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Petrophysics Under Stress

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Abstract

Petrophysical quantities like porosity, permeability, compressibility and wave velocities all depend on stress. Quite often in laboratory petrophysical studies, measurements are performed under ambient or isotropic stress conditions. Log data are obtained from the near well environment, and are therefore influenced by the stress concentration in this zone. The reservoir is however in a different stress state, which is changing as a result of depletion. Therefore, corrections for stress effects are required in order to reliably use petrophysical data in dynamic reservoir modelling. In some cases, permanent damage are generated by the stress release occurring during coring, or on the formation nearest to the bore-hole wall, making such corrections particularly important and difficult to make. This Paper reviews a number of experiments, most often with synthetic sandstones manufactured under stress, performed in order to quantify stress and stress release effects on petrophysical properties.

Introduction

There are two main reasons why this paper is written. The first is a request from the chairman of the 6th Nordic Symposium on Petrophysics (Loermans, 2001). The second is a wish to make rock mechanics a more integrated part of petrophysics than is currently the case.

Reservoir stresses, near borehole stresses, and laboratory stresses

Figure 1 illustrates the stress evolution during reservoir depletion, as compared to that near a borehole during logging, and in the laboratory during standard petrophysical measurements under applied isotropic load. The in situ stress state of an example reservoir is taken as 60 MPa (vertical), 50 MPa (isotropic, horizontal), and 30 MPa (pore pressure). When the reservoir is produced by pore pressure depletion, the effective stresses are increasing. The rate of increase in effective horizontal (σ_h') vs. effective vertical (σ_v') stress is given by the parameter κ;

$$\Delta s'_h = k \Delta s'_v \tag{1}$$

Here we have introduced the concept of an effective stress, which is not well defined. If we want to describe the strain (compaction) of the reservoir, then effective stress follows from Biot's theory of poroelasticity (Biot, 1962) as

$$s'_{ij} = s_{ij} - a d_{ij} \tag{2}$$

where d_{ij} is the Kronecker delta; =1 for i=j and =0 otherwise. Physically, that means that the pore pressure is subtracted from normal stresses, not from shear stresses. The Biot coefficient a is 1 (close to 1 for soft rocks; < 1 for stiff rocks). The reason we say the effective stress is not well defined is that it depends on which physical quantity we are interested in (Boutéca & Guéguen, 1999). Thus, if we are interested in porosity changes, then the effective stress principle for porosity (in linear Biot poroelastic theory) is just like Eq. (2), except that the relevant α parameter =1. If we are interested in permeability, or in wave velocities, then the corresponding α parameters for those are not really known, but they are certainly neither equal to Biot's α nor equal to 1.

Nevertheless, the main focus here is that the stresses change during depletion. The parameter k in Eq. (2) depends on mechanical properties of the reservoir rock and its surroundings (Addis, 1997), on reservoir geometry, on the ability of the overburden to shield the reservoir stresses etc. It is hence not known before a reservoir is produced, but it may be measured by monitoring stress changes during depletion, or it may be predicted based on a priori knowledge of the factors described above. The reservoir may stay within the failure envelope of the reservoir during production (as in Figure 1), or it may reach the failure envelope, in which case active faulting takes place and seismicity is observed.

Clearly, petrophysical characteristics may change during this process – in particular if the failure criterion is reached. With the increasing use of so-called 4D (time-lapse) seismics, the need for a dynamic petrophysical characterization also increases.

