Characterization of fracture shearing for 4D interpretation of fractured reservoirs

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Summary

Fractured reservoirs and their successful production my need to involve fracture shearing. This important mechanism may result in slight dilation of the fractures, and therefore substantial maintenance of conducting aperture, despite effective stress increase. Unless fractures are sealed with hard minerals, and channelized flow is occurring, closure would be likely with the standard geophysics model of one set of stress-parallel fractures. The minimum principal stress would close the fractures unless they were very rough and in hard rock, such as limestone. These scenarios suggest the need for fracture characterization, with a view to geomechanical coupled modeling, so that 4D reservoir monitoring results can be interpreted better than with continuum 'stress and strain' arguments, which have little relation to the detailed reality of continued fracture flow during production of petroleum.

Introduction

The usual geophysics interpretation of shear wave splitting, seen in much of the literature of this decade, is that a stress aligned set of microcracks, or a single set of stress-aligned fractures are responsible for the polarization into fast and slow axes, parallel and perpendicular to the assumed micro or macro structures. Of course this is convenient, but do single sets of either feature constitute a naturally fractured reservoir? What about the geomechanics argument of Barton, 2006 that fractures, with their extreme aspect ratio and 'softness', may actually be almost closed at these high minimum horizontal stress levels? Shearing is needed, and estimation of shearing potential requires fracture characterization.

Rock mechanics characterization of fractures

The index tests summarized in Figure 1, allow one to acquire suitable input data for geomechanical (rock mechanics) modeling. The parameters JRC concerning roughness, and JCS concerning wall strength, are fundamental, but easily and cheaply obtained. They can be used to calculate shear strength, shear and normal stiffness, and dilation. JRC_0 (the 100mm scale of roughness) allows conversion from conducting (hydraulic) apertures to average physical apertures. Shear stress-dilation-permeability coupling, and normal stress-closure-permeability coupling have been part of distinct element modeling for many years in rock mechanics, such as in UDEC-BB (Universal Distinct Element Code, where BB refers to the Barton-Bandis constitutive model). The details of local fracture deformation and flow determine 4D response, not 'stress and strain', as speculated by some geophysicists.

Evidence of the need for shear stress and deformation

Figure 2 shows a set of deep-well data, in which the hydraulically conductive fractures were distinguished from non-conductive fractures, by means of the interpreted shear stress. This data applied to fractures in harder rock. In fractured reservoirs, shearing would be even more needed to help explain continued production with depletion of reservoir pressure. The exception to this opinion would be minerally 'fixed' and channelized fractures, as are common in some petroleum regions. The coupling of shear with dilation and permeability increase for 'normal' joints and fractures, was described and modelled in detail by N.Barton et al., 1985. (Note unrelated Bartons).

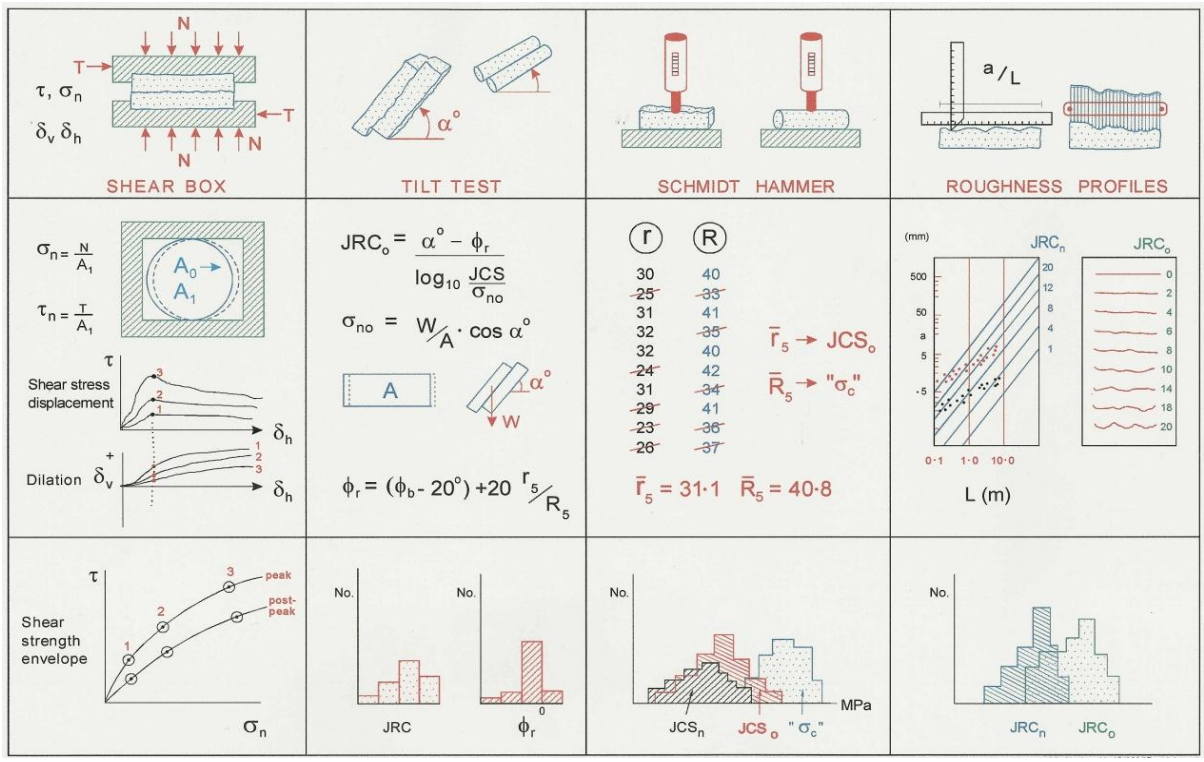

Figure 1. Index tests for characterizing joints or fractures in civil and petroleum engineering. Scale effects (e.g. JRC_0 reducing to JRC_n) are caused by increased block size. The left-hand column represents direct shear tests, but since access to samples will be limited it is more practical for geologists to use index tests. The three parameters JRC, JCS and φ_r provide estimates of shear strength, dilation, coupling to hydraulic aperture, and also address closure, and loss of permeability. Barton, 2006, Chapter 16.

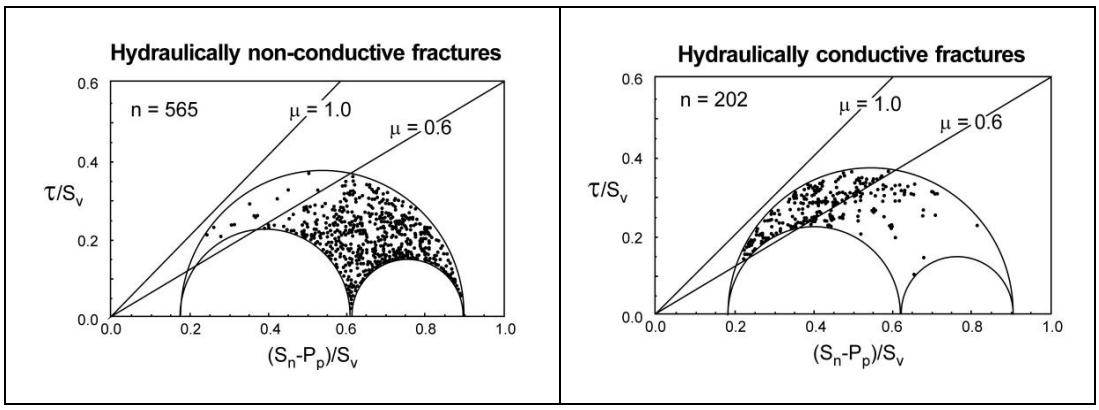

Figure 2. Classic University of Stanford (C.Barton et al., 1995) demonstration of the need for shear stress mobilization to explain conductive as opposed to non-conductive fractures. This is fundamental for many fractured reservoirs, and may be 'automatic' in the case of domal reservoirs having two conjugate steeply-dipping sets of fractures.

Evidence of conjugate jointing and potential for shear

Since the 'single-set' conceptual model used by geophysicists to explain shear wave splitting, may not represent very convincing conditions for fractured reservoir development, it is of interest to review data showing evidence of conjugate fracture sets. In other words, fractures that could be under shear stress. From the extensive review of Barton, 2006 will be chosen two cases, reproduced in Figures 3a

and 3b. These show evidence of (potentially permeable) alternatives to the structure-parallel-to-stress model cited by so many.

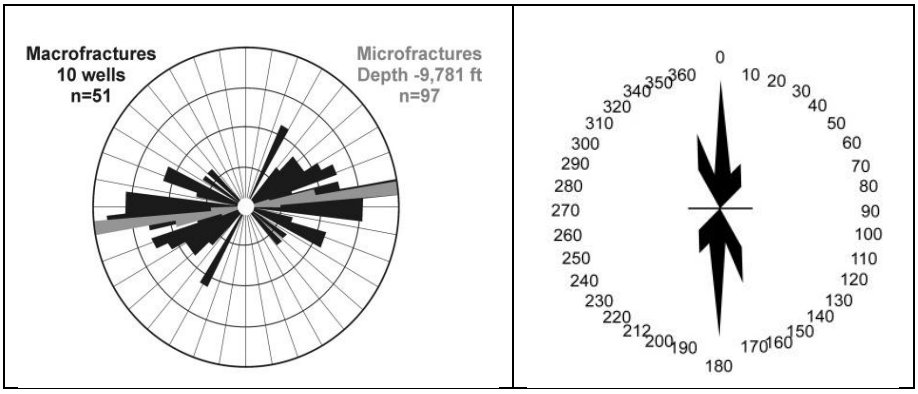

Figure 3a. Differentiation of stress-aligned microcracks and conjugate macro-fractures, from Laubach et al., 2002. Figure 3b. Fracture-strike data, considering injection/production pairs of wells, collected from successfully water-flooded fractured reservoirs. Heffer, 2002.

