SEISMIC Q, ROCK QUALITY Q, ROCK JOINT COMPLIANCE, AND ANISOTROPY

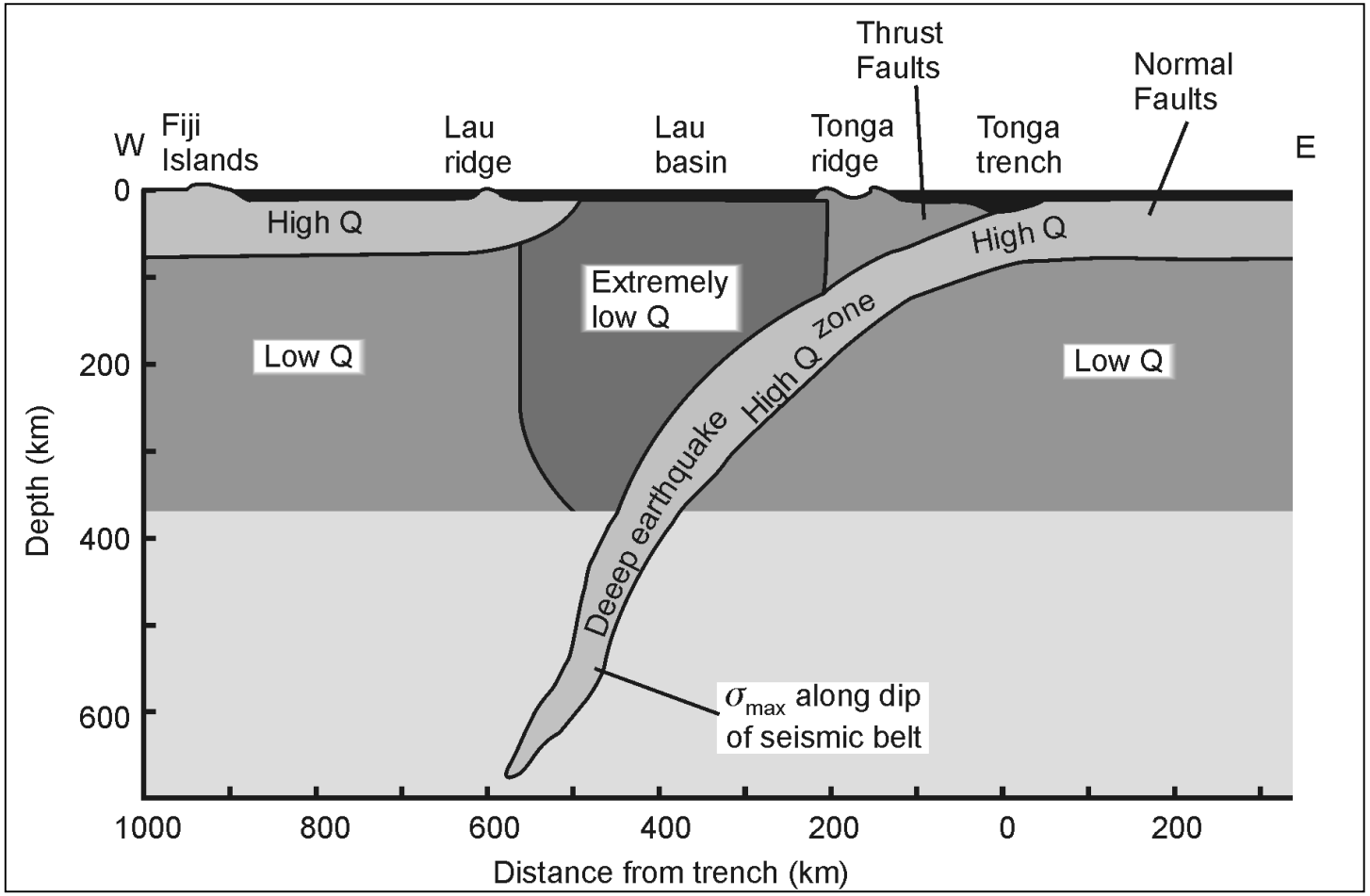
Nick Barton, EAGE, Madrid, 2005

Measurements of ***seismic Q*** proliferate in the geophysics literature, from a multitude of rock types and depths:

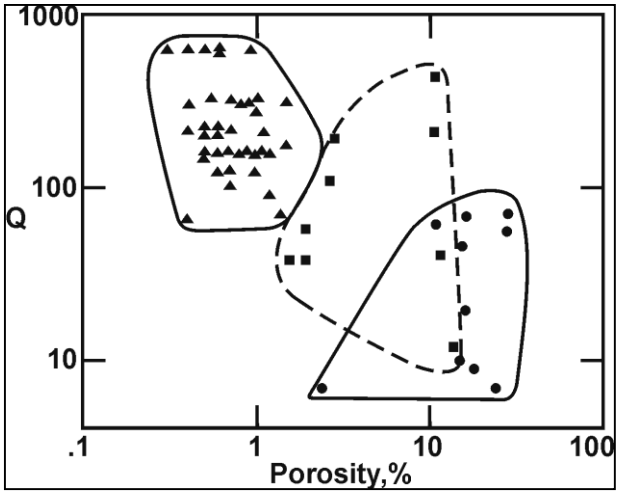
- laboratory tests on highly confined matrix
- large scale in situ estimation of Q from geothermal areas and from earthquake coda
- more recent measurements in and above anisotropically fractured hydrocarbon reservoirs from walkaway VSP using multi-azimuth sources
- data from mid-ocean spreading ridges, in young rocks of different ages from three or more kilometres under the Atlantic and Pacific oceans

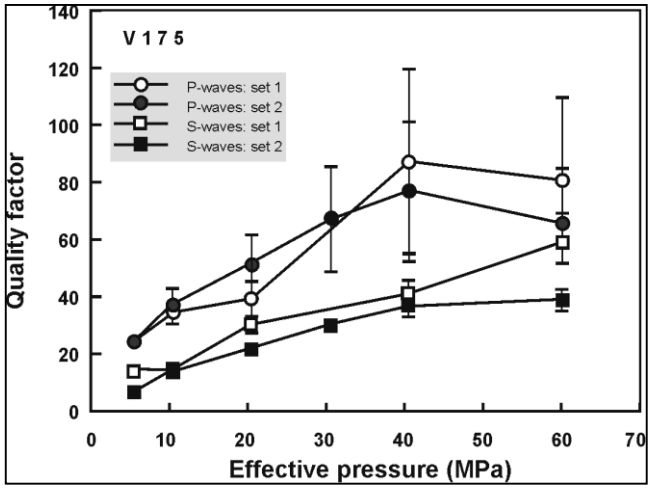
As for velocity, seismic Q also seems to show sensitivity to depth, to rock quality and to direction (Barton, 2005). The same is true for ***rock mass quality Q.***

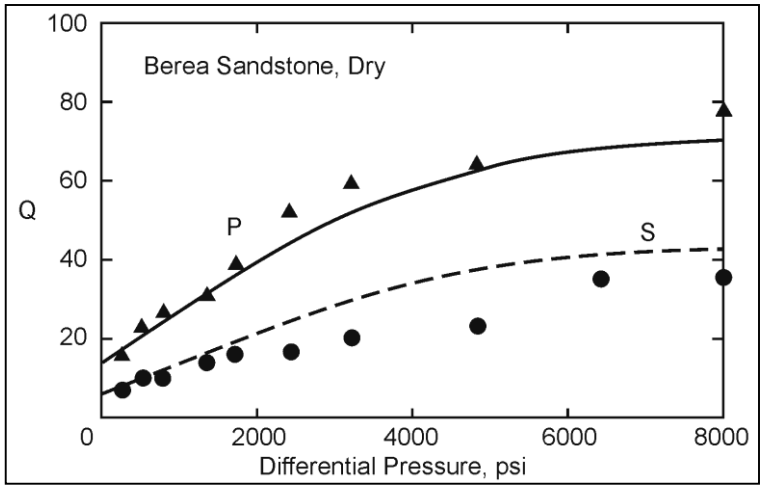
Tectonic crustal scale seismic Q is of course of larger magnitude than ‘engineering-depth’ seismic Q