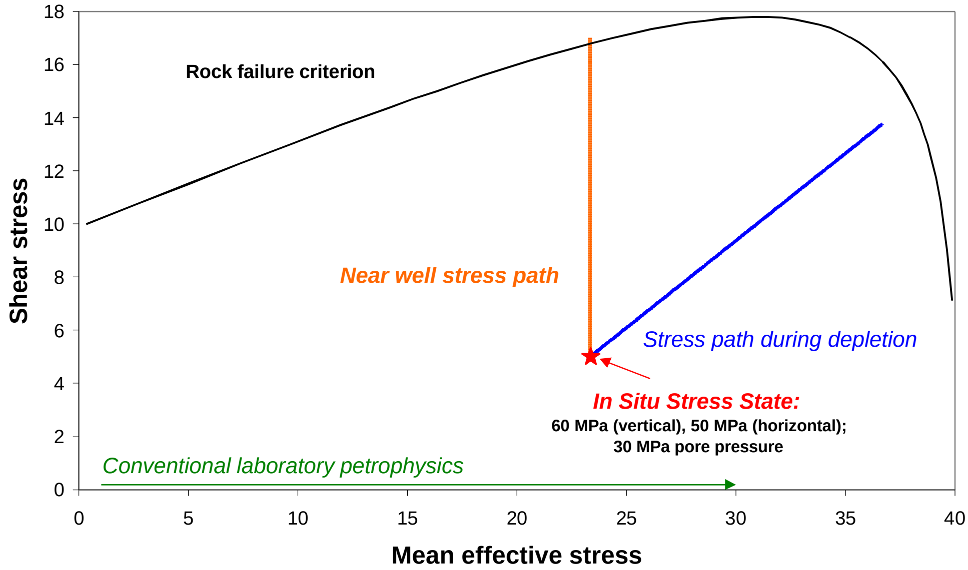

Figure 1: Illustration of states of stress occurring in a reservoir during depletion, in the vicinity of a borehole during logging, and in the laboratory during most types of conventional petrophysical measurements.

Figure 1 also shows a sketch of the stress path of the subsurface formation near a borehole as the hole is drilled. The stress state at the borehole wall is altered since the solid rock has been replaced by a fluid at a certain pressure. Usually this leads to a stress concentration, with the radial effective stress at the borehole wall being very small (close to zero), and compensated by an increase in the tangential (hoop) stress around the hole. The formation at or near the borehole wall may or may not reach failure. Sometimes failure is reached during drilling, being responsible for stuck pipe and tight hole incidents (borehole instabilities). Sometimes failure is reached during production, leading to particle production. In any case, the petrophysical properties of the formation near the borehole may change – and hence influences log measurements. This is particularly relevant if the log recording is made in the near vicinity of the borehole wall.

In view of these considerations, it is maybe surprising that almost all petrophysical analysis is performed at ambient or under isotropic stress conditions (as indicated by the bottom line in Figure 1). The question is: What errors are made by neglecting stresses (and shear stresses in particular) in formation evaluation? We will try to provide some answers to this, leaning on 10 - 15 years of experimental experience through several - generic and field oriented – studies. We will first look at effects that may affect log interpretation, and then consider petrophysical evaluation from core data.

Synthetic rocks manufactured under stress

Throughout these examples, we will to a large extent use experience from laboratory studies performed with synthetic sandstones manufactured under stress (Holt *et al*., 2000a). Sand and sodium silicate solution was mixed into a slurry, loaded to a preset state of stress (representative of the reservoir effective stress state) and then hardened through a chemical process by injection of CO_2. The cemented samples were either

i) loaded from their "*in situ*" stress state to simulate depletion,
ii) unloaded to simulate the stress alteration near a borehole or
iii) unloaded to simulate the stress release during coring.

In this way, the petrophysical consequences of stress changes in the reservoir during depletion, and the alterations affecting log and core data may be quantified through controlled experiments.

Near well stress effects on logs

Figure 2 shows the stress state near a vertical borehole as a result of drillout and / or further well pressure change during logging. The well pressure controls the radial stress at the borehole wall, and hence the amount of splitting between the tangential and the radial stress components. If the pressure is reduced, the split increases, and hence the risk of damage. Notice that this figure is based on linear elasticity theory.

