TIME-LAPSE INTERPRETATION USING FRACTURE SHEAR PHENOMENA

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ABSTRACT
If production causes down-dip shearing on conjugate dipping fractures, as deduced a long time ago from rock mechanics modelling and from new slickensiding in the case of Ekofisk, then temporal changes to the pseudo-static compliances, and changes to hydraulic apertures due to slight dilation, must each be expected. There may also be changes in the stretching over-burden in the case of the subsidence, which will cause temporal changes to the strength of shear-wave anisotropy and attenuation, due to intra-bed joint opening and shear. It is insufficient in each of the above cases to refer to 'stress or strain' effects, as if a continuum alone was reacting to the multiple effects of production in a multi-km^3 fractured reservoir, with a multi-km^3 overburden.

Compliance and fluid effects
The problem of vertical shear wave propagation in jointed or fractured media with *off-vertical dips* was addressed by Sayers, 2002, using the example of two conjugate sets with oppositely oriented dip angles. The shear wave components qS_1 and qS_2 depend here on both the shear *and* normal compliances, since the incident angles are no longer parallel to the fracture planes.

As normal compliance is *reduced* (i.e. stiffened) by fluids of non-zero bulk modulus, a moving gas to oil front should also be distinguishable by respectively greater followed by less shear wave anisotropy, as the stiffening effect of the oil makes the fracture normal stiffness less contrasted to the back-ground medium (Van der Kolk et al., 2001). For dipping joints or fractures, there proves to be a significant *decrease* in shear wave anisotropy if the fluid has a higher bulk modulus, making the normal *stiffness* of the fractures greater when oil replaces gas.

Discontinuous behaviour of fractured chalk
Carbonate or chalk reservoirs of high porosity, and therefore rather low strength, with steeply dipping, as opposed to flat-lying jointing or fracturing, can apparently continue to be successful oil producers despite strong compaction, because of a remarkable joint shearing mechanism. Down-dip shearing can occur despite the one-dimensional (vertical) strain boundary conditions that apply during the production-induced compaction of a large tabular reservoir. Matrix shrinkage under an increasingly large increase of effective stress, actually 'makes space' for down-dip shearing of the fractures. This helps to maintain joint aperture due to shear-induced dilation.

When intense investigations were occurring in the mid-eighties, to try to understand the scope and mechanisms behind the unexpected seabed subsidence above the 3 km deep Ekofisk reservoir, efforts were made to investigate the *discontinuous* natures of reservoir compaction *and* subsidence, which are normally ignored because of modelling size-limitations. This was done at two specific scales, both of which now prove to have potential influence on current 4D time-lapse interpretation options, both for the reservoir and for the over-burden.

Phillips Petroleum geologist's core logging interpretation (H. Farrell, pers. comm.. 1985), of the *conjugate* steeply-dipping jointing or fracturing in the porous, highly productive sections of the reservoir, indicated about 10 to 12 dominant (perhaps > 1 m long) set #1 joints crossing a '1 m window', with oppositely dipping set #2 joints showing about 4 to 6 shorter joints (perhaps 30-50 cm long) in this same 'volume'. These are shown in Figure 1a in an idealized form with constant dip within each set. This of course is a simplification of reality.

The assumed jointing in Figure 1 can be shown to represent an accumulated (two-set) *crack (or fracture) density* ($\varepsilon = N.\ r^3/V$) as high as 1.4, which is much higher than the more limited range often referred to in geophysics literature (Barton, 2006). When fracture densities are as high as 1 to 2, as in such well-jointed, domal chalk reservoirs, dimming of the amplitudes of the slow shear-wave, due to

Figure 1 a) An idealized discontinuous jointed model for 1D compaction modelling, based on the geological description of conjugate jointing in the porous Ekofisk chalk. b) UDEC-BB modelling of the resulting 1D compaction of the jointed chalk. Joint shearing, depicted by the relative size of the symmetric 'flags', was of the order of 4 mm (max.) and 0.4 mm (mean), for the case of the 40% porosity chalk. This was apparently enough to help maintain permeability. .Barton et al. 1986, 1988.

greater attenuation caused by lower seismic Q tend to correlate with the most productive parts of the reservoir, as also experienced where the measurable shear-wave anisotropy is greatest. The down-dip shear mechanism may help to maintain apertures (and lower seismic Q), despite high effective stresses in the presence of this weaker, high porosity rock.

If the crack or fracture density is contributed to by two sets of oppositely dipping conjugate fractures, one can expect shear *and* normal compliance contributions from both sets to the slowness of the slow shear-wave, which may be < 2 km/s. The response is strongest when fractures are gas filled, as gas does not stiffen the normal compliance. Attenuation anisotropy should be enhanced in the case of oil-filled fractures, due to the greater contrast of their normal and shear compliances.

