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Non-linear shear strength descriptions are still needed in petroleum geomechanics, despite 50 years of linearity

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ABSTRACT: Despite utilizing multi-discipline teams in petroleum and service companies, and despite the remarkable abilities of these same companies to produce petroleum in many forms and in highly adverse environments, there appears to be a misalignment between the *geomechanics used*, and *rock mechanics*, the latter apparently *not used*, judging by workshop presentations. Is it possible that this is because *geomechanics* specialists are not aware of long-available non-linear description of shear strength, for both the fractures and matrix, in NFR and gas shales? Description of the non-linearity has been a goal of many in rock mechanics for the last 50 years, with a well-known start by Patton, 1966 reporting in the first ISRM congress held in Lisbon. His bi-linear strength envelope was an immediate improvement on Mohr-Coulomb linearity, and set the scene for others to improve upon this bi-linear description. The 1973 non-linear JRC- and JCS-based criterion of the present author was considered too complex by Byerlee, 1978, who favoured use of a friction coefficient. Shear strength represented in *geomechanics* remains linear, so is often unrealistic.

1. INTRODUCTION

Due to remarkable educational compartmentalization, there is widespread use of linear shear strength assumptions in the *petroleum geomechanics* taught in university courses. This is further applied by many oil companies and oil service companies, actually on both sides of the Atlantic, and indeed even in the Middle East. This is undoubtedly due in part to the application of Byerlee's well-known friction coefficients by Zoback and co-workers at the University of Stanford during the last several decades. The linear frictional strength assumptions are applied to signify probable critically stressed fractures, first in deep wells, later in naturally fractured petroleum reservoirs, and in the more recently exploited unconventional gas shales. Linear shear strength assumptions are also applied to the intact rock, which is usually described by simplified linear Mohr-Coulomb, despite many tens of MPa change of effective stress during the sometimes short lives of the reservoirs.

The commonly used Byerlee-type friction coefficient to signify that fractures may be critically stressed, with values quoted typically from 0.6 to 0.85, actually gives no insight into pre-peak phenomena, which include the beginnings of roughness and dilation mobilization, giving potential permeability enhancement in the case of gas shales and critically stressed fracture sets in NFR.

The more serious linearization of matrix strength, which is actually something with strong curvature when matrix porosity is present, is even more surprising, in view of the 30 to 60 MPa increase in effective stress which is often experienced during production. Linearization is also not consistent with the strong non-linearity demonstrated by tectonophysicists such as Mogi (and indeed Byerlee) back in the 1960's when applying high confining stresses to small intact triaxial rock samples.

Strength culminating in a maximum strength identified as a 'critical state' ($\sigma_{1\ max} = 3\sigma_{3\ crit}$) by Barton, 1976, led Singh et al. 2011 to demonstrate that the *horizontal critical state* of the strength envelope for a given rock matrix is reached when the confining pressure reaches the approximate *level of uniaxial compressive strength*. This simplification works well for the majority of rocks.

In contrast, shear strength suggested by linearity 'goes on forever'. Obviously it cannot, and the *highly stressed* 'island asperities' of even relatively planar shearing fractures, if with insufficient static deformation moduli as in the case of some gas shales, may be the reason for some very short production lives. Such were indicated in interviews with the industry, in Ghassemi and Suarez-Rivera, 2012 who mostly studied proppant-sustained hydraulic fractures at Schlumberger/TerraTek facilities.

The extensive 'fracking' of shales review by King, 2010 and the fracture shear mechanisms illustrated by Dussault, 2013 (see later), indicate that it is the *fracture shearing* well beyond the 'central' propped region, which is responsible for the necessary drainage volume, and for the associated clouds of microseismic activity. What goes on along the natural fractures (not substitute saw-cut samples), especially across their too-highly stressed 'island asperities' while shearing, may govern the production life. Highly non-linear behaviour may be involved, quite different from what is taught and modelled in commonly applied *geomechanics* routines.

2. THE NON-LINEARITY OF THE MATRIX

Figure 1 is a simple example of a typical *geomechanics* assumption (linear shear strength according to Mohr-Coulomb) and a more representative model of reality, meaning non-linear shear strength envelopes, because effective stress changes, often by tens of MPa (or by tens of thousands of psi), during petroleum production.

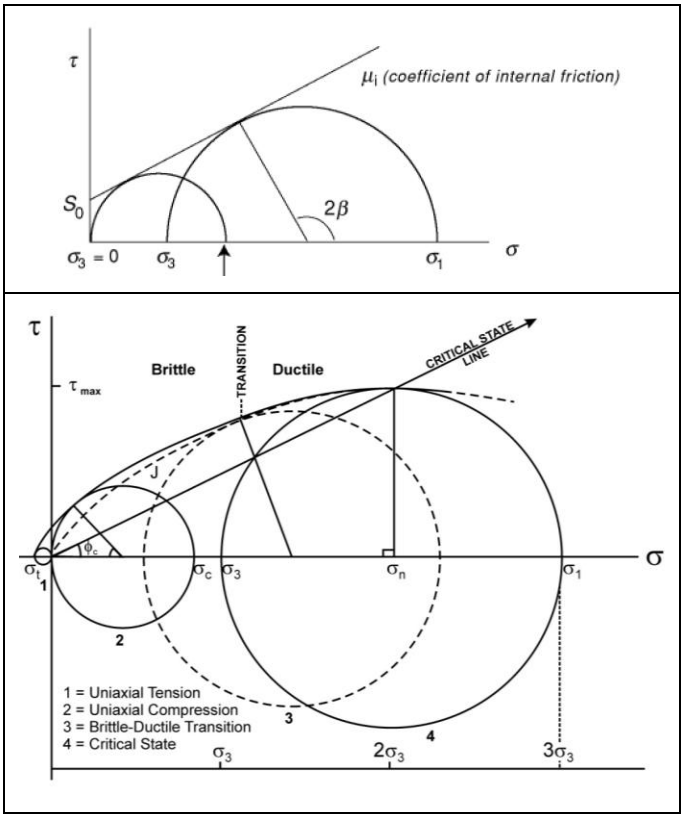

Fig. 1. Top: The simplicity but erroneous nature of linear Mohr-Coulomb, assuming large changes of effective stress are involved. Bottom: The acknowledgement of non-linearity and of a critical (maximum strength) state at critical confining pressures as high as UCS. Barton, 1976 and Singh et al., 2011.

Recently, Singh et al. 2015 extended their simple MMC (modified Mohr-Coulomb) criterion to anisotropic rocks such as slates and phyllites, and find that 1.25 x UCS is the typical critical confining pressure needed to reach the maximum horizontal part of the Mohr envelope. Their work from 2011 and now 2015 clearly deserves ISRM 'suggested method' status', since finally solving the necessary non-linearity, and requiring fewer triaxial tests at lower confining pressure, in order to define the whole curved envelope. Figure 2 indicates that significantly greater curvature than Hoek-Brown may be needed. So less triaxial tests are needed.

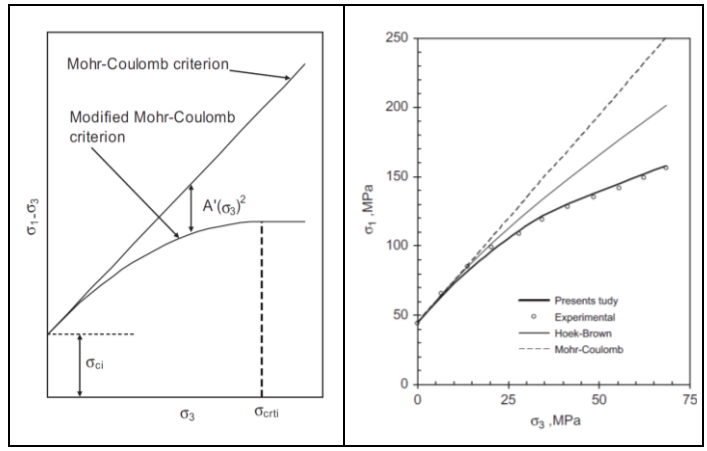

Fig. 2. The modified Mohr-Coulomb (MMC) criterion of Singh et al. 2011. The necessary deviation from linear M-C is quantified, and curvature greater than Hoek-Brown is also indicated.

Those doubting where these strong curvatures come from, and why they seem to be of more concern in rock mechanics (and tectonophysics) than in *'geomechanics for petroleum'* can refer to Figs. 3 and 4, which were part of the original motives for trying to accept the reality of strong curvature, as detailed in Barton, 1976.