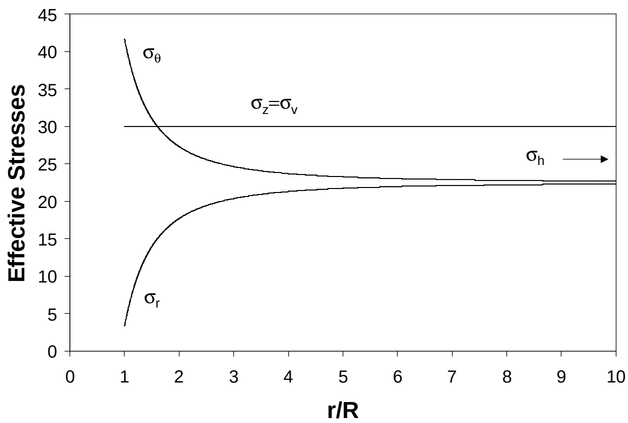

Figure 2: Stress state near a vertical borehole, showing the splitting of the horizontal far field stress into a radial and a tangential principal stress component near the borehole wall (r: distance from wall; R: borehole radius). From Fjær & Holt (1999).

Sonic logs

Sonic logging tools excite waves that travel along the borehole, and – depending on the source – receiver separation and the tool frequency, scans the elastic properties within 30 – 100 cm penetration depth. In this zone, the readings may be influenced by filtrate invasion, but also by the stress release exemplified in the figure above. P-waves are usually measured, and using dipole sources and receivers, also shear waves – and even shear wave anisotropy (Brie *et al.*, 1998) may be recorded.

Fjær & Holt (1999) showed, using the synthetic sandstone method described above, that the stress release occurring as a result of stress release near a borehole will lead to large and anisotropic velocity changes. The velocity of a P-wave propagating parallel to the borehole axis will be strongly affected only in the very vicinity of the borehole wall. The laboratory data were translated into the borehole coordinate system, anticipating an elastic model for the formation. The resulting velocity profile is shown in Figure 3. In this particular case – which of course is rather synthetic – the extent of the disturbed zone is between 0.5 and 1 borehole radius. Field observations have been made in underground caverns in salt (Holcomb & Hardy, 2001), showing a disturbed zone with largely reduced velocities of 1 - 2 m thickness. Plona *et al.* (1999) interpreted dipole shear data in terms of a damaged zone extending to about 30 cm. Clearly; the extent of the zone depends on the material itself, and also on its stress history. The synthetic rock used in our study was formed under a given stress state, and no further attempts were made to mimic influences during the continued history of the rock. Tectonic activity, uplift – burial sequences etc may have changed the rock and made it more stress sensitive; thus giving rise to larger damaged zones.

The damaged zone causes uncertainty in evaluation of sonic log data. With appropriate processing and logging tools, the existence of such a zone may however permit estimation of the *in situ* stress state (Plona *et al.*, 1999; Plona, 2001).

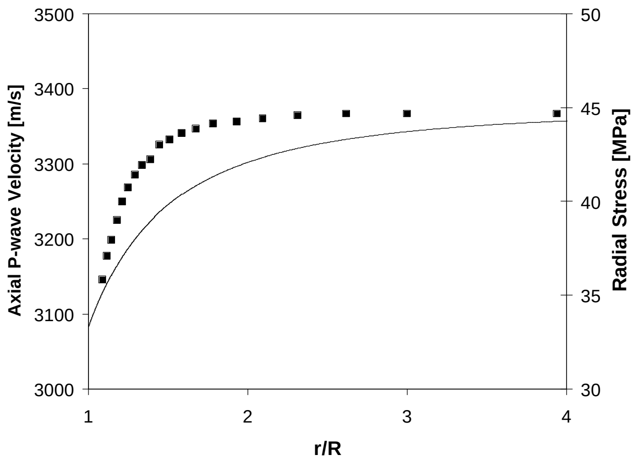

Figure 3: P-wave velocity vs distance from borehole wall, based on laboratory tests with synthetic sandstone undergoing a stress path similar to that of a rock near a borehole (cf Figure 2). From Fjær & Holt (1999).