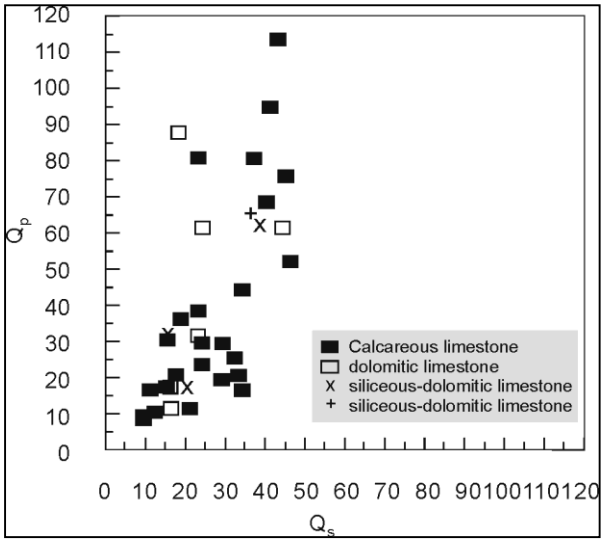


A ‘random’ selection of lower – magnitude seismic Q – from the literature









ROCK MASS QUALITY Q

In rock engineering there is worldwide use of another quality term ‘the Q-value’, for estimating the quality of drill-core, for estimating tunnel support and rock reinforcement needs.

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF}$$

RQD is the % of competent drill-core sticks > 100 mm in length in a selected domain

$\mathbf{J_n}$ = the rating for the number of joint sets (9 for 3 sets, 4 for 2 sets etc.) in the same domain

$\mathbf{J_r}$ = the rating for the roughness of these joint sets or filled discontinuities

$\mathbf{J_a}$ = the rating for the degree of alteration or clay filling of the joint set or filled discontinuity

$\mathbf{J_w}$ = the rating for the water inflow and pressure effects

SRF = the rating for faulting, for strength/stress ratios in hard massive rocks, for squeezing

$\boldsymbol{RQD / J_n}$ = relative block size

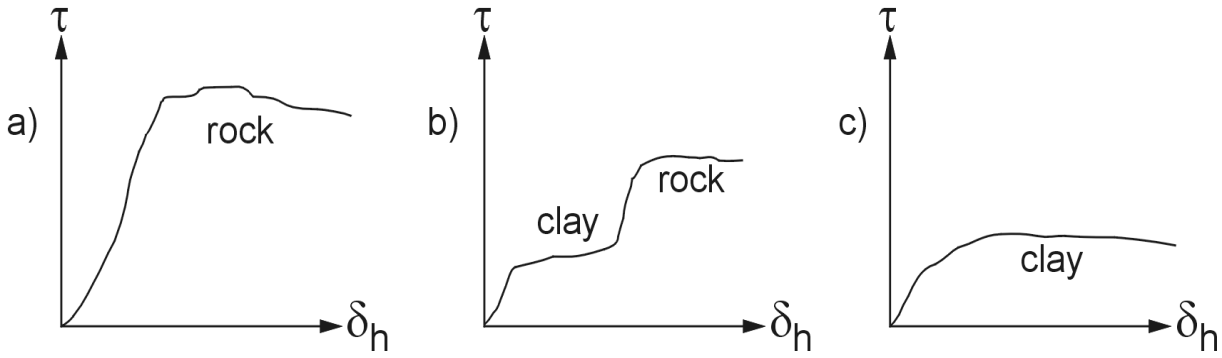
$\boldsymbol{J_r / J_a}$ = relative frictional strength

$\boldsymbol{J_w / SRF}$ = relative effects of water, faulting, strength/stress ratio, squeezing etc.

EACH OF THESE ‘Q- PARAMETERS’ (and pairs of parameters), HAVE LOGICAL CONNECTIONS TO ATTENUATION:

- number of joint (or fracture) sets, ‘blockiness’ (scattering?)
- joint roughness, clay fillings, frictional strength (friction ?)
- presence of water (permeability, pressure) (squirt ?)
- faulting, local fracturing, (all of above?)
- stress-to-strength (compaction) effects (reductions of above?)

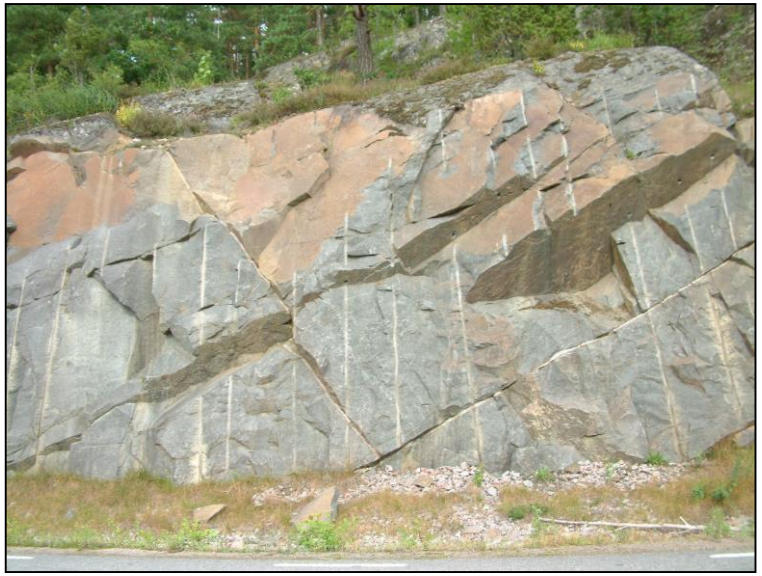
TWO OF THE Q-VALUE PARAMETERS, AND THEIR (FRICTIONAL) MEANING



(a) Rock wall contact

(thin coatings)

	Ja/Jr =	0.75	1.0	2	3	4
		$\tan^{-1}(Jr/Ja)^{\circ}$				
A. Discontinuous joints	4	79º	76º	63º	53º	45º
B. Rough, undulating	3	76º	72º	56º	45º	37º
C. Smooth, undulating	2	69º	63º	45º	34º	27º
D. Slickensided, undulating	1.5	63º	56º	37º	27º	21º
E. Rough, planar	1.5	63º	56º	37º	27º	21º
F. Smooth, planar	1.0	53º	45º	27º	18º	14º
G. Slickensided, planar	0.5	34º	27º	14º	9.5º	7.1º



EXAMPLES OF LOW, MEDIUM, HIGH AND EXTREMELY ATTENUATING ROCK

Q = 1000 (or better)

Q = 100/0.5 x 4/0.75 x 1/1

Q = 0.001 (or worse)

Q = 10/20 x 1/8 x 0.5/ 20

(The wide numerical range of Q-value reflects the huge differences in rock mass properties)

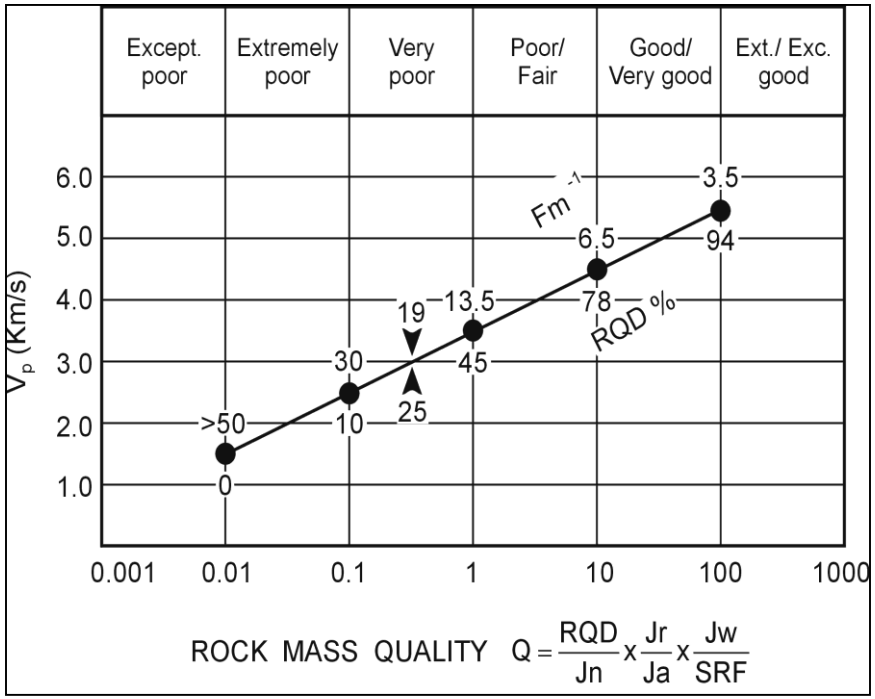
A preliminary link between near-surface Vp, RQD (% of core pieces > 10 cm length), and fracture or joint frequency.

