DIFFERENT SCALES OF DISCONTINUOUS BEHAVIOUR IN PETROLEUM ENGINEERING

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Resumo
Na engenharia de petróleo, o comportamento de meio descontínuo ocorre numa grande variedade de escalas, embora a moda, no geral, tenha sido dirigida para o uso de modelos contínuos para representar o meio descontínuo. Na escala do reservatório, fatores de relevância na produtividade como: o importante papel desempenhado pela intensa atividade tectônica na disposicão de volumes substanciais de petróleo, o surgimento de forças de cisalhamento durante a ocorrência de fenômenos relacionados com subsidência-compactação - de influência no colapso de revestimentos - ou a existência de planos conjugados de juntas, são abordados e discutidos pelo autor. As propriedades fundamentais da mecânica das rochas, são de tolerância limitada, no caso das tensões diferenciais originadas nos folhelhos sobrepostos a camadas de arenito. Estas conduzem ao aparecimento de uma tensão principal mínima no folhelho, a qual induz a formação de uma descontinuidade por tensão, considerado um dos fatores de maior importância na vedação dos reservatórios de petróleo. Na escala do furo de sondagem, quando se consideram os poços de exploracão, os planos de cisalhamento na forma de espiral logarítimica, desenvolvendo-se próximo às regiões submetidas a tensões elevadas, comprovam, sem relutância, a violação dos princípios contidos nas hipóteses sobre o comportamento de um meio contínuo, isotrópico. A teoria de Mohr-Coulomb, admitindo uma mobilização simultânea da resistência ao atrito e da coesão, constitui-se na principal fonte de erro, já que as superfícies de ruptura se desenvolvem com deformações menores do que aquelas exigidas para a mobilizacão do atrito.

Abstract
Discontinuous behaviour is occurring at many different scales in petroleum engineering, despite the fashion for continuum modelling in general. Major faulting activity that has greatly affected in-place volumes of petroleum, bedding plane shearing in a compacting-subsiding environment causing numerous casing collapses, and shearing of conjugate reservoir jointing which helps to maintain productivity in a depleting reservoir will each be examined. The fundamental rock mechanics property of limited tolerance of differential stress in cap-rock shales, and therefore higher minimum stress in the shale, giving a stress discontinuity, is one of the most important sealing requisites for petroleum reservoirs. At borehole scale the log-spiral shear planes that can develop around over-stressed sections of exploration wells, actually violate the usual assumptions of isotropic continuum behaviour. The Mohr-Coulomb assumption of simultaneous mobilization of cohesive and frictional strength is the main source of error, since failure surfaces develop at smaller strain than needed to mobilize friction.

Keywords
Fault, joint, subsidence, shearing, borehole stability, effective stress

INTRODUCTION

In this keynote lecture, a rapid journey through widely different geological and petroleum engineering scales will be made – seeing the possible effects of regional faulting across sedimentary basins, shearing bedding planes in sedimentary overburden, joint deformation in reservoir rocks, and fracturing at borehole scale. An important effect is even seen at the grain-boundary, micron-size scale of discontinuities. This is the effect of weakening caused by water when water-flooding. Some of the phenomena reviewed are positive for petroleum production, others are negative

As in much of engineering design, we will often be comparing stresses and available material strength, or more precisely – *induced effective stresses* and the available strength of the rock or rock discontinuities. There is an interesting principal involved in this area, which is fundamental to today's presence or absence of oil and gas in petroleum reservoirs. Sometimes we will also be comparing fluid pressures and existing minimum rock stresses, to investigate hydraulic fracturing potential.

UNEQUAL PETROLEUM RESERVES

A start can be made by broadly comparing the petroleum fortunes of Russia and Norway in the 1,000,000 km^2 Barents Sea region of the Arctic north. There are proven reserves of 'only' 0.3 billion Sm^3 (oil-equivalent volume) on the Norwegian side (already about to be developed at Snøhvit). By comparison there are proven reserves of 8 billion Sm^3 on the Russian side (and possibly as much as 100 billion Sm^3 yet-to-be discovered reserves). This huge inequality obviously deserves some attention, since the Russian's *proved* reserves are already three times more than all the British and Norwegian North Sea reservoirs together [1]. At a petroleum conference in Northern Norway in 1989, Western oil experts were first convinced that the Russians had added one too many zeros, in their description of the 3.2 *trillion* m^3 reserves of gas in their newly discovered Shtockman reservoir, which is of the order of 30x40 km in area.

Understanding why oil and gas is, or is not found, despite available source rocks, and a similar level of drilling (50 exploration wells) and extensive seismic investigations (costing a total of about USD 2.5 billion during 25 years, for

each country) can first be simplified to the different degrees of tectonic activity in the two territorial halves of this Arctic sea. Large scale faulting occurred mostly in the (western) Norwegian territorial area during the Tertiary-Cretaceous period, during tectonic/volcanic opening of the Atlantic Ocean. These differences are indicated in Figure 1.