NMR logs

Nuclear Magnetic Resonance (NMR) logging tools are reading from shallow depth, typically a few inches behind the borehole wall. The NMR measurements are obviously flavoured by mud invasion. One may also ask to what extent the NMR data are influenced by the stress altered zone. van der Zwaag *et al.* (2001) find from NMR measurements during rock mechanical tests that the relaxation time spectrum is altered as a result of crack evolution within their sample. Also, the diffusion coefficient appears to be sensitive to cracks.

The existence of cracks may affect the pore size distribution and hence the relaxation times measured. In multiphase situations, these cracks will attract the wetting phase and hence the stress release will alter the saturation distribution within the pore space. These effects remain uninvestigated.

Stress and stress release effects on core behaviour

When a core is drilled, the *in situ* stresses are released. This occurs (Figure 4) by a gradual removal of the vertical stress as the coring bit is approaching from above (vertical hole assumed), and a subsequent horizontal stress release once the core is drilled free from the surrounding formation. During a certain interval in time, the vertical effective stress is therefore much lower than the horizontal effective stress(es), and the core is prone to mechanical damage / failure. The damage is manifested by microcracks (or broken grain bonds), in particular horizontally oriented cracks. Because shearing may occur during stress release, these cracks may not be closed by subsequent reloading to the *in situ* stress.

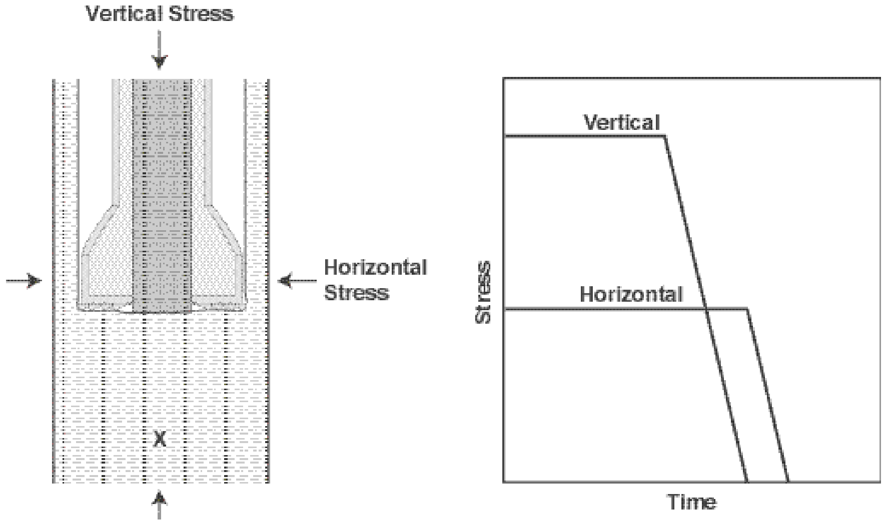

Figure 4: Sketch of stress release occurring during coring in a vertical well. From Holt *et al*. (2000).

Compressibility

The main part of our work with synthetic sandstone has been devoted to quantification of core damage effects on compaction behaviour, and on how to correct measured core compressibilities for such damage. The results are described in detail in Holt *et al.* (2000). The main conclusion is that the microcrack formation softens the core with respect to the *in situ* rock. Thus, core measurements, if uncorrected, are likely to overestimate reservoir compressibility (by a factor of 2-3 in the synthetic sandstones used in our study), in particular during initial depletion. At high levels of depletion, the reservoir rock may also become damaged, and the core and reservoir compressibilities become comparable. These results are confirmed by discrete particle modelling (Holt *et al.*, 2000b).

Acoustics

The effects of stress release on elastic wave velocities has been studied extensively using the synthetic rock forming procedure described above (Holt, 1999; Holt *et al.*, 2000; Nes *et al.*, 2000). The main conclusions from these studies are:

