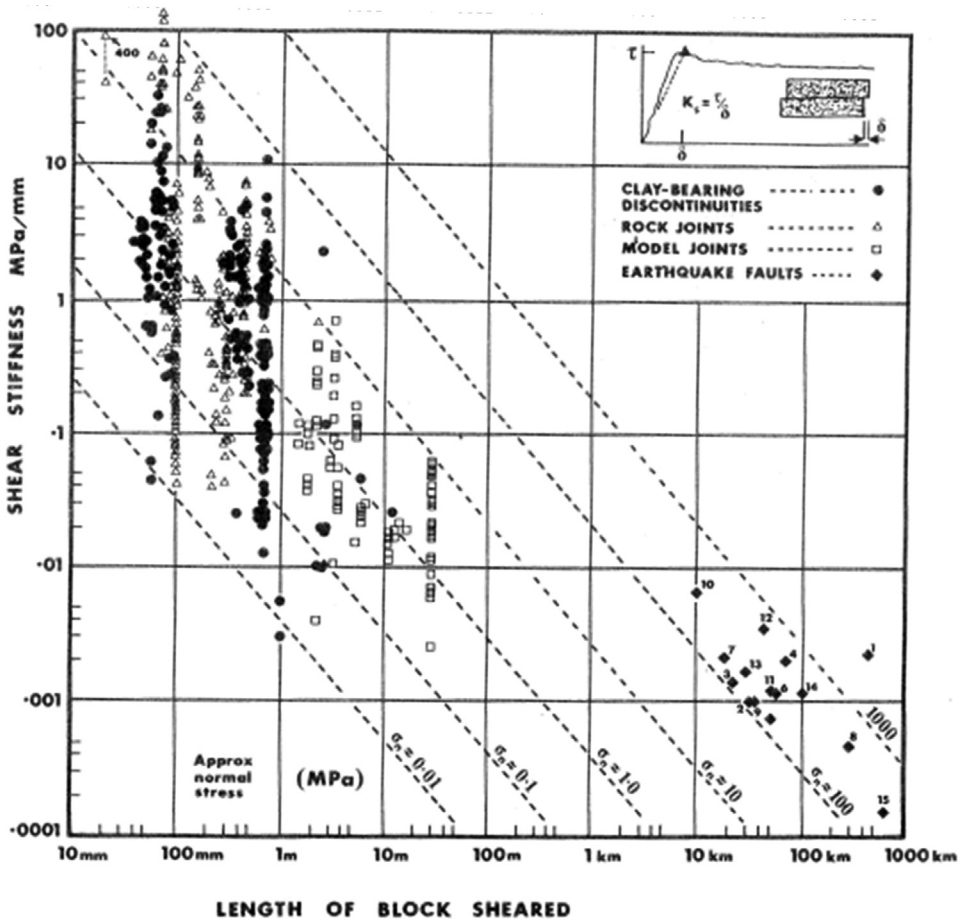

Fig. 26. A compilation of peak shear stiffness data measured for rock joints, clay-filled discontinuities, tension fractures (model joints) and tentative earthquake unloading stiffnesses. Barton (1982). This data is reproduced here because of the frequently erroneous and misleading (too high K_s) values seen in distinct element modelling publications.

case of CO_2 sequestration. A helpful diagram reproduced from Rutqvist et al. (2014) in Fig. 24, illustrates the fluid pressurization progressing in permeable strata, in this case with the possibility of triggering fault slip and seismicity. The thermal over-closure 'message' for such a case would be that the probable bedding planes and perhaps sub-vertical cross-joints or inter-bed joints will be likely to have different degrees of roughness. If this is correct then any smoother more planar cross joints (or bedding planes) are likely to open more than those which are rougher since these may be thermally over-closed. In other words, the local cooling may result in an anisotropic enhancement of rock mass permeability, with directional-flow implications. In the illustrated case (Fig. 24) this could accelerate or decrease the likelihood of seismicity, if the injected fluid is preferentially led towards or away from the fault zone. The cooling effect and the enhanced permeability would be a self-sustaining effect as the flow gradient would be preferentially maintained in the direction of greatest permeability.

Based on the data reviewed in this report, including several *in situ* block tests, it must be expected that the roughest five of the ten JRC profiles shown in Fig. 25 will be potential candidates for *thermal over-closure* effects. Interestingly, numerical modellers using 3DEC, modelled a combination of the planar joints response and 'therefore' zero dilation angles for their distinct element dynamic modelling of Yucca Mountain disposal scenarios for DoE, and therefore 'experienced' a remarkable quantity of rock block debris on top of and around the rail-mounted disposal cannisters, following numerous simulated earthquakes. One would have thought this would *unfairly* disqualify the part of the proposed waste disposal site in the jointed non-lithophysal. The following apparently incompatible input data were used: $\varphi = 41°$, $c = 0.1$ MPa (the latter are equivalent to JRC = 11 with JCS = 100 MPa at an effective normal stress of 10 MPa) yet the dilation angle d_n was assumed to be an incompatible 0°.

Remarkably the Yucca Mountain disposal drift modellers assumed $K_n = K_s = 50$ MPa/mm. (Such equality is a common and erroneous UDEC assumption). Investigations by the writer at the time on behalf of DoE suggested that Kn should be about 750 MPa/mm for fully consolidated joints following Bandis closure modelling (over the stress increment 7.5–12.5 MPa). The shear stiffness on the other hand should have been as low as 3–4 MPa/mm. Almost without exception $K_n > K_s$ by a factor of 10–50. (Barton, 2006, Ch. 16). In near-surface modelling, K_s can be as low as 1 MPa/mm (or the less comprehensible 1 GPa/m).

Extensive data sets of K_s assembled in a 1982 ONWI study (Barton, 1982: see Fig. 26 reproduced below) suggest rock joint *K_s values in the neighbourhood of 4 MPa/mm*, for ½ m block sizes and 10 MPa normal stress levels. It is remarkable how such dissimilar parameters as shear and normal stiffness can be given equal values by modellers. Why a 'global' friction angle of 41° would be chosen is unknown, when the opportunity existed to simply differentiate the joint set properties. Such differentiation will be very important if geothermal energy (and CO_2 sequestration) are to be realistically modelled in the future.

Let us imagine what changes would occur if the UDEC-BB modelling (Fig. 27) of the previously planned TBM-driven access ramp tunnel for the UK Nirex Sellafield LLW/ILW nuclear waste repository had thermal over-closure input data instead of ambient temperature testing results. The joint index testing was performed following convention, i.e. at ambient temperature, in an on-site laboratory jointly operated by NGI and Atkins (UK). Normal closure tests followed by DST (and occasional CSFT) were performed in our laboratory in Oslo, also at ambient temperature. *If instead we had heated the joint samples of ignimbrite/welded tuff to the same temperature as their formation temperature* of presumably several 100 °C, we would have registered significantly higher JRC (i.e. JRC_{TOC}) and in reality perhaps even tensile strength. The joint apertures would have been smaller, with much less hysteresis in the normal

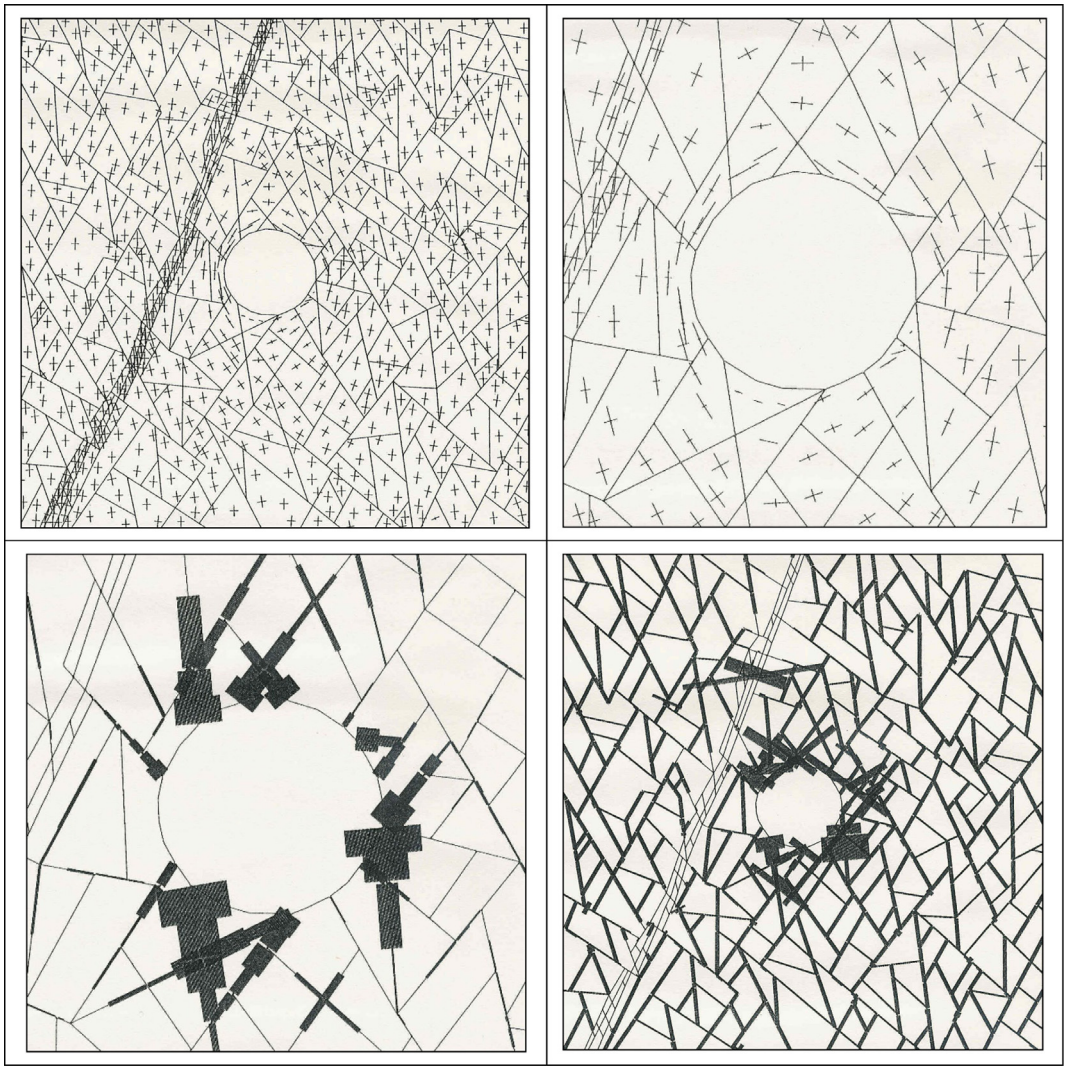

Fig. 27. UDEC-BB model of a 650 m deep section of a spiral TBM access tunnel to a previously planned nuclear waste repository at the Sellafield site in NW England. The input data was based on the results of very extensive Q-logging of many kilometers of recovered core, and included tilt tests, Schmidt hammer tests, and direct shear tests of joints in the welded tuff or ignimbrite. The basic joint-related input data for UDEC-BB is JRC_0, JCS_0, φ_b, φ_r, and mean block size L_n for each of the different joint sets. The four diagrams show principal stresses in an EDZ_1 of at least one diameter beyond the tunnel (note extent of principal stress rotations), and perturbations of joint shearing of max.7.6 mm and locally increased conducting apertures with a max. 2.0 mm block-corner or displaced wedge result. These joint perturbations represent EDZ_2 which is sometimes detectable out to about 1½–2 diameters. Maximum radial deformation was10.6 mm. An EDZ_3 would be blast damage of ½–1 m which is not modelled in UDEC but could be roughly added 'manually' though without the dynamic effect and blast gas penetration. The modelling depicted in Fig. 27 was performed by Harald Hansteen formerly of NGI. (UK Nirex contract report, Barton et al. (1991), see also Barton (2000) re TBM excavation responses).

closure cycling (refer to Fig. 21a), so the deformation modulus would therefore have been higher, and overall deformations would have been reduced. Joint shearing would have been reduced too. The conventional problem is the disturbance caused by core-drilling and core-handling, and of course the relatively cool, indeed 'extremely cold' 20°–25 °C temperature when testing in our conventional laboratories.