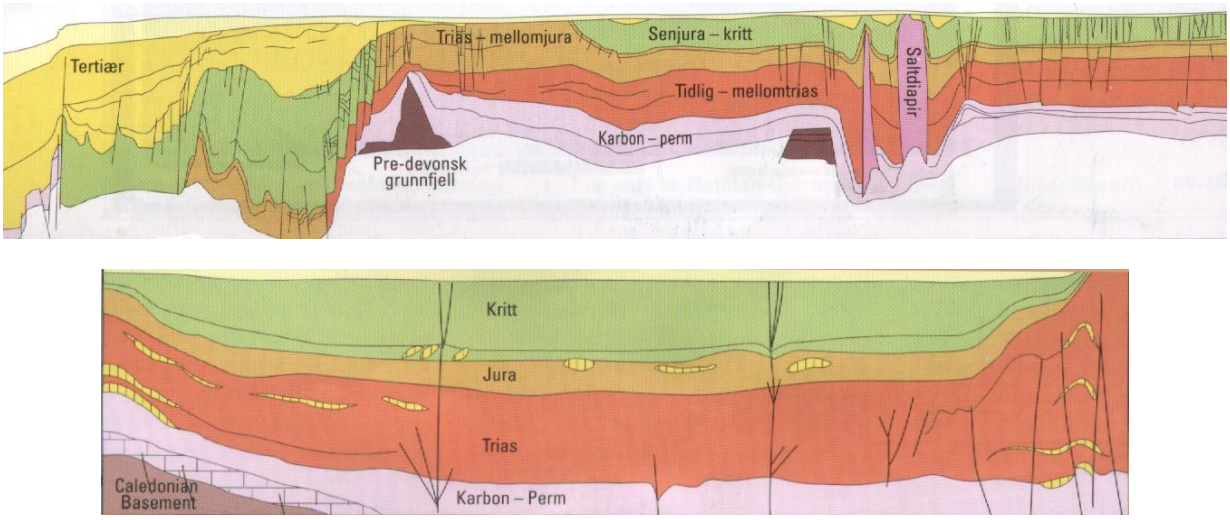

Figure 1. Contrasting intensities of faulting across the Norwegian and Russian sectors of the 1 million km^2 Barents Sea, as shown, and the development of 'non-sealing', hard cap-rocks, have caused great differences in proven and likely petroleum reserves in the Norwegian and Russian sectors [1].

The shale overburden in much of the Norwegian sector apparently lost its impermeability, and enormous quantities of petroleum were lost. Stress-permeability testing of discontinuities from these actual 'cap-rock' shales at NGI, showed that their compressive strength was in fact *too high* – meaning in this case that they were too brittle to self-seal. Coupled stress-shear-flow testing (CSFT) did not produce enough gouge for effective sealing at reservoir effective stresses. As is well known, faulting, *per se*, is often a mechanism for trapping petroleum when there are inclined reservoir beds, but not in this case.

The most typical petroleum-bearing scenario is a porous reservoir sandstone overlain by more deformable shale. The important rock mechanics principle referred to above is simply that a *good* cap-rock shale does not tolerate big differential stress due to its limited shear strength. Therefore when measuring the minimum stress in a shale-sandstone sequence, as shown in Figure 2, the hydraulic fracturing method gives evidence of a *higher* minimum stress in the shale than in the sandstone. The latter is strong enough to tolerate higher differential stress, and also maintain its valuable pore-volume, despite the high effective stress. We will return to this phenomenon later.

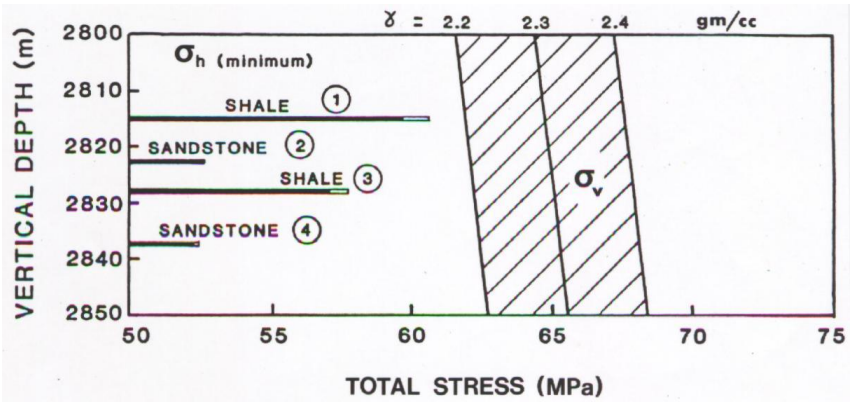

Figure 2. The different shear strengths of reservoir sandstone and ideal 'cap-rock' shale cause higher σ_h(minimum) in the weaker shale, giving it improved sealing and fracture containment [2].

The shale is usually a good cap-rock, especially if the magnitude of σ_h(minimum) in the shale is several MPa higher than in the sandstone, as in Figure 2, because it will then also manage to contain a hydraulic fracture (MHF) treatment, as often used for enhancing production from a tight sandstone layer (or layers). So the property of discontinuous stiffness and shear strength between layers is also responsible for a favourable discontinuity in the minimum stress. Without these rock mechanics details, there would perhaps be negligible reserves of readily producible petroleum today. So shear strength, either low as here, or high enough to support mountain slopes, is arguably one of

the world's most important rock mechanics parameters. Crushing strength high enough to support pore space perhaps comes first in such a hierarchy when considering fluid storage in general.

LARGE SCALE SUBSIDENCE AT EKOFISK

A move can now be made to a slightly smaller scale of problem in a very large North Sea reservoir, this time caused by human activity. It is said that a supply boat captain was the first to question whether the 2m spaced wave baffle holes in the central Ekofisk oil storage tank, were showing evidence of increased depth of sea – by some 4 metres in 1984. A 'before' and 'after' comparison (from 1973 to 1986) is shown in Figure 3.