- The unloaded cores have strongly reduced velocities as compared to the *in situ* velocities. Velocity measurements at ambient conditions are therefore completely useless, at least in brittle rocks with low strength with respect to depth of origin, for assessment of *in situ* velocities. On the other hand, the velocity anisotropy of the unloaded core is directly related to the *in situ* stress anisotropy, and may be used to determine stress directions.
- When a stress-released core is reloaded, it does not recover the *in situ* velocity even if reloaded to the exact *in situ* stress state (as was done in the synthetic rock studies). This indicates permanent damage. In most of the tests performed, the permanent velocity reduction is around 10%.
- The virgin synthetic material is not very stress sensitive; i.e., the velocities do not change much if the stress is increased directly after the sample is formed. Noteable changes occur only when the material is loaded beyond its yield point and damage starts to develop. The synthetic core (the unloaded – reloaded material) on the other hand, is strongly stress sensitive, also above the stress state where it was formed. This is illustrated in Figure 6. A

possible consequence is that stress sensitivity of wave velocities to a large extent is a core damage effect. We should however have in mind that the *in situ* reservoir rock may have been through different stress cycles after diagenesis was completed, and therefore may be more stress sensitive than our idealized virgin material. This problem relates to how core data may be used to evaluate possible stress / pore pressure effects to be seen during time-lapse seismics.

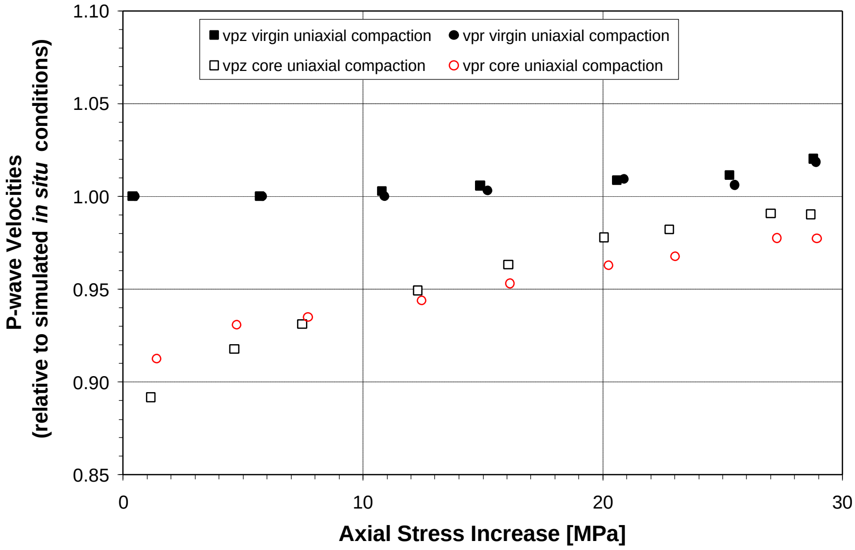

Figure 5: P-wave velocities of virgin and simulated core synthetic sandstones, showing the larger stress sensitivity of the cores. From Holt (1999).

Porosity

Conventional porosity measurements are performed at ambient or low pressure conditions and then corrected to *in situ* porosity by a correction factor obtained from a few tests performed under isotropic stress conditions. Normally the core is then loaded to the effective overburden stress, and the measured porosity is then corrected to account for the *in situ* stress anisotropy. This is often done without sufficient knowledge of the stress state, using a standard correction factor, as was done by e.g. Juhasz (1986). Several questions can be raised regarding these procedures. Obviously, the use of a standard correction factor is not recommended. Another crucial question is to what extent the use of an isotropic stress path in the laboratory tests is valid.

In a recent paper, Holt *et al.* (2001) performed a systematic study of the factors influencing the porosity correction. From poroelastic theory, it was pointed out that the effective stress for porosity (provided a homogeneous rock matrix; Berryman, 1992), is simply the external stress minus the pore pressure. Provided the rock is elastic, the use of isotropic tests can also be defended. This was checked by use of synthetic rock tests, and also by discrete particle numerical simulations. Both approaches demonstrated that the reloaded core stress – strain behaviour is highly nonlinear, but largely elastic. Volumetric strain was found to depend on the mean stress, which implies that isotropic loading conditions may indeed be used for porosity corrections. The porosity needs to be measured at the effective mean *in situ* stress; thus the *in situ* stress state needs to be known. The results from these studies were verified in a field core study, where cores from a given well were stressed along three different stress paths. The resulting porosity showed no significant stress path dependency (Figure 7). A further recommendation from this study is to obtain both pore and bulk volume strains during the tests.

