EFFECTS OF CORING ON PETROPHYSICAL MEASUREMENTS.

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ABSTRACT

When a core sample is taken from great depth to the surface, it may be permanently altered by several mechanisms. This Paper focusses on possible effects of stress release on petrophysical measurables, such as porosity, permeability, acoustic velocities and compaction behaviour. The results are obtained through an experimental study, where synthetic rocks are formed under simulated *in situ* stress conditions, so that stress release effects can be studied in a systematic way.

INTRODUCTION

Core measurements provide important input data to petroleum reservoir evaluations. Uncertainties in reserve estimates and predicted production profiles may originate from uncertianties in core data. In addition to measurement errors, such uncertainty may be a result of core damage (see e.g. Santarelli and Dusseault, 1991). By core damage we mean permanent alteration of core material so that the material is no longer representative of the rock *in situ*. It is important to distinguish here between core alteration, which can be repaired by reinstalling the *in situ* conditions, and permanent core damage. A general advice would be to perform any core measurement as close to *in situ* (stress, pore pressure, temperature, fluid saturation) conditions as possible. In the case of a damaged core, this does however not warrant a correct result. The focus of this Paper will be on unrepairable core damage, and where the damage is caused by a mechanical failure of the rock. We shall look briefly into mechanisms that may cause such damage, how permanent core damage may affect various petrophysical parameters, and how one may correct for or reduce such core damage.

CORE DAMAGE MECHANISMS

When a core sample is taken from the subsurface, damage may occur immediately (by drill-out; by action of the drill-bit) or during retrieval to the surface. There is a further chance of core damage by handling, transport, storage and preparation. A number of mechanisms may cause core damage in all these phases. One should remember that the importance of a specific damage mechanism depends on the rock property that we want to determine: For instance, a mechanism that changes the structure of pore fill material, is likely to influence strongly on permeability, whereas it should have a much less significant effect on mechanical properties. On the other hand, if the rock is brought to mechanical failure during coring, this will have a dominant effect on mechanical behaviour, whereas the expected effects on porosity and permeability are less.

The following damage mechanisms should be considered: Stress, pore pressure and temperature release, and exposure to non-native fluids.

External stress release.

The *in situ* stress field in the earth previous to drill-out is represented by a vertical stress σ_V, and two horizontal stresses σ_H and σ_h ($\sigma_H > \sigma_h$). In addition, in a porous and permeable formation, there is also a pore pressure p_f. During coring, at the mud - rock interface, the vertical stress is given by the weight of the mud column (p_W), and the effective stress is largely reduced. The amount of overbalance (p_W - p_f), the rock permeability, and its ability to establish a mud-cake, determine to what extent the mud invades and pressurizes the rock from above. For a point at some distance below the coring bit, the vertical stress starts to reduce as the bit is approaching from above, with little or no change in the horizontal stress. When the bit comes closer, and in particular when the core is drilled free from the surrounding rock, the horizontal stress is also released. Depending on the shape of the coring bit, there will be a zone of compression (underneath the teeth of the bit) and a zone of vertical tension (around the external side of the core, just above the bit, and near the core axis) (Santarelli and Dusseault, 1991; Dyke, 1989; Maury *et al.*, 1988). If the coring bit is sufficiently thick (as in most petroleum operations), it was pointed out by Maury *et al.* (1988) that shear failure due to the compressive zone can be neglected as a source of damage, and that tensile failure is the most likely mechanism associated with stress release. The stress release initially leads to the formation of microcracks in the core, and these cracks will be oriented with respect to the principal stress directions; i.e. most cracks will open up in the direction perpendicular to the maximum *in situ* stress. This is the basis for the anelastic recovery (ASR) technique (e.g. Teufel, 1982), which has proven successful in establishing earth stress directions from core samples rig-site. If the stress situation however at some point exceeds the failure envelope of the formation, the rock may fail macroscopically, often with a disced appearance. The shape of the discs can be related to the *in situ* stress anisotropy (Maury *et al.*, 1982). If the stresses exceed the yield envelope of the formation, permanent mechanical damage will occur, without necessarily causing a visible mechanical damage. This is an important case to consider, because since the core looks intact, it will be taken to the laboratory and used for petrophysical measurements.