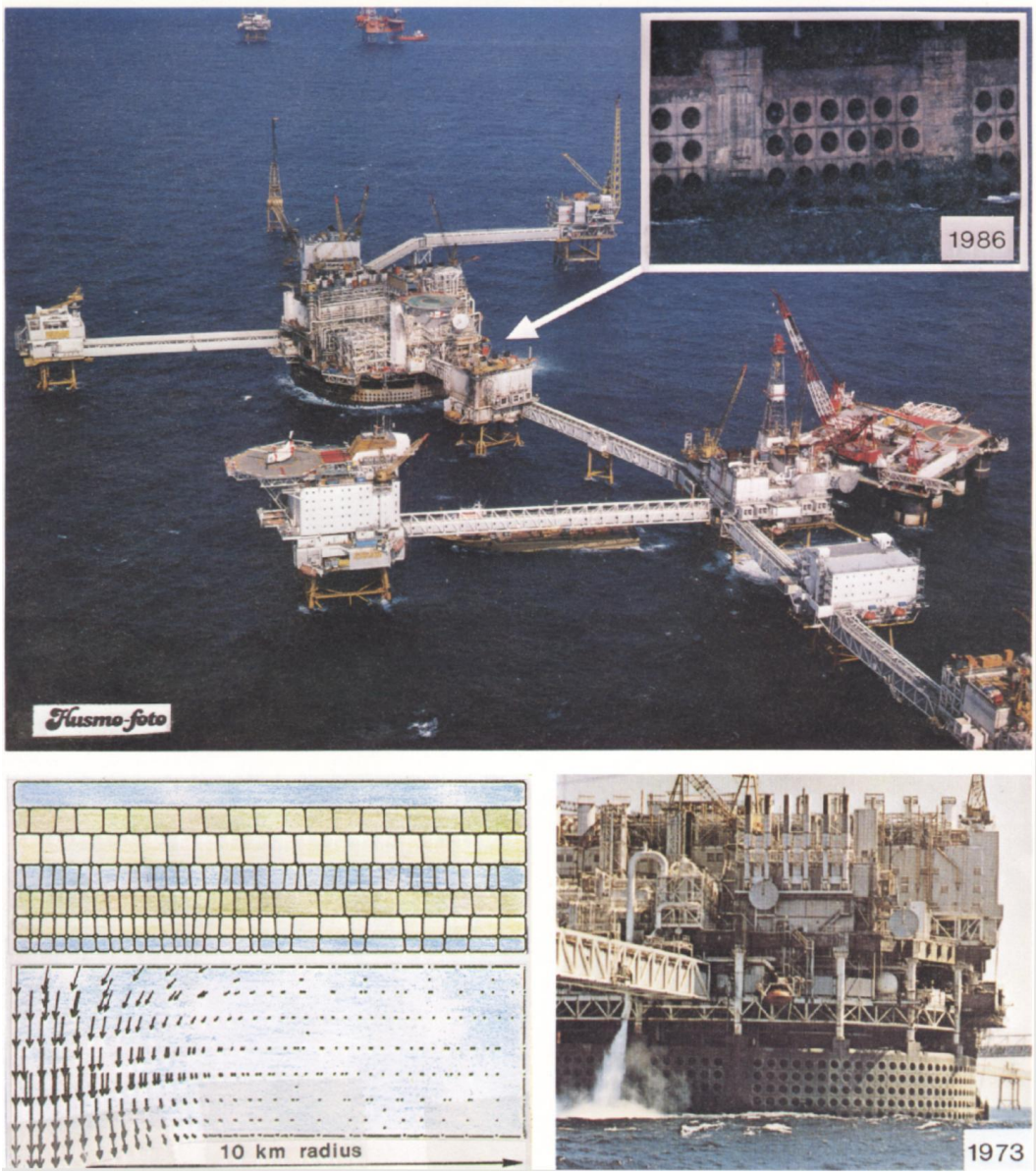

Figure 3. The Ekofisk Centre (temporary) oil storage tank, showing almost 4m increase in local sea depth between 1973 and 1986. A 2D UDEC subsidence model is also shown [3].

Evidently, between start-up in 1971 and 1986, when the top-inset picture was taken, two rows of wave baffle holes had disappeared beneath the horizon of seaweed, representing almost 2 x 2 = 4m of subsidence of the seabed in this central location above the 14 x 9 km reservoir. This was serious in this location, because of the (by-now) more than 30m high '100 year waves' – of which there had been several since production began. Vibrating-wire pore pressure gauges confirmed the increase of sea depth, other gauges showing only 30cm of conventional tank-foundation compaction.

The 300m thick reservoir of porous and extensively jointed chalk (resembling a weak, porous limestone) was located beneath 3 km of mostly shale overburden. Taking the total volume of rock that was involved in the surface subsidence (S) and deep-seated compaction (C), we were dealing with some 150 km^3 of deforming material. This is actually 22 orders of magnitude (10^{22}) larger than the volume of rock (chalk) cylinders that, many years earlier, should

have been subjected to the now standard one-dimensional (axial) strain triaxial tests – in which confining pressure is used to prevent radial strain.

The closest we come to soil mechanics principles in this lecture is to refer to the two sets of alternative 'stress-strain' curves in Figures 4a and 4b. The left-hand diagram shows how different chalk porosities affect the mean effective stress level at which pore-collapse (or non-linear behaviour) occurs. The right-hand diagram shows three stress-axial strain curves, and the degree of fit with NGI's plastic cap model [3, 4]. Since 1971, when production began, there was by 1985 a maximum of 20 MPa increase of effective stress due to this reduction of pore pressure. (This increased to 24 MPa before water flooding eventually controlled the pressure draw-down.) The vertical effective stress at reservoir depth had changed, by 1985, from 14 to 34 MPa, causing pore collapse of the most porous volumes of chalk.