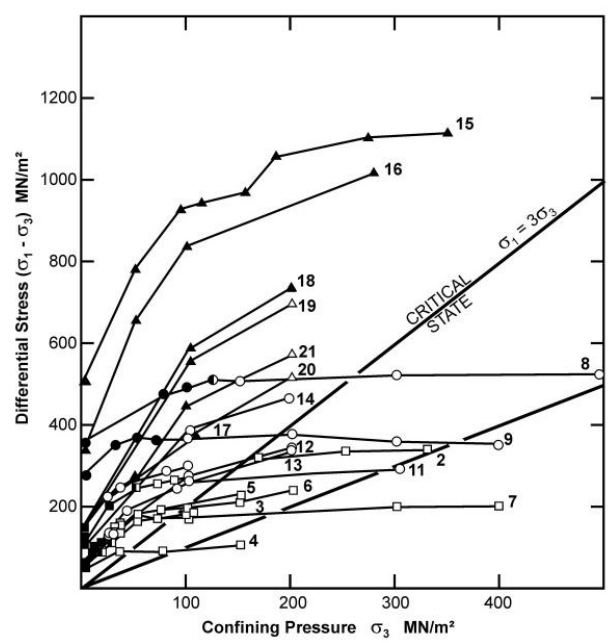

Fig. 3. High-pressure triaxial tests reported by Mogi, 1966 for dry carbonate rocks. The tentative critical state line was added in Barton, 1976. The next figure shows silicates.

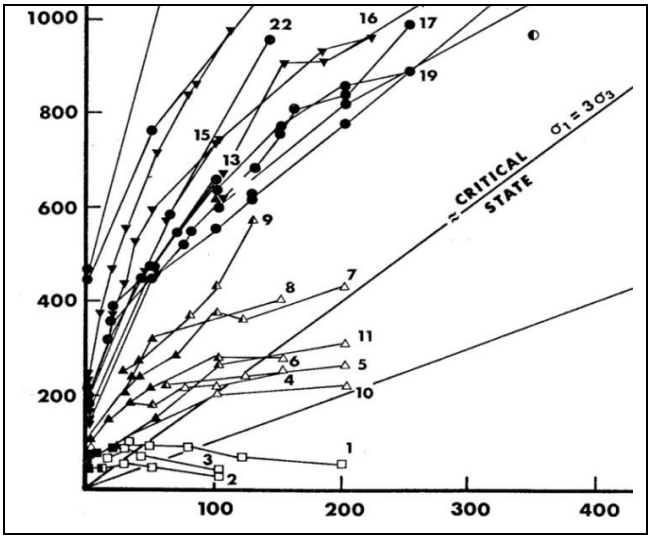

Fig. 4. High-pressure triaxial tests reported by Mogi, 1966 for dry silicate rocks. (Extracted data: same axes as Fig. 3). The tentative critical state line was added in Barton, 1976.

Of course the confining pressures used by Mogi, 1966 (and similar triaxial series reported by Byerlee), were extreme, and we need to look close to the axis (say up to 100 MPa confining pressure, or 4 km equivalent depth) where nevertheless extreme curvature is evident. So why do we see only the linear Mohr-Coulomb envelopes, in both structural geology and geomechanics textbooks, such as Zoback, 2007?

3. THE NON-LINEARITY OF THE JOINTS

In a significant number of countries and 'earth-science' disciplines the word 'rock joints' is commonly used in place of 'fractures', which is widely preferred elsewhere: flow network modelling, geomechanics, some nuclear waste communities. Let us agree that we are describing the same planar or non-planar breaks in the intact rock, which are often arranged in sets. These discontinuous surfaces have actually challenged rock mechanics, rock slope and large-dam designers for more than fifty years.

Now there may be as many as 50 articles per year on the subjects of shear strength, roughness description, and flow modelling – in joints and fractures - in the last decade. Many have been seen as a frequent reviewer and author. Recently 47 equations were assembled by an author in one table for estimating JRC, a useful parameter rejected by Byerlee, 1978 and ignored by leading actors in geomechanics for the last few decades.

The writer was fortunate to start his carreer in rock mechanics 50 years ago, one month after the classic Patton, 1966 work with rough joints *in situ*. Which 'i' values should one use (?) led to a lot of shear tests in Ph.D. student years, some 200 tests in 1967 alone. Joining a group at Imperial College (Peter Cundall, John Sharp, and especially our first mentor David Pentz) led us to 'non-linear acceptance' from the beginning. We had joined a group who already had a large-scale direct shear machine for testing large-diameter cored rock joints from RTZ open pits in southern Spain. Of course non-linearity was seen. This was 50 years ago.

In contrast to this promising start, the writer was recently informed by a reliable source who has worked as a consultant in several petroleum companies, that they do not yet perform *shear tests on fractures*. Of course some service companies may do – but saw-cut samples are naturally a bit too simplistic. It is hard to believe, with 60% of the known petroleum resources to be recovered from fractured reservoirs, that fractures are still not tested very much. Maybe our shear testing, tilt testing, roughness measurement, and Makurat's CSFT (coupled shear flow testing) of natural fractures from the 3 km deep Ekofisk chalk reservoir in 1985 and 1986, remains a seldom activity. We got used to seeing two to three orders of magnitude increase in permeability with 2 to 3 mm of shearing, when normal stresses were not too high.

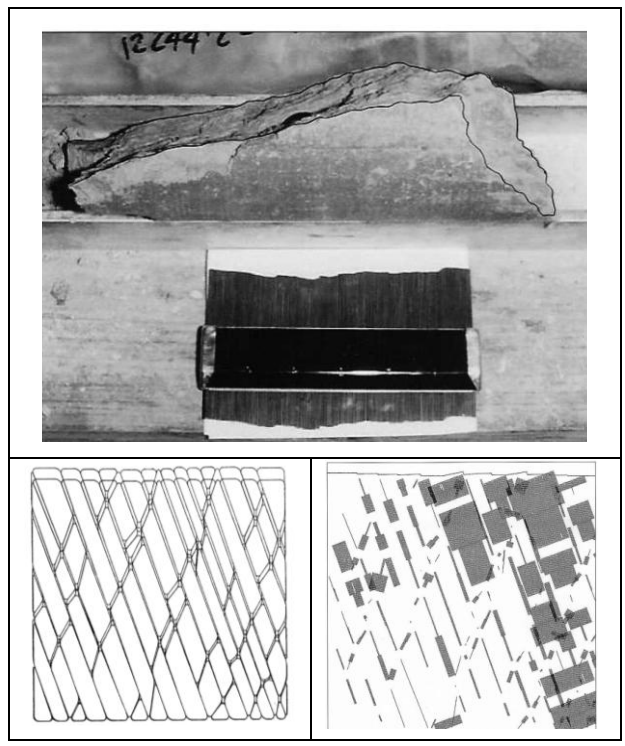

Fig. 5. Top: One of numerous natural fracture samples of Ekofisk chalk from a deviated 12,244 ft. well. These were tested at NGI for the Norwegian Petroleum Directorate, in connection with the off-shore reservoir compaction. Bottom: UDEC-BB (Itasca-NGI) compaction modelling of a unit of the fractured reservoir by Mark Christianson: in Barton et al. 1986.

The work of Colleen Barton et. 1995 at Stanford University some ten years later, was further evidence of the conductive tendencies of shear-stressed fractures, and the non-conductive tendencies of insufficiently stressed features. Their classic results, added to later by Townend and Moos and by Zoback, 2007 in his book on reservoir geomechanics, was a welcome confirmation of

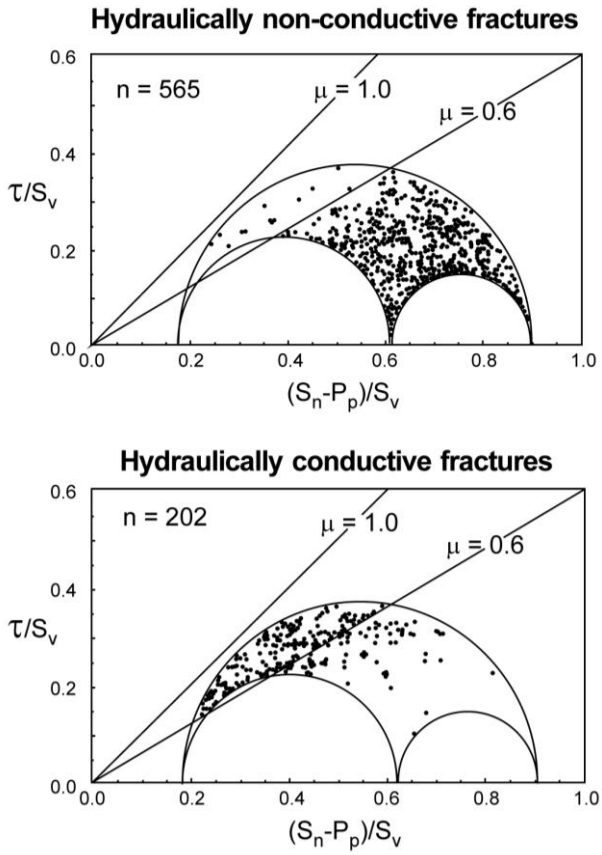

Fig. 6. The importance of transformed shear stress in distinguishing between non-conductive and conductive fractures in deep wells. C. Barton, Zoback and Moos, 1995.

the importance of shear stress. Figure 6 shows one of their sets of in situ data (Cayon Pass granites). Nevertheless, while interpreting the probable magnitude of near-well in situ shear stress, one has to neglect the likely value of the mobilized dilation angle (which should be added into the sin 2β and cos 2β stress transformation equations, in order to get the correct magnitude of the normal and shear stresses. This was demonstrated 'the hard way' in $1m^3$ diagonally-fractured shear tests by Bakhtar and Barton, 1984. Reminders of our widespread earthscience error, neglecting mobilized dilation, was given in Barton, 2006 and 2013.