Pore pressure release.

In low permeability rocks, the pore pressure is not released immediately after drillout. Rather, the *in situ* pore pressure will be maintained in the interior of the sample, and decreases upon retrieval with a time constant representative for drainage between the outside and inside of the core. The drainage is driven by the difference between the mud pressure and the internal pore pressure, and the mud pressure is decreasing as the core is retrieved from the hole. Since the external stresses are released instantaneously upon drill-out, this implies that tensile failure may occur inside the core as it is lifted up the borehole. The time constant t_p is from poroelastic theory (see e.g. Fjær *et al.*, 1992):

$$t_p \approx \frac{r_c^2}{C_D} \tag{1}$$

where r_c is the radius of the core, and C_D is the diffusion constant, given as

$$C_D \approx \frac{kK_f}{\eta\phi}\left[1+\frac{K_f}{\phi(K_{fr}+\frac{4}{3}G_{fr})}\right]^{-1} \tag{2}$$

Here k is the permeability, η is the pore fluid viscosity, ϕ is the porosity, K_{fr} and G_{fr} are bulk and shear moduli for the rock framework, and K_f is the bulk modulus of the pore fluid. Inserting realistic numbers into Eqs, (1) and (2), one finds that the pore pressure is instantaneously drained unless the permeability is very low. With a 10cm diameter core and water as pore fluid, the time constant is of the order of minutes when the permeability is 10^{-4} - 10^{-5} Darcy, i.e. well below the values found for typical reservoir rocks. With a high viscosity oil, however, such tensile failure may occur in chalk and perhaps in low permeability sandstone. It is however expected to be the most prominent core damage mechanism in shales taken from deep boreholes. Shale permeabilities are in the nanoDarcy range and below, so the pore pressure drainage is extremely slow. Weak shales will therefore always be damaged, which explains e.g. the difficulties in preparing shale samples for testing. Additional damage will occur if the pore fluid contains dissolved gas which will exsolve at some pressure (see Santarelli and Dusseault, 1991).

Temperature release.

The reduction in temperature when taking a specimen from a deep borehole to the surface leads to release of thermal stresses. Macroscopically, this can be handled in the same way as stress release described above, simply adding the thermal stress change as an effective stress change. Microscopically, however, different minerals may have different coefficients of thermal expansion, leading to microcrack formation upon cooling. Furthermore, the pore fluid and the rock framework may also have different thermal expansion coefficients, which in low permeability rocks may lead to damage. Temperature also affects rock-fluid interactions through physico-chemical effects.

Exposure to non-native fluids.

The drilling fluid may alter the formation in many different ways. This is usually considered mainly in connection with formation damage, but the same mechansims are also responsible for core damage. Rocks which are rich in clay minerals are prone to this type of damage (see e.g. Krueger, 1986). If the chemical potential (salinity) of the drilling fluid is different from that of the pore fluid, this may cause alteration by e.g. swelling of clay minerals (in particular montmorillonite) when a clay-rich core is taken to surface. pH differences may in addition alter the surface potentials of different minerals, which may trigger release of weakly bonded minerals (mica, feldspars) from the pore walls. This will have an effect first of all on permeability, but may also affect rock mechanical properties. Clay dehydration may also cause sample damage and fracturing which in many cases may resemble core discing due to stress release.

LABORATORY SIMULATION OF STRESS-RELEASE INDUCED CORE DAMAGE

An experimental study has been performed where the effect of stress release on mechanical and petrophysical properties of weak sandstone has been studied systematically (see also e.g. Holt and Kenter, 1992; Holt *et al.*, 1994). The strategy employed involves the formation of a synthetic sandstone under simulated *in situ* stress conditions. This permits the properties of the material to be assessed while in its virgin state (at stresses equal to or higher than the stress at which diagenesis was completed), as well as following an unloading (simulating the stress release during coring) - reloading cycle. If the synthetic rock can be made with properties resemblant of a given reservoir rock, then this yields a method whereby core damage due to the stress release mechanism can be quantified in a field situation. It also provides a method for systematic studies of core damage effects.