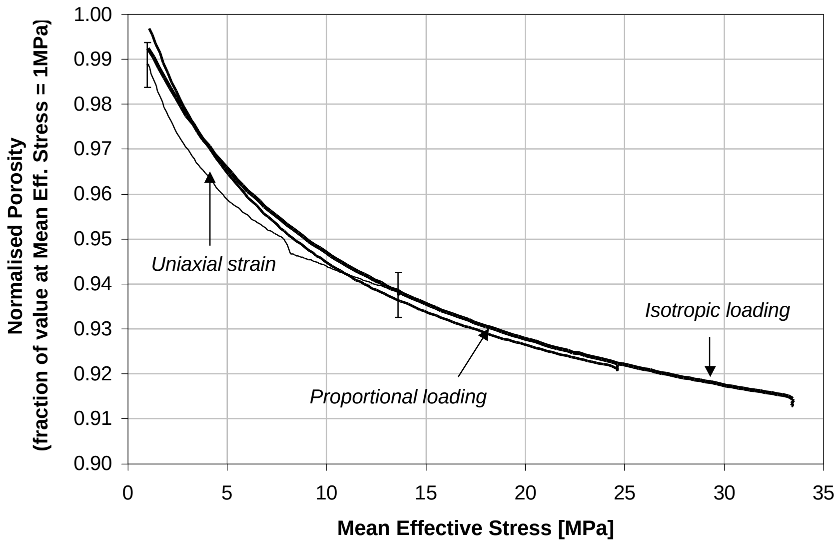

Figure 6: Porosity correction factor vs. mean effective stress for the 3 different stress paths employed. Porosity values are normalised with respect to measurements at 1.5 MPa confining and 0.5 MPa pore pressure. From Holt et al. (2001).

In cases of weak and high porosity cores, core damage may be an issue. In the synthetic rocks this was found to lead to a permanently reduced porosity (by 0.5 – 1.5 % units for 30 % porosity sandstones) as a result of an unloading (simulated coring) – reloading cycle. Physically it is due to grain rearrangements and strong compaction during stress release, when the vertical core stress is low, and the core material still experiences the full horizontal stress. In such cases, no current correction procedure will apply.

Permeability

Overburden correction of permeability is an issue similar to that described above for porosity. This topic has not yet been addressed explicitly in our studies, but is more difficult than porosity correction, because permeability is anisotropic and hence will not depend on the mean stress, and because the effective stress principle for permeability is not established.

During depletion of a reservoir, permeability changes may occur as a result of reservoir compaction. As long as the reservoir is in an elastic state, the permeability alteration is likely to be small – and reasonably predictable. Figure 7 shows permeability measured in a triaxial test with an outcrop sandstone (Red Wildmoor; porosity 25%). The confining pressure was 40 MPa. The data show that the permeability decreases steadily during the initial hydrostatic loading and until the peak stress is reached. This permeability decrease is in good agreement with the expected decrease as a result of the porosity decrease during compaction, i.e. from the Kozeny-Carman equation

$$k \propto \frac{j^3}{(1-j)^2} \tag{3}$$

After the peak stress has been reached, however, the permeability decline is much stronger than predicted by Eq. (3). This may be caused by formation of fines during shear sliding, or by the formation of a horizontal compaction band consisting of essentially crushed grains. This feature has been observed by Olsson (1999). Holcomb & Olsson (to be publ.) observed 2 orders of magnitude permeability decrease during compaction of a Castlegate sandstone sample. Clearly, if reservoir conditions permit the generation of a compaction band, it will be a permeability barrier that may significantly affect production. Several laboratory observations (Morita *et al.*, 1984; Holt, 1990; Ruistuen & Hanssen, 1996) underpin that when a reservoir rock exceeds the damage surface in stress space, strong permeability reductions are likely to occur in high porosity, compliant sandstones, whereas permeability maintenance or even slight increases may occur if the rock is low porosity and exhibits dilatant behaviour.

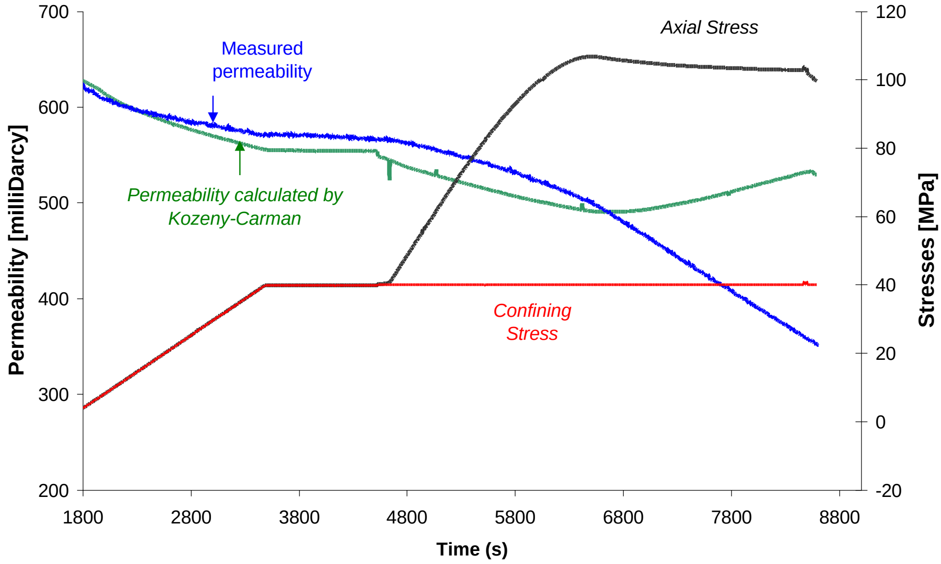

Figure 7: Permeability measured during a triaxial test with Red Wildmoor sandstone. Also shown is the permeability as predicted by the Kozeny-Carman equation, using only the porosity term, derived from bulk strain measurements on the core. From Lutnes (1999).

Core based stress determination?

The results presented above demonstrate the stress sensitivity of core measurements. Often, like in the case of wave velocities, stress sensitivity may be caused by the stress release during coring. The crack pattern of the unloaded core has some memory of the previous stress state, and this gives some promise that the *in situ* stress state may be estimated from core data. One possibility for direct utilization of the stress memory is through the Kaiser effect, which means that a material will start to generate acoustic emissions (AE) once it is loaded back to its most damaging previous state of stress. By realising (see Figure 2) that this is the stress state during coring (Kenter *et al.*, 1998), it was demonstrated on the basis of laboratory modelling (Pestman *et al.*, 2001) and discrete particle modelling (Holt *et al.*, 2001b), that it is feasible to obtain both horizontal (effective) stresses from a true triaxial test with a core sample. The core has to be loaded along different stress paths in the horizontal stress space, keeping the vertical stress equal to the mud overbalance applied during coring. The *in situ* horizontal stress state is then marked by a knee in the damage surface recorded by onset of AE.

Conclusions

In this Paper, a number of examples has been presented, demonstrating how stresses may affect log and core measurements of petrophysical parameters. The work is largely based on experiments performed under controlled conditions with synthetic sandstones manufactured under stress. Stress release, either during coring, or in the vicinity of a borehole, may lead to microcracking and eventually permanent damage of the core or of the borehole. In such cases, petrophysical measurements are not reliable, and have to be corrected in order to be applied. In most cases, the core alteration makes the unloaded core inappropriate for quantitative determination of petrophysical properties. Reloaded cores should ideally be brought to the *in situ* effective state of stress, although in some cases (like with porosity measurements), isotropic stress conditions may suffice. The stress release effects do however also provide possibilities for *in situ* stress determination, from shear wave anisotropy measurements in sonic logs, or from acoustic emission generation in cores.

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