Derived in mostly hard, low porosity rocks, from 120 km of shallow refraction profiles and 2.1 km of nearby appropriately deviated borehole core.

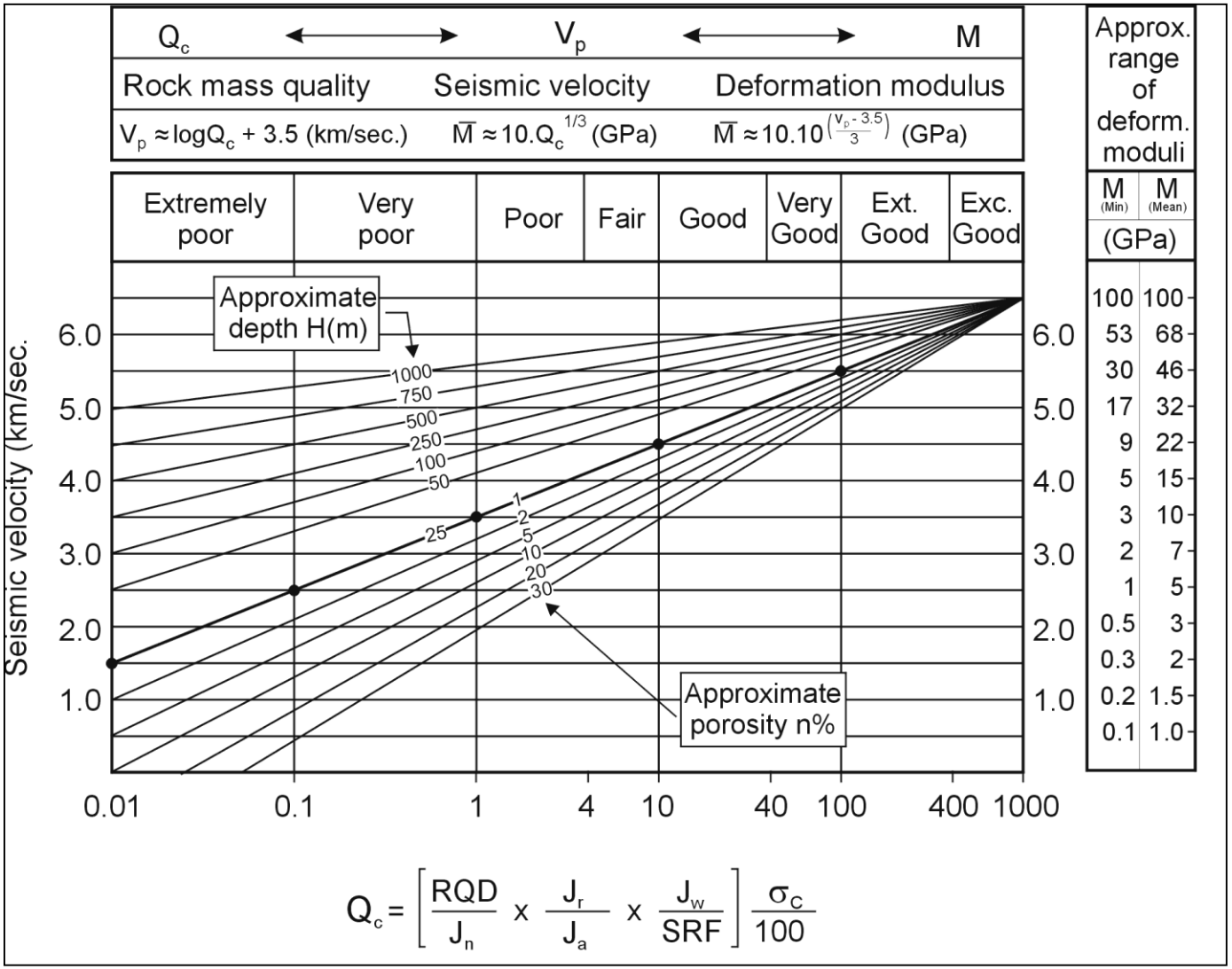
Sjøgren et al. 1979.

The lower ‘Q’ scale was added by Barton, 1995. Strictly a hard rock, low porosity, near-surface Q-Vp relation.

(NOTE CENTRAL DIAGONAL IN NEXT FIGURE – IT IS SAME AS HERE)

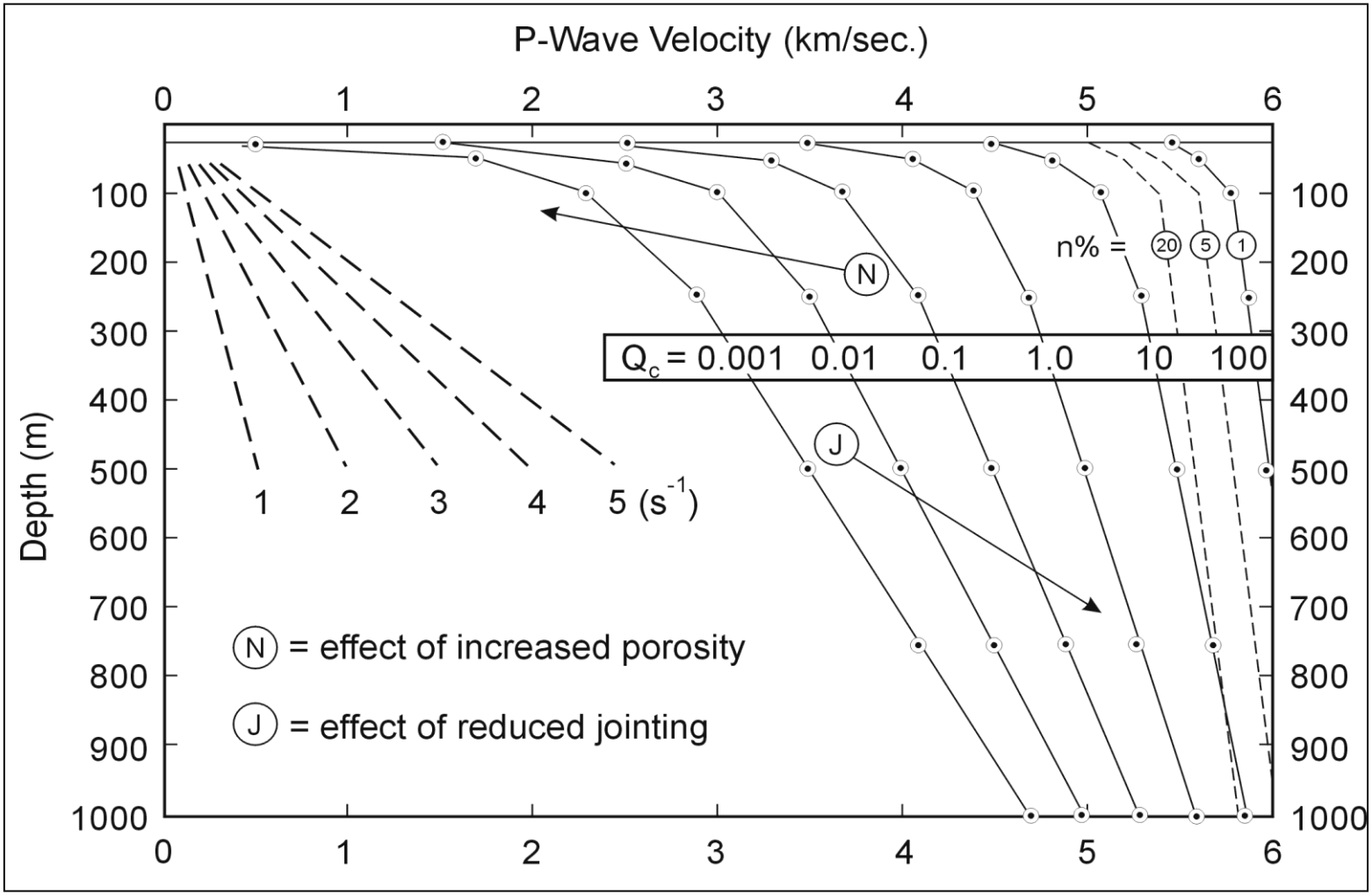


A comprehensive empirical Vp – depth – porosity – Q – E_{mass} (static modulus) relation