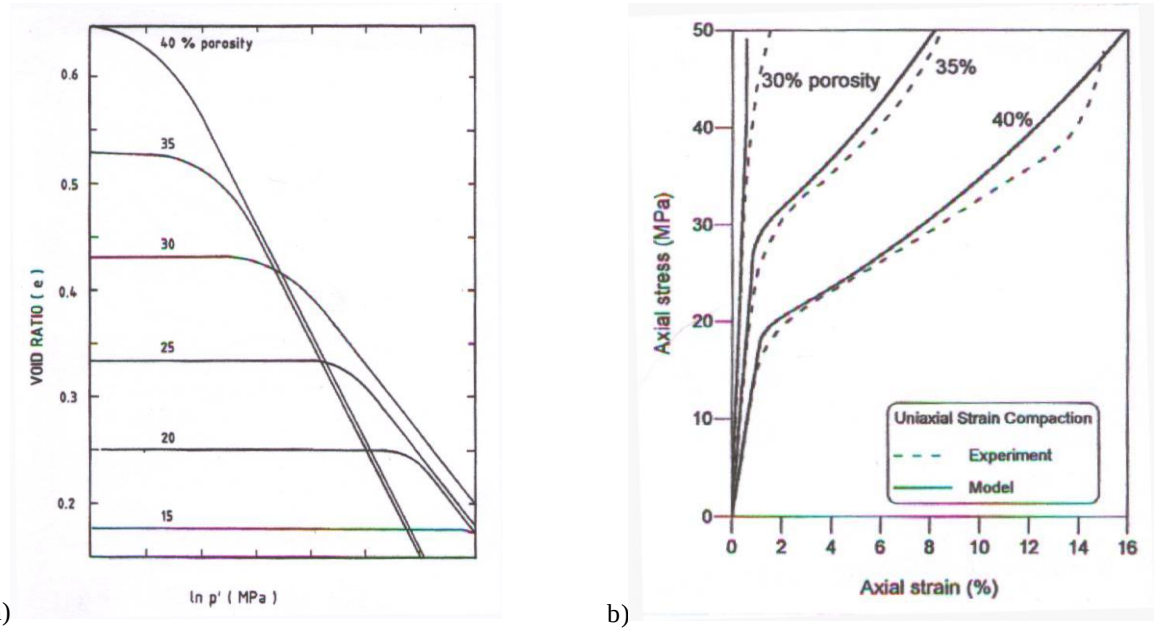

Figure 4. a) Void ratio – effective mean pressure relations (simplified) for chalk of different porosities [3]. b) Axial stress – uniaxial strain behaviour (and cap model) of three Ekofisk chalks [4].

Various approaches for modelling the compaction and subsidence process were used by Phillips Petroleum Co. consultants and by the Norwegian Oil Directory consultants. Fully coupled methods such as CONSAX and DYNAFLOW were used to model the effect of pore pressure draw-down on the radial- and depth-varying porosity distributions.

At greatest 'radius' and at the base of the pear-shaped reservoir, for example from 4 to 6 km from the centre, porosities were lower than 15%, while in the central 2 km they could be close to 40% where greatest compaction was occurring. A radius- and time-dependent distribution of compaction was therefore computed for the top of the reservoir, while the over-lying 3 km of overburden could be modelled as an elastic or elasto-plastic continuum, or as a discontinuous medium with elastic layers of different moduli. As is usual in our subject, the three-dimensional modelling assumed continuum behaviour, while the discontinuum modelling was limited to two-dimensional (radial) sections.

An example of a UDEC model of 10 km radius and 3 km depth is shown in Figure 5, from studies performed by NGI on behalf of the Norwegian Oil Directory. The lower boundary compaction 'shape' of each such model was obtained from the non-linear, fully coupled modelling of pore pressure draw-down effects. In the case shown, the central (r = 0) ratio of S/C was 4.8/5.5 = 0.87. A series of models with increasing draw-down scenarios (prior to sea water injection for 'pressure maintenance') showed a gradually increasing ratio of S/C, as the compaction problem worsened.

It is important to note that all the discontinuum models performed were using large effective block sizes to represent sections through the enormous volume (150 km^3) of deforming overburden. Consequently, appropriately low values of bedding plane and joint (or 'fault') shear stiffness were needed. When a relevant K_s value of 0.01 MPa/mm was used [5], as appropriate to 250-500m block sizes at appropriate effective stress levels, the ratios of S/C ranged from 0.86 to 0.95, the highest values with increasing compaction. If on the other hand, scale effects were ignored and higher, small-block-size stiffnesses were used, the behaviour resembled that of the continuum models.