A triaxial apparatus (for further description, see e.g. Holt and Kenter, 1992) has been used for the formation of synthetic sandstone. Sand and sodium silicate solution is mixed and loaded to the required state of stress (normally 15 MPa axial and 7.5 MPa radial stress), where CO_2 gas is injected, causing a rapid cementation by amorphous silicic acid. This permits the formation of a relatively weak sandstone, with controlled stress history, controlled grain size distribution, and to some extent controlled porosity, permeability and mechanical properties. The sample (1 1/2" diameter and 3" length), once formed inside the triaxial cell, is then tested according to stress paths as sketched in Figure 1. Stress path A gives a measurement of virgin rock behaviour, whereas path B simulates unloading by coring, and subsequent reloading to the previous stress state. The unloading in a B-test will normally be done anisotropically ("B1"), i.e. by reducing the axial stress as much as possible before the radial stress is released. In some cases, however, the sample was unloaded isotropically down to zero ("B2"). This represents an "idealized" stress path which can not be achieved in practical coring operations, but which gives a measure of how the rock would behave if as little damage as possible was imposed during coring. The B1 unloading can be performed rapidly (a few seconds; to simulate real coring rates), and slowly (typically half an hour).

During the tests, axial (ε_z) and radial (ε_r) strains are measured, giving a possibility to calculate volumetric strain ($\varepsilon_v = \varepsilon_z + 2\varepsilon_r$). The volumetric strain is linked to the change in porosity during the experiment. If the grains are assumed incompressible compared to

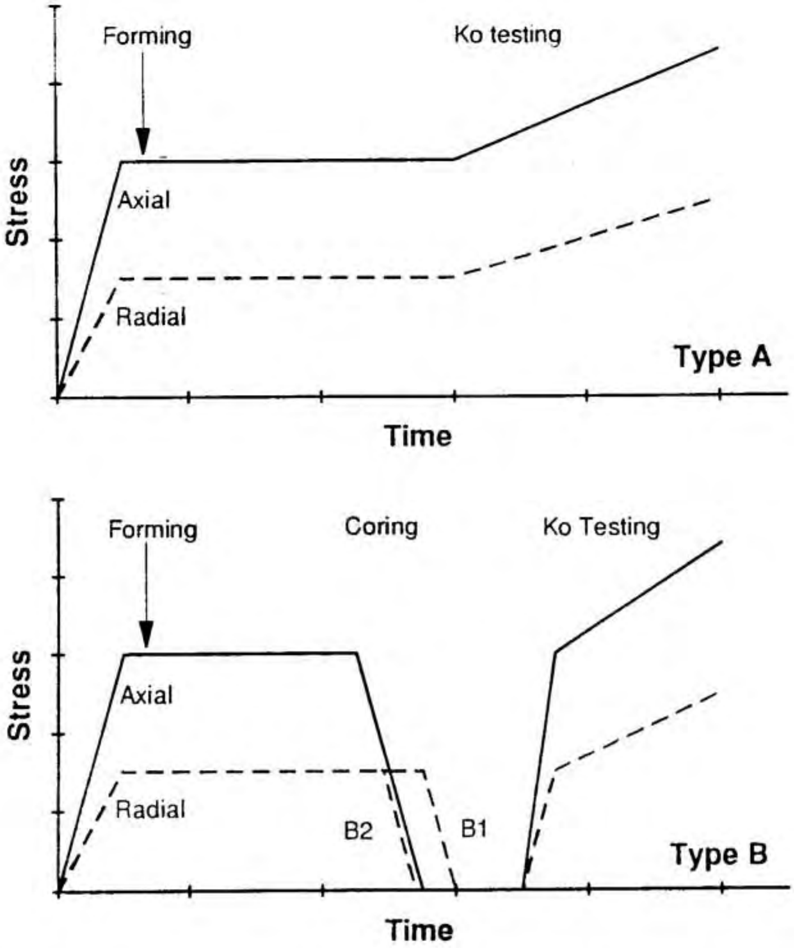


Figure 1: Axial (solid) and radial (broken lines) stresses vs. experiment type in test types A and B. The arrows indicate the onset of cementation. The stress paths used in coring simulation (B1 and B2) are also shown.

