Geomechanics and geophysical processes in naturally fractured reservoirs

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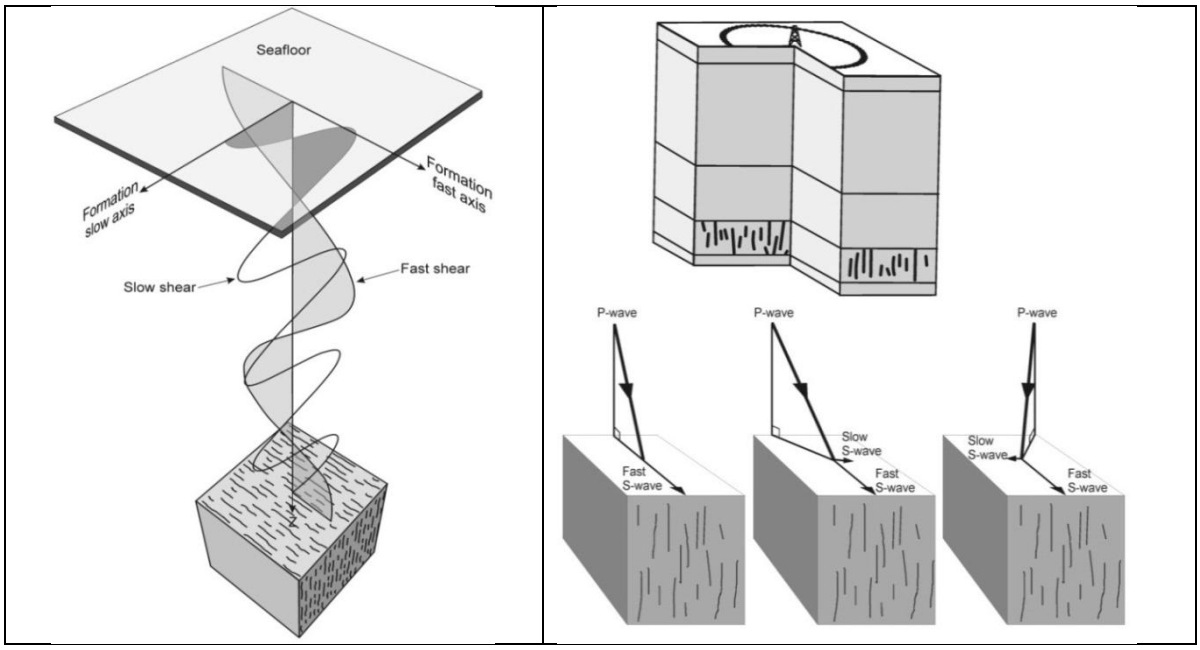
Introduction

In the case of domal reservoirs, production may cause down-dip shearing on conjugate dipping fractures. This mechanism was deduced a long time ago from rock mechanics modeling, and from not previously seen slickensiding of fractures, in the case of the Ekofisk reservoir in the North Sea (Barton et al., 1988). There may also be changes in the stretching over-burden in the case of the compacting reservoir causing the over-burden to subside. This 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. The relatively 'early' consideration of discontinuous behaviour at Ekofisk is presented in this classic 'carbonates region' of the Middle East, in the hope of stimulating the modelling of fracture deformation, and coupled behaviour, which still seems to be rare, despite being needed for realistic 4D interpretation. The possibilities of making good use of geomechanics understanding has improved a lot since LOF monitoring/interrogation of reservoirs was slowly introduced in this last decade, starting in the North Sea.

Standard geophysics interpretation of shear wave polarization

From a remarkably broad range of geophysics literature, from petroleum reservoir exploration, and from geothermal reservoir interpretation, one finds the interpretation of shear wave polarization explained as if resulting from the assumed effect of a set of stress-parallel microcracks, or from the effect of one set of (reservoir) fractures. Two examples are shown in Figures 1a and 1b. As suggested elsewhere (Barton, 2006, 2013) this does not make a very convincing model for a producing petroleum reservoir, or for geothermal energy production. More than one set of fractures, and fractures preferably acted on by significant shear stresses, one would assume were needed.



Figures 1a and 1b. The 'one fracture set' conceptual model used in geophysics interpretation of shear wave polarization. This seems to be missing the geomechanics and production mechanisms needed to explain conductive fractures, and connectivity, at many kilometers depth. From Barkved et al., 2004, and Horne, 2003.

Discontinuous behaviour of overburdens

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 expected *discontinuous* natures of reservoir compaction *and* subsidence. An example of the subsidence modelling is shown in Figure 2a. Normally, discontinuous behaviour is ignored because of modelling size-limitations. The modelling was performed 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. The 'stretching' effects associated with the subsidence bowl depicted by shading in Figure 2b, actually applies to the overburden above the neighbouring Valhall fractured chalk reservoir. Above Ekofisk, deformation is much larger, and pear-shaped, but a gas 'cloud' complicates any clear graphic presentation.