One does not actually get any closer to solving the shear *strength* side of the equilibrium conditions, when using the 'friction coefficient' style of representing the (approximately) transformed shear stress. The linear friction coefficient, resembling the so-called Byerlee, 1978 'law', is actually a very poor approximation to the shear *strength* of fractures – *if they are non-planar*. Figure 7 is Byerlee's own figure (but using mostly the writer's summary of test data from Barton, 1976. The poor relevance of this $\tau = 0.85\ \sigma_n$ linear equation at low stress is clearly evident. Even at effective normal stress levels of many 10's of MPa, there is still significant variation, from rock to rock and fracture to fracture. Byerlee, 1978 was quite wrong in assuming that the rock type played little role. He also had some negative concl-

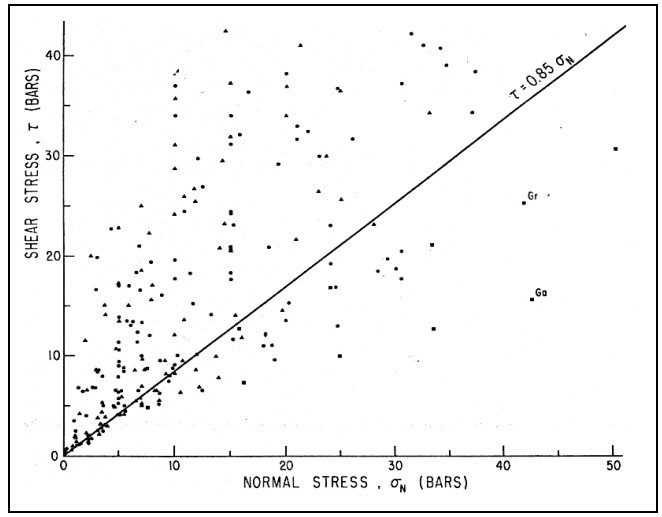

Fig. 7. Fracture shear strength and the Byerlee, 1978 suggestion of a (relatively) 'low-stress' (non-fitting) equation.

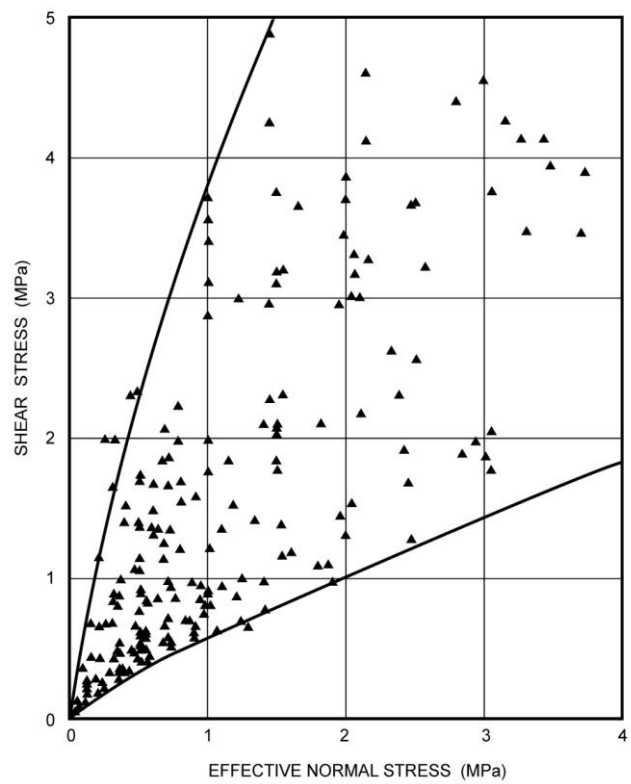

Fig. 8. The shear strength of joints/fractures at low stress, from an assembly by Barton 1976, as used by Byerlee in Figure 7.

usions about two simple parameters (JRC and JCS), now used widely by experimentalists and field staff in rock mechanics and engineering geology. Quoting from Byerlee, 1978 concerning the JRC and JCS method:

'There are so many variable (sic), whose precise value is uncertain, in the equation, (sic) that its validity cannot be tested'. In Byerlee, 1978 he referred to the Barton, 1973 and Barton, 1976 version of the JRC-JCS-φ_b equation. He managed to give this author first the initials 'M' and then 'H' in reference to these two papers. Their future fate – *in geomechanics* - was perhaps sealed by his lack

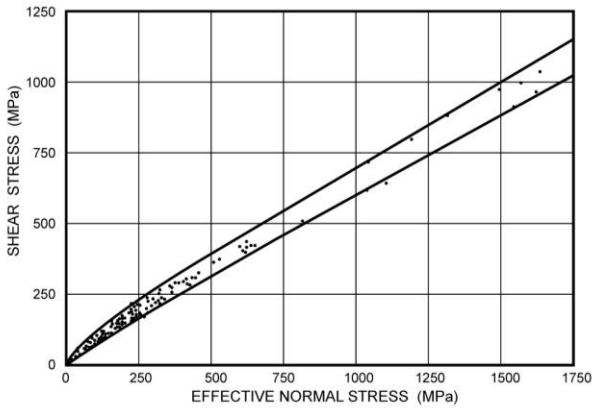

Fig. 9. The shear strength of small samples of fresh fractures, tested at very high stress, from an assembly by Barton 1976.

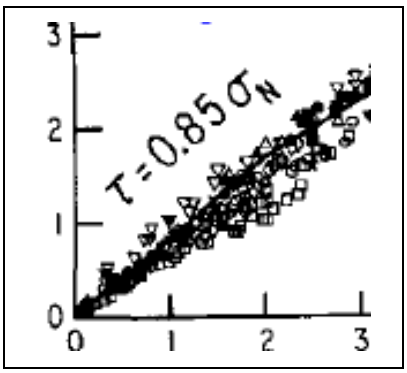

Fig.10. A deliberately clipped 'limited' normal stress range of 0 to 3000 bars, or 0 to 300 MPa, from the best available pdf of Byerlee, 1978. His equation continues to be a crude fit to a wide range of data, though the 'fit' is better than its obvious failure with the 0 to 5 MPa normal stress range of Figure 7.

of care. He had also expressed the erroneous view that rock type 'has little or no effect on friction'. So we have a seriously negative opinion from a no doubt influential professor at Stanford, which might have set the scene both for subsequent *linear geomechanics*, and failure of the next generations at Stanford to take any interest in the non-linear work occurring across the Atlantic. By 1982 there would be a formal development of a scale-corrected model for shear strength, with physical and conducting apertures and possibilities for M-H coupled modelling also included. Ironically some of this work was funded by the USA's ONWI (and by Canada's AECL). By 1985 the Barton-Bandis model was already programmed in UDEC as UDEC-BB, and commercially available through Itasca Inc., Minnesota.

No mention of this widely used method of describing shear strength was made in Zoback, 2007 in his text book concerning *reservoir geomechanics*. Contrary to a 'not yet seen' position or deliberate choice (?), some of the interesting work of Colleen Barton, Zoback, Moos and Townend was naturally referenced in an 800-references text book by Barton, 2006 the year before.