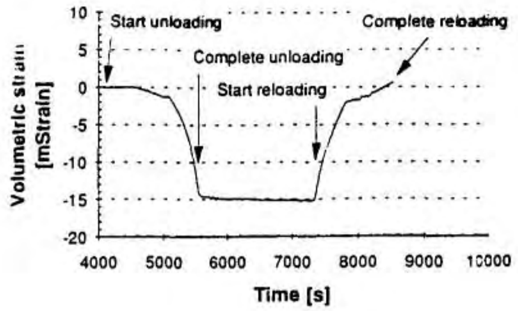
the pore space, then the porosity ϕ at a given stage in the test is related to the initial porosity ϕ_0 and the volumetric strain as follows:

$$\phi = \frac{\phi_0 - \varepsilon_v}{1 - \varepsilon_v} \tag{3}$$

Further, P- and S-wave velocities are measured for propagation along the axis of the sample as well as in a diametrical direction.

Porosity.

Very weak (unconfined strength < 5 MPa) synthetic sandstones have been studied, with a porosity close to 30% at the forming stress conditions. In the case of isotropic (B2) unloading, the volumetric expansion during unloading (~ 15 milliStrain, or 1 % unit porosity <u>increase</u>) is almost compensated by the volumetric contraction upon reloading. For the anisotropically unloaded (B1) specimens, however, the volumetric expansion during unloading is much smaller (7 milliStrain for the slow and 0 for the rapid unloading). This is examplified in Figure 2. The main cause of this is that the sample contracts strongly (and way beyond the limits of elastic behaviour) in the radial direction once the vertical stress is reduced below the value of the horizontal stress.



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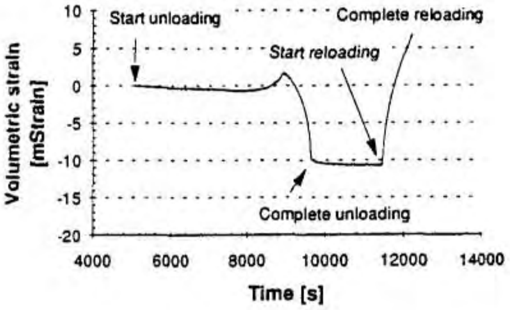

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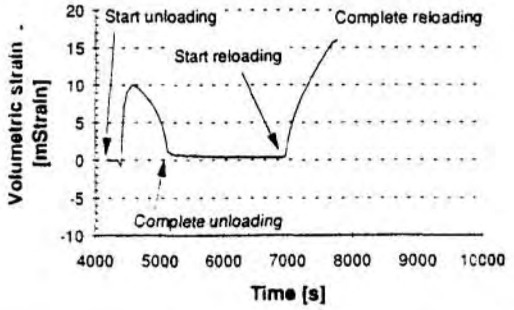

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Figure 2: Volumetric strain vs. experiment time during an unloading - reloading cycle for three different unloading paths.

The microscopic explanation must be that grain bonds are broken and grains are squeezed into new positions, once the axial stress becomes smaller than the radial stress. This effect is prominent in all weak materials tested. Since the strain during reloading is approximately the same, independent on unloading path, the anisotropically unloaded specimens will always have permanently reduced porosities (0.5 - 1 % units) after a full unloading - reloading cycle. In more competent, lower porosity rocks, one would not expect grain bonds to break to the same extent. Rather, one expects that microcracks (at grain bonds, normally) open up, and lead to a more dilatant behaviour. As a result of this, a strong core would probably have a slight positive bias in porosity estimates.

Permeability.

Permeability was so far not measured in these tests. In previous experiments with a natural sandstone (Holt, 1990), the change in permeability was seen to follow the porosity (volumetric strain) change quite close to a Kozeny-Carman relationship:

$$k = \frac{\phi^3}{5k_0 T^2 S_v^2 (1-\phi)^2} \qquad (4)$$

Here k_0 is a grain shape factor, T is the tortuosity, and S_V is the specific surface area. T is itself a function of porosity. If the porosity effect described above amounts to a permanent porosity reduction of 1 % unit, the associated permanent permeability reduction will be between 10 and 15%. If the microscopic failure involves changes in grain structure so that the specific surface area is increased, then the permeability effect should be even larger. Notice that this is valid for a weak sandstone. In a competent material, where the porosity change is dominated by cracks, the permeability effects are expected to be small.