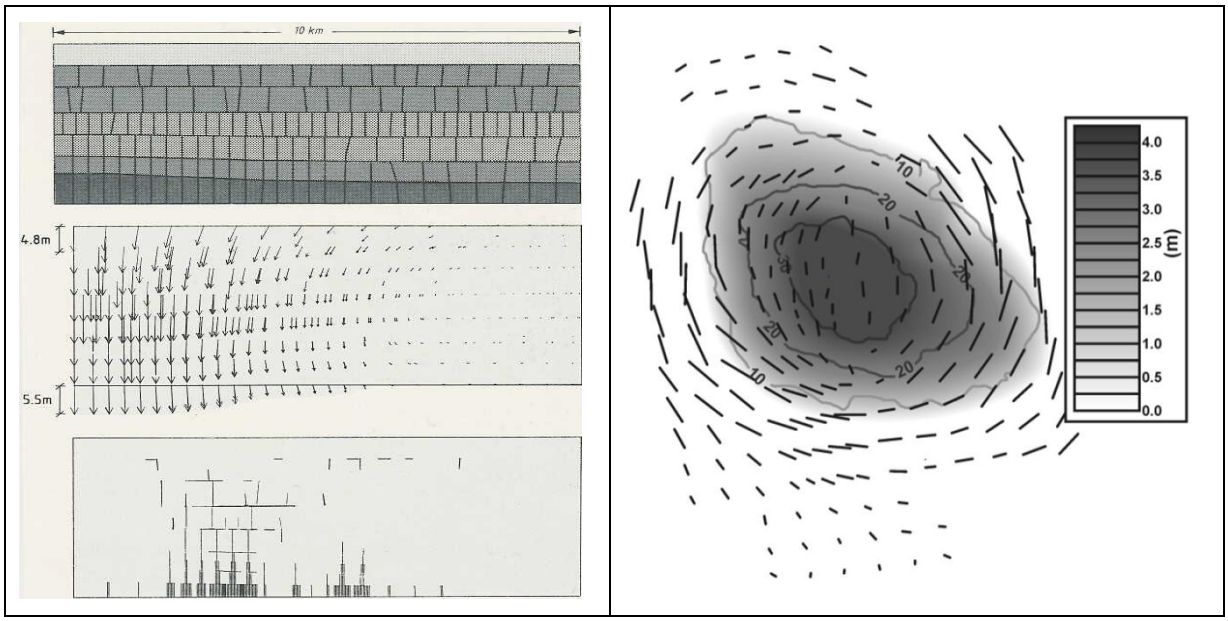


Figure 2a. A large-scale version of overburden stretch effects seen in 10 km radius axi-symmetric subsidence modelling, designed to represent the Ekofisk overburden, reported in Barton et al.,1988. The ratio of subsidence to compaction (S/C) typically modelled exceeded 0.85, corresponding well to reality. Different deformation moduli separate the sub-horizontal sedimentary layers. Figure 2b. Shear-wave splitting and polarization results for the shallow overburden above the compacting Valhall reservoir. Olofsson and Kommedal, 2002.

The partially 'square' lines seen in Figure 2b show the fast shear wave qS_1 direction, with their length corresponding to the (qS_1-qS_2) time 'lag'. The 'rotation' may correspond to the relative 'visibility' of sub-vertical (bedding-limited?) joints caused by 'stretch' in all directions. Such 'structural' mechanisms could explain the shear-wave polarization 'squareness' seen surrounding the superimposed subsidence bowl shape. This is perhaps a more structurally viable explanation than 'stress and strain', as suggested by one set of 'continuum' focussed authors.

Discontinuous behaviour of a fractured reservoir

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 petroleum 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 have to apply during the production-induced compaction.

In the case of such a large tabular reservoir (Ekofisk measures 9 x 14 km), an overall 1D compaction is an inevitable average. Matrix shrinkage under an increasingly large increase of effective stress,

actually 'makes space' for down-dip shearing of the fractures, without violating the 1D compaction control. This shearing apparently helps to nearly maintain joint aperture during production, despite the likely increase in effective stress as fluid pressures reduce. The joint aperture 'preservation' apparently occurs due to slight shear-induced dilation. Ekofisk is expected to produce for another forty years, doubling its present life. Presumably fracture and fault shearing are important here.