The rock mass depicted in 2D in both Figures 1 and 2, tolerated an original *vertical effective stress* of the order of $\sigma_v' \approx 62\text{-}48 = 14$ MPa, with a lower horizontal effective stress. During the first 20 years of production this vertical effective stress had built up to about 38 MPa, due to the 20-24 MPa pore pressure reduction caused by production prior to large-scale water-flooding. As is well known, this initially unsuccessful attempt to control compaction was followed by 6 m jack-up of all platforms, and final relocation of central platforms, due to the risk of platform damage from large storm waves (up to 30 m), in the increasing depth of sea.

It may be noted from Figure 1b that the dominance of the 'right-dipping' fracture set also causes unequal magnitudes of shearing, and logically this would bias eventual shear wave polarization in relation to the secondary set. It is therefore suggested that unequal amounts of pre-peak (even post-peak) shear on fracture sets with different strike could explain temporal rotation of attenuation axes in 4D monitoring, such as in the Cornwall Hot Dry Rock project in the 1980's (see Crampin and Booth, 1989 and an alternative interpretation in Barton, 1986,), and in the Ekofisk and Valhall chalk reservoirs in this century (various references, see Barton, 2006).

The operator Phillips' core-logging geologists reportedly detected *slickensides* on conjugate joint or fracture sets, when drilling new holes during the 1980's development of pressure maintenance, using equilibrated sea-water injection. Slickensides had reportedly *not been detected* in earlier exploration of the Ekofisk field in the late 1960s, where production started in 1971.

In view of the fact that the numerical-model evidence for shearing was not at first believed outside NGI, it is of interest to note that Albright et al., 1994 mentioned Ekofisk as exhibiting '*shear fracture*

micro-seismicity, possibly indicating that subsidence is caused by a combination of pore collapse and shear sliding'. They also stated that subsidence surpassed early model estimates based on (continuum-based) pore collapse modelling, indicating that there were other mechanisms at work. By implication shearing was also occurring at fault scale.

The conjugate shear mechanism

The physical models of 10 m long tension fractures shown in Figure 2a, help with visualization of a more subtle process that is initiated by shear stress application. In addition to showing the beginnings of dilation, an opposite rotation of 'open' and 'rock-to-rock' contacting areas can also be seen, when fractures are non-planar, as detailed in Figure 2b. All the fractures shown have exaggerated roughness, and also show exaggerated dilation, due to constant normal stress. No gouge-production due to shear is shown. The over-lapped asperities in Figure 2b is where gouge would result.

Figure 2. a) Re-constructed direct shear tests on 10 m long simulated tension fractures, Barton 1973. Top: high normal stress and pre-peak. Bottom: low normal stress and post-peak. b) The conjugate shear mechanism. Note opposite rotations of O (open) and R (rock-to-rock) and the necessary dominance of shear on one set. See Barton, 2006 for more details.

Overburden stretch and temporal polarization effect

Barkved et al., 2004 referred to the world's first time-lapse, marine, multicomponent (3D/4C) survey, as that performed in September 2002 at the Ekofisk jointed-chalk reservoir in the North Sea. This baseline was subsequently compared with a monitoring survey acquired in December 2003, and of course subsequently this has been repeated. In each case, seabed cables were used to acquire data with a wide range of azimuths. With 'only' about 3×10^8 m^3 of oil out of a total of about 1.1×10^9 m^3 produced by 2003, and production expected to 2050, it is clear that the 'belated' shear-wave technology still has an important role to play also at Ekofisk. Even this first limited time-lapse of 15 months indicated some small changes in the *direction* of the fast shear wave, and in the difference between fast and slow shear velocities. The differences were not consistent across the field.

According to Barkved et al., 2004 the reasons for the small changes detected by the S-waves 'had yet to be understood'. As already noted, the small-scale joint-shearing mechanism identified in distinct element (UDEC-BB) studies for the Norwegian Petroleum Directorate (Barton et al., 1986), that was discussed earlier, was later 'confirmed' by slickensided conjugate joint faces, in core recovered from subsequent wells (post 1985) for water-flooding and production.

According to Phillips Petroleum Co. geologists this slickensiding had not previously been noted, and nor was it noted in the older jointed cores made available to NGI for laboratory direct shear and coupled shear-flow-temperature (CSFT) tests. The shear mechanism may seem surprising in view of the 1D-strain ('roller-boundaries') boundary condition, since a 9 × 14 km reservoir of 300 m thickness can hardly expand laterally during compaction: this occurs more in the stretching, subsiding, overburden as 'seen' by shallow shear-wave splitting at Valhall, to be reviewed shortly.