Acoustic Velocities.

Figure 3 shows the vertical and horizontal P-wave velocities as well as the velocity of the vertically propagating S-wave as function of experiment time throughout a B-type test with a weak synthetic sandstone. The main features illustrated here are common for all synthetic rocks tested.

The velocities decrease dramatically during unloading (30 - 50% or more), and the velocity decrease largely reflects the anisotropy of the stress state. In the case shown, the signal amplitudes become too small to be detected (due to increased acoustic attenuation) near complete unloading. In cases where signals can be detected after complete unloading, it was observed that the vertical P-wave velocity was still smaller than the horizontal, even when an isotropic ("zero") stress state was reached. The permanent velocity anisotropy is thus a measure of the *in situ* stress state, but also a sign of core damage. This anisotropy is not only reflected in the ratio between the two P-wave velocities, but will be detectable through the v_P/v_S ratios as well.

When reloading back to the previous stress level, the velocities do not recover their previous values. The amount of permanent velocity reduction is typically 5 - 15% in weak sandstone. In a more competent sandstone the permanent velocity reduction may be larger, because of less grain reorganization and a more pure microcrack mechanism. The velocity reductions are roughly the same for all modes. They are larger for B1 than for B2 unloading paths, but do not seem to be particularly sensitive to the rate of unloading.

The wave velocities are strongly stress dependent when reloading after a coring simulation. When loading past the previous stress state in e.g. a uniaxial compaction test, or during continued cyclic loading, the unloaded and reloaded rock will still show a significant stress dependence in its velocities, whereas the rock representing the "virgin" reservoir, shows much less stress dependence.

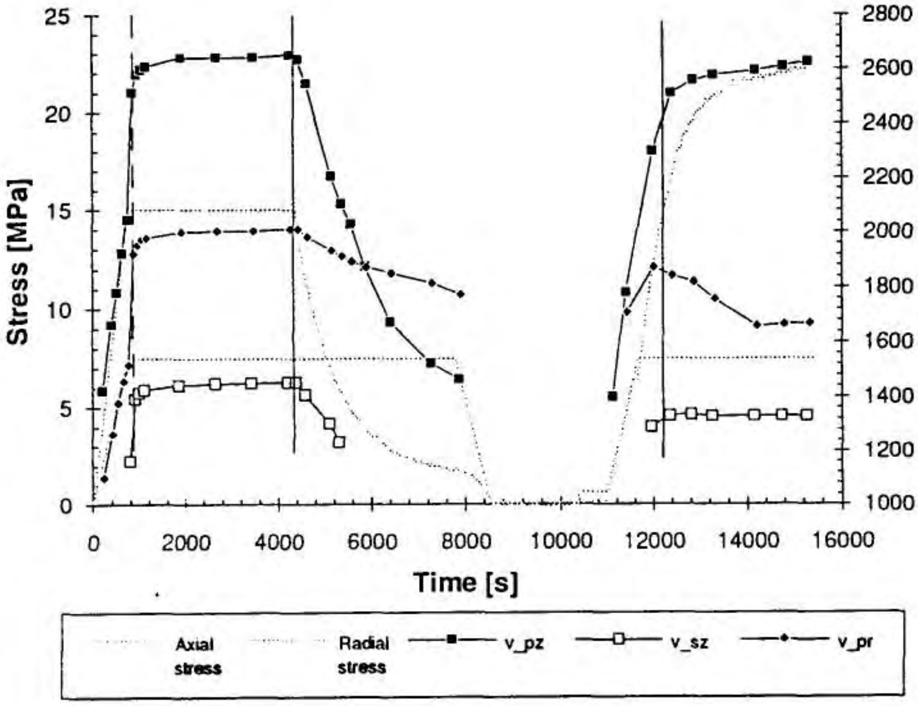

Figure 3: Acoustic velocities vs. experiment time during a B1s test. The dimmed curves are the axial and radial stresses. The vertical solid lines indicate the start of unloading and completed reloading. The dashed line marks the onset of cementation.

Compaction Behaviour.