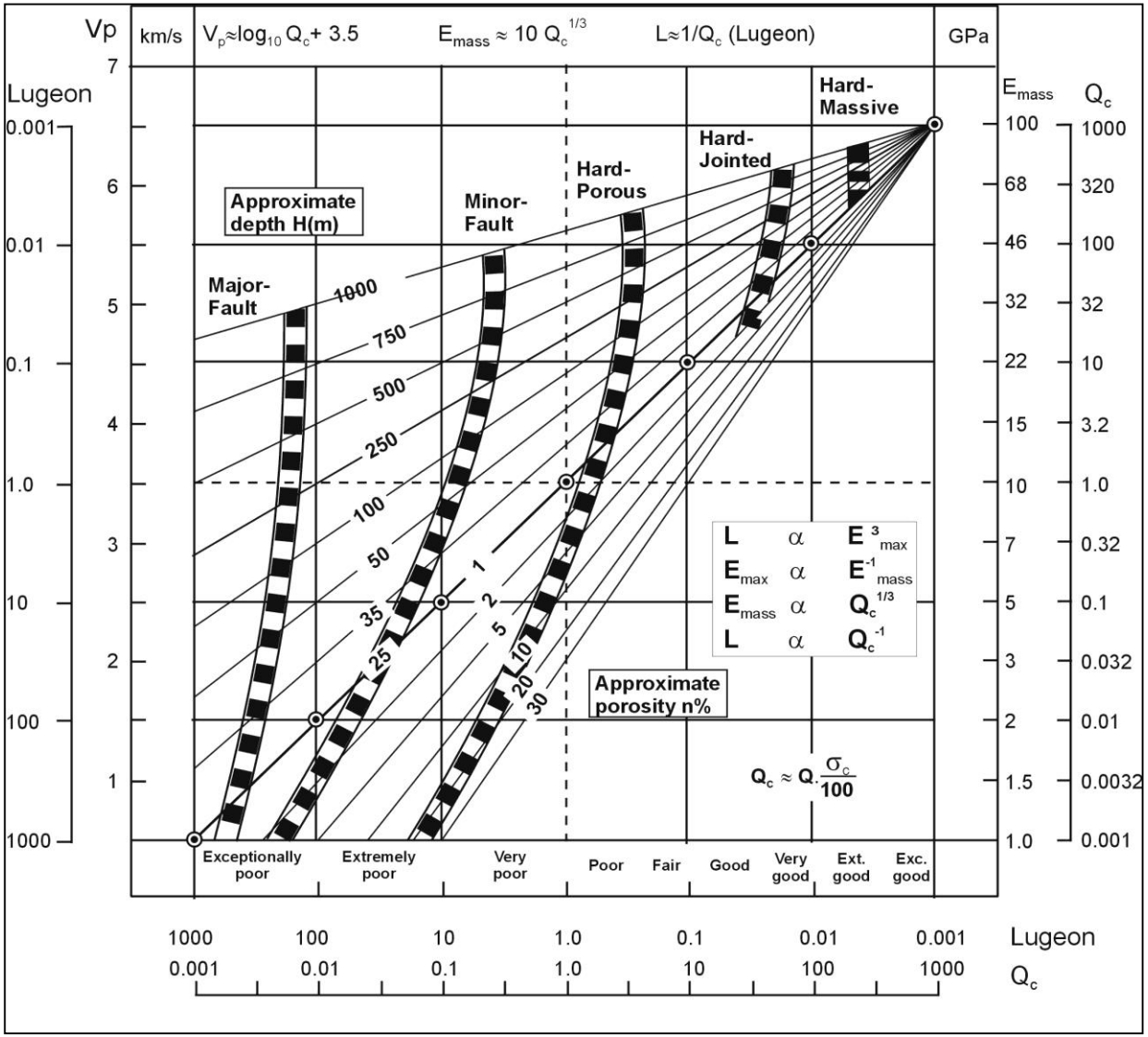


$$Q_c = \left[\frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF}\right] \frac{\sigma_C}{100}$$

THE V_p – DEPTH MODELS FOR SPECIFIC Q_c – VALUES



THE INTEGRATED MODEL



- The Vp-Q-depth model is dominated by joint closure and clay-compaction effects in the top 250m or so. It has since been compared to numerous Vp-depth models in geophysics literature, in Barton 2005.

- The rock mass quality Q-value probably ranges from about 1 to 1000, in the context of typical locations where *seismic Q* has been calculated from spectral frequency analysis by geophysics professionals.

- Although seismic Q has been interpreted across faults at depth in petroleum reservoirs (e.g. Worthington and Hudson, 2000), it most likely has not been attempted in the case of surface or shallow exposures of faults, where the rock quality Q-value may be only 0.1 or 0.01.

- One can suspect that attenuation would be 'complete' in such unstressed, clay-bearing locations, where Vp may be as low as 1.5 to 2 km/s.

- So the loss of energy per cycle definition of *seismic* Q^{-1} would dip below the range mostly seen in the literature: about 2 to 1000, and higher in the case of a descending crustal plate.

ANISOTROPY

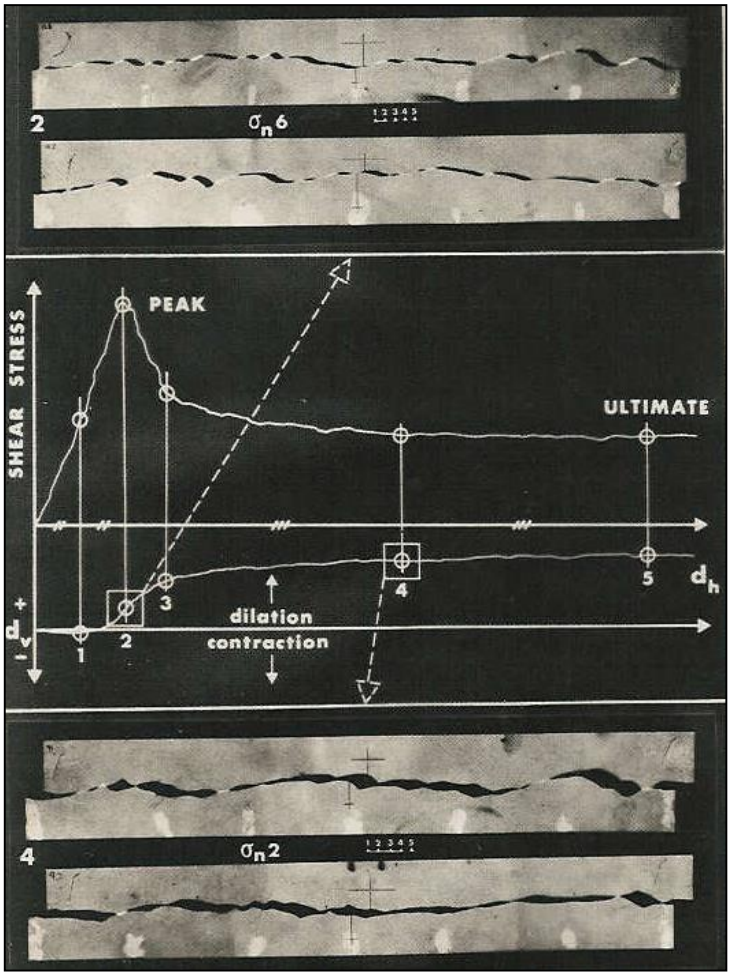
Recent multiple-scale-of-fracture analytical models (e.g. Chapman, 2003), have made multi-azimuth work with P-waves, and shear-wave splitting analysis of polarized fast and slow arrivals, into an exciting new *geotechnical* area, where rock mechanics can perhaps assist in interpretation, due to ***compliance – stiffness*** inversion.

There are already possibilities to broadly interpret :

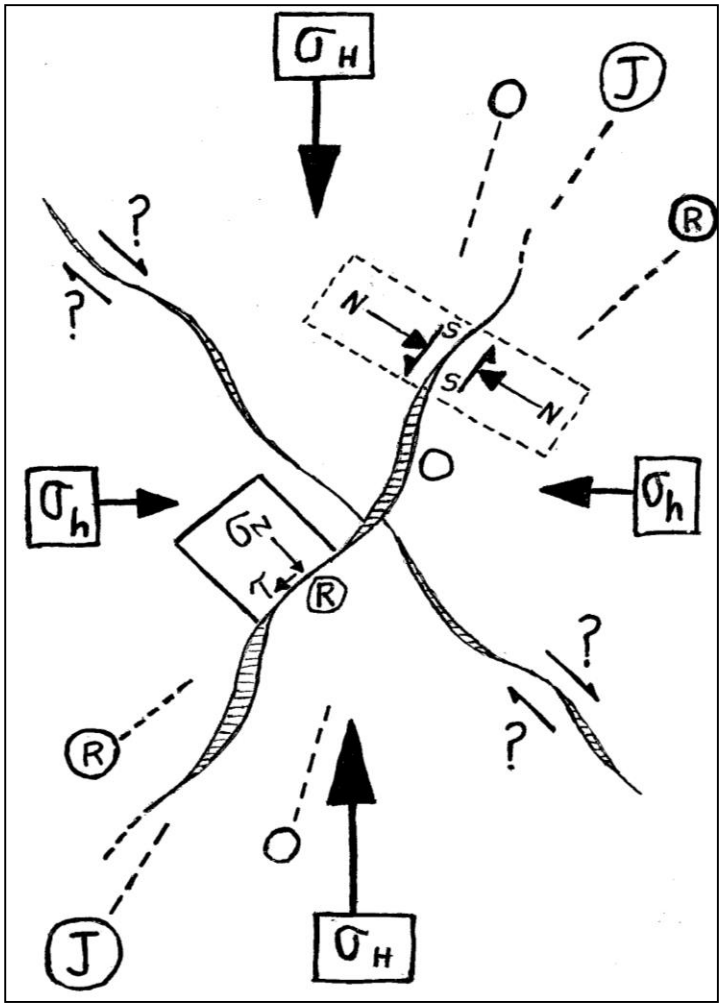
- where reservoir volumes will have good productivity
- fracture density and possible dimensions
- approximate fracture orientations –
- in relation (or near-relation) to the major horizontal stress direction –
- or perhaps in relation to ***sheared, conjugate fracture sets***

An important *detail* is the frequency dependence of the degree of anisotropy, due to squirt flow attenuation in microcracks and fractures of different sizes, giving ‘relaxed’ or ‘stiffened’ behaviour according to frequency.

‘OPEN’ FRACTURES (?) AND ATTENUATION ANISOTROPY ....DON’T WE NEED SHEAR (i.e. minor faulting) TO GET SUFFICIENT PERMEABILITY AT e.g. 3 to 5 km DEPTH?



FRACTURES ≈ PARALLEL TO MAJOR STRESS (?) (and almost closed)…OR ACTUALLY CONJUGATE SETS (with the advantages of shear-induced dilation)?



NOTE FOLLOWING:

- 10º to 15º ‘rotation’ of most of the fluid-bearing ‘lenses’ from the mean fracture plane, while the load-bearing parts (showing local asperity crushing) actually end up ‘rotated’ in the other direction.

- Could such shear events, with their ‘fluid rotation effect’, be important for attenuation magnitude and for attenuation anisotropy respectively?

- When reviewing shear-wave splitting phenomena, with polarization of the fast wave supposedly (exactly?) parallel to the major fracture set at lower frequency, (and perhaps parallel to stress-aligned microcracks at higher frequency?), one can sometimes notice an actual discrepancy of angles between the calliper-log-interpreted major stress direction, and the polarized parallel-to-open-fractures fast shear wave.

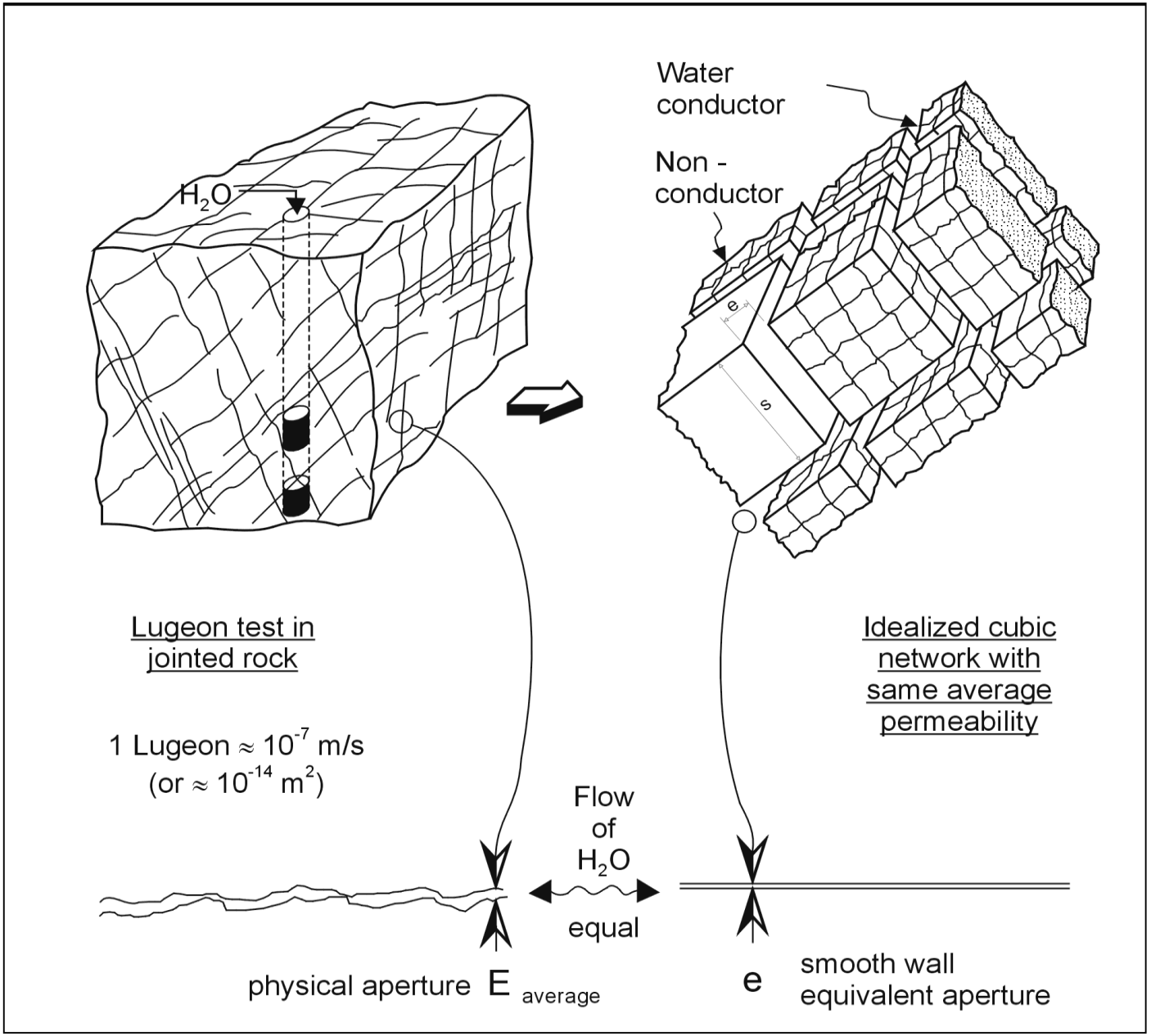
- Could the above ‘fluid rotation’ in the case of slightly sheared, non-planar (and therefore very conductive fractures) also have something to do with this?

- Are we actually seeing the *net component* from conjugate (and sheared) sets?

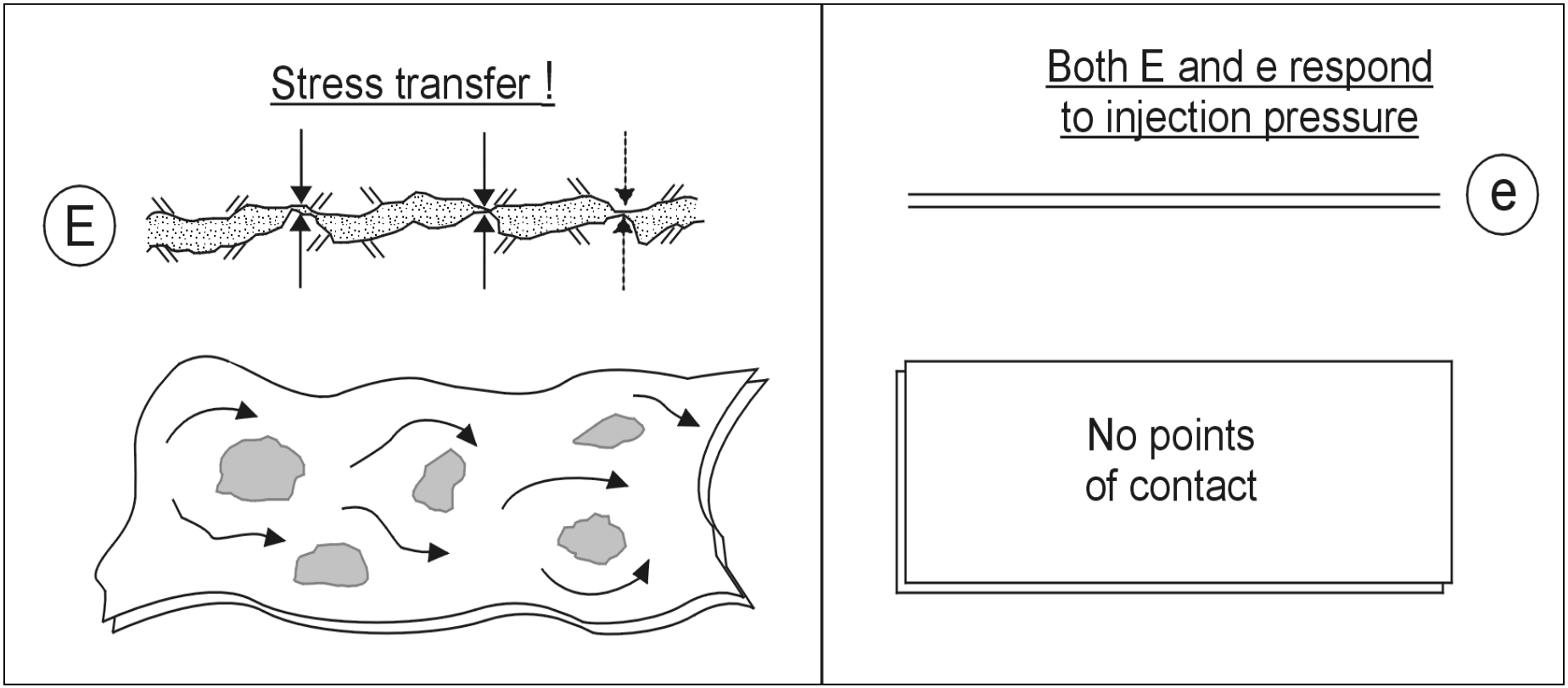
- **In view of the positive magnitude (generally) of the *minimum* effective horizontal stress holding fractures 'closed', or with small apertures of e.g. 1 to 10 microns, where do the desirable 'open' fractures come from?**

- **In partial answer, and in relation to the diagnostic use to which *seismic Q* is now being put, it is appropriate to mention the inequality of the hydraulic aperture (e) and the average physical aperture (E), which is shown to be roughness (JRC) dependent (Barton et al. 1985).**

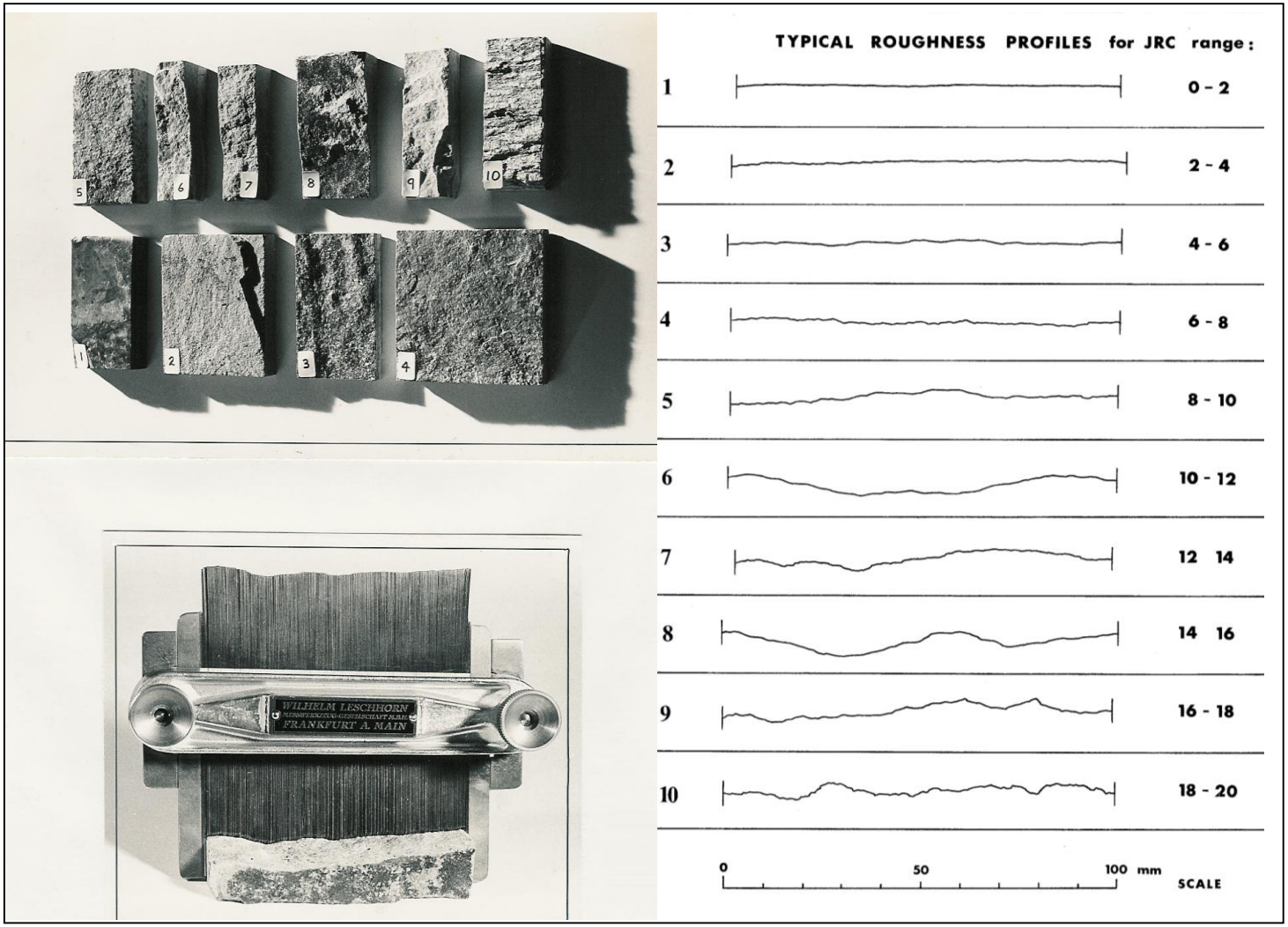
- **This inequality may influence the intended operation of the *aspect ratio* used by geophysicists in their diagnostic models. In other words 0.0001 for squirt response may be 0.001 for volume of fluid. Perhaps this is important for diagnostic work with seismic Q.**


Water conductor
Non - conductor
H_2O
e
s
Lugeon test in jointed rock
1 Lugeon ≈ 10^{-7} m/s
(or ≈ 10^{-14} m^2)
Idealized cubic network with same average permeability
Flow of H_2O
equal
physical aperture $E_{average}$
e
smooth wall equivalent aperture

E > e means that a given ‘aspect ratio’ has two meanings



JRC estimation from profile matching



FRACTURE COMPLIANCES ARE UNLIKELY TO BE EQUAL

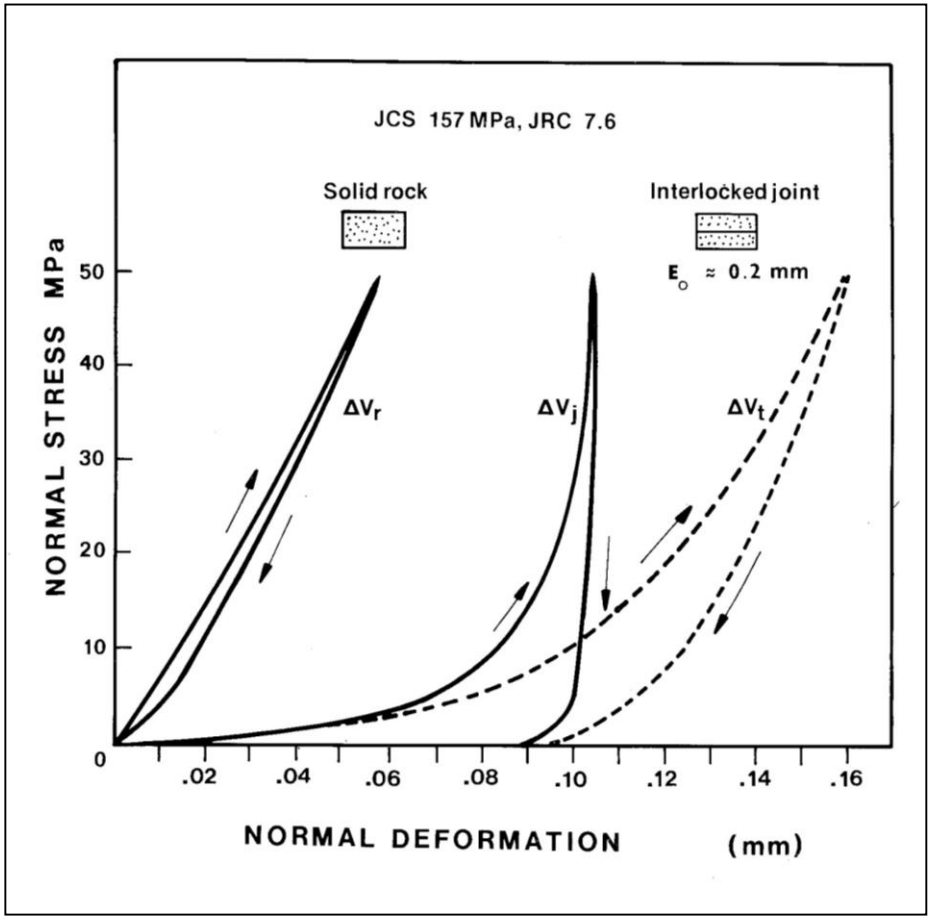
- There is much comment in the literature about fracture compliances Zn and Zt (the approximate inverse of joint normal and shear stiffness Kn and Ks, as better known in rock mechanics).

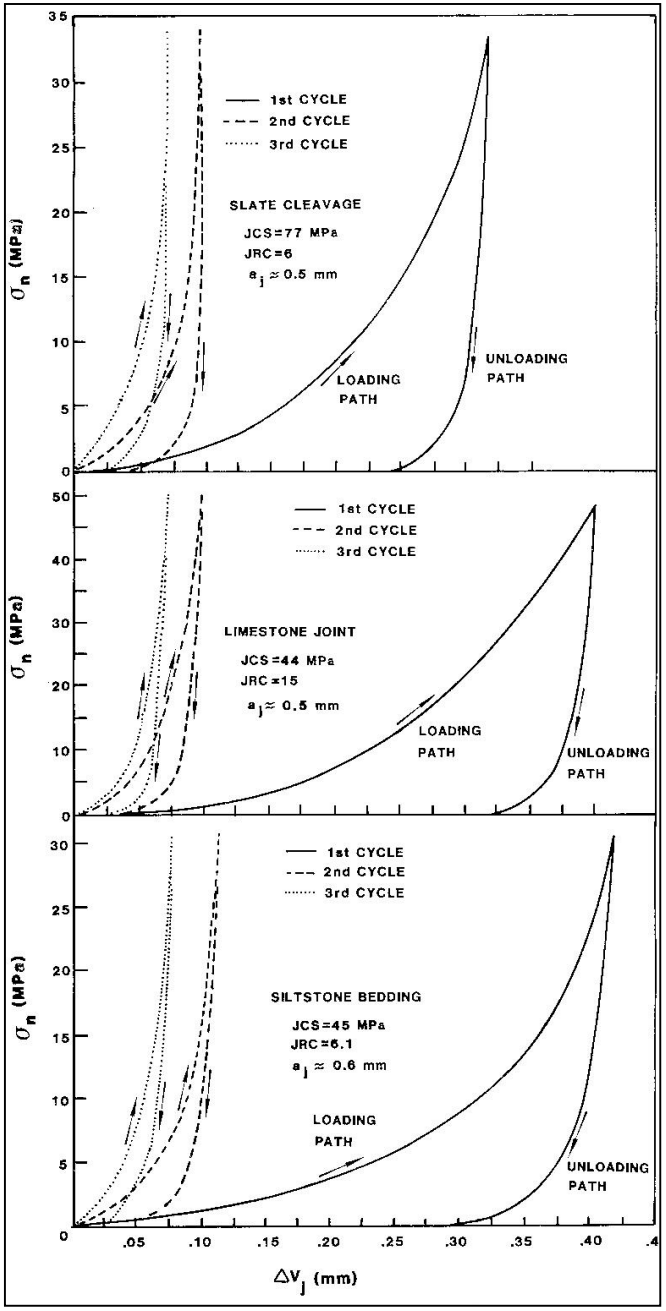
- Zn and Zt are small increment (dynamic) events along the inverted Kn and Ks curves.

- Zn = 10^{-12} $Pa^{-1}m$ from geophysics measurement is perhaps equivalent to Kn = 1000 MPa/mm from rock mechanics.

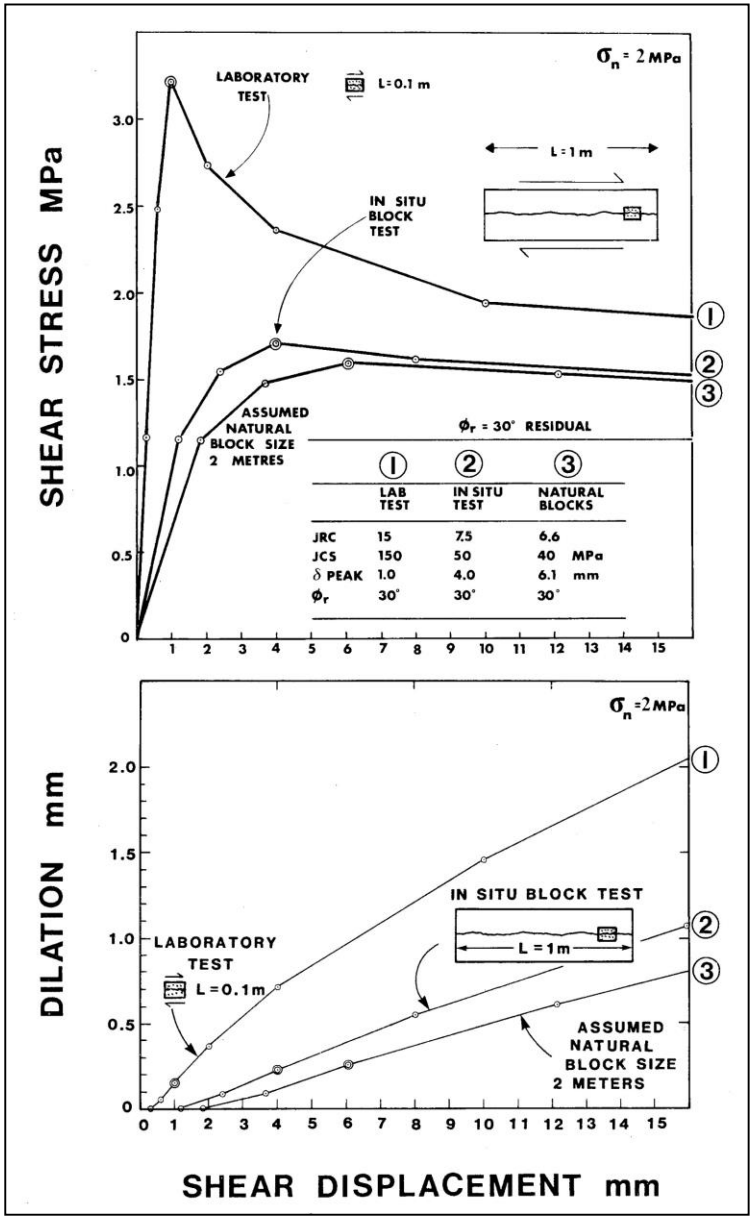
- The non-linear, normal-stress-and-block-scale dependent peak shear stiffnesses, from Barton and Bandis 1982, and of course the stiffer non-linear normal stiffness, have each been incorporated in Cundall's distinct element (UDEC-BB) model since 1985.