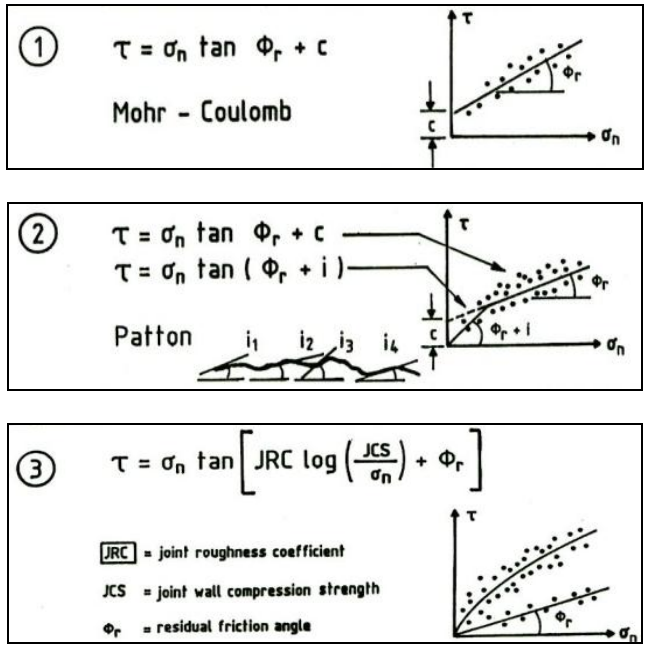

Fig. 11. Top: Mohr-Coulomb linearity: the widely preferred *geomechanics* approximation apparently now based on Byerlee's 'laws'. Centre: The important exploration of roughness by the USA's Patton, 1966 at the start of rock mechanics. Bottom: The non-linearity suggested in Barton, 1973 and generalized in Barton and Choubey, 1977 as a result of testing 130 joint samples, with some degrees of weathering, therefore replacing the flat surface *unweathered* φ_b with a lower residual frictional strength φ_r to represent *weathered* or altered joints .

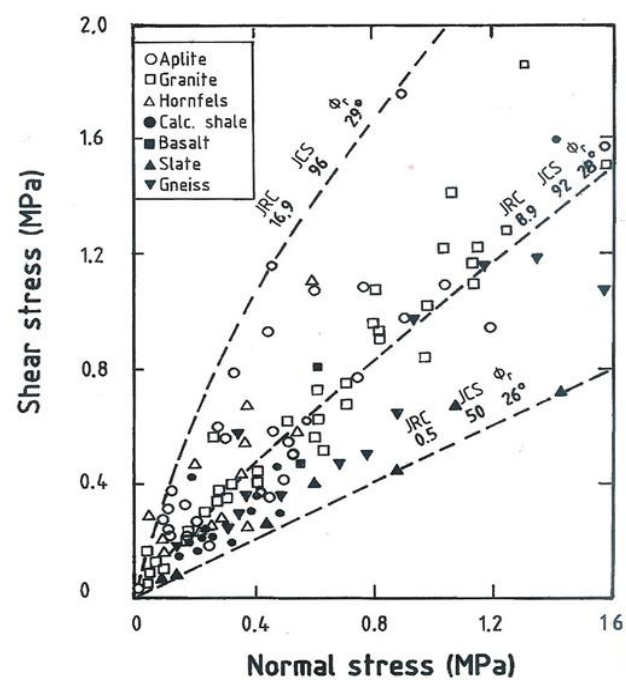

Fig. 12. Validating what Byerlee (and possibly Zoback) assumed could not be validated. A total of 130 rock-joint samples were tilt tested, Schmidt hammer tested, roughness-profiled, and finally direct shear tested. Three curved peak shear strength envelopes are shown here, with JRC, JCS and φr values as examples. Barton and Choubey, 1977.

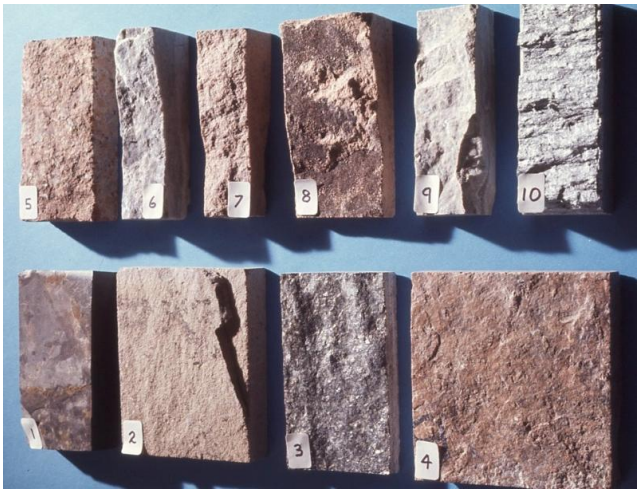

Fig. 13. Examples of the 130 joint samples tested by Barton and Choubey, 1977. Byerlee's *'rock type has little or no effect'* error was certainly not relevant nor considered in this researh.

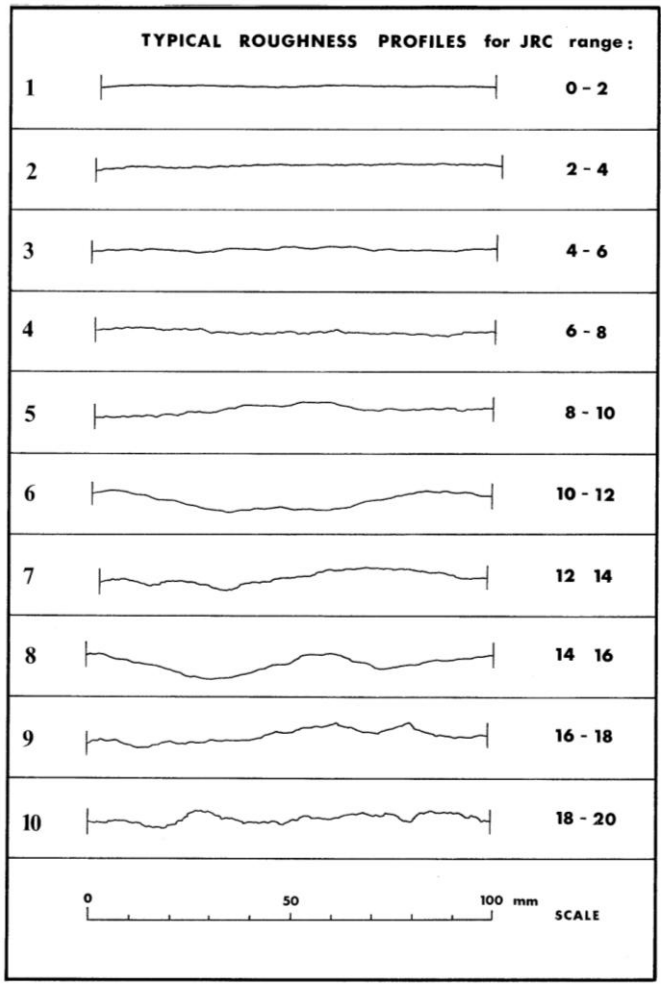

Fig. 14. Ten example profiles from Barton and Choubey, 1977. Those who are responsible for gradually contributing to the 47 (!) tabulated equations for estimating this widely used (*in rock mechanics*) JRC value, seem not to have realised that tilt tests are recommed. Following the work of Bandis et al. 1981, we have a block-size dependent scaling of both JRC and JCS. There is also an 'amplitude/length' (a/L) method from Barton, 1981, which can be glimpsed in Figure 17b, top-right.

Fig. 15. These large-diameter cored samples were direct shear tested in the USA, and subsequently back-analysed by the writer. The 250-350mm long samples gave the joint roughness coefficients shown. The rock is welded tuff from Yucca Mt.

The simplicity of tilt testing, and the fact that the 3D surface is sampled in a manner of relevance to shear resistance, seems to have been neglected by those analysing 3D roughness with ever greater 3D-laser accuracy, and subsequent mathematical complexity.

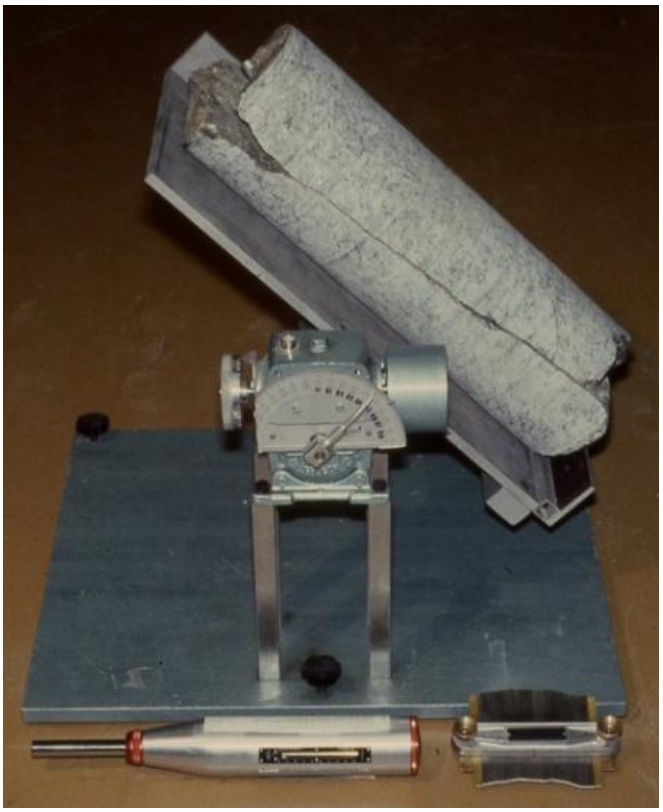

Fig. 16. The tilt test. By inverting the equation seen in Figure 11.3, or following the equation given in the second column of Figure 17a, JRC can be readily back-calculated. Note the need for a Schmidt hammer for rebounds r and R, and the standard roughness profiling for recording the approximate JRC for reporting purposes. A similar apparatus was used when the writer was working in TerraTek (1980-1984), but may no longer be used (by Schlumberger), if fractures are not tested.

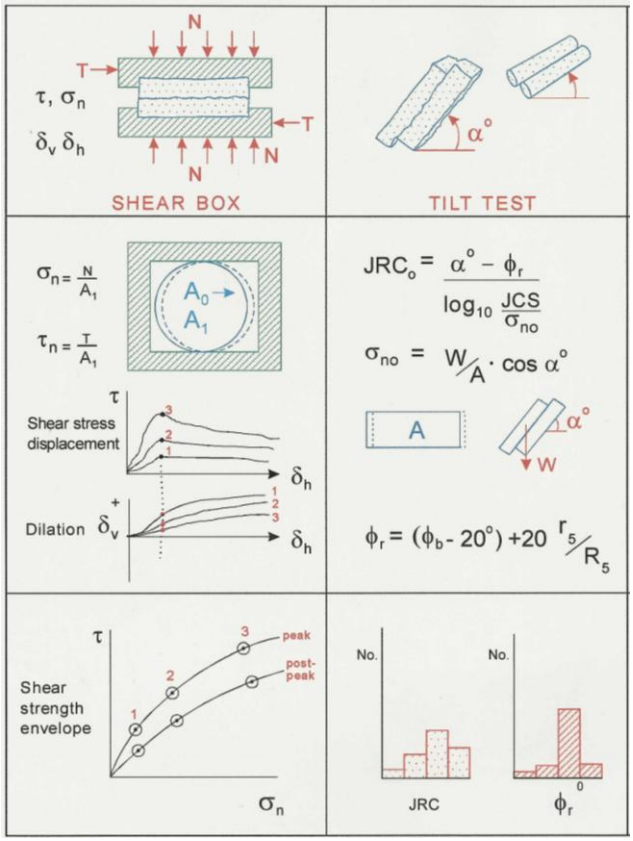

Fig. 17a. Left: Shear box test principles and typical results. Right: Alternative index testing, using tilt tests for JRC and for φ_b from which difficult-to-measure φ_r can be estimated.

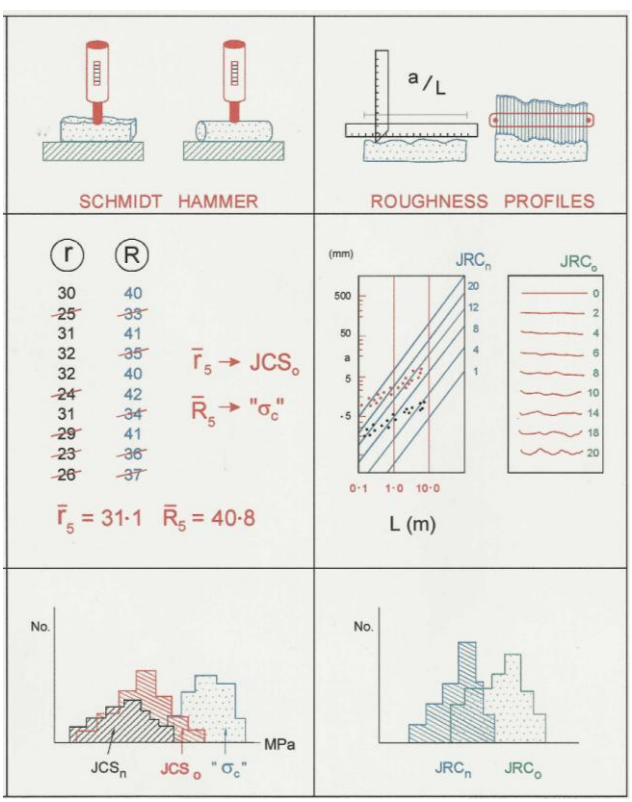

Fig. 17b. Left: The Schmidt hammer rebound tests on the joint or fracture (r) and on the unweathered core (R). Note use of *top 50%* for best accuracy. Right: a/L and approx JRC profiles. All data should be presented as histograms.

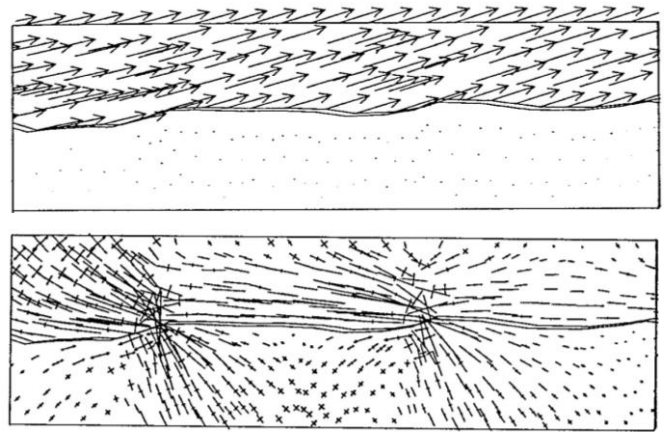

Fig. 18. UDEC simulations of shearing a non-linear joint, performed by Marte Gutierrez (Gutierrez & Barton, 1994).The modelled (dilation-affected) displacement was 0.5 mm and the maximum stress at the contacting asperities was 38 MPa.

The phenomena modelled in Figure 18 deserve more than one 'friction coefficient' to describe possible NFR or gas-shale fracture shear-behaviour. In similar vein, the development of shear strength and dilation (and permeability) shown in Figure 19, tell much more than one 'friction coefficient' (somewhere near the 'peak').

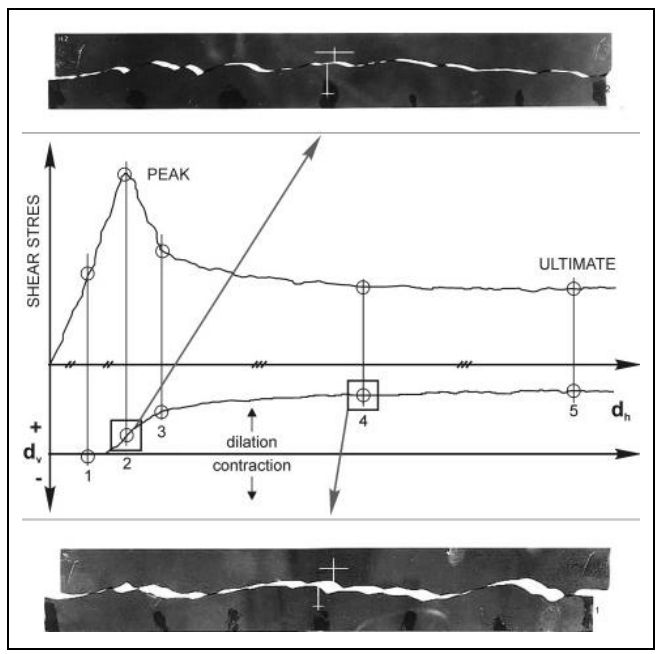

Fig. 19. Shear-strength-displacement and dilation are shown just as measured in the direct shear tests, performed in 1967. These replicas have exaggerated tension-fracture roughness, but are useful for illustrating phenomena (Barton, 1973).

How far does a single value of $\mu = 0.85$, or $\varphi = 40.6°$ explain shale gas production, when realizing the range of behaviour exhibited in Figures 18 and 19, even before peak shear strength is reached? For instance we will have slight dilation, aperture increase, permeability increase, possible crushing of asperities, finally reaching peak shear strength when the dilation angle and asperity failure component $\boldsymbol{a_s}$ are maximized. Bandis et al. 1981.