A main aim of these experiments has been to study possible coring effects on compaction behaviour, so that uncertainties in reservoir compaction and surface subsidence predictions can be minimized. This is evaluated by comparing the uniaxial (zero lateral strain) compaction behaviour in an A test (starting from the formation stress) and in a B test (after reloading to the same formation stress). These experiments are presented in much more detail in Holt et al. (1994). The main finding is that the unloaded - reloaded ("cored") rock is (50 - 100%) softer than the virgin "reservoir" formation during initial loading. Thus, core data would from this tend to overestimate reservoir compaction in weak sandstone. However, by continuing to increase the effective stress on the sample (continued depletion in the field), the static stiffness becomes more equal to that of the virgin formation. In a competent sandstone, the effects may be similar, because the reduction in static compaction modulus is related both to grain bonds breaking and to opening of dilatant microcracks.

DISCUSSION

The experiments above provide a method whereby core damage effects on petrophysical parameters may be quantified. In principle, this method can be extended also to include studies of pore pressure and temperature effects, although new methods for manufacturing synthtetic rocks would have to be developed for that purpose. The use of synthetics is of course valuable only if the synthetics behave in the same manner as real rocks. Clearly, the formation procedure is different from a true diagenesis. The judging factor needs to be, however, the extent to which the synthetic cores behave - mechanically and petrophysically - similar to the real target cores. This was checked for the synthetic rocks manufactured in this study, and with good results.

Stress - release induced damage will affect weak and competent rocks differently. If the rock is sufficiently weak to suffer from grain bond breakage during coring, then permanent porosity reduction may occur. This is expected in several of the weak North Sea reservoir sandstones, and one may foresee a similar effect in chalk. For more competent rock a microcrack driven mechanism takes over, but for many materials the two mechanisms are likely to interplay. The apparent contradiction in the data presented here that porosity and sound velocity both decrease as a result of an unloading - reloading cycle is an example of that: The cracks formed during unloading have a dominant effect on sound velocities, while they mean little porosity wise. The grain reorganization clearly affects porosity, but porosity affects sound velocities less than cracks. The same holds for the compaction behaviour: In a sandstone, this is more sensitive to cracks (in particular sliding cracks, which can be activited through dilatant cracks opened during unloading) than to porosity.

The permanent reduction in porosity implies a bias in core derived porosity estimates, even in cases where the *in situ* stress is perfectly reinstalled, amounting to 0.5 - 1 % units in very weak, high porosity sandstones. This means that reserve volumes may be underestimated, and is of particular concern in marginal fields. The permanent reduction in sound velocities is another measure of core damage. It is important, because it can in principle be obtained by comparing log data and core data, using the real cores. In this way, core damage in the field may be assessed quantitatively. The observed stress dependence in sound velocities of a real core is most likely a result of the coring process.

CONCLUSIONS

Core damage may occur by different mechanisms, like external stress release, pore pressure release (only important in very low permeability rocks), temperature release and exposure to non-native fluids. Use of synthetic rocks formed under stress has been introduced as a method to quantify stress release induced core damage effects on mechanical and petrophysical properties. For weak high porosity sandstones, porosity is permanently reduced as a result of an unloading (simulated coring) - reloading cycle. This represents a bias in core derived porosity estimates. Sound velocities are also permanently reduced after such a cycle. Static compaction stiffness is permanently reduced at low stress levels above the simulated *in situ* level.

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REFERENCES

Dyke, C.G. (1989): Core discing: Its potential as an indicator of principal in situ stress directions. In V.Maury & D.Formaintraux (eds.) *"Rock at Great Depth"*, A.A.Balkema, pp.1057-64.

Fjær, E., Holt, R.M., Horsrud, P., Raaen, A.M., and Risnes, R., (1992): *"Petroleum Related Rock Mechanics"*, Elsevier; 338pp.

Holt, R.M. (1990): Permeability reduction induced by a non-hydrostatic stress field. SPE Formation Evaluation **5**, 444-48.

Holt, R.M. and Kenter, C.J. (1992): Laboratory simulation of core damage induced by stress release. In J.R.Tillerson and W.R.Waversik (eds.) *Proc. 33rd US Rock Mechanics Symposium*, pp. 959-68.

Holt, R.M., Brignoli, M., Fjær, E., