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Details related to ‘the ten’ JRC profiles and further work with the Barton-Bandis criterion – why JRC, JCS and φ_r.

by Nick Barton, NB&A, Oslo. 2021.

Why JRC, JCS and φ_r

This highly illustrated article, with minimal text, is basically an abstract followed by many figures and figure texts. It ends with a reference list that goes beyond Barton and Choubey, 1977 – which is where many published articles 'stop' in relation to work performed on the BB criterion – which has been part of UDEC-BB since 1985. There are by now more than 60 prolile-related equations in the literature, and hundreds of articles, all addressing JRC. Many do not reference the source of JRC anymore, assuming it is an 'established parameter'. It is however liberally criticised, with justification of why 'the current research' was funded and reported. This article is designed to try to put to rest some misconceptions and errors made by many who see 'the ten JRC profiles' and assume (correctly) that they represent a far too subjective method for estimating peak shear strength. In fact, the ten selected profiles, with suggested ranges of JRC like 8 to 10, 14 to 16 were just to illustrate the range of surfaces tested. We characterized and tested130 natural rock joints, from seven different rock types. There are 390 other roughness profiles, since three per sample. The main focus was the accuracy of the peak shear strength prediction. We used gravity tilt or (horizontal) pull tests at mostly < 0.001MPa normal stress for comparison to the DST tests on the same samples at normal stresses of approx. 0.1 to 1.5MPa, so up to one thousand times higher stress. Tilt, push and DST are 'real' 3D behaviour, 2D profile predictions are not. Some of the latter developments have been erroneously based on the assumption that we used 1mm diameter 'brush' profilers commonly found in hardware stores. Some 'creative' authors even drew stepped profiles imagining steps in ours (there are none) and misleading the profession to assuming 100 z-coordinates per 100mm long sample. This has spawned incorrect science and conclusions. The reality was an unusually precise Leschhorn gauge with 3 or 4 'shims' (blades) per mm. (See Appendix and Figure 3). A significantly stepped fine-pencil trace was not possible. Those not reading past our 1977 article miss scale effects and coupled behaviour, which of course depends on normal stiffness and apertures, both physical and hydraulic. The following figures give some indication of where JRC, JCS and φ_r have been used in the years following 1973/1977.

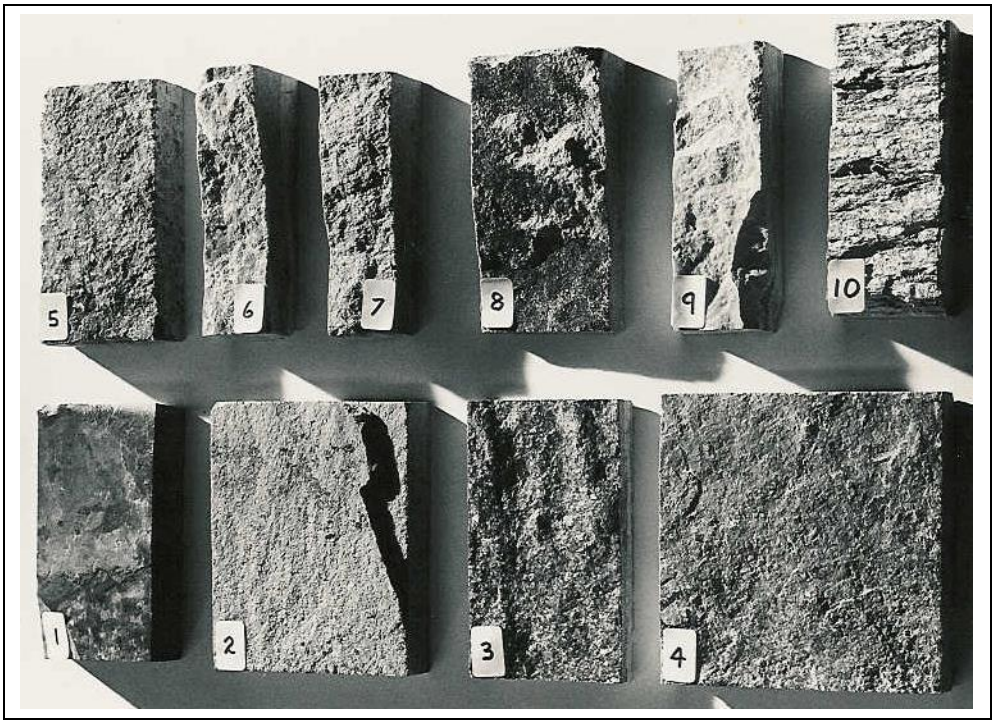


Figure 1 'The ten' joint sample surfaces (lower half) with profiles to follow in Figure 4. JRC_0 values ranged from approx. 0 to 2 up to 18 to 20 in the case of these (L_0 = 100mm) lab samples. These were selected to represent the range of roughness seen in our characterization and testing of 130 samples.

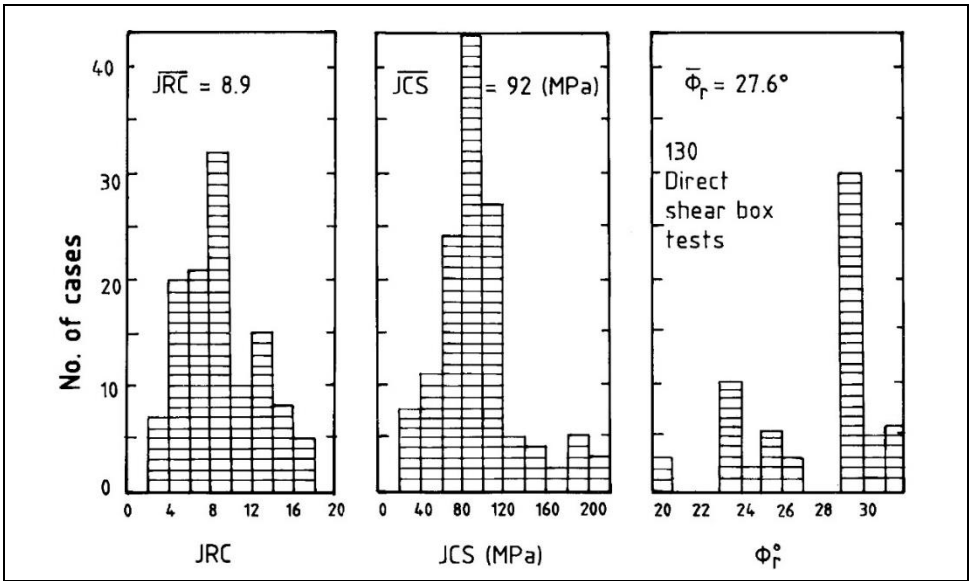


Figure 2 Statistics for JRC, JCS and φ_r for 130 joint samples tested by Barton and Choubey, 1977.

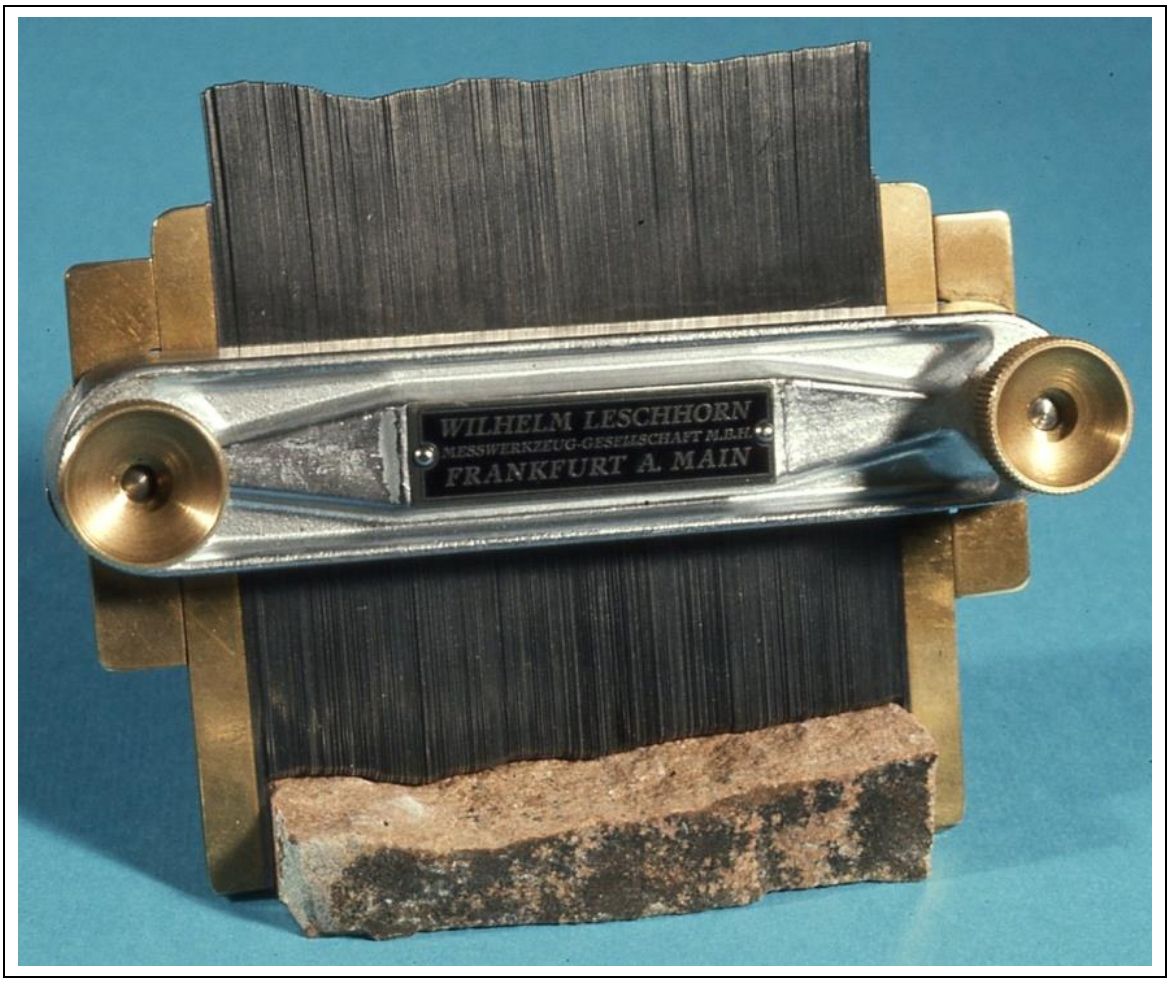


Figure 3 Note the high-quality gauge used for roughness measurement by Barton and Choubey, 1977. It did not have the assumed (Tatone and Grasselli) 1mm resolution with 'steps' that they and others assumed. This has mislead many. The Leschhorn profiler consists of flat stainless steel metal shims, approx. 3 per mm. It is/was not 'rods' of 1mm diameter, as so many have assumed from current and past hardware store experiences. The writer has also used these simpler devices, and in Iran (Karun 4 dam) witnessed an 800mm composite version. Useful nevertheless despite 1mm rods.

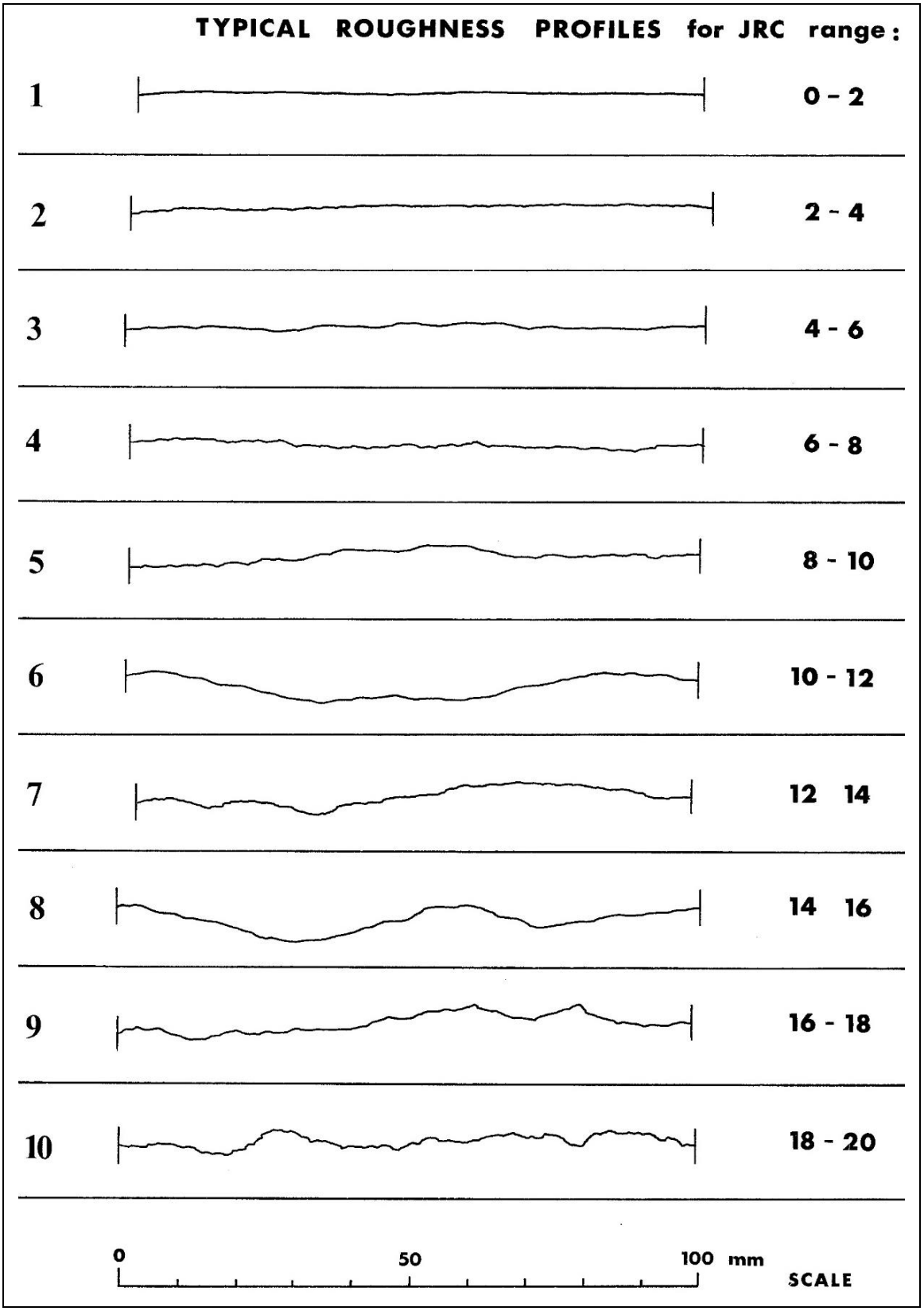


Figure 4 The ten selected profiles – selected from 400 profiles (three per sample). Note that only rough guidance on likely JRC value ranges was given – no decimal places. Barton and Choubey, 1977. Steps on the profiles are hard to see. They have been assumed to exist by others based on incorrect assumptions regarding the resolution of the profile gauge used – which was not from a hardware store (see Figure 3).