Summarizing: it seems to the writer that petroleum geomechanics considers: *linear* Mohr-Coulomb for the intact rock, and *linear* Mohr-Coulomb (or Byerlee μ) for the fractures. In reality there is far more to the frictional strength of fractures or joints than μ = 0.6 or 0.85. We have important-for-production behaviours such as pre-peak mobilization of friction, dilation, permeability, pre- and peak-shear stiffness (which is doubly scale-dependent: a big advantage for gas shales), and post-peak loss of shear strength, i.e. reduced JRC.

Furthermore there is a rich mix of inter-locked and un-mated normal stiffness, and the effects all the above may have on *physical apertures* and their conversion to the equivalent *hydraulic apertures*, i.e. permeability for gas or oil drainage. All the above are part of *rock mechanics*. Unfortunately, all the above are apparently absent in the reservoir *geomechanics* seen in workshops and courses on both sides of the Atlantic and in various places in the Middle-east, all in the last 2 to 10 years. Maybe secrecy is in operation, competing companies not 'telling all'?

As suggested in the abstract, multi-discipline teams in petroleum companies and service companies, seem not to be so 'multi-discipline' in the seemingly neglected area of (non-linear) rock mechanics. *Rock mechanics* is not even a keyword among thousands of options, in a major geoscience engineering organization.

4. STRESS TRANSFORMATION, JRC mobilized

An important subject that goes beyond the more common distinction that we make between constant normal stress and 'constant' normal stiffness shear testing of rock joints (the latter actually not constant in reality), is the correct transformation of stress.

The subject of concern is the transformation of stress from a principal (2D) stress state of σ_1 and σ_2 to an inclined joint, fault or failure plane, to derive the commonly required *shear and normal stress components* τ *and* σ_n. If the surface onto which stress is to be transformed does not dilate, which might be the case with a fault at residual strength, or for a thickly clay-filled discontinuity, *then* the assumption of co-axial or co-planar stress and strain is no doubt *more* valid.

If on the other hand dilation is involved, then stress and strain are no longer co-axial. In fact the plane onto which stress is to be transferred should be an *imaginary plane* since continuity is assumed. Non-planar rock joints, and failure planes through dense sand, or through over-consolidated clay, or through compacted rockfill, are neither imaginary *nor are they non-dilatant* in nature.

This problem nearly caused a rock mechanics related injury, when Bakhtar and Barton, 1984 were attempting to biaxially shear a series of ten 1 m^3 samples, applying

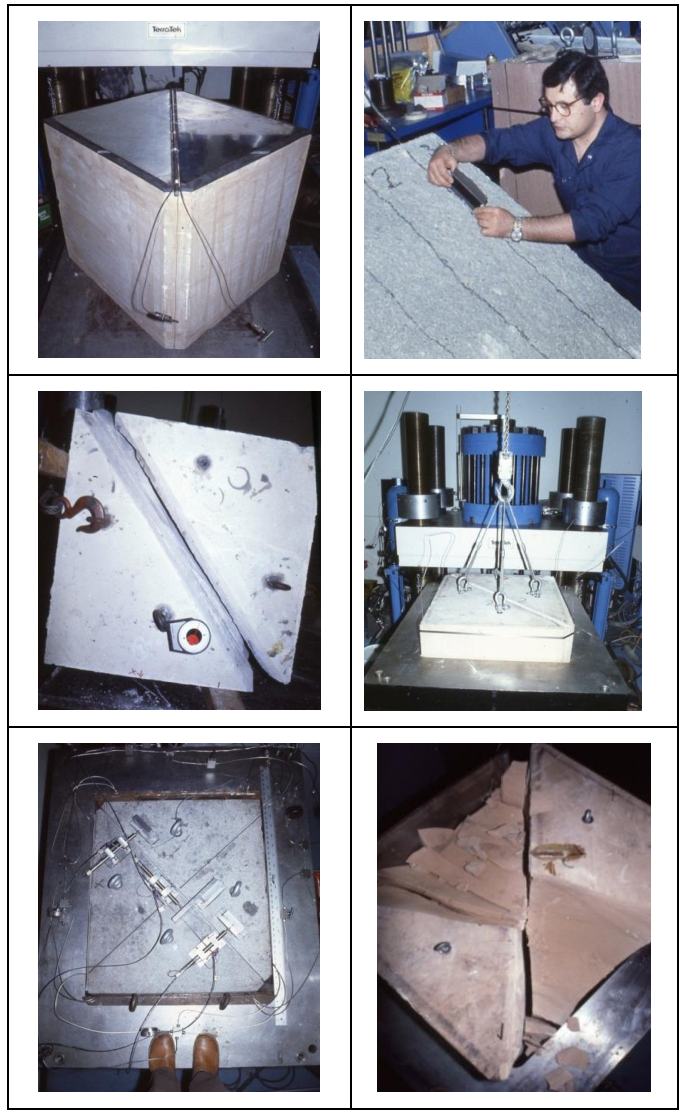

Fig. 20. Sample preparation and index testing of 1 m^3 samples of rock, hydrostone and concrete by TerraTek colleague Khosrow Bakhtar in the early 1980's (in a pre-Schlumberger era). Note the tilt testing (at 1 m^3 scale), lowering a lightly clamped sample into a test frame, LVDT instrumentation, and (a rare) sheared sample of an undulating fracture in sandstone.

shear and normal stress to the 130 cm long diagonal fractures (which were without weathering effects). The experimental set-up and various index tests are shown in Figure 20. The sample preparation was unusual because of principal stress (σ_1) controlled-speed-tension-fracturing: (see triangular flat-jacks in top-left photo). This allowed fractures to be formed in a controlled manner, with less roughness than typical with tension fractures. Figures 21 and 22 show the stress application and related assumptions, presented in three stages.

The rock mechanics near-injury occurred when a (σ_1-applying) flat-jack burst at 28 MPa, damaging pictures on the laboratory walls and nearly injuring the writer who was approaching to see what the problem was. The sample illustrated in Figure 20 (with the photographer's shoes, pre-test stage) was transformed into ejected slabs,

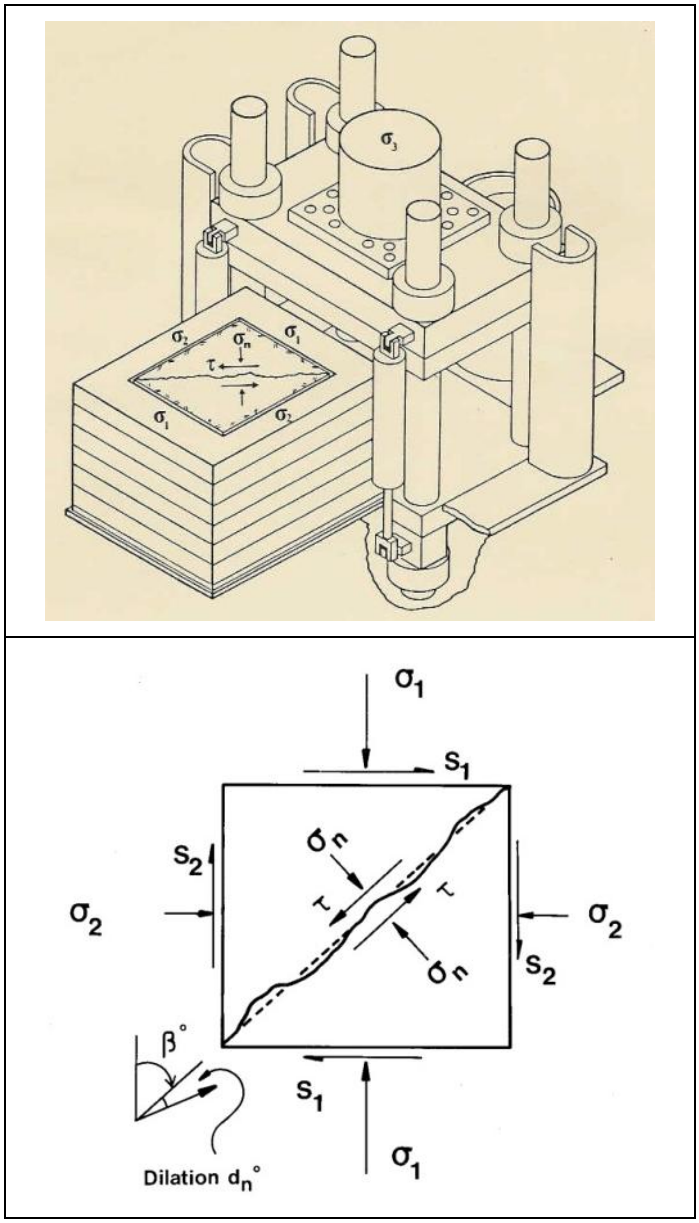

Fig. 21. a) The TerraTek 'cube-machine' test set-up b) The assumed stress transformation components. Bakhtar and Barton, 1984.

and ejected high-pressure oil, as a result of the explosive flat-jack burst. These 1.3m long tension fractures gave tilt angles varying from 52° to 70°, and large-scale (L_n = 1.3 m) joint roughness coefficients (JRC_n) varying from 4.2 to 10.7. A clear scale effect was exhibited in relation to the 100mm long JRC_0 profiles shown in Figure 14.