A *possible* explanation for the small changes of polarization direction and of shear-wave anisotropy at Ekofisk, can perhaps be found in this conjugate (or single) shear mechanism, that was also illustrated in Figure 2a. This mechanism could also be a possible explanation of a larger polarization rotation at the Cornwall hot dry rock geothermal project noted in the 1980's. (Crampin and Booth, 1989). With potential 'opposite-rotation' of fluid lenses and rock-to-rock contact areas seen in Figure 4a, there could be subtle domination of effects from the primary relative to the secondary conjugate joint set. If the 'O-R' mechanism seen in Figure 4a can be detected by shear waves, *and if the strike of the two conjugate sets is not equally oriented*, then a small rotation of anisotropy axes could be explained.

Variation about the Ekofisk field, with 'radially' trending jointing and rotating principal stress, would easily explain variation of such trends. Others might quote EDA-(micro)-cracks and stress rotation as the possible cause. More subtle structural mechanisms may be at work, and additional complications in the neighbourhood of fault zones are almost inevitable.

At the Valhall Field, quite close to Ekofisk, BP installed a *permanent* seabed cable array, covering 45 km^2 area, to monitor changes using regularly repeated 3D multi-component seismic surveys, to help determine the best reservoir drainage strategy. Olofsson and Kommedal, 2002 presented the first results of shear-wave splitting in the *shallow* overburden, indicating a remarkable, and very convincing match to the assumed 'stretch' of sub-vertical jointing caused by subsidence. Figure 3a shows the result of their shallow overburden shear-wave polarization, with lines showing the qS_1 direction, with their *length* corresponding to the qS_2 time delay or 'lag'.

Barkved et al., 2004 also commented on the above near-surface Valhall result, and stated the following: 'The actual mechanism causing the shallow shear-wave splitting is not known. Azimuthal anisotropy is usually associated with fracturing, stress or lithology. In this case the amount of anisotropy is small at the centre of the field, where the subsidence is largest, but the anisotropy is large on the flanks and small again farther from the centre. This strongly points to shear-wave splitting being sensitive to changes in stress or strain.'

The various authors have not apparently focussed on *intra-bed* jointing as the likely source of the partial 'squareness' of some of the strongest anisotropy (i.e. the 'NNE-trending' and longest lines). The depth giving this possible dominant 'imprint' to the polarization and velocity anisotropy is of course not known. Large-scale (axisymmetric, 10 km radius) distinct element modelling of the *Ekofisk* overburden response to modelled compaction, using numerous coarsely 'bedded-jointed-and-faulted (2D) UDEC models (Barton et al., 1986, 1988), showed distinct 'joint' opening and some 'bedding' shear in the overburden, due to the stretch caused by the subsidence. The modelled shearing is shown in Figure 3b. These effects worsened with increased compaction profiles, the subsidence/compaction S/C ratio exceeding 0.85 as compaction approached 10 m. Naturally, the stretch is strongest where bending of the strata is largest, and implicitly would show a good match to the consistent Figure 3a shear-wave polarizations.

Figure 3 a). Shear-wave splitting and polarization results for the shallow overburden above the compacting Valhall reservoir. Lines show the qS_1 direction, with their length corresponding to the qS_1 - qS2 time delay or 'lag'. Olofsson and Kommedal, 2002, also Gaiser and Van Dok, 2003 and Barkved et al., 2004. The 'rotation' may correspond to the relative 'visibility' of sub-vertical (bedding-limited?) joints caused by 'stretch' in all directions. Such 'structural' mechanisms could readily explain shear-wave polarization 'squareness' in a shallow over-burden. b) A large-scale version of overburden stretch effects seen in 10 km radius axi-symmetric subsidence modelling, reported in Barton et al., 1986, 1988.

A 3D version of such discontinuum modelling (with the 3DEC code, also developed by Cundall), would obviously have shown similar reactions from other perhaps perpendicular 'joint' sets. This 'joint' opening occurred most strongly where bending was strongest, and *least* both centrally and further out beyond the flanks. It is therefore suspected that the 'stress or strain' referred to by Barkved et al., 2004 could rather be termed intra-bed *joint-opening effects,* since the strength and location of these phenomena are likely to match the subsidence-bowl shape at Valhall. Where the polarization is 'diagonal', (i.e. 'NE-SW' or 'NW-SE' relative to the 'N-S' page), presumably the components to polarization (i.e. joint compliance) from both sets could be operating.

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