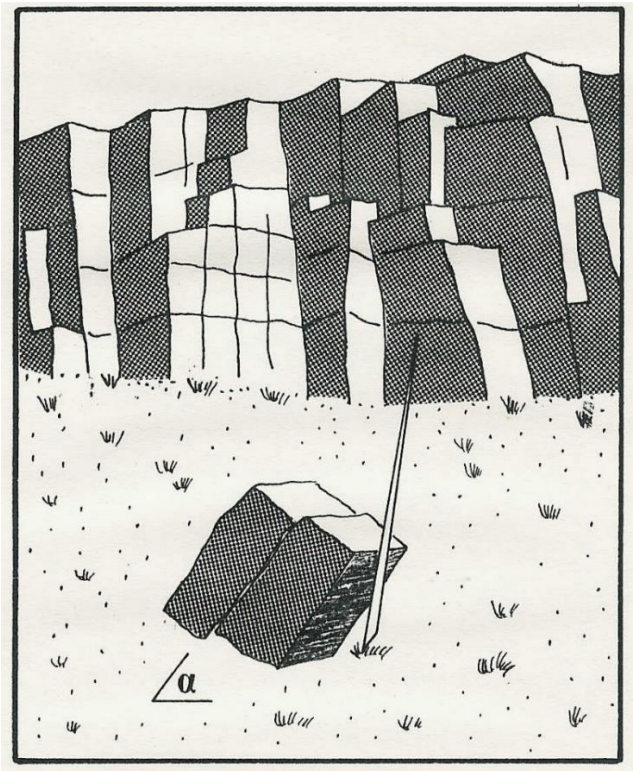


Figure 5 Tilt test concept – on the ideal natural block size. The reality was lab-samples, 130 in number, and tested a total of 400 times, since three times per sample. For the case of the roughest joints, pull tests (horizontal, gravity load only) had to be performed, as the steep tilt angles resulted in toppling.

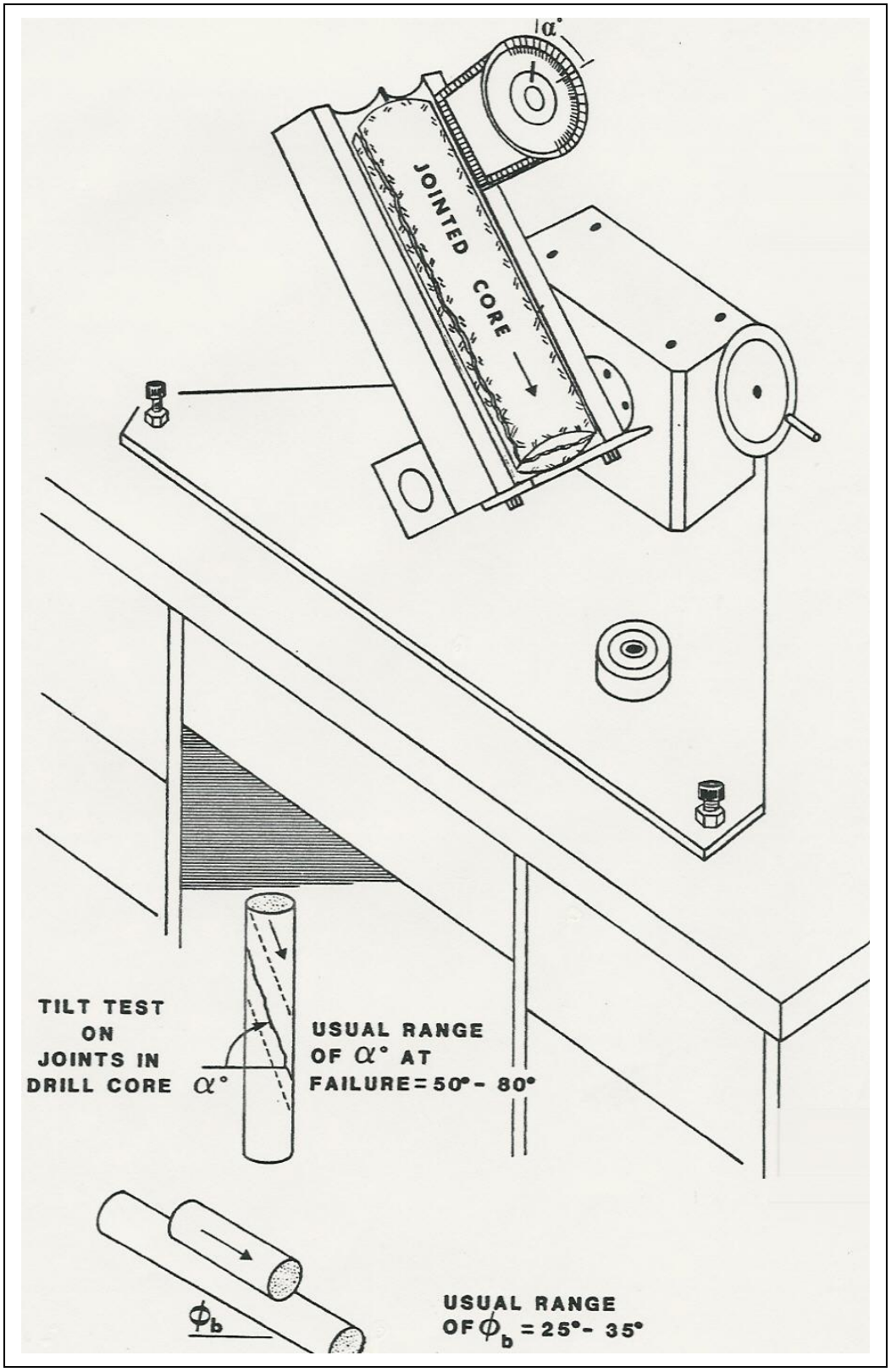
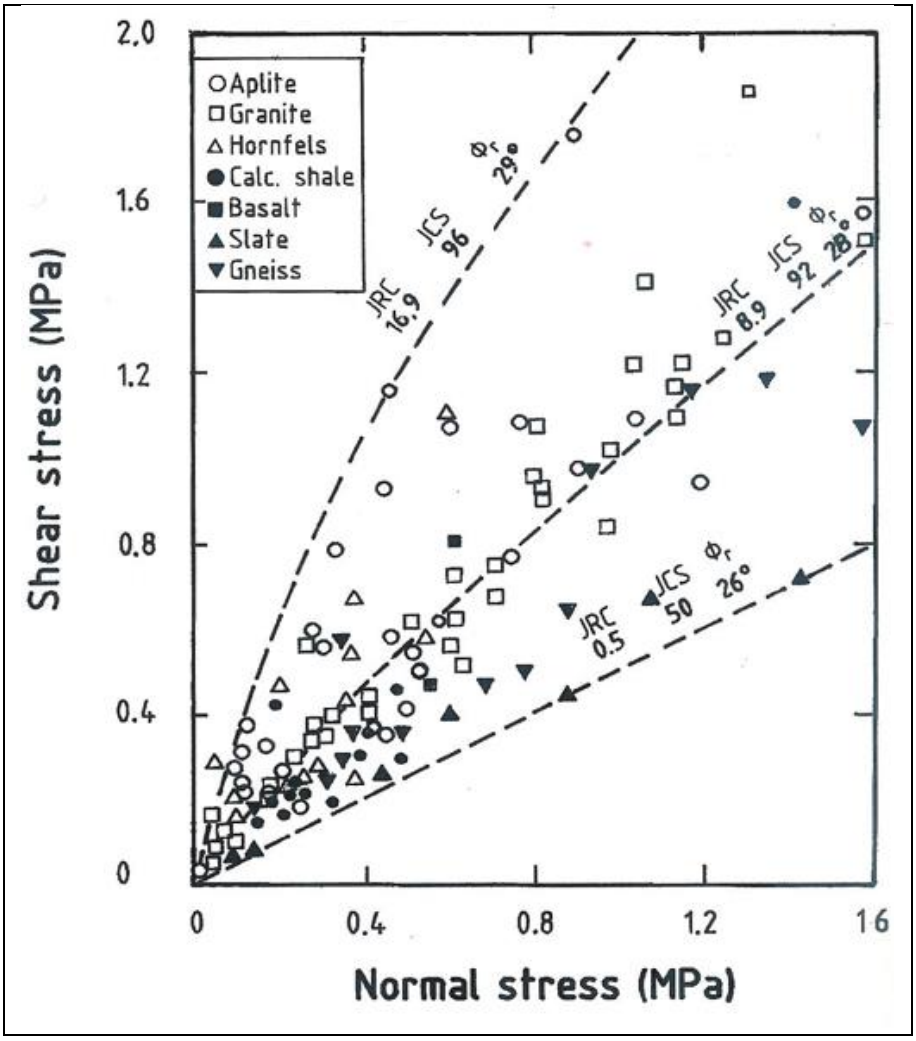


Figure 6 Tilt test set-up (reduction gear on steel plate) with ideal (axial) and sawn joint samples, and in-line tilt tests on core without ridges or polishing for φ_b. Table 1 in NB and VC, 1977 gives typical values of φ_b from the literature. Do not use peak friction minus peak dilation: this is not φ_b.



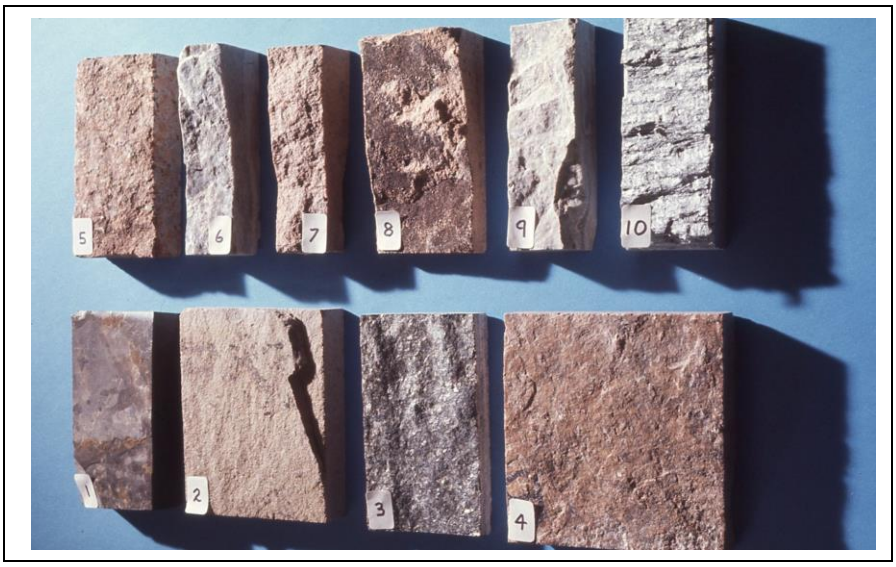
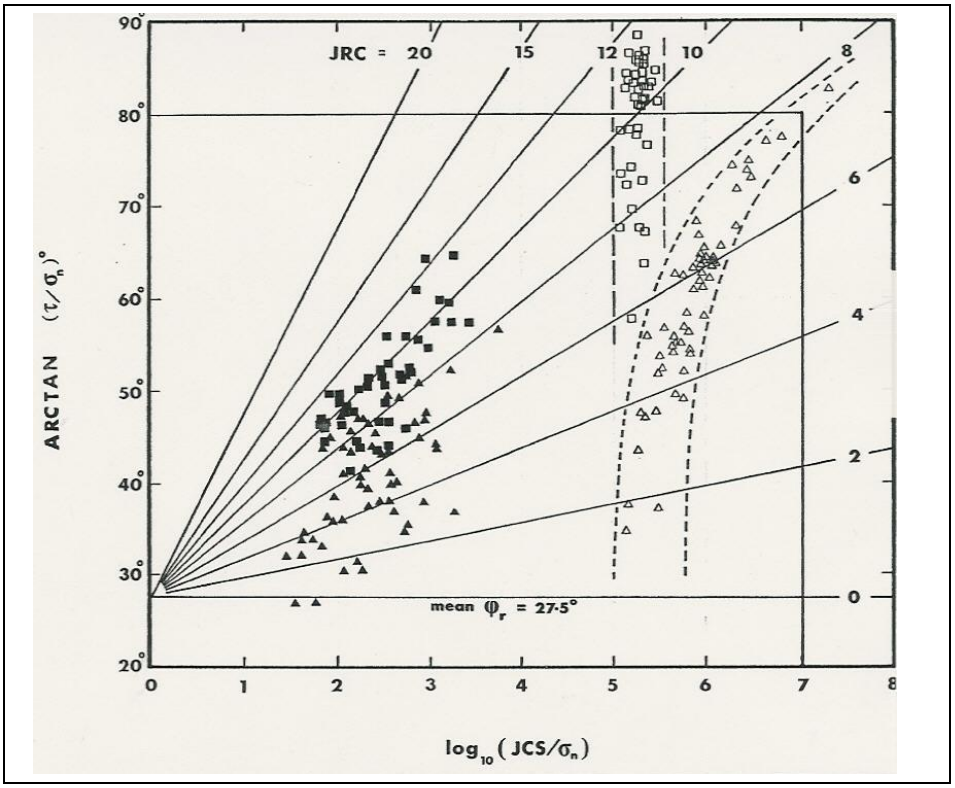


Figure 7 Peak shear strength results from DSTs of the 130 joint samples derived from seven Oslo-area rock types. Note maximum, mean and minimum values of JRC, JCS and φ_r and the corresponding shear strength envelopes, with more non-linearity as JRC increases. Note also that there is no cohesion intercept, as samples with opposed steps were avoided.



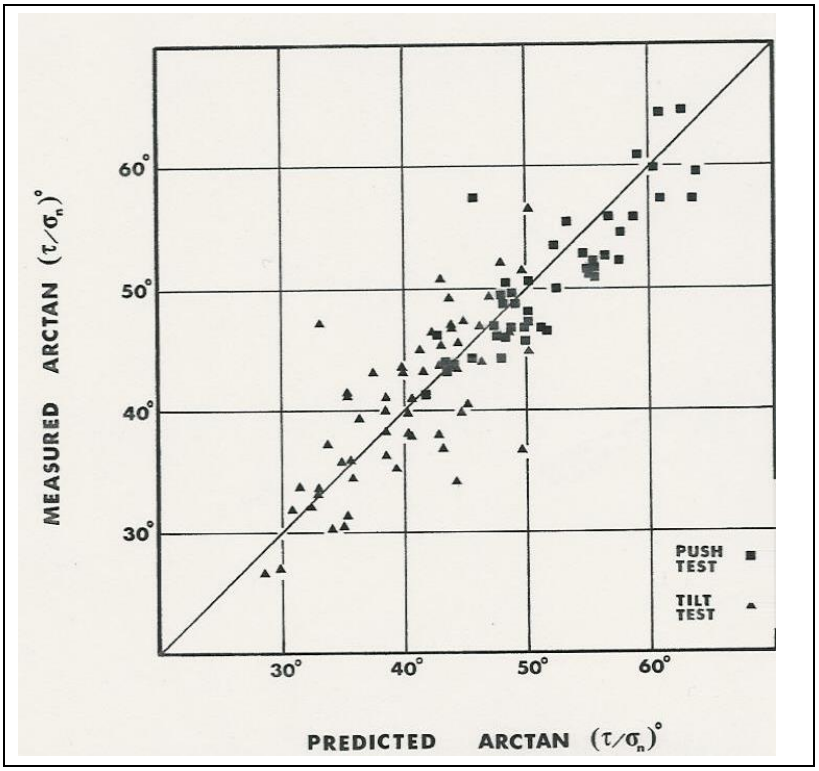


Figure 8 The 3 to 5 orders of magnitude stress range involved in the Barton and Choubey, 1977 joint characterization and DST study of 130 joint samples. The lower diagram indicates DST measurement and tilt or push test predictions – the reason for publishing. Some USA research pronounced that JRC-tilt was ½ x JRC-DST. This erroneous result, unfortunately quoted by others, was due to a 'ploughing' style DST with smaller top sample. If it was realistic (but it never occurs in nature) there would of course never have been a Barton-Choubey publication.

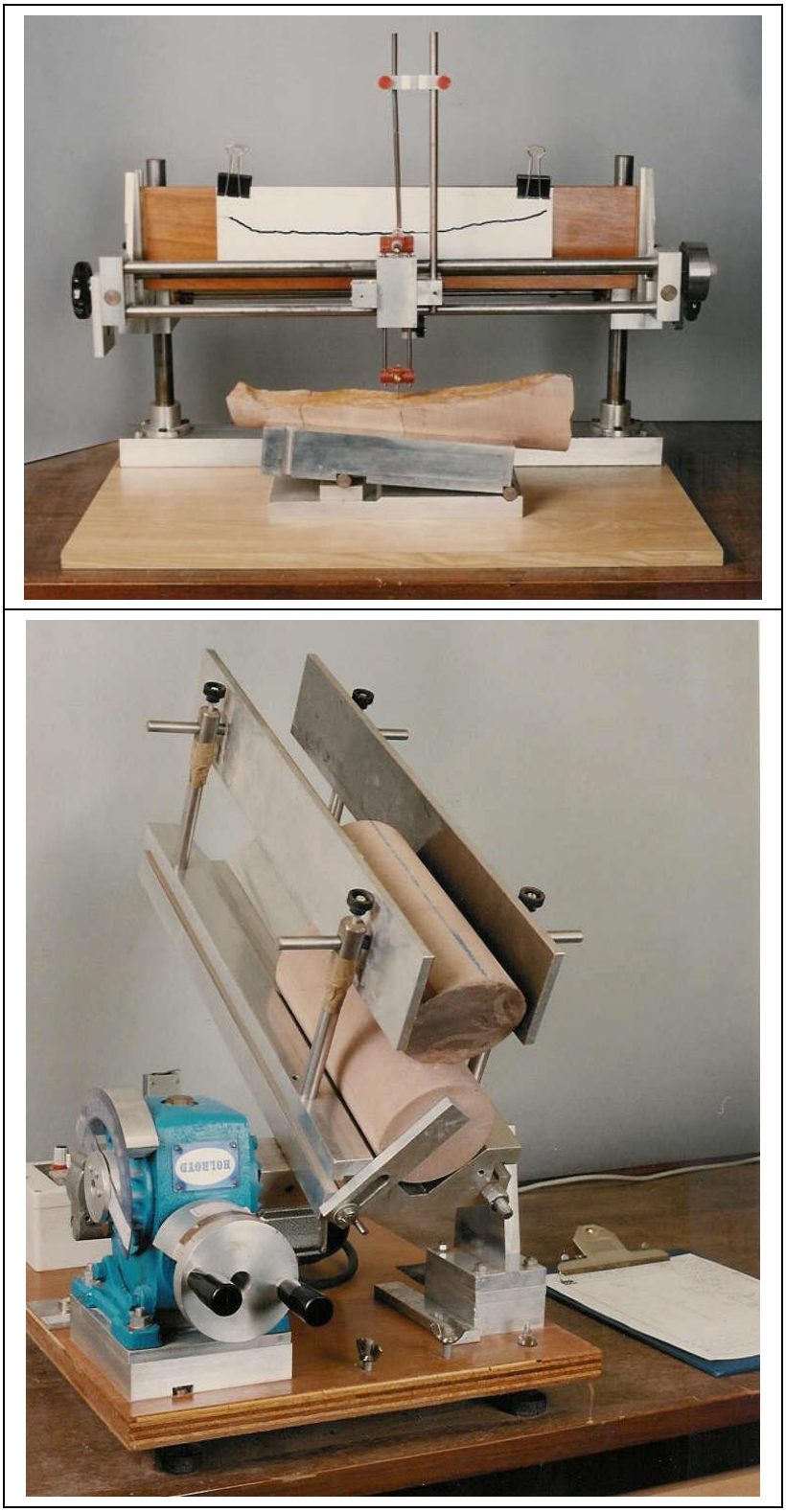


Figure 9 a) A profilometer used at NGI during our six-years UK Nirex project. Barton et al. 1992. b) Measurement of φ_b from core-sticks tilted in line contact. No ridges, no polishing, just a quick sand-blast to expose mineralogy. NGI UK Nirex project, 1990-1996. Note use of two cores for (unweathered) φ_b. Three cores cause wedging and false (high) values. $\varphi_r = (\varphi_b - 20^o) + 20\ r_5/R_5$.

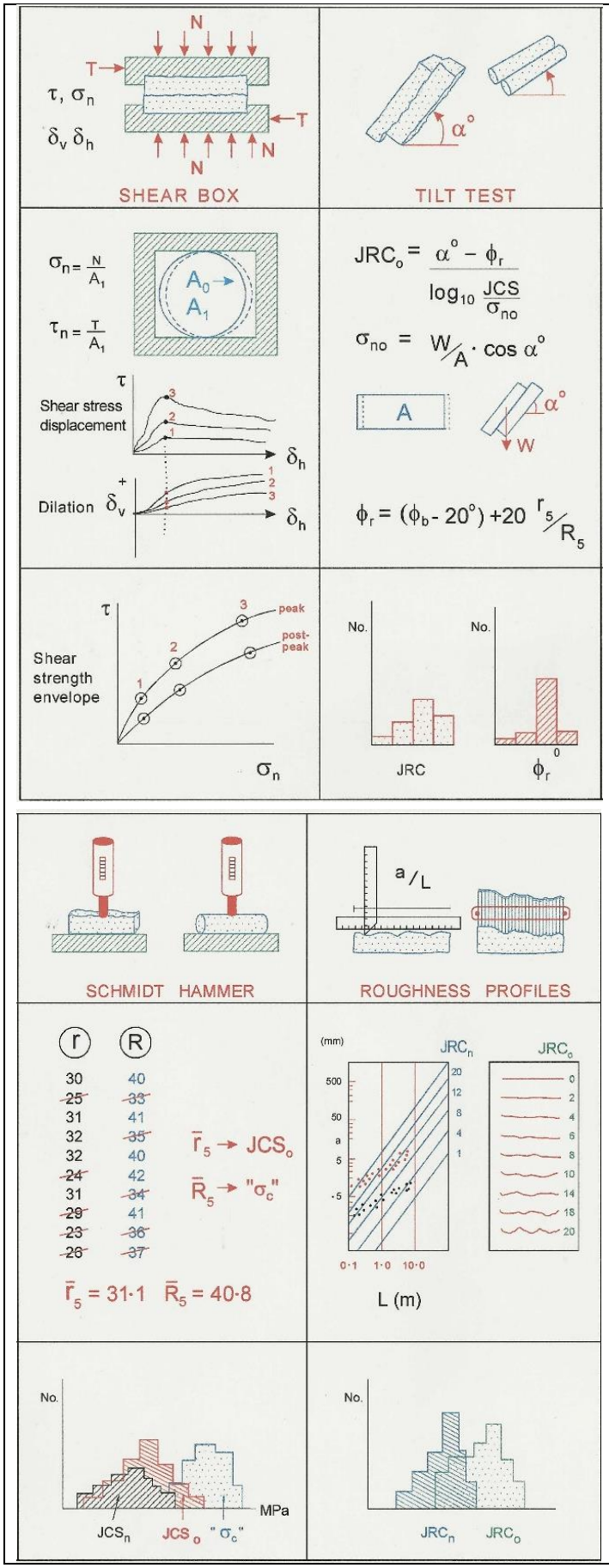


Figure 10 Recommended DST and index testing for using the Barton-Bandis criterion, as coded in UDEC-BB. Note that the DST is shown schematically – there should be no moment applied to the sample. Note the subscripts to denote lab-scale JRC_0 and JCS_0 and larger-scale JRC_n and JCS_n parameters. Instructions concerning this index testing will be found in Barton and Bandis, 2017 – the first chapter of a five-volumes review edited by Prof Xiating Feng.

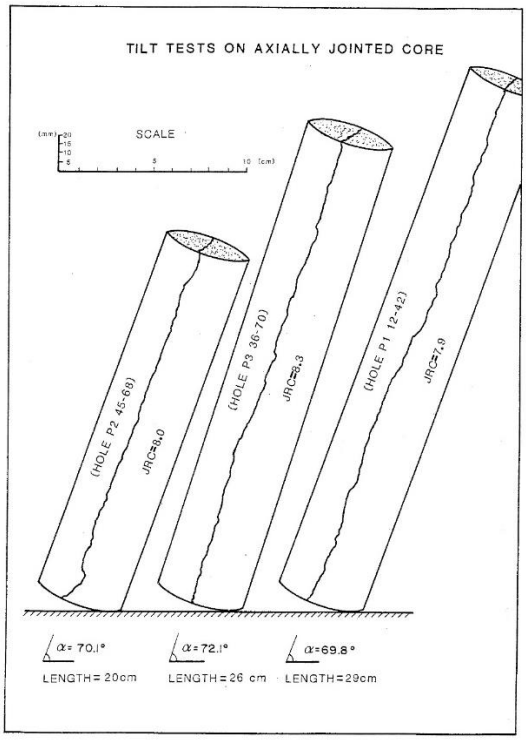


Figure 11 Examples of tilt tests on axially jointed core that was extracted from the TerraTek heated block test, where the cross-hole permeability was registered as a function of normal stress, shear stress and temperature. Barton, 1982.

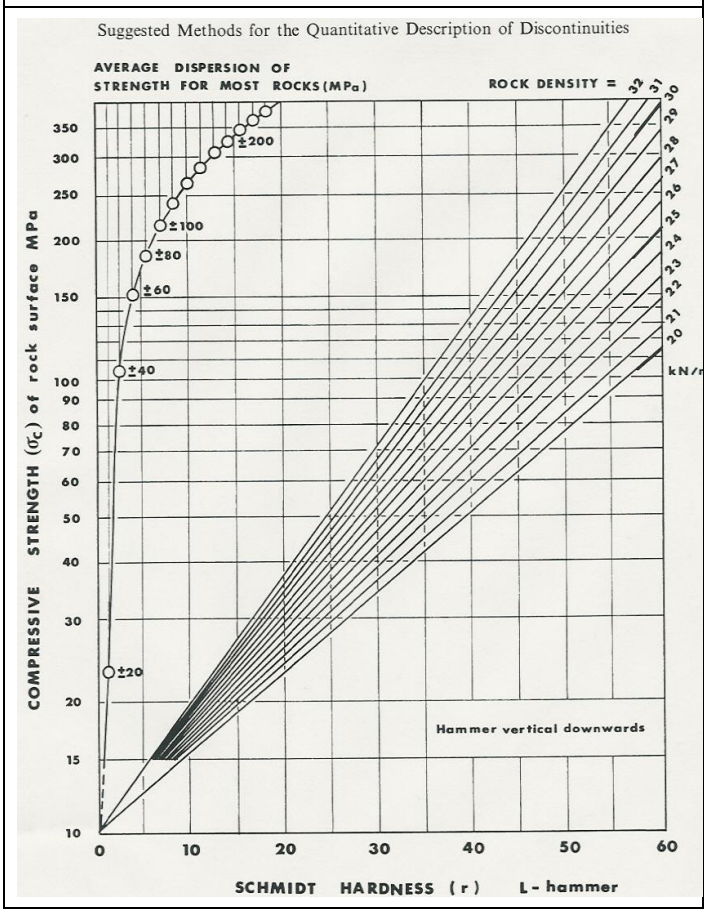


Figure 12 Schmidt L-hammer for estimating JCS_0 if weathering makes this significantly less than the UCS value of the rock. A saturated joint sample is advised. NGI-Atkins UK Nirex partner in action.

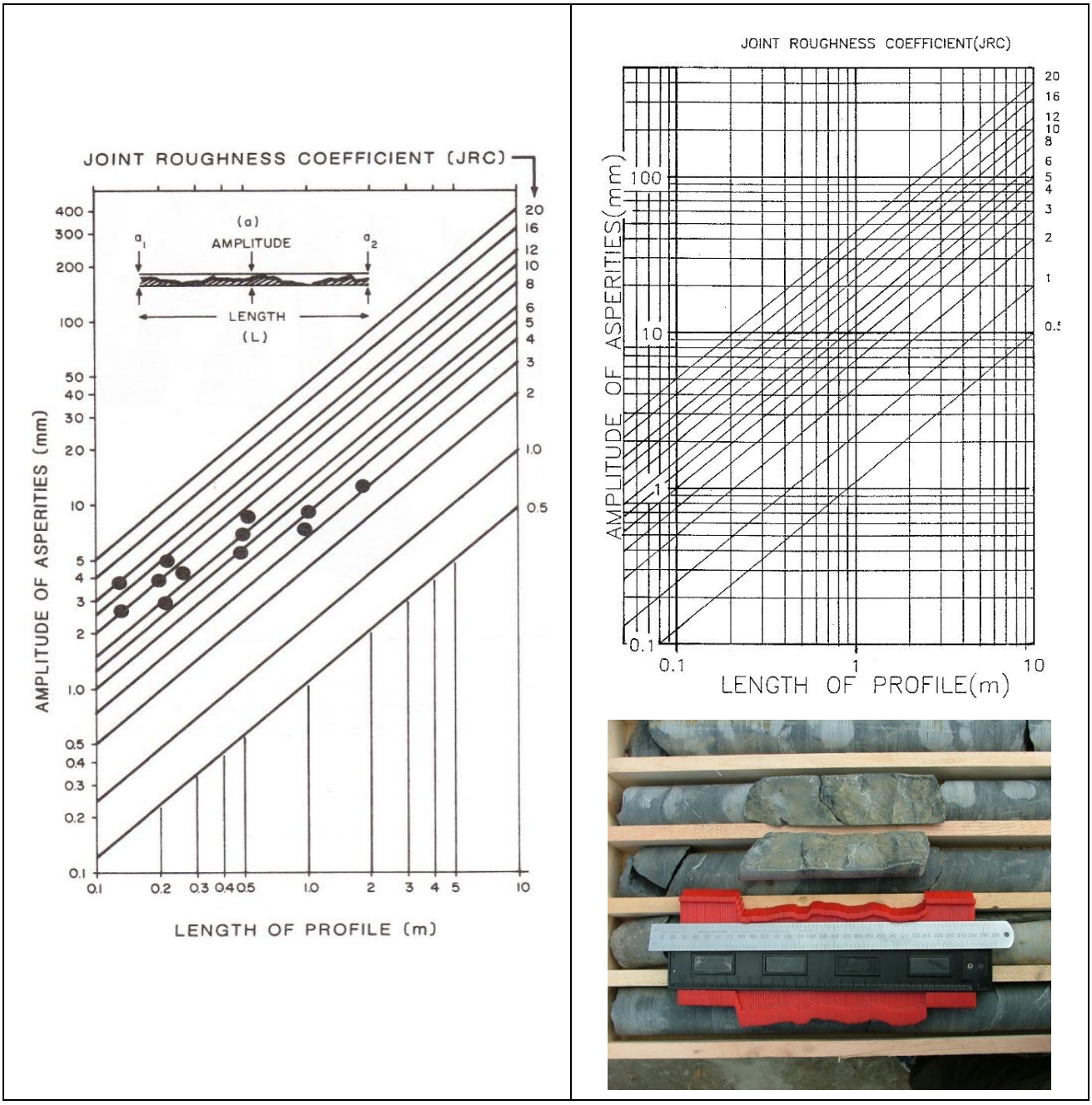


Figure 13 A largely ignored technique for JRCn (scale corrected) estimation. Barton, 1981. It is usual to have roughly elliptically-shaped point clouds for each joint set that is roughness-logged. The JRC 'iso-lines' are crossed as block size increases, giving lower JRC_n despite increased amplitudes of roughness at larger scale. Photo inset: Rapid registration of roughness and a/L at the Bærum Rail tunnel, for input to NB&A pre-grouting estimation, since JRC is the basis for estimating mean physical (and groutable) apertures from the theoretically estimated hydraulic apertures.

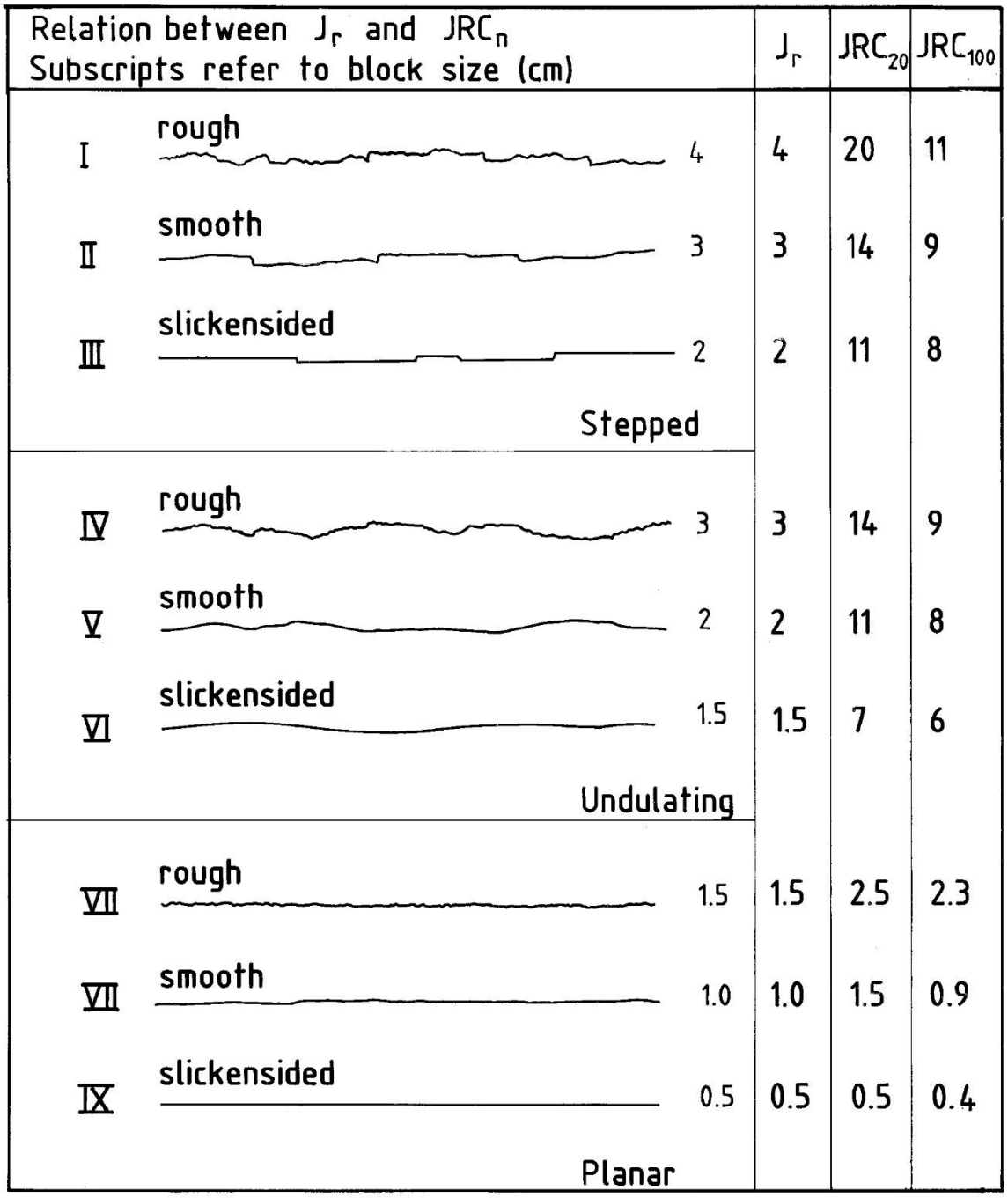


Figure 14 A suggested rock joint descriptive system, from ISRM, 1978. The JRC_{20} and JRC_{100} values were illustrative estimates of the possible scale effect encountered with 20cm and 100cm block sizes. The Jr ratings are from the Q-system. The writer was coordinator of this 44-man working group.

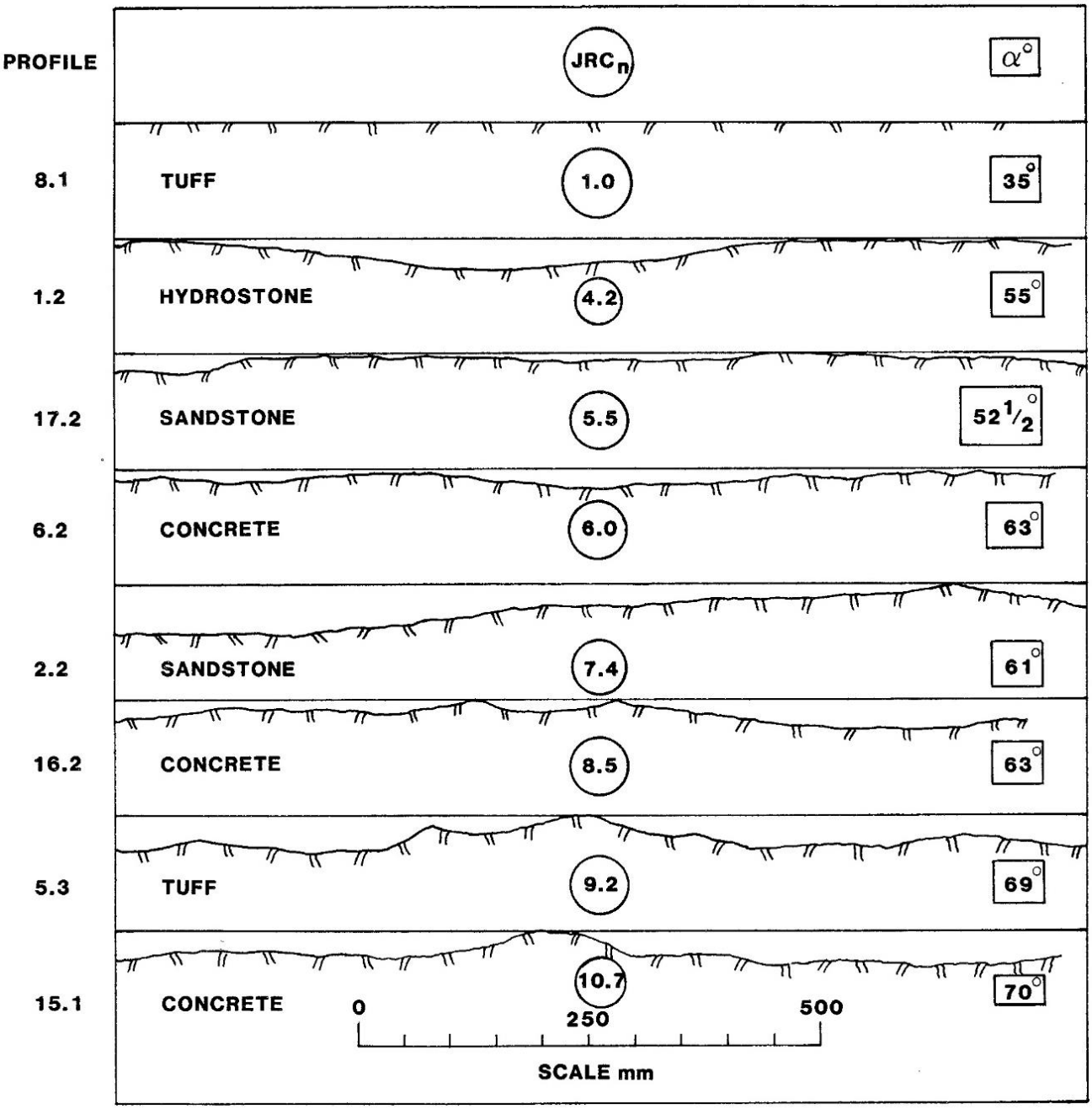
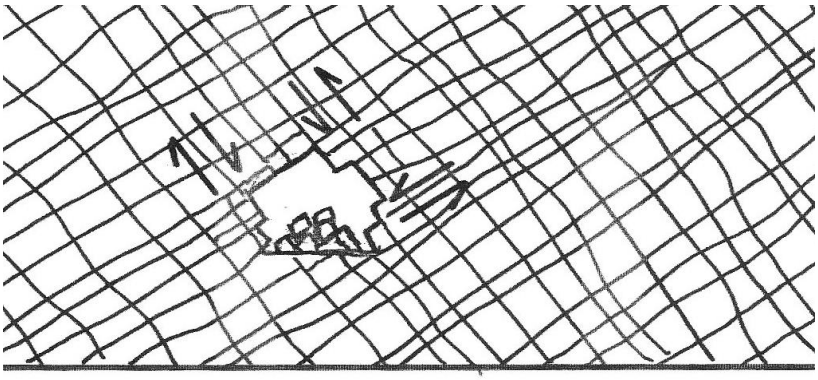


Figure 15 Large-scale (L_n= 1300mm) diagonally fractured 1m^3 blocks, that were profiled and tilt-tested (angle α°) at approx. 1.5 tons scale in TerraTek, Salt Lake City by the Dr. Khosrow Bakhtar to be. Bakhtar and Barton, 1984. Note the significantly reduced JRC_n values compared to the lab-scale JRC_0 value ranges in Figure 4.

$$JRC = \frac{\alpha^\circ - \phi_r^\circ}{\log\left[\frac{JCS}{\sigma_n}\right]}$$



BARTON-BANDIS (scaled)

$$\tau = \sigma_n . \tan\left[JRC_n . \log\left(\frac{JCS_n}{\sigma_n}\right) + \phi_r\right]$$

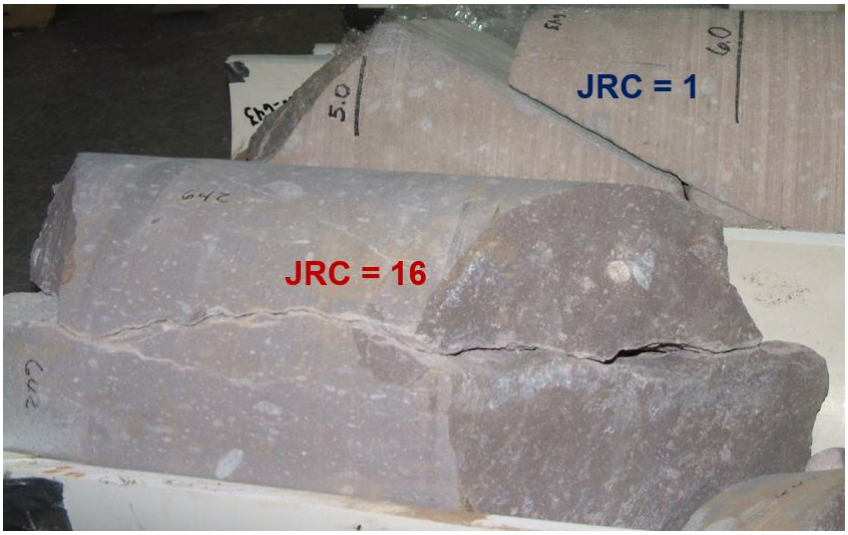
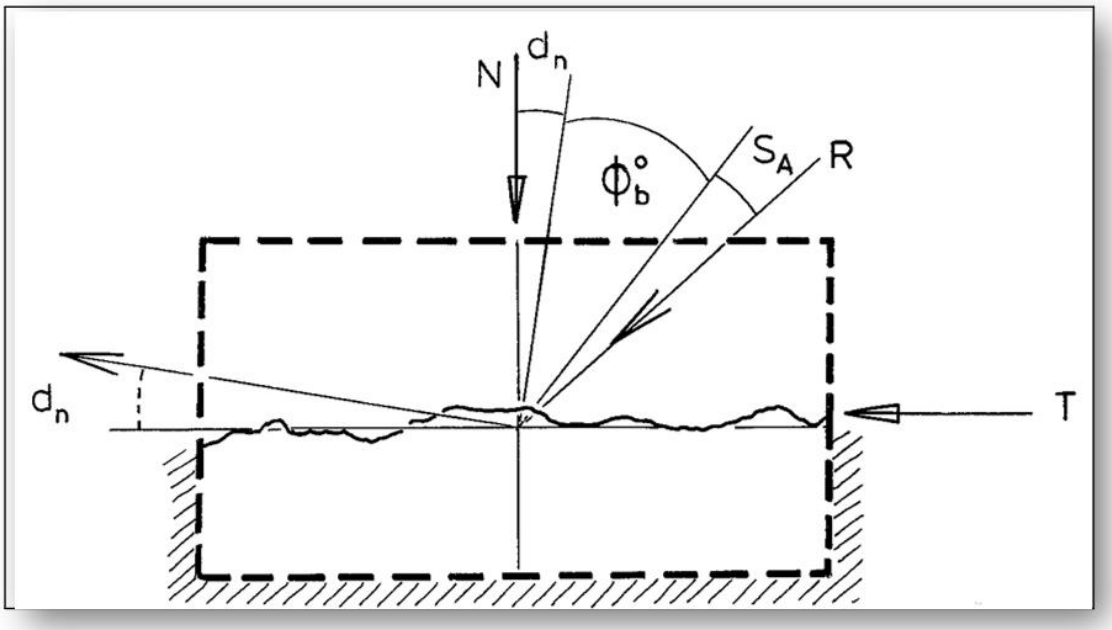


Figure 16 JRC at any scale can be back-calculated from the top equation. At lab-scale (L_0 = 100mm) α° might be 70 ° and JRC_0 = 14. At 'in situ block scale' (say L_n = 1m) the tilt angle might again be 70° but JRC only 9 because of the higher normal stress at failure.



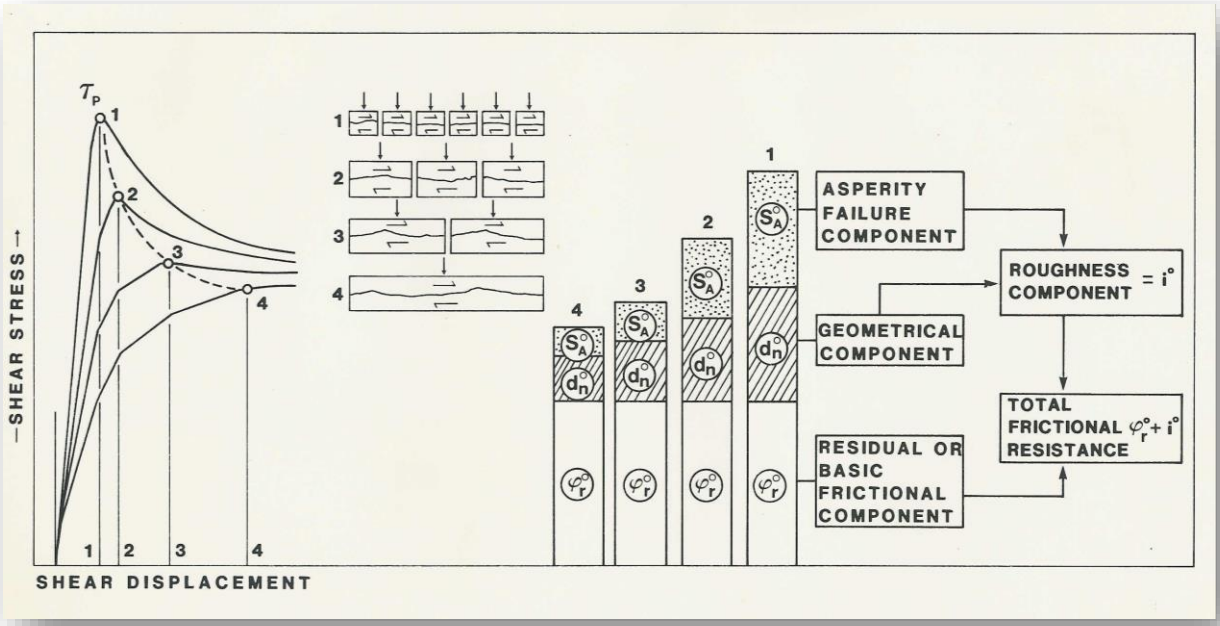


Figure 17 Top: Asperity strength component from Barton, 1971. Bottom: Do not subtract the peak dilation angle from the peak friction angle and imagine it is the φ_r value. It is not as there is a significant asperity strength component (S_A) not accounted for. It may easily be 10° at small scale. As shown by Bandis et al. 1981, both d_n and S_A are scale dependent.

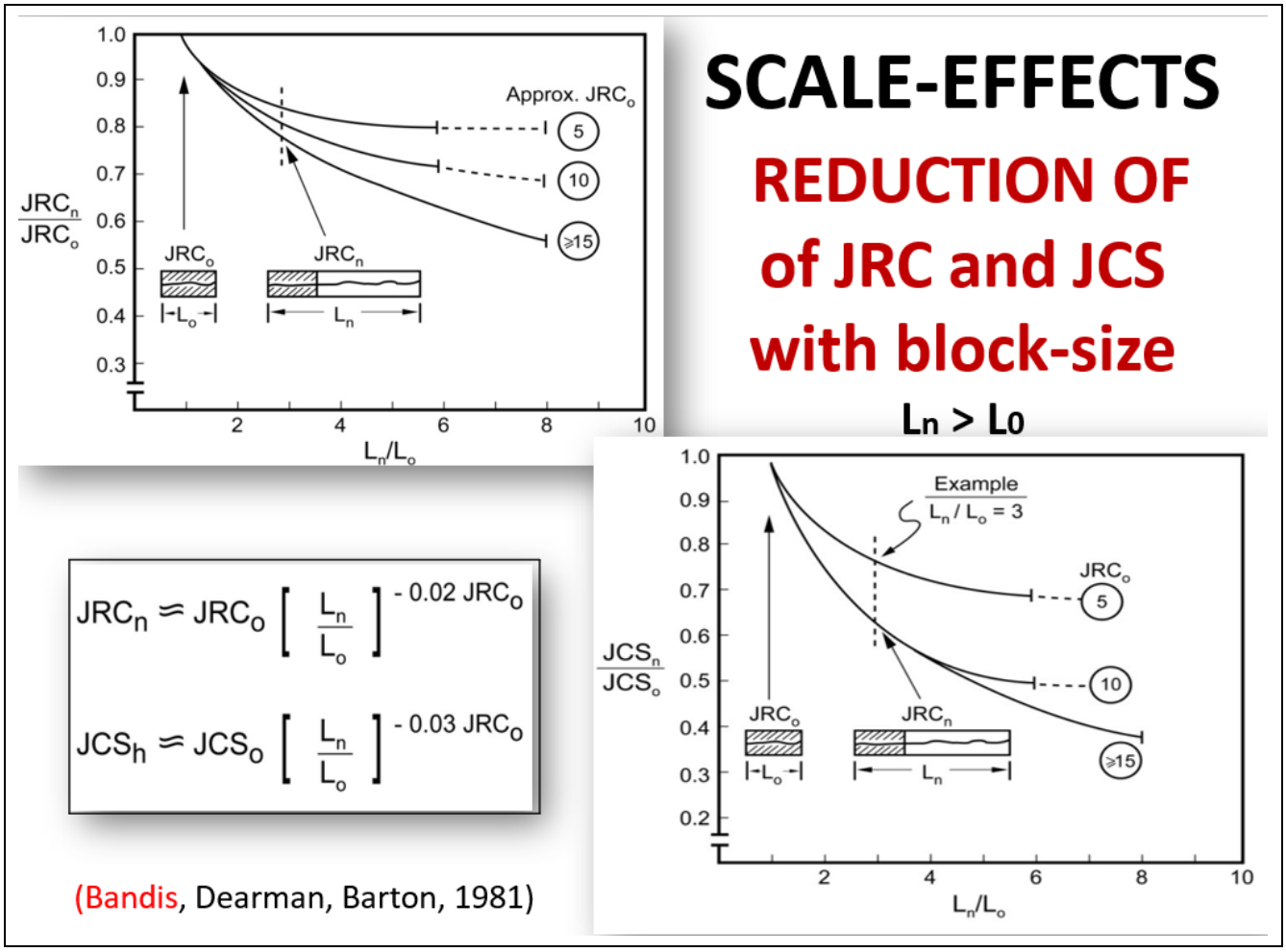


Figure 18 These suggestions for correcting JRC_0 and JCS_0 for scale effects from Bandis in 1981 give very similar results to recent Chinese work with large-scale joint exposure profiling and calculation of JRC at different sampling lengths.

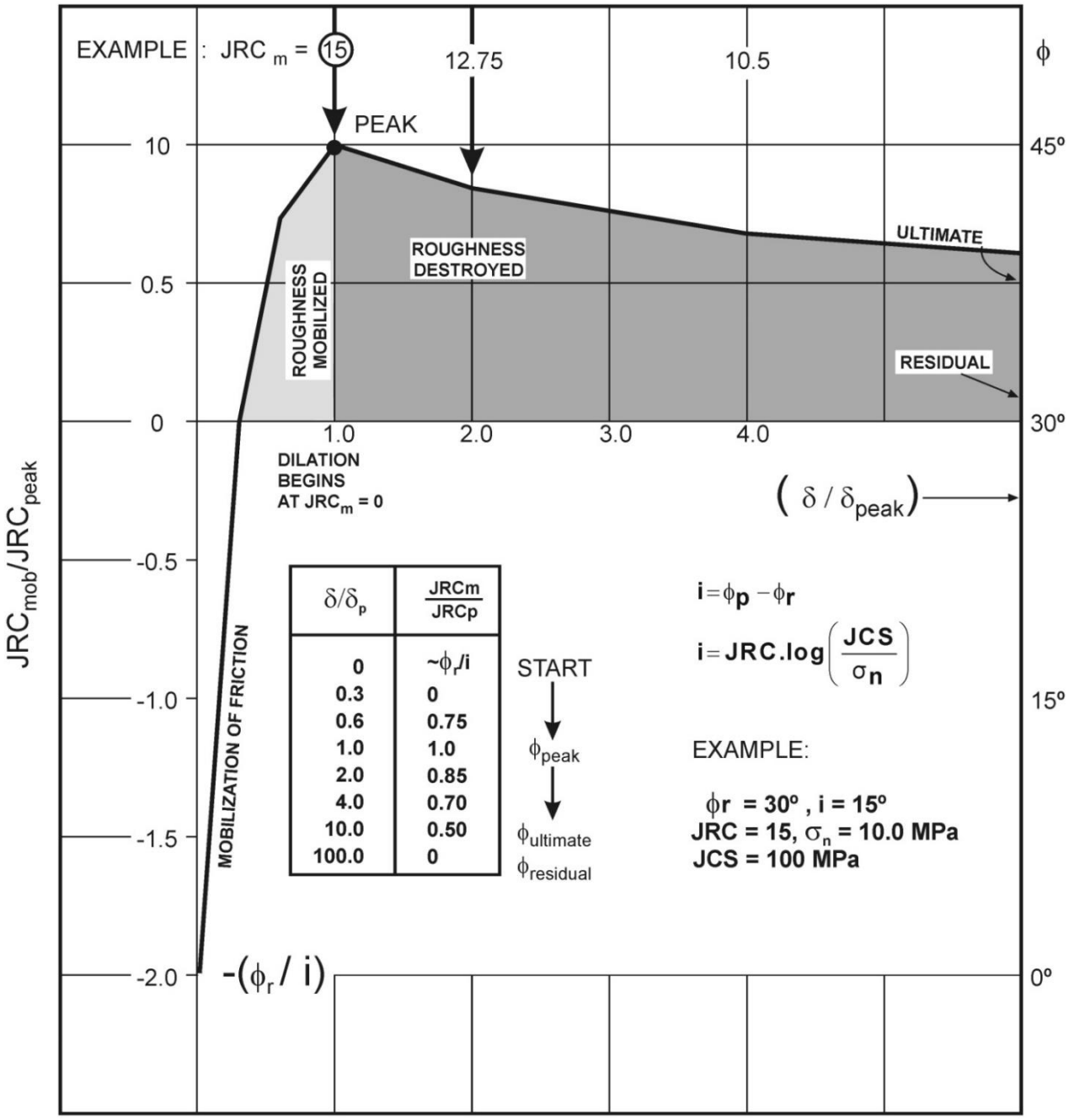


Figure 19 So far we have only considered peak shear strength. In order to follow actual shear strength shear displacement paths the concept $JRC_{mobilized}$ was developed in 1979 in order to model tension fractures in large physical models. This version of the dimensionless ratios was published in Barton, 1982 and was used for 'hand-calculation' of the scale effects shown in Figure 20. In other words, it is simple, and since 1985 is coded in UDEC-BB, but as a more smoothed version.

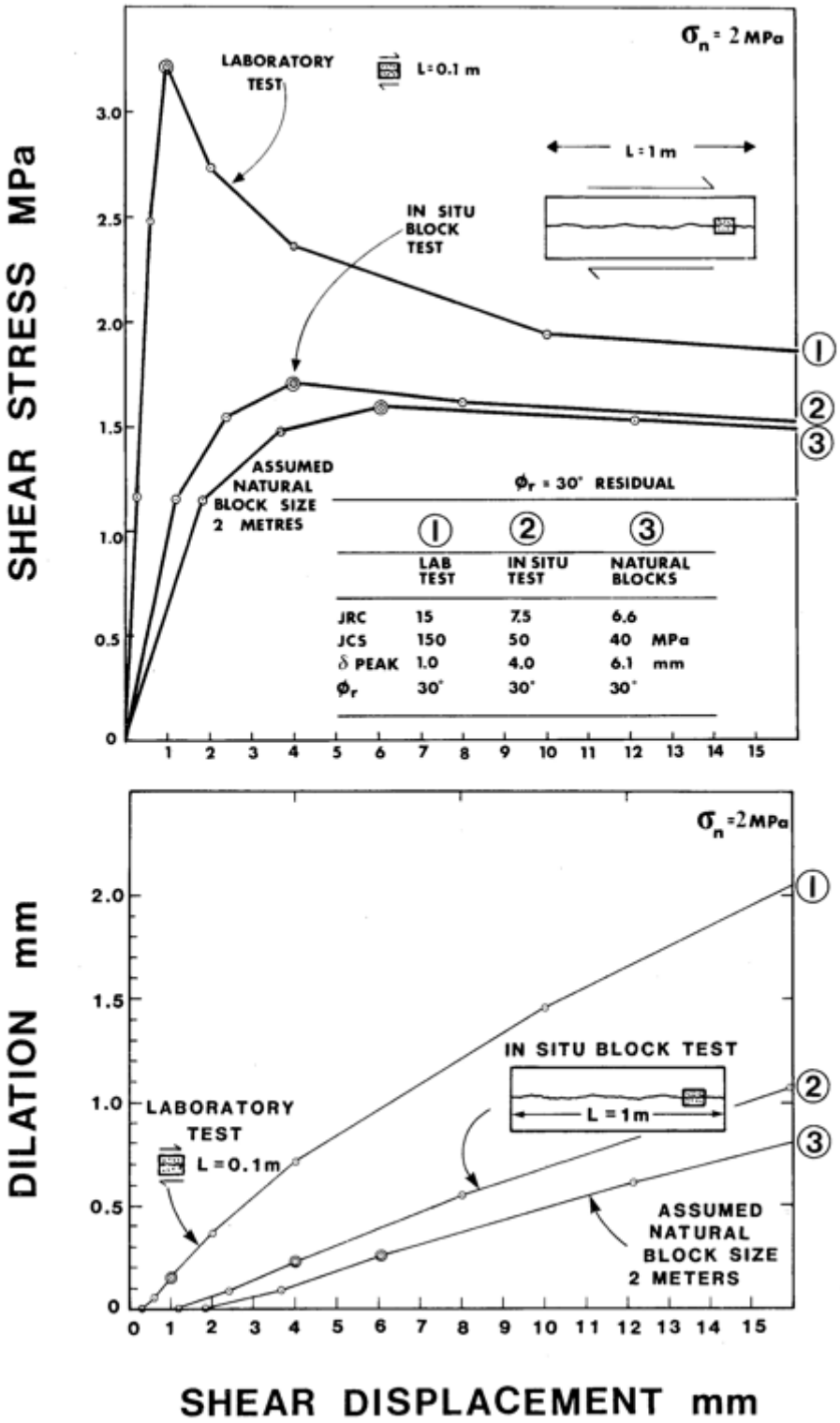


Figure 20 A demonstration of $JRC_{mobilized}$ and how in dimensionless form it can be readily used to generate shear strength-displacement-dilation curves at different scale. Barton, 1982. Note that the scaled properties shown in the inset are derived from Figure 18 empiricism.

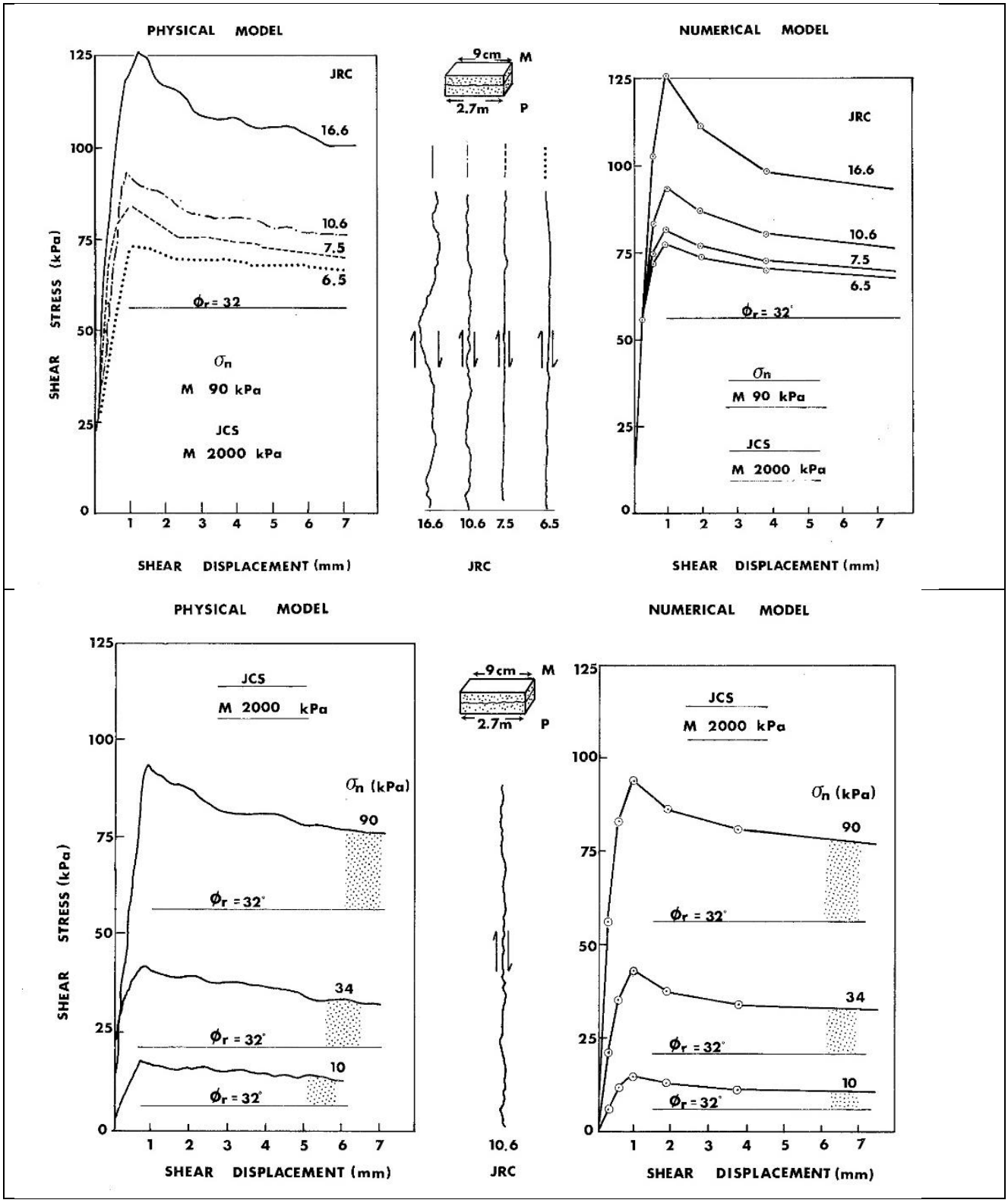


Figure 21 Matching the shear strength-displacement behaviour measured by Bandis 1980 in his joint replica tests. Top: Four replicas of different roughness tested at the same normal stress. Bottom: one of the samples tested at three different normal stress levels. Barton, 1982.

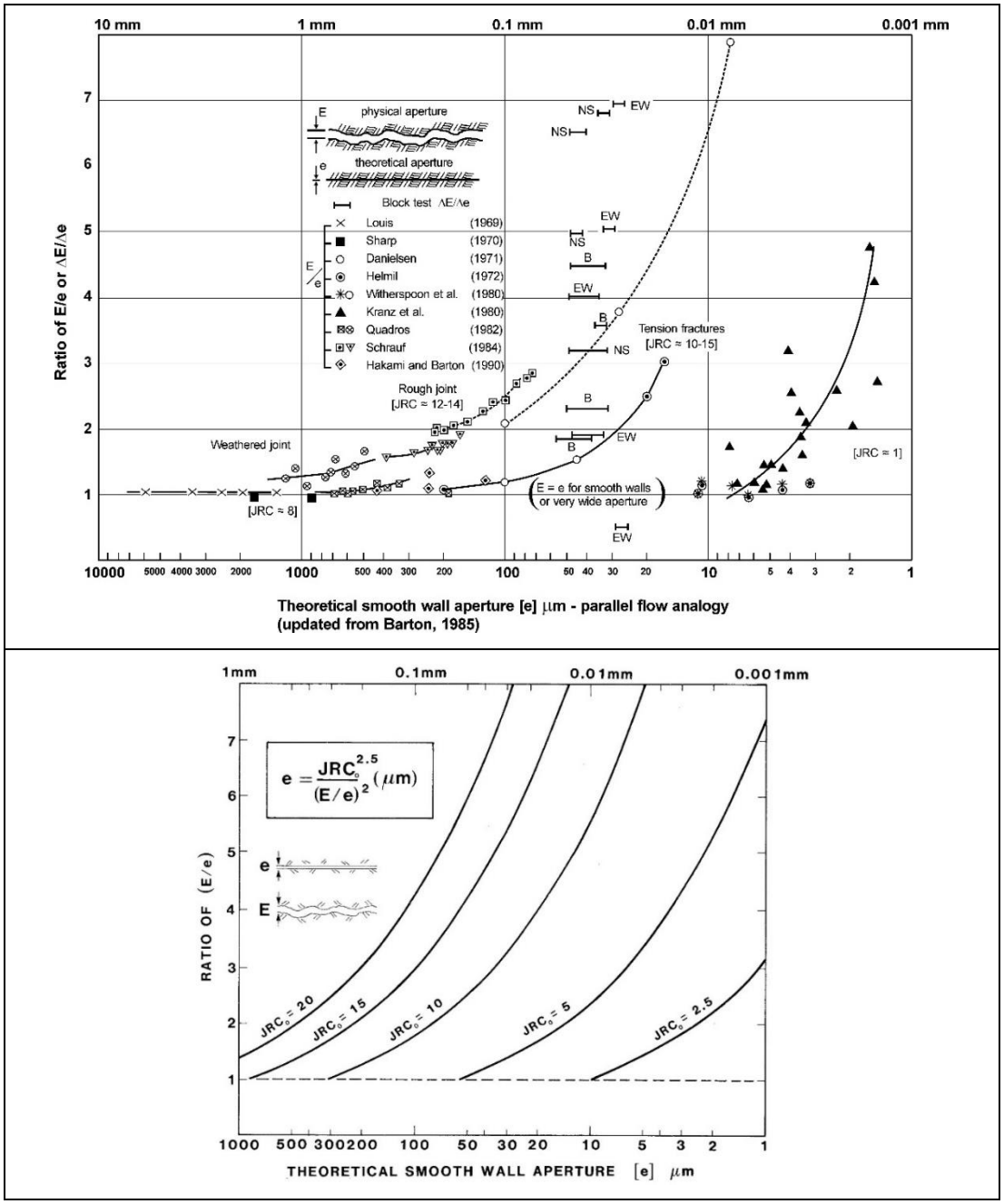


Figure 22 Top: Test data from which joint apertures e and E (or Δe and ΔE) were measured (Barton et al. 1985, updated by Quadros in Barton and Quadros, 1997. Bottom: The empirical model for converting between these two apertures was developed in Barton, 1982 and became a part of UDEC-BB in 1985. Note that: $e \approx E^2/JRC_0^{\,2.5}$. *Joint permeability can be estimated from* $K = ge^2/12\nu = 8175\, e^2$ *(cm/s), or from* $K \approx 8175\, [E^2/JRC_0^{2.5}]^2 \times 10^{-10}$ *m/s. See Barton and Bandis, 2017 for details. Note that when there is significant gouge production, a simple* $JRC_{mobilized}$ *based conversion from E to e is used. Details are given by Olsson and Barton, 2001.*

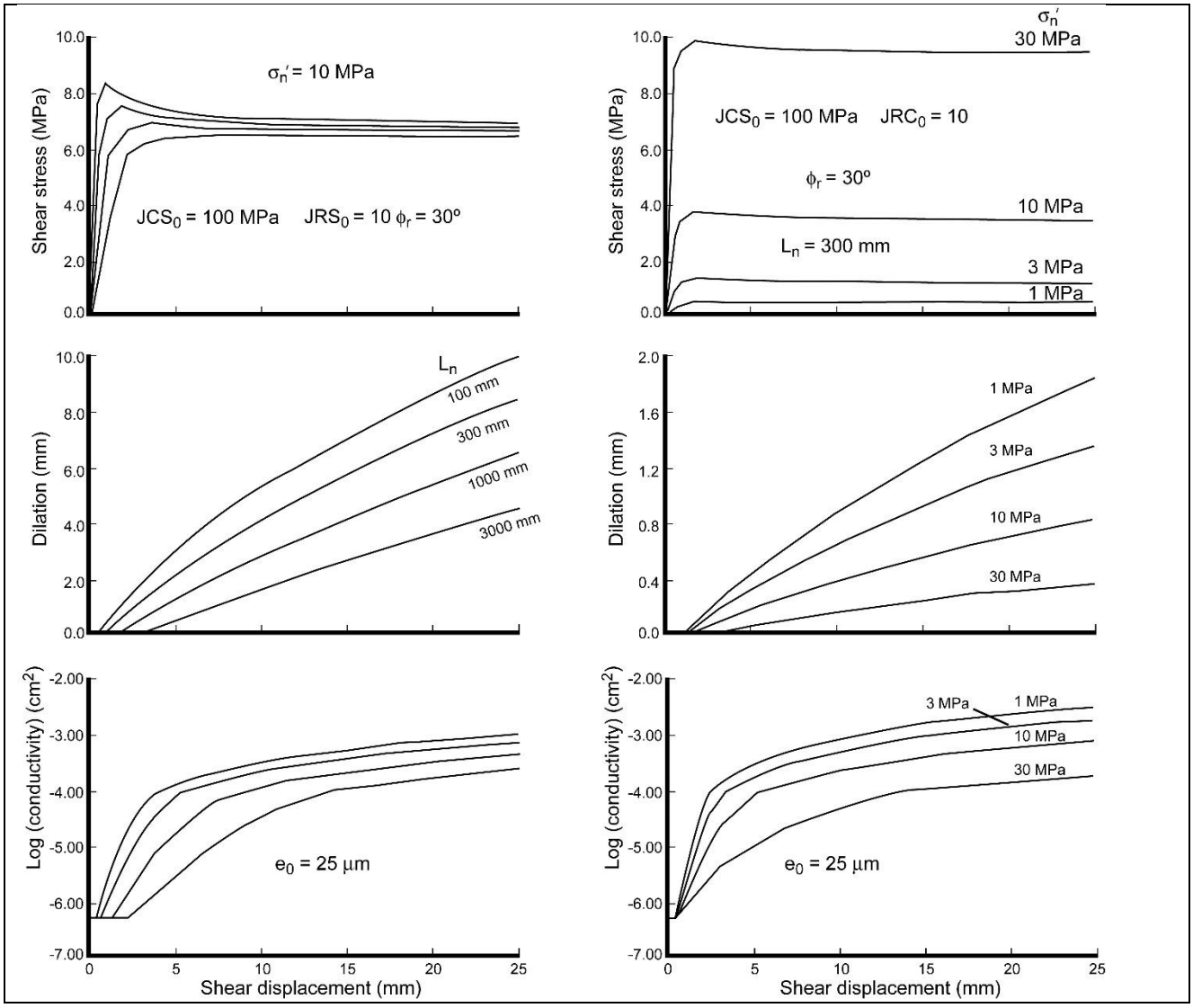


Figure 23 Examples of 'coupled' shear-dilation-conductivity modelling with the Barton-Bandis modelling assumptions. No gouge production reductions in permeability are assumed here. When block-size variations are involved (left) the delayed dilation and therefore delayed conductivity change can be noted. These curves were produced in 1983 by Bakhtar using a programmable HP calculator and the BB equations by now assembled in Barton, 1982. Funding of this work by ONWI (USA) and AECL (Canada) is acknowledged for the 'finalization' of the BB model prior to its further programming (by Mark Christiansson of Itasca) into the distinct element code UDEC-BB. The above graphics from Barton and Bakhtar, (1983 TerraTek contract) (1987 CANMET).

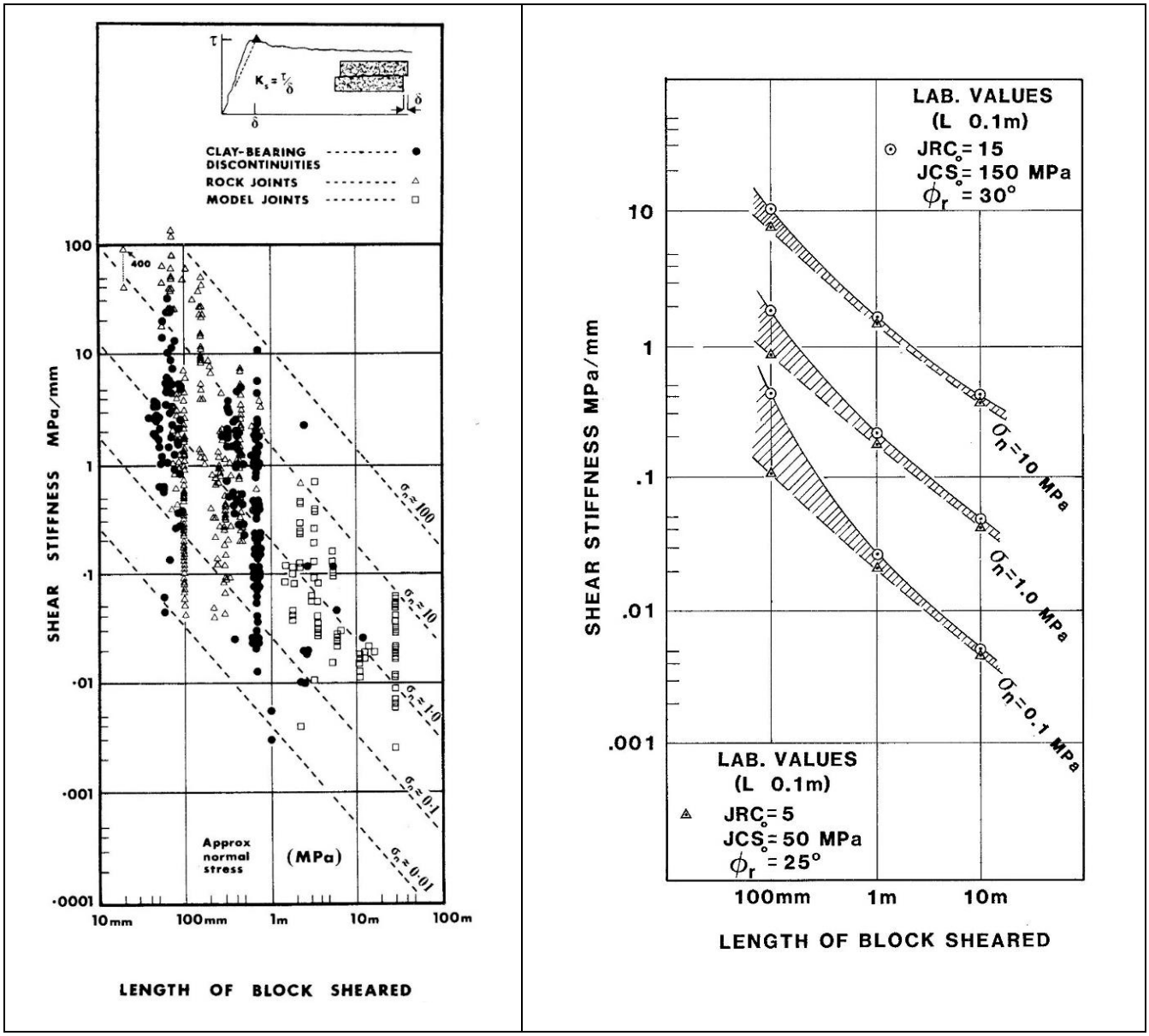


Figure 24 Left: Several hundred DST data for a variety of joints, filled-discontinuities and model-material replicas of joints. Note the strong scale effect, and also the approximate influence of the effective normal stress. Right: Predicted block-size scale and stress effects for a rough joint in hard rock, and for a smoother joint in weaker weathered rock. Care is needed when selecting Ks for modelling, as instruction manuals usually have the ratio Kn/Ks too small, even 1.0. This is incorrect. A ratio of 10:1 and up to 50: 1 is advised. Barton, 1982. (Kn = normal stiffness: see following summary from some of Bandis, 1980 work on normal stiffness).

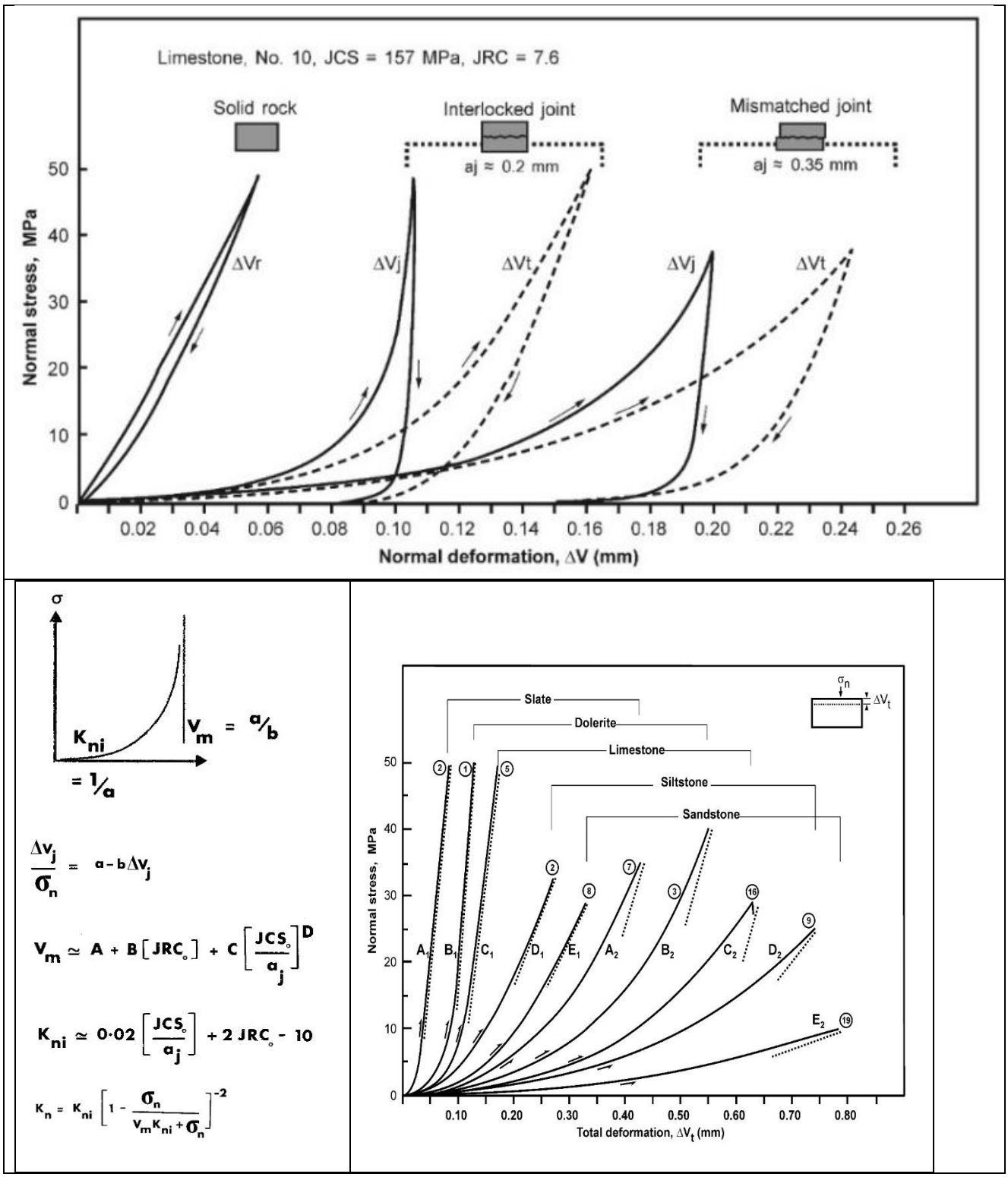


Figure 25 Left: The hyperbolic function) and related equations chosen by Bandis, 1980 to describe the highly non-linear behavior of closing interlocked rock joints. (This method and numerous experimental results were published in Bandis et al. 1983). The normal stiffness expression is a derivative of the hyperbolic function. Right: Experimental evidence acquired by Bandis show strong dependence on rock-type and on the rock-type-characteristic values of JCS and JRC.