It appears that the UDEC 'fault-scale' result was closer by far to the high incremental rates ($\Delta S/\Delta C$) being observed at the time, prior to attempts to arrest the 45 cm/year subsidence with massive sea-water injection. When using

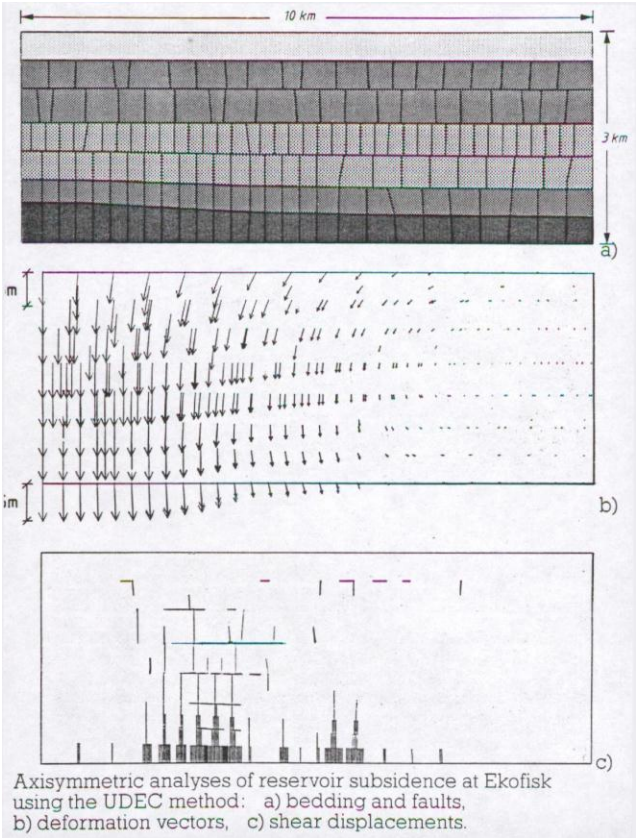

Figure 5. Axisymmetric, 2D UDEC discontinuum analysis of an assumed, and greatly simplified Ekofisk overburden, showing S/C=4.8/5.5, and areas of joint ('fault') and bedding plane ('contact interface') shearing [5].

continuum models in which S/C was usually closer to 0.6, artificially low shear moduli were needed to match observations. The discontinuum (UDEC) modelling also gave steeper, and more correct, seabed subsidence profiles compared to the large three-dimensional finite element continuum codes such as DYNAFLOW, suggesting that *discontinuous behaviour* was actually occurring in practice, probably predominantly on large scale, lower stiffness discontinuities like major bedding planes, rock contact 'horizons', and sub-vertical faults.

In an earlier, landmark case of reservoir compaction ; the Wilmington Field in Long Beach, California, a 75 km^2 subsidence bowl of up to 9 metres caused the harbour to sink beneath the sea, and hundreds of well casings were damaged due to the several metres of 'stretching' and differential bedding plane slip. The problem of numerous casing collapses gradually developed also at Ekofisk, a problem easily appreciated when looking at the modelled regions of bedding plane slip (e.g. Figure 5).

In 1987, in order to ensure safe operation of the complex of production platforms connected by up to 2 km of bridges, the entire Ekofisk Centre was jacked up by 6 metres, and in 1989 a 106m high and 137m diameter concrete wall was also added to protect the storage tank shown in Figure 3. The planned cost of these measures was USD 400 million. By the end of 1994, despite an extensive program of pressure maintenance through massive injection of sea water through new wells, the subsidence had reached 5.5 metres, and was continuing at about 40 cm/year. The decision was then taken to abandon the central complex at Ekofisk, and develop a new complex of platforms near the edge of the subsidence bowl, at a planned cost of USD 2.9 billion. Damage to existing well casings was an additional heavy cost.

Today, the central subsidence has reached 8 metres at Ekofisk, partly because the sea water injection has weakened the chalk, despite an eventually well-controlled pressure maintenance. However, the weakening of the chalk and the eventual (2001) 800,000 barrels per day water flood has greatly improved the production from the field [6]. There is now extensive use of 4D 'time lapse' seismic, to help map both the compaction and the best locations for oil recovery. Numerous horizontal wells are now used to increase the extraction ratio, which may reach 50% eventually, at the end of perhaps 60 years of production (to 2030).

The weakening of the chalk by the seawater, perhaps due to 'stress corrosion' of the grain-boundary micro-cracks, has given a 'compaction drive' behaviour, which is now supplemented by the sophistication of a seismically steered water-drive and better control of reservoir fluid pressures.

DIFFERENT SCALES OF DISCONTINUOUS BEHAVIOUR AT EKOFISK

The extensive casing damage to numerous wells at Ekofisk is one set of evidence of discontinuous behaviour, due to stretching of the overburden and differential bedding plane slip. At Wilmington, shearing of up to 24 cm was registered, and there was even a seismic event caused by sudden slip. A new source of evidence for discontinuous

behaviour during the compaction at Ekofisk is seen in the results of 'time lapse' seismic. A 1989 to 1999 'time lapse' comparison [6] appears to show fault related discontinuities in the estimated 'tomogram' of compaction magnitudes, and also a somewhat larger compaction (> 8m in the central 1.5 x 2.0 km) as compared to the 'smoother' continuum calculations of a geomechanical model [7].

An additional, but little publicised discontinuous behaviour phenomenon, at much smaller scale, but probably widespread, was discovered in the 1985-1986 modelling and joint characterization performed by NGI [3]. A typical joint structure provided by Phillips Petroleum Co. geologists, when combined with joint roughness (JRC) and joint wall strength (JCS) characterization in a coupled UDEC-BB discontinuum model, showed that down-dip shearing could be occurring on the conjugate jointing in the reservoir. A deformed joint structure and lines ('flags') proportional to joint shearing magnitudes are shown for the highest porosity case in Figure 6.

This model represents roughly a 1x1m 'window' in the 300m thick reservoir, where jointing is well developed. The modelled joint structure was subjected to one-dimensional vertical strain (between roller boundaries) and loaded by an internal reduction of pore pressure from 48 to 28 MPa, under a total vertical stress of 62 MPa.