14. Conclusions

1. Numerous HTM *in situ* experiments, some of them heated block tests, others consisting of larger scale heating and cooling of the rock mass, have demonstrated a consistent phenomenon of changed properties caused by joint closure during heating. It is suspected that the HM, HTM and HTMC modelling communities have not yet taken mechanical over-closure and *thermal over-closure* (TOC) sufficiently seriously to attempt to allow for its potential impact in numerical modelling. Its numerous effects have also not yet been included in the Barton-Bandis HM constitutive joint model either, since we believe there is a need for further test results before definitive conclusions are drawn.
2. High-level nuclear waste disposal in geologic repositories, using such schemes as envisaged by SKB and POSIVA, will require respect for local joint characteristics when siting (drilling) and actually disposing of the waste-containing copper cannisters. The phenomena of TOC (thermal over-closure) affect normal stiffness (initially softer, subsequently stiffer), likewise deformation modulus, thermal expansion coefficients, shear strength, permeability, and seismic velocities. This is quite a significant list for effecting the results of numerical modelling, and it has been experienced in various (mostly adverse) ways. It is apparently ignored in predictive numerical MHT and MHTC modelling up to this time.
3. The TOC effect in coupled HTM numerical modelling will require 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. The mechanism of improved joint closure is believed to be due to 'TEFI' (*thermally enhanced frictional interlock)* for which we must assume initially mated joints. The TEFI mechanism is different to the commonly assumed *asperity shortening*, which the writer believes only applies to less common unmated, sheared and perhaps dilated joints, which may then have damage due to shear.

4. During the cooling phase of an HLW repository, one may experience rougher joints that have been thermally over-closed, and that may not open during the cooling phase. These joints have increased cohesive and frictional strength and reduced aperture. They may also be preferentially involved in chemical deposition and sealing since of smaller aperture. Assumed site permeabilities will be locally reduced and the required hydration of the bentonite surrounding the disposal cannisters might even be compromised.
5. 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 in a locally unfavourable way. This should alert designers and future HLW disposal contractors to avoid the continuous and more planar features in their disposal canister deployments.
6. In the case of geothermal projects, and also relevant to CO_2 sequestration, a temperature reduction at the injection well must be expected. If for instance all joint sets (or a specific set) which have JRC_0 greater than approx. 10 remain thermally over-closed, then the smoother set or sets may have to compensate with more opening. This could lead to reduced strength, larger aperture due to the forced opening, and shearing-induced dilation, with the possibility of resultant micro- seismic events. The resulting geothermal reservoir may develop in unplanned directions, as in the Cornwall HRD and at Fenton Hill, to name just two cases.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Glossary of abbreviations

CSFT: coupled shear-flow tests (of a joint or fracture in rock)
DST: direct shear test (of a joint or fracture in rock)
EDZ: excavation disturbed zone (several components of EDZ will be described)
e and E: joint hydraulic and mean-physical apertures
E_0: unstressed mean-physical aperture
HDR: hot dry rock
HLW: high level (nuclear) waste
HTM: hydrothermomechanical (*hydrothermalmechanical*) coupled behaviour
HTMC: hydrothermomechanicalchemical (*hydrothermalmechanicalchemical*) coupled behaviour
JRC: joint roughness coefficient, JRC_{OC} and JRC_{TOC} (over-closed, thermally over-closed)
JCS: joint wall compressive strength
NGI: Norwegian Geotechnical Institute, Oslo
NSTF: Near Surface Test Facility
MHF: massive hydraulic fracturing
ONWI: Office of Nuclear Waste Isolation
Q: rock mass quality rating based on joint characterization ratings (Q = RQD/Jn x Jr/Ja x Jw/SRF)
UDEC: Universal Distinct Element Code (developed by Dr. Peter Cundall, Itasca)
UDEC-BB: Barton-Bandis coupled HM joint constitutive model as UDEC sub-routine
TEFI: thermally enhanced frictional interlock (alternative to 'asperity shortening')
TOC: thermal over-closure
V_P: P-wave velocity