In order to minimize boundary friction, molybdenum-greased double-Teflon sheets (virtually fluid boundaries) and pairs of stainless-steel, 0 to 30 MPa flatjacks were used on all four sides of the 1 m^3 blocks.

The conventional stress transformation equation 1, and the dilation-corrected equation 2 are shown in the next column. It will be noted that a dimensionless model for mobilization of roughness (JRC_{mob}) is finally needed.

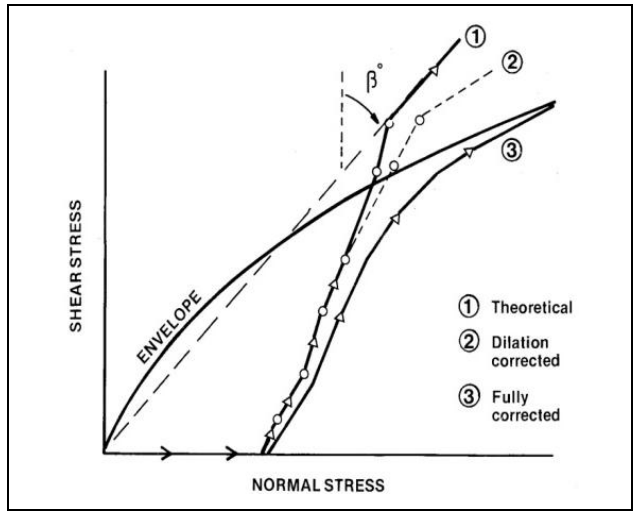

Fig. 22. The two-stage corrections for out-of-plane dilation and boundary friction. It was assumed at first that failure was 'long overdue' when *apparently* reaching the location #1. In fact we were only just approaching the strength envelope, at location #3, so shear failure could not yet have occurred. Bakhtar and Barton, 1984.

$$\left.\begin{aligned}\sigma_n &= \frac{1}{2}(\sigma_1+\sigma_2)-\frac{1}{2}(\sigma_1-\sigma_2)\cos(2\beta)\\ \tau &= \frac{1}{2}(\sigma_1-\sigma_2)\sin(2\beta)\end{aligned}\right\} \quad (1)$$

$$\left.\begin{aligned}\sigma_n &= \frac{1}{2}(\sigma_1+\sigma_2)-\frac{1}{2}(\sigma_1-\sigma_2)\cos[2(\beta+d_{n\,mob})]\\ \tau &= \frac{1}{2}(\sigma_1-\sigma_2)\sin[2(\beta+d_{n\,mob})]\end{aligned}\right\} \quad (2)$$

where angle β is the acute angle between the principal stress σ_1 and the joint or failure plane. The peak dilation angle and mobilized dilation angle can be written as:

$$d_n^0(\text{peak}) = \frac{1}{2}JRC(\text{peak})\log(JCS/\sigma_n') \quad (3)$$

An estimate of the mobilized dilation angle $d_{n\,(mob)}$ for adding to the joint angle β, is as follows:

$$d_n^0(\text{mob}) = \frac{1}{2}JRC(\text{mob})\log(JCS/\sigma_n') \quad (4)$$

$JRC_{(mob)}$ is an important component of the Barton-Bandis joint behavior criterion. It is shown in Figure 23. It was developed by Barton, 1982 while analyzing the results of TerraTek's ONWI-funded 8m^3 *in situ* heated HTM (hydro-thermo-mechanical) block test, which was performed by colleagues Hardin et al. 1982, at the Colorado School of Mines experimental mine. The writer was fortunate to be introduced to this test, and to help analyse it, when first joining TerraTek in 1980.

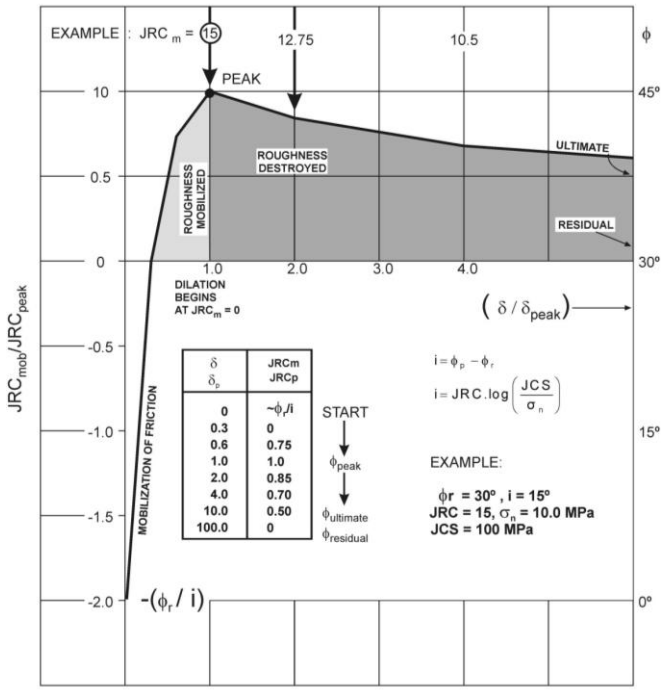

Fig. 23. The dimensionless JRC $_{(mob)}$ method was designed to match the details of fracture behavior during direct shear testing. A preliminary simpler version was tested in 1980. Note the different level of information compared to one 'peak' friction coefficient μ (top point of figure only). Barton, 1982.

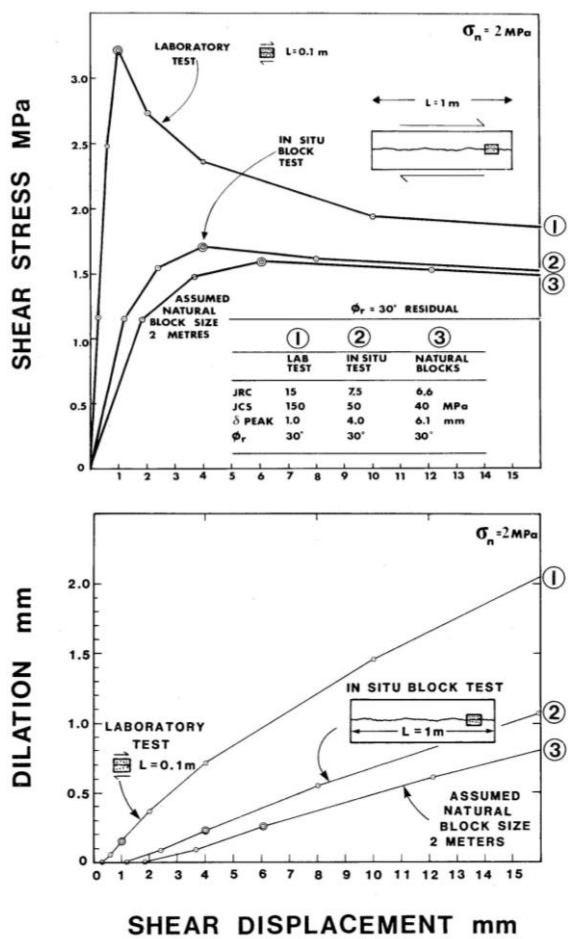

Fig. 24 Generating shear-displacement-dilation behaviour predictions, for three different block sizes. Barton, 1982.

5. STRENGTH, DILATION, CONDUCTIVITY

An example of application of the JRC$_{(mob)}$ method, which is coded in UDEC-BB, but with more coordinates for added smoothness, is shown together with Barton-Bandis scale-effect (block-size) corrections in Figures 24. The level of (predicted) information exceeds by orders of magnitude, a single (peak?) friction coefficient.

Naturally, the dilation accompanying the shearing of even non-planar joints or fractures, generally provides an increased void space for flow to increase. This was demonstarted in numerous CSFT tests in projects at NGI during the period 1985 to 1995. The coupled BB model predicts such effects when no gouge is produced to block the void space. Reduced permeability-change with dilation was modelled by Olsen and Barton, 2002, to allow for gouge production from crushed asperities.