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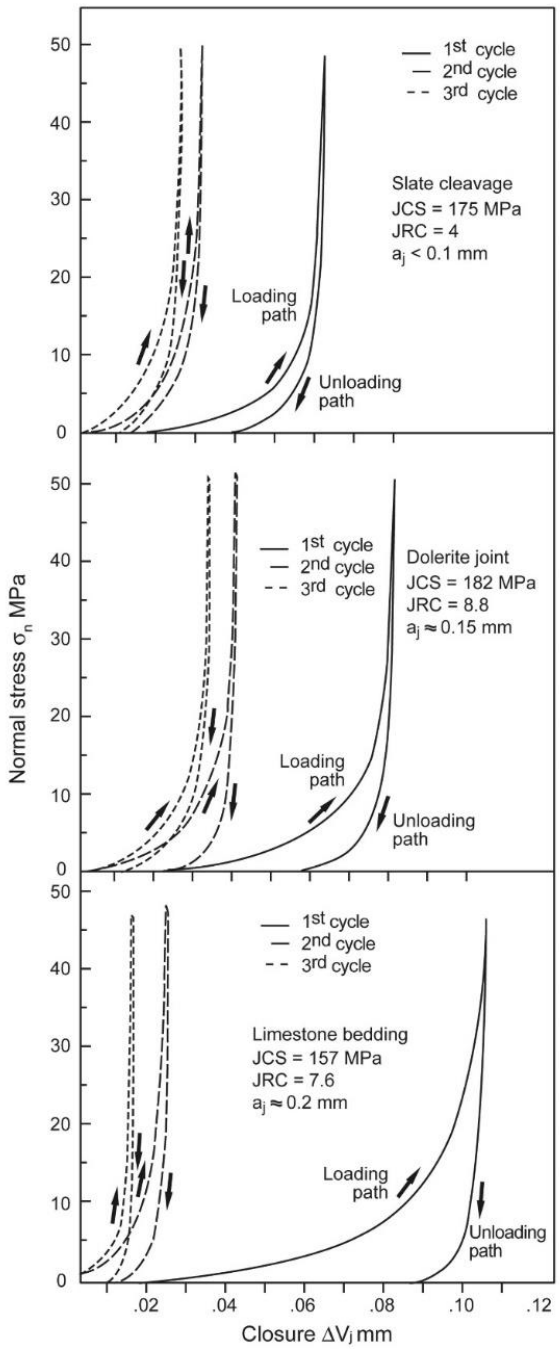


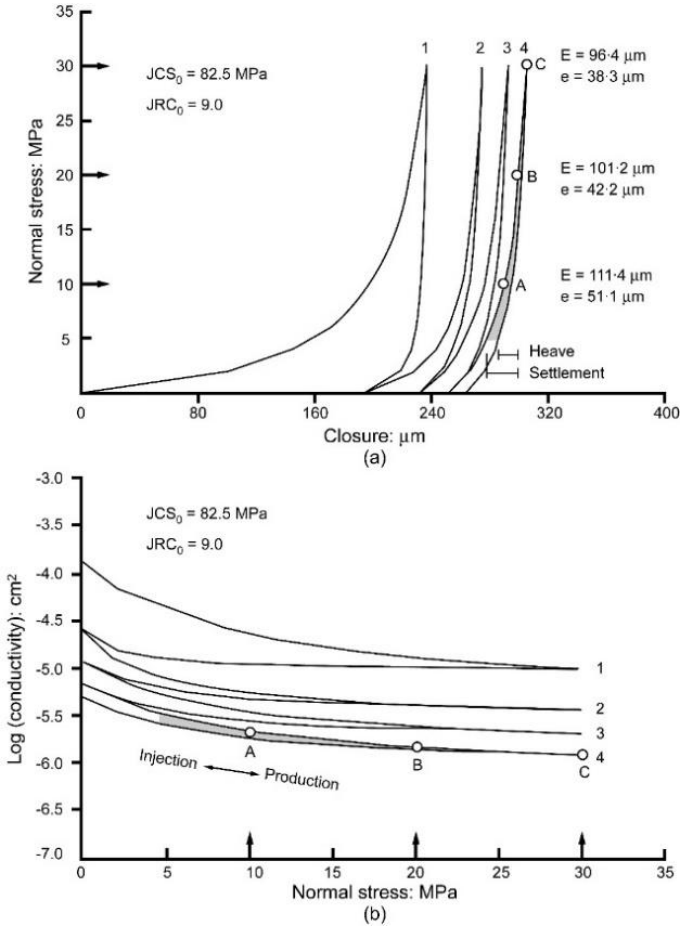
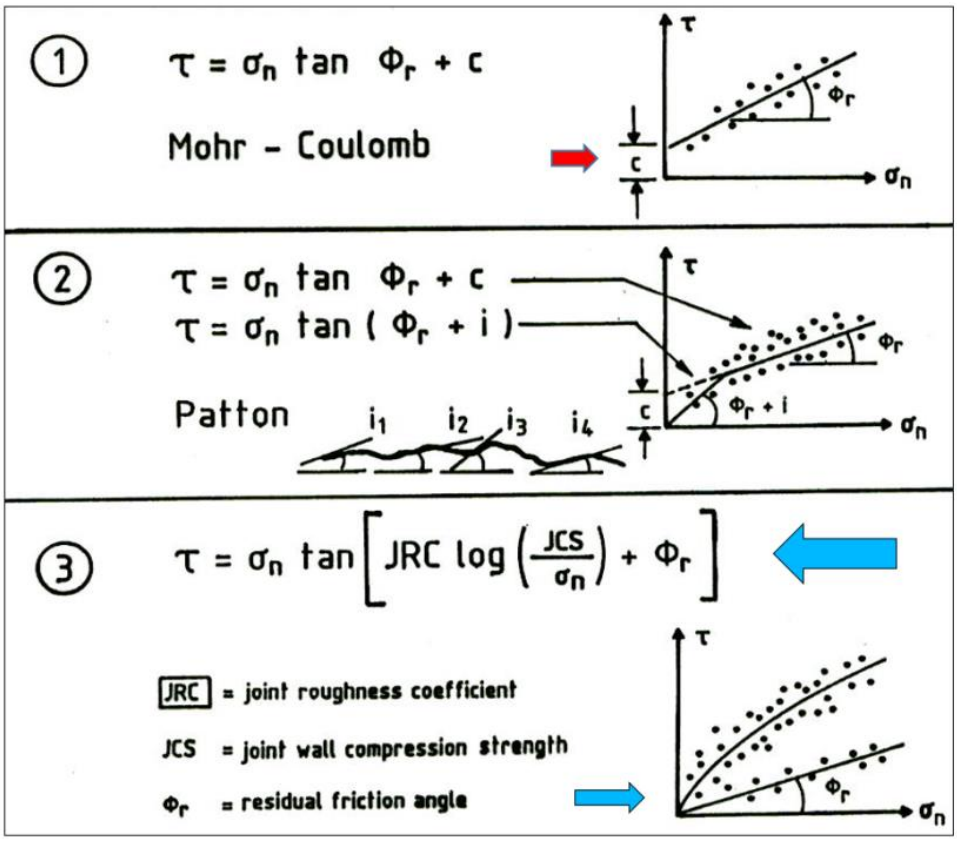


Figure 26 Left: Examples of normal stress-closure cycles for a cleavage joint in slate, for a rougher joint in dolerite, and bedding in hard limestone, from Bandis et al. 1983.. Right: Using the BB-plotting routine programmed by Bakhtar on an HP calculator, to demonstrate the consolidating cycles seen on the left, and the assumed 'undisturbed behaviour' 4th cycle, onto which the modelled apertures e and E have been written at 10, 20 and 30 MPa. Potential 'reservoir' drawdown and injection effects have been shaded on the conductivity curves. Barton et al. 1985.



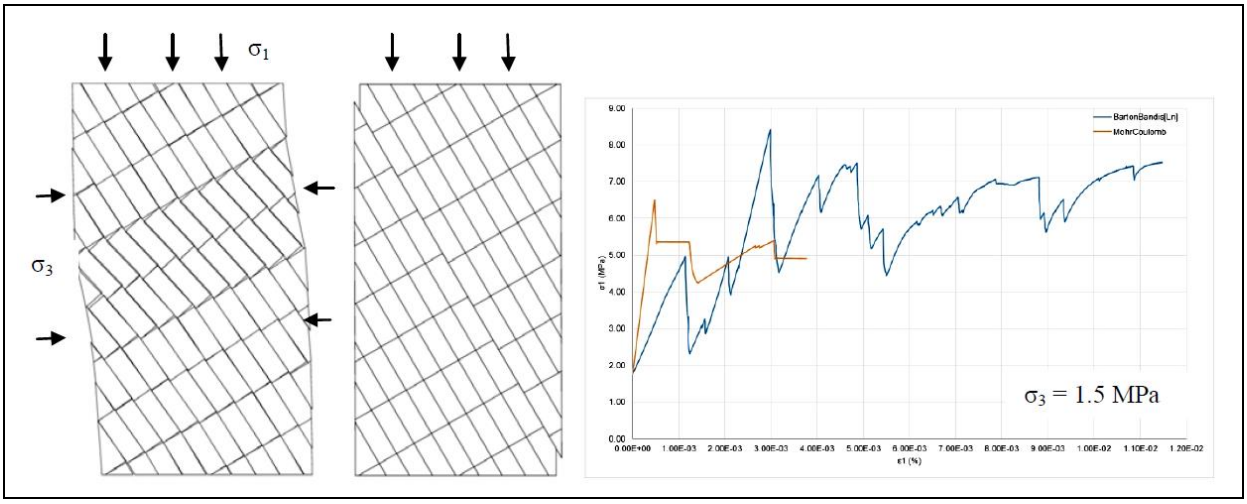


Figure 27 Linear (bi-linear) Mohr-Coulomb or non-linear Barton-Bandis? There are major differences. There is contrasting stiffness and strength behaviour, assuming non-linear (BB – left block plot) and linear (MC – right block plot). Due to the non-linearity of BB simulations compared to the linear (or bi-linear 'ramping') in the case of MC, significant block rotations are seen with BB which tend to be absent with MC. A comprehensive set of comparisons with numerous geometric and boundary conditions are given by Barton and Bandis (in preparation). Why are kink-bands seen in nature? Because shear strength and dilation are inevitably real and non-linear – when joints are non-planar.

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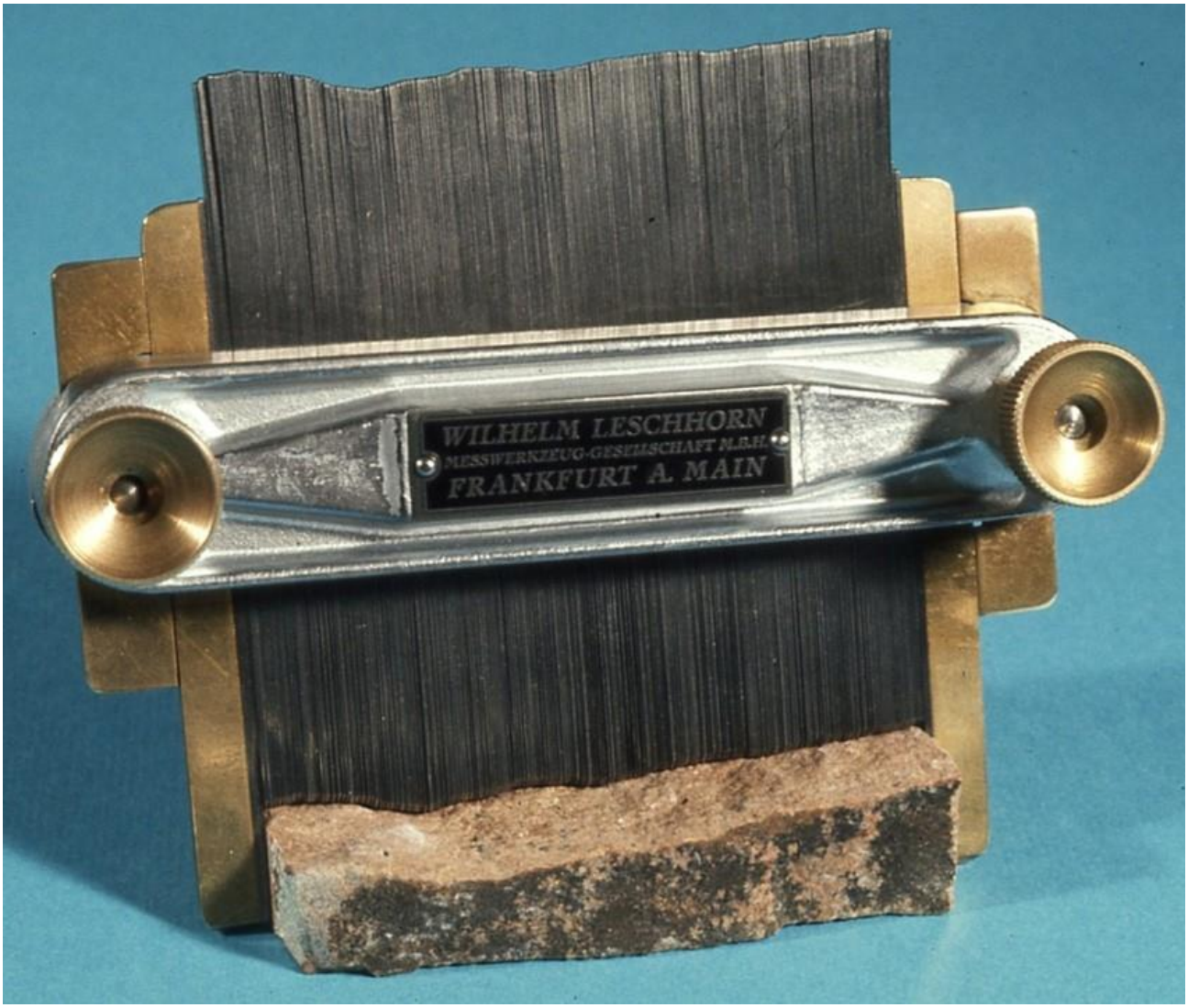
Note: There are now hundreds of articles about JRC. The origin (1973) and the 'ten profiles' (1977) are usually referenced, sometimes not even these. Most articles 'stop' referencing at 1977 regarding further work with this parameter by the originators. The above list is for those who might be curious where JRC (and JCS and φ_r) has been used after 1977 by the author and numerous colleagues. The list is of course very incomplete.

APPENDIX.



Top: Small steps (1mm) in hardware profilometer version, Bottom: No detectable stepsin profilometer used by Barton and Choubey, 1977. (Probable 0.33mm or 0.25mm wide stainless-steel blades) Tatone and Grasselli 'stair-stepping' assumption needs to be ignored. It, and earlier assumptions have mislead many researchers. New analyses and equations needed by many since so many have used wrong assumptions. It may be easier to do tilt tests. There are billions of potential joint samples in the world's collections of core boxes – sometimes 1,000km per major mining project and 10's of kilometers in major civil engineering projects. All that is needed is to saw parallel to the joint planes if not sufficiently axially jointed. Note: in Phillips Bartlesville extensive core sheds, the author was informed he was the first ever to want joint samples (from the 3km deep Ekofisk reservoir) – in 1985. Even though the oil does not get to the wells without joint/fracture flow since the chalk matrix has extremely low permeability.

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