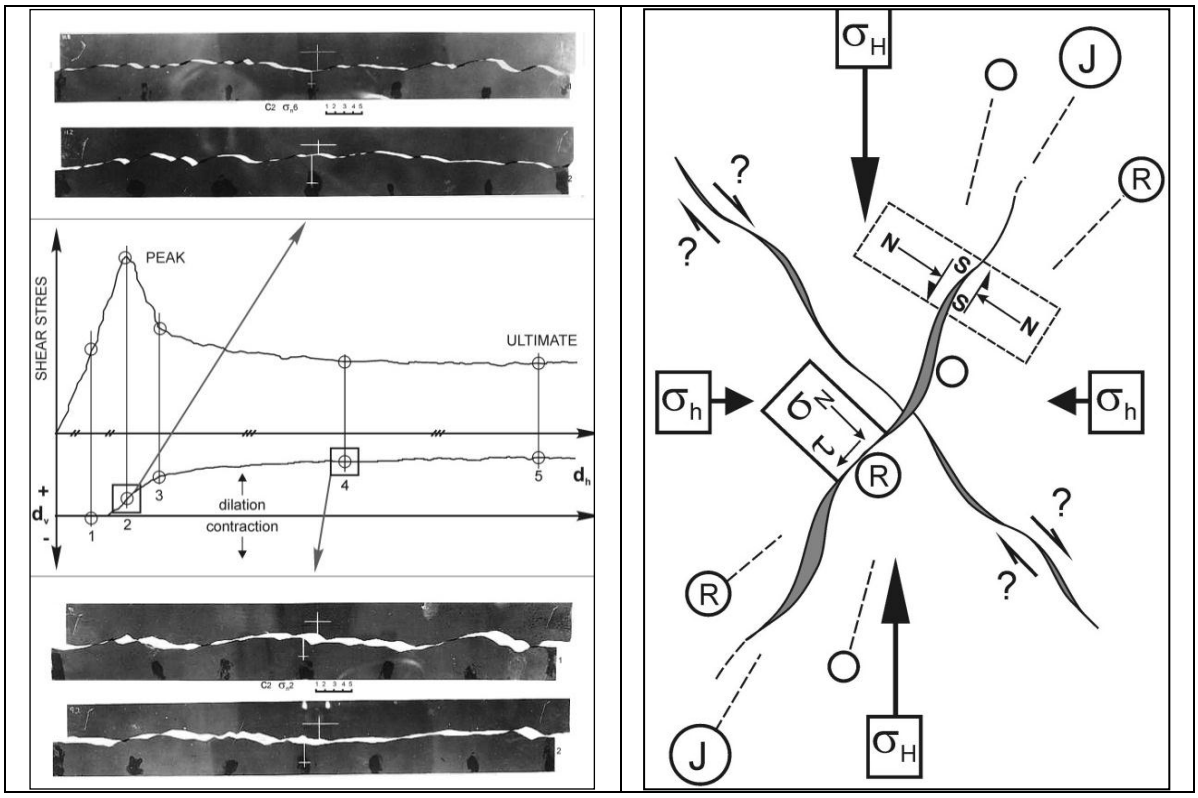

Figure 4a. Reconstructed shearing and dilation of rough fractures, shown in relation to pre-peak and post-peak behaviour. Figure 4b. A somewhat idealized conjugate shear model, with one fracture (set) deliberately dominant, from Barton, 2006, 2007.

Figures 4a and b show shearing of non-planar fractures. The roughness profiles and shear-dilation paths shown in Figure 4a, represent actual results from shear tests on rough-undulating tension fractures in weak brittle model materials, and when scaled up to prototype rock strengths, were effectively measured on fractures of 10m length. At higher reservoir stress levels there would be

crushing and gouge production, but not closure. The dominant set of fracture(s) (J) illustrated in Figure 4b, but with both sets potentially under a desirable shear stress, means that shear wave polarization could be deviated or rotated away from the principal horizontal stress direction.

Evidence for such deviation was collected and discussed in Barton, 2006, Chapter 15. Quite recent 4D interpretations of LOF repeated reservoir 'interrogation' at Valhall and Ekofisk in the North Sea, have in fact shown rotation of both the anisotropy and attenuation axes. This can only be explained by dominance of shear on one of the conjugate sets. It could not occur with the standard geophysics model of stress-parallel (one fracture set) structure. Shearing during compaction, of relevance here due to one dominant set, is shown modelled in Barton, 2013, this workshop.

The important link between fracture hydraulic apertures (e) using a parallel-plate permeability $K = e^2/12$ approximation, and the average physical (rough-walled) fracture apertures (E), with both sets expressed as statistical log-normal distributions, is based on the small-scale joint roughness coefficient JRC, illustrated in Figure 5a. This also has an important influence on the shear stiffness K_S of fractures, with numerous tests assembled in Figure 5b..

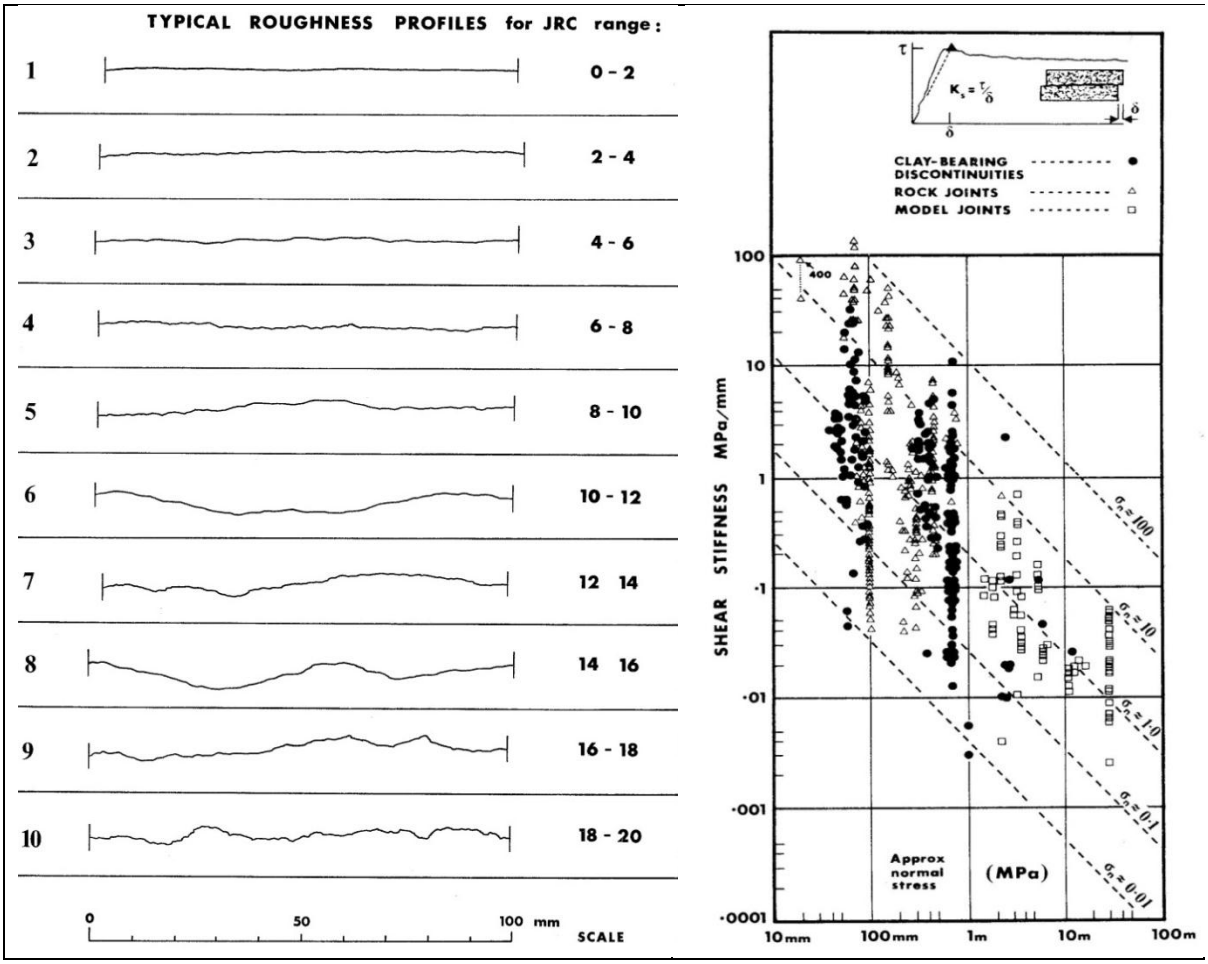

Figure 5a. The simple scheme for small-scale fracture roughness estimation. The ratio of hydraulic aperture (e) and average physical aperture (E) as directly modelled in the code UDEC-BB before conversion to (e), is given by the following empirical model, from Barton et al., 1985: $E \approx (e \times JRC_0^{2.5})^{1/2}$. *Figure 5b. The shear stiffness of rock fractures is very low: they are much more compliant than suggested by the dynamic compliance* B_T.

References

Barton, N., Bandis, S. & Bakhtar, K. [1985]. Strength, deformation and conductivity coupling of rock joints. Int. J. Rock Mech. & Min. Sci. & Geomech. Abstr. 22: 3: 121-140.

Barton, N. [2006]. Rock Quality, Seismic Velocity, Attenuation and Anisotropy. Taylor & Francis, UK and Netherlands, 729p.

Barton, N. [2007]. Anisotropy and 4D caused by two fracture sets, four compliances, and sheared apertures. *The Leading Edge, SEG*, Sept. 2007, 1112-1117.

Barton, N. [2013]. Geomechanics and geophysical processes in naturally fractured reservoirs. 2nd EAGE Naturally Fractured Reservoirs workshop, Muscat, 4p.

Barton, C.A., Zoback, M.D. and Moos, D. [1995]. In situ stress and permeability in fractured and faulted crystalline rock. *Mechanics of Jointed and Faulted Rock.* Rossmanith (ed.) 381-396. Balkema, Rotterdam.

Heffer, K. [2002]. Geomechanical influences in water injection projects: An overview. *Oil & Gas Science & Technology – Rev. IFP, 57:5:* 415-422.

Laubach, S., Marrett, R. & Olson, J. [2000]. New directions in fracture characterization. *The Leading Edge*, July 2000, 704-711.