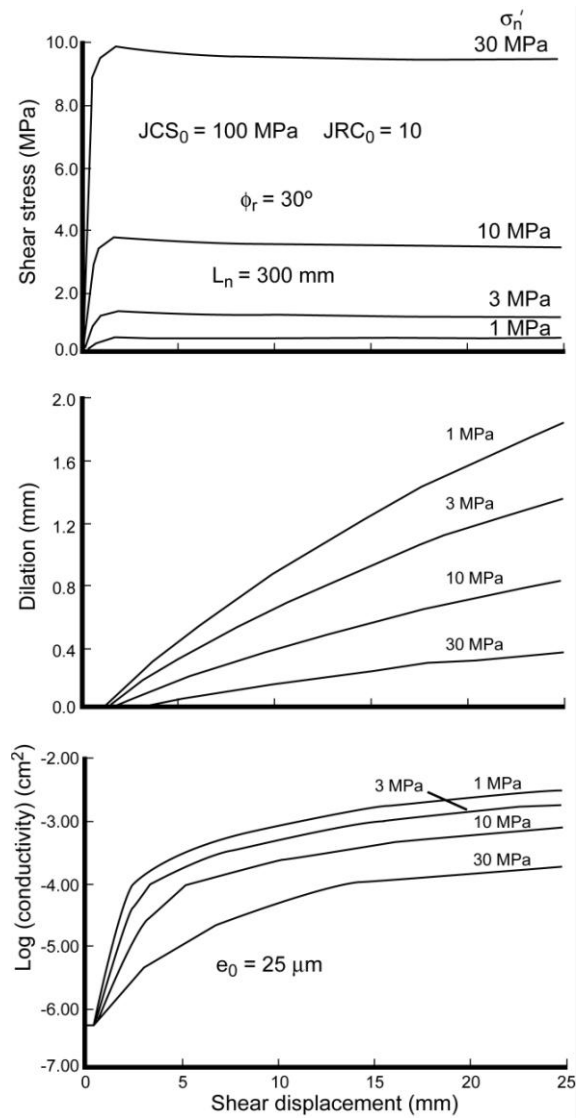

Fig. 25. Generation of coupled shear strength, dilation, and conductivity, using Barton-Bandis input data as shown. Note the 'delayed' onset of dilation with stress, as also seen when the block-size is increased, as in Figure 24. This plotting routine was HP-calculator programmed by Bakhtar from BB behaviour. Barton and Bakhtar, 1987 (contract work in 1983).

The subject of shear-induced dilation and potential permeability enhancement, as illustrated in Figure 25 may be vitally important for production from gas shales. Figure 26 shows an interpretation of what is likely to be happening (in principle), obviously well outside the central hydraulically-fractured and sand-propped region in a gas shale development. Shearing of natural fractures in the gas shale can explain the surrounding clouds of microseismic activity, and the necessary drainage of a larger volume. Shale is too impermeable and lacking significant porosity without this 'natural' mechanism.

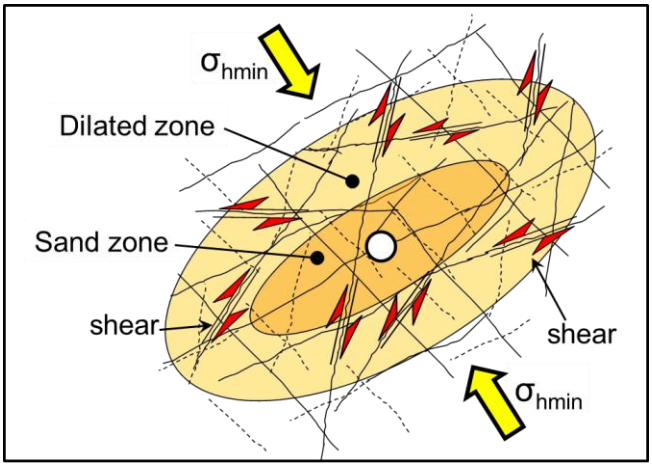

Fig. 26. A hypothetical but important interpretation of natural fracture *involvement* in production from tight gas shales, as a result of fracking, as envisaged by Dusseault, 2013.

DISCUSSION

Understanding the shear strength of rock masses, far beyond the limits of friction coefficients and linear strength envelopes, is urgently needed in *geomechanics*. The shear strength of rock masses is a subject with somewhat mixed *progress* since Leopold Müller's 1966 observations about 'the remaining strength of joints' after rock bridges are broken. It seems to have taken forty more years for researchers in Canada (Martin, Kaiser, Hajiabdolmajid) to re-identify the need to treat 'c' and 'φ' separately when attempting to describe the shear strength of rock masses in continuum analyses. So far this is mostly ignored. See Barton and Pandey, 2011.

In the often jointed or fractured reality, we are dealing with a cascade of shear resistance, as can be symbolized by Figure 27. We can lament the linearization of at least three components of the shear strength of rock masses, in the case of *geomechanics*. We should be 'cascading' from one to the other of the illustrated components at different strains. All of them may be non-linear, quite different to geomechanics over-simplifications, which therefore can introduce errors in reservoir interpretation. The time to change to non-linearity is long over-due.

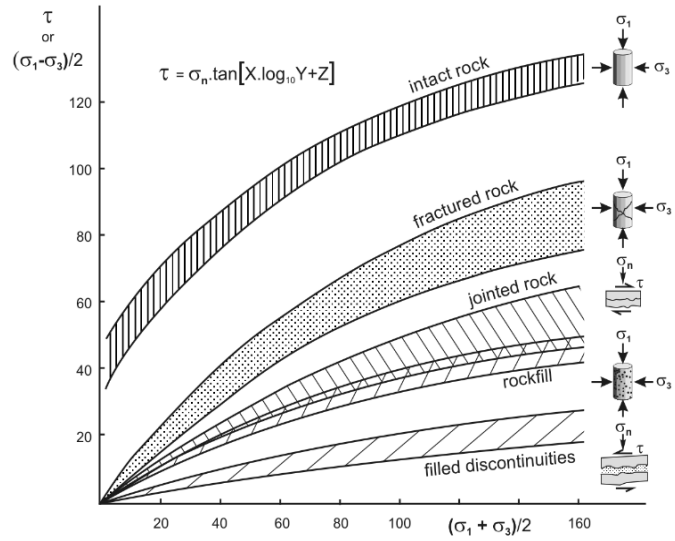

Fig. 27. Non-linearity applies inevitably to the shear strength of intact rock, if it is a moderately to porous reservoir rock loaded by 10's of MPa by pressure draw-down. Failure of intact portions of the rock mass at small strain, cause shearing on the newly created fractures, followed by mobilization along those joint sets oriented in a suitable/capable direction. Finally there may be mobilization along clay-filled discontinuities. Only this component – the weakest – may exhibit linearity, unless the natural fractures are consistently planar. We should note that the planar fractures we typically see, may be over-exposed at the surface due to their inherent weakness.

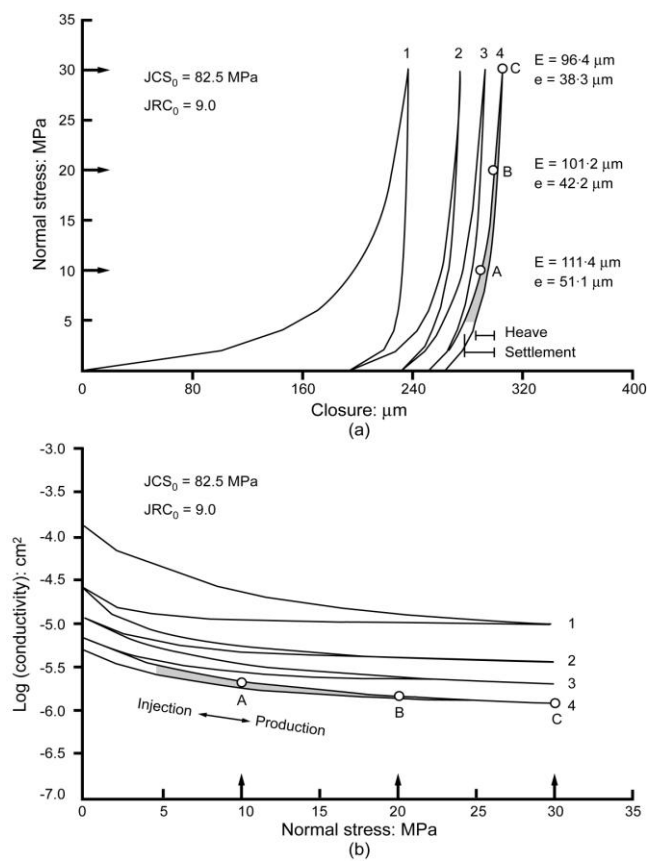

Fig. 28. Finally we must not forget the extreme non-linearity which is involved in stress-closure, as in the unwanted response of a stress-sensitive reservoir. Barton et al, 1985.

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