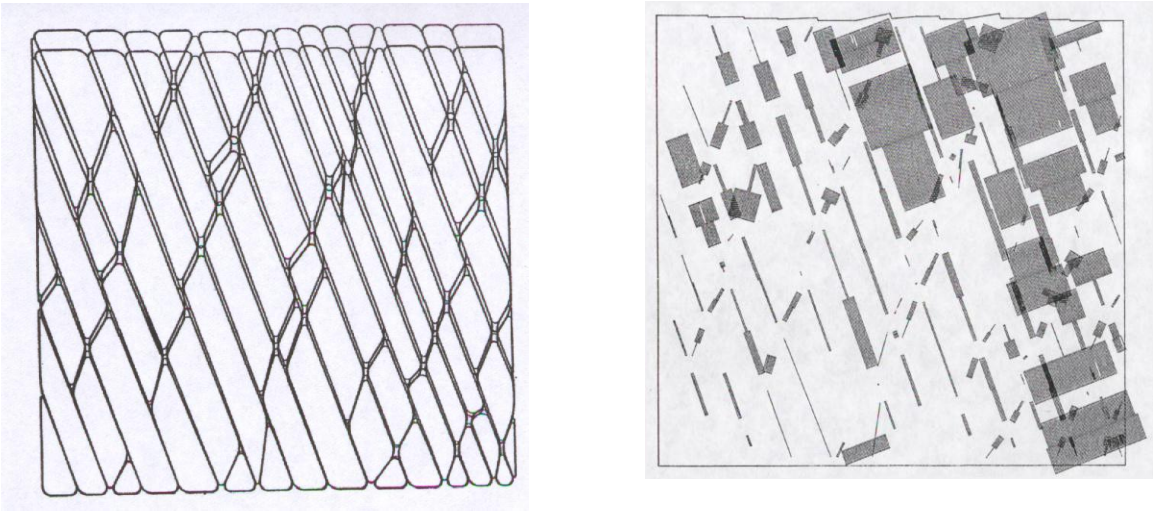

Figure 6. Coupled, one-dimensional strain UDEC-BB modelling of typical porous Ekofisk reservoir joint structures under a 20 MPa increase in effective vertical stress from 14 to 34 MPa. Note that the 4.8% vertical strain is *less* than for intact chalk, due to the joint shearing-related increase of k_o [3].

Normally, one would expect a dramatic reduction in productivity (and rock mass permeability) when such a large increase of effective stress occurred. However, an important detail of the behaviour is that the matrix reduces in volume due to the 20 MPa increase in effective stresses, 'making space' for down-dip joint shearing, despite the uniaxial strain, roller boundaries. With the most porous chalk simulated (n=40%), and a modulus of only 0.33 GPa, a maximum of 3.9mm joint shearing was modelled, with an average for all joints of 0.39mm. On average, this high pressure shearing caused only 2 μm of modelled joint closure – in other words permeability was almost maintained despite the depleting fluid pressure scenario.

Most significantly however, was that the jointed models developed a higher mass deformation modulus than the unjointed material, due to an enhanced build-up of horizontal stress (and k_o) due to the joint slip.

This was confirmed several years later by Gutierrez, in models with even higher increases in effective stress (24 MPa) and a larger range of input data. Here (in Figure 6) we were seeing 4.8% compaction (shortening) compared to 6.0% for an unjointed block of chalk with the same matrix porosity.

It is probably correct to observe that this joint shearing and rock mass stiffening phenomenon was not given much credence by reservoir engineers at this time (1985). However, when slickensided joints started to be recovered in new wells (for the first time at Ekofisk), acceptance of such phenomena was gradually developed.

It is interesting to also consider the comparative fate of horizontal or flat-lying reservoir joints to similar pressure draw-down and therefore to greatly increased effective stresses (They would be closed and would cease to conduct fluids effectively). It is clear that steeply inclined joints (when under shear stress) give enormous advantages for maintenance of petroleum production in a gradually depleting reservoir.

A POSSIBLE EFFECT OF WATER FLOODING

Today's effects of water flooding, besides pressure maintenance and an improved 'steering' of production, is thought to be a continued weakening of the chalk matrix and therefore an important 'compaction drive' component to the good productivity. In this connection it is of interest to consider the likely course of 'rock mechanics events' when starting the water flooding. The rubbleized nature of more recent core recovery may have disguised a very important mechanism that is likely to precede such weakening of the matrix.

It is logical to assume that injected seawater first reaches joint planes that have sufficient aperture to conduct fluid more rapidly than the matrix. If grain boundaries suffer 'stress corrosion' due to the water softening effect, this is likely to start in the portions of the joint planes where stress levels are highest. In earlier work on the shear strength of rock joints the writer has shown that the ratio of normal stress to compressive strength, or σ_n / JCS, is similar to the measured ratio of real to assumed joint contact area A_o/A_1. This means that the real stress level at the stress-transferring asperities in contact is approximately equal to the available joint wall strength JCS. A weakening of JCS at these same locations, caused by the seawater, would certainly stimulate an accelerated down-dip shearing due to reduced shear strength. Such a mechanism could explain why it was so difficult to limit compaction with the pressure-maintenance objective of the initial water injection. It is also possible that such a mechanism – i.e. a water-softening enhancement of Figure 6 mechanisms – is still active in the less permeable parts of the reservoir, as a production-enhancing supplement to matrix softening and rubbleization in the more porous chalks.

THE DISTURBED ZONE AROUND BOREHOLES

Drilling deep wells for petroleum exploration and for eventual production is expensive, especially in offshore environments. The Barents Sea explorations have been mentioned at the beginning of this paper, together with the price tag, for 50 holes and a lot of seismic surveys. Unlike tunnelling, with which most of us are more familiar, there is no room or facility for providing 'rock bolts and shotcrete', prior to final lining of a deep well. The well driller has mud (of different weights and compositions) for 'temporary support', and a final steel tubing, which will need explosive 'shaped charges' to make perforations where production or stimulation measures are later to be developed.