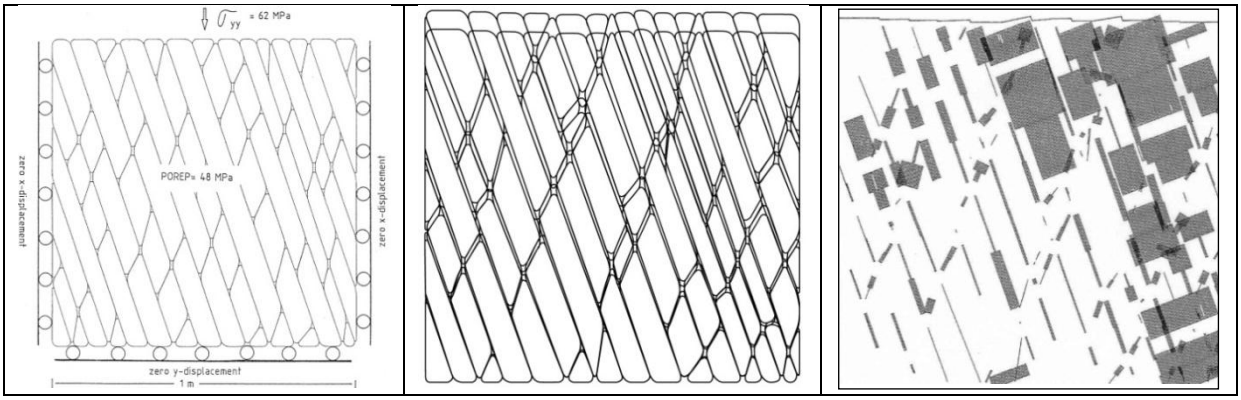


Figure 3. A 1m vertical 'window', looking into an idealized and well fractured part of the Ekofisk chalk, at approximately 3 km depth. The coupled discrete element UDEC-BB model, with compaction restrained to 1D (roller boundary) simulation, had input data derived from the rock mechanics parameters JRC, JCS and φr. These joint roughness and wall compressive strength parameters were derived from standard index tests, which are reproduced in Figure 1 of Barton, 2013.

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 fractures, crossing a '1 m window', with oppositely dipping set #2 fractures, having less continuity. These are shown in Figure 3 in an idealized form with constant dip within each set. This is obviously a simplification of reality, and there may be strong variations.

The rock mass model depicted in 2D in Figure 3, was simulating loading by 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 petroleum production, prior to large-scale water-flooding. As is well known, this initially unsuccessful attempt to control compaction, due to softening of the rock, was followed by 6 m jack-up of all platforms, and final relocation of all central platforms, due to the risk of platform damage from large storm waves (up to 30 m), in the many meters increased depth of the North sea, focussed above the 100 km^2 reservoir.

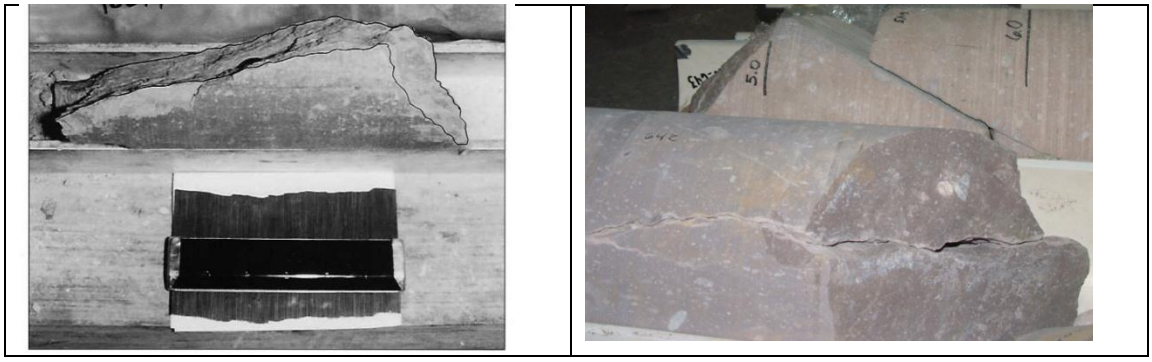


Figure 4a. Example of an Ekofisk fracture. Figure 4b. Fractures in tuff with measured JRC_{300} (300mm samples) of 1.0 and 15.0. Ekofisk fractures lie between these two 'extremes'.

Some geophysics and cross-discipline interpretations

The fracturing in Figure 3 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 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 therefore lower seismic Q), despite high effective stresses acting on this weak, high porosity rock. As a point of interest from cross-discipline observations, the seismic Q value used by geophysicists, which is the inverse of attenuation, is numerically very close to the (static) deformation modulus, E_{mass} typically obtained by large-scale tests on rock masses, when this is expressed in GPa. This 'logic' appears through a large body of rock physics data reviewed by Barton, 2006, and applies over a typical range of about 2.5 to 100 (GPa), covering much of rock engineering behaviour, from which we have measured and back-calculated-from-excavation in situ data.

It may be noted from Figure 3 that the dominance of the 'right-dipping' fracture set also causes unequal magnitudes of shearing (as also illustrated in Barton, 2013), and logically this would bias eventual shear wave polarization, because of the dominant effect of set #1 in relation to the secondary set. Unequal amounts of pre-peak (even post-peak) shear on fracture sets with different strike could also 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).

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