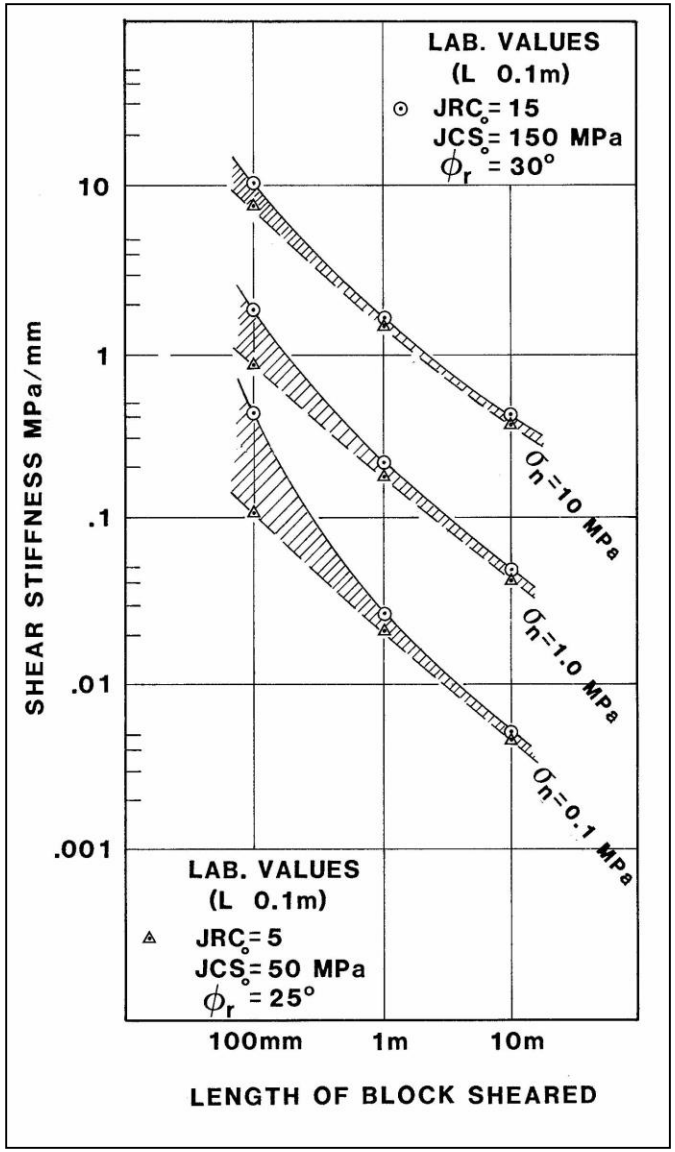
- Many of the attenuation-causing details of rock masses are modelled in the Barton-Bandis subroutine of UDEC-BB.





THERE IS COMPLETELY DIFFERENT STIFFNESS (Kn), and therefore compliance Zn, on first (disturbed) and subsequent (compacted) cycles. Zn is probably much smaller than usually modelled, because Kn is so large.


SHEAR STRESS MPa
σ_n = 2 MPa
LABORATORY TEST
L=0.1 m
L=1 m
IN SITU BLOCK TEST
ASSUMED NATURAL BLOCK SIZE 2 METRES
ϕ_r = 30° RESIDUAL
① ② ③
LAB TEST
IN SITU TEST
NATURAL BLOCKS
JRC 15 7.5 6.6
JCS 150 50 40 MPa
δ PEAK 1.0 4.0 6.1 mm
ϕ_r 30° 30° 30°
DILATION mm
σ_n=2MPa
IN SITU BLOCK TEST
L=1m
LABORATORY TEST
L=0.1m
ASSUMED NATURAL BLOCK SIZE 2 METERS
SHEAR DISPLACEMENT mm


LAB. VALUES
(L 0.1m)
JRC$_o$= 15
JCS$_o$= 150 MPa
ϕ_r = 30°
σ_n=10 MPa
σ_n=1.0 MPa
σ_n=0.1 MPa
LAB. VALUES
(L 0.1m)
JRC$_o$= 5
JCS$_o$= 50 MPa
ϕ_r = 25°
SHEAR STIFFNESS MPa/mm
100mm
1m
10m
LENGTH OF BLOCK SHEARED

- At typical reservoir effective pressures, compacted (e.g. approx. 4th loading cycle) joints suggest ('static') ratios of Kn/Ks from about 5 to 50 for in situ block sizes. This is different from equal values sometimes seen in geophysics.

- Kn is also extremely stress-sensitive, increasing by a factor of 5 to 10 (at least) from an unstressed (but pre-compacted) state, to high reservoir effective stresses. The contact area ratio ($A_{CONTACT}$ /A_{TOTAL}) is likely to approximate σ_n'/JCS.

- The 'universality' of Kn/Ks >>1, or Zt/Zn << 1, and the relatively low shear strength of major jointing in reservoir scenarios, compared to strength in perpendicular directions, and the fact that these large-scale components are so much more compliant than microcracks, due to their much smaller aspect ratios, are each important factors in seismic Q diagnostics, in the dispersive nature of Q, Vp, qS1 and qS2, and therefore in the related anisotropy magnitudes.

Q AND Q AND PERMEABILITY

- *Seismic Q* and rock quality Q seem to have a great deal in common.

- This is intuitive due to the scattering from details of structure, and due to the squirt-flow potential and frictional strength of all the joints that we are describing when characterizing the quality of a rock mass.

- By chance, *'Q-seismic'* and 'Q-rock' have similar dimensionless numerical magnitudes, roughly 1 to 1000 in the first kilometres of interest, when ignoring near-surface, intensely attenuating faults.

- Q and Q both appear to be depth-sensitive, potentially anisotropic, and are perhaps linked to permeability in the absence of clay-fillings.

In the case of rock mass quality Q, we also use the term Q_C (but this is not related to the earthquake coda). $Q_C = Q \times \sigma_c/100$, which is a normalization of Q if rock matrix uniaxial compression strengths are more or less than 100 MPa.

As a rough rule-of-thumb, $L \approx 1/Q_c$, where L= Lugeon, and 1 Lugeon ≈ 10^{-7}m/s or 10^{-14} m^2.

So when Q is a typical near-surface, three joint sets value of 10, and rock strength is only 10 MPa, we would estimate a rock mass permeability of 10^{-7} m/s, or 10^{-8} m/s if the rock was ten-times stronger (and without matrix porosity).

There is also a new term Q_{H20} that gives depth-dependent permeability. This is a more scientifically correct application of the six Q-parameters for flow resistance, and also uses the joint wall strength JCS, borrowed from the BB model.

Key References

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