As perfectly illustrated in Figure 7, from work with deviated wells [8], the 'temporary support' in the form of a certain mud weight (or density) presents a dilemma when mixed rock conditions are involved. We have already seen from Figure 2 that rock layers of different strengths may have different magnitudes of minimum stress, due to their different tolerance of differential or shear stress.

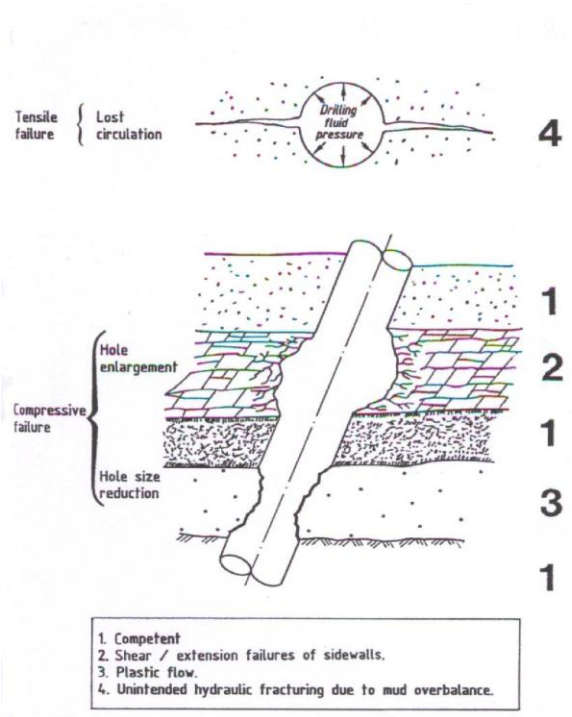

Figure 7. The problem of well stability, matching the needs of extra mud weight for weaker layers, is often in conflict with hydraulic fracturing risks for more competent layers, which often have lower minimum stress [8].

This may mean that a mud weight suitable for keeping a 'plastic' shale or rock salt from creeping and binding the drill string, is actually too high for a stronger and/or jointed rock (having lower σ_h minimum). Hydraulic fracturing and mud loss may then result. This lost circulation possibility is illustrated in Figure 7, together with the problematic plastic flow horizon (layer #3).

Due specifically to the above dilemma and the constraints it presents, and to the fact that the selected mud weight may not give the desired pressure gradient in comparison to the variable minimum stress gradient, there may be varying degrees of 'distress' or over-loading in some plastic layers. In other words the theoretically induced maximum tangential stresses ($3\sigma_H - \sigma_h$) will be too high in the weaker material layers (and they will then no longer follow the elastic Kirsch equations). Likewise, the stronger material with too low minimum tangential stress ($3\sigma_h - \sigma_H$) may be uncomfortably close to hydraulic fracturing in the vitally necessary attempt to 'radially support' the over-stressed layers.

Figure 8 shows some physical model-based 'realities' that might be encountered in these situations. The upper drawing and photograph is of a three-dimensional (poly-axial) loading chamber for applying equal or unequal values of σ_v, σ_h and σ_H to 0.5x0.5x0.5m blocks of weak (0.5 MPa) rock simulant. Model wells could be drilled into this stressed environment, at various angles to the principal stresses if desired [9]. The single or double sets of log-spiral shear failure surfaces, their shape and anisotropy depended on the combinations of stresses and well inclinations. That depicted is more complex than most.

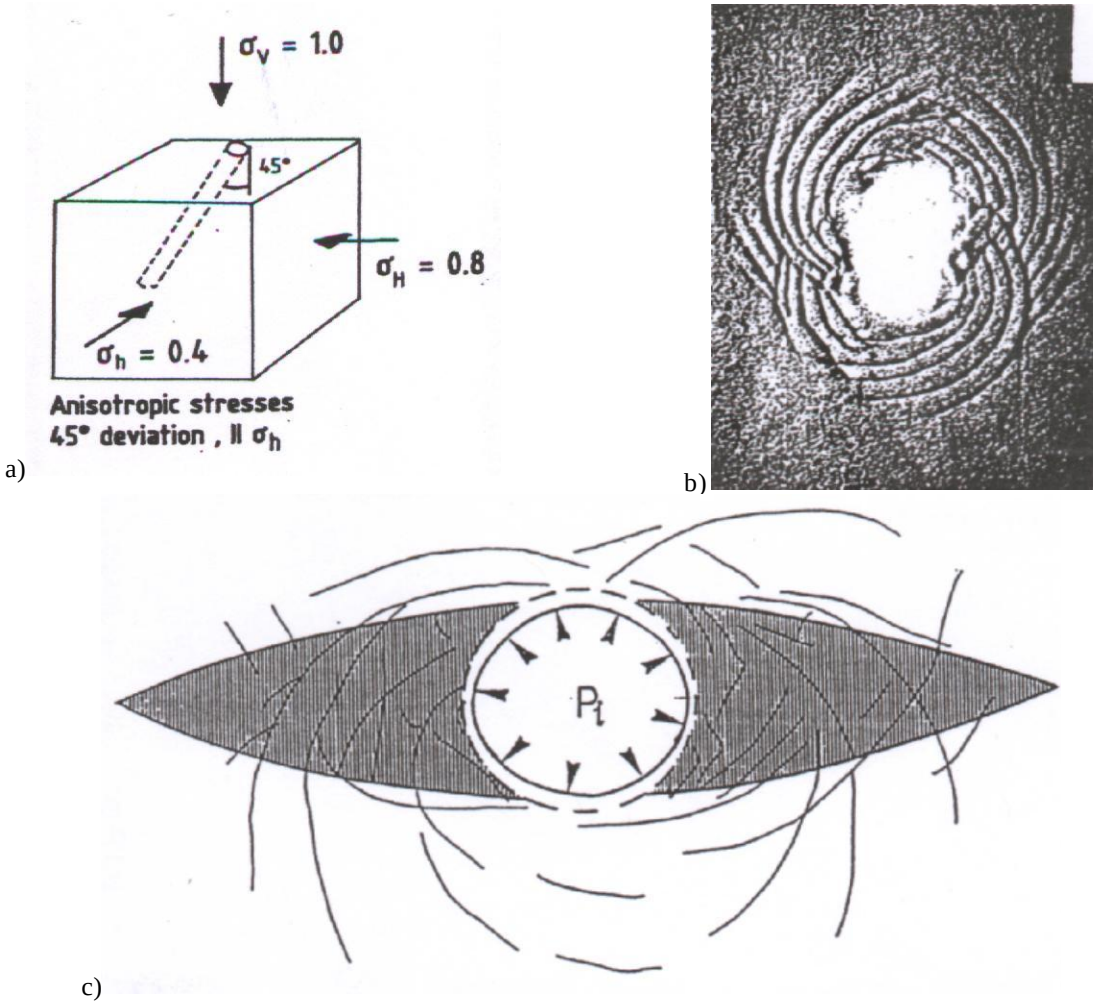

Figure 8. Log-spiral failure surfaces around experimental boreholes violate the assumptions of 'elasto-plastic continua', due to slip on the discontinuities [9]. The predicted plastic zone (shaded) has little relation to the 'reality.'

Two important principles were evident. Firstly that the log-spiral surfaces actually *sheared* – presumably to relieve the high shear stresses in the tangentially strained excavation disturbed zone (EDZ). Secondly, that these surfaces therefore violated the continuum assumptions necessary for developing the closed-form, elasto-plastic solution of an elliptical 'plastic zone', as in Figure 8b. The 'reality' was a stress-induced '*discontinuum*', which would probably have an enhanced permeability. Is it possible that such a zone could even cause circulation loss during drilling? Perhaps the answer is no, if the log-spiral surfaces are almost non-dilatant.

It is pertinent to mention in conclusion that elastic and elasto-plastic continuum models do a very poor job in describing the actually observed failure modes and volumes around highly stressed circular excavations in rock. The long-applied Mohr-Coulomb model which implies simultaneous mobilization of cohesion and friction and certain equations for transforming principal stresses to shear planes is in need of replacement, at least in rock engineering, as it does not give the observed failure modes. Two areas for improvement would be the *full* acknowledgement of dilation in the stress transformation equations [10] and separate mobilization, first of 'c', then of 'ϕ' in numerical models. In the Q-system of rock mass characterization it is now possible to select different combinations of 'c' and 'ϕ' for the same Q-value. Different susceptibilities to rotational modes of failure and to translational failure are implied. The 'selected' mode of failure proves to be a function of the block sizes, and also a function of the roughness of the joints and discontinuities in relation to the scale of the problem.

CONCLUSIONS

1. Discontinuities from 10's of kilometres scale to micron-size have affected, and are still affecting, the production of the world's petroleum reserves. Large scale faulting can trap oil in many circumstances – but can also have been responsible for immeasurable losses to the atmosphere in the distant past. This is when the sealing layers like shale have not only been faulted, but also strengthened and made more 'brittle' by tectonic events.
2. Cap-rocks like shale usually provide low permeability sealing properties due to their intolerance of significant stress differences. The magnitude of their minimum stress is therefore higher than in the reservoir sandstones.
3. Petroleum production, and other sources of fluid extraction, may cause serious compaction at reservoir level, followed by overlying subsidence, if high porosity materials have insufficient strength to tolerate the effective stress increase, and if the overburden is also weak. At Wilmington there was 9m of subsidence, at Ekofisk , beneath the North Sea, the subsidence is now 8m following a maximum 24 MPa increase in effective stress. Well casings are damaged in large numbers by the resulting, discontinuous inter-bed slip, which is also predicted in discontinuum modelling. Enormous costs may be involved in relocation of facilities, but the rewards may also be large.
4. Carbonate or chalk reservoirs with steeply dipping, as opposed to flat-lying jointing, are successful producers because of a remarkable joint shearing mechanism, despite the one-dimensional (vertical) strain constraint. Matrix shrinkage under the large increase of effective stress, 'makes space' for down-dip joint shearing. The latter helps to maintain joint aperture, and provides a pseudo-confinement effect (increased k_o) which makes the jointed reservoir actually stiffer than the unjointed rock. Water flooding may have stimulated this mechanism due to preferential weakening at highly stressed joint-wall contacts, prior to softening of the less permeable matrix.
5. Stress-induced fracturing around exploration or production wells may be caused in weaker layers, due to the limited mud weights that can be used if reservoir sandstones or other harder layers have too low minimum stress levels. Experiments show that log-spiral failure surfaces in the over-stressed layers are actually shearing, curved discontinuities. Elasto-plastic continuum assumptions and calculations may therefore not reflect reality. Simultaneous mobilization of cohesion and friction is incorrect for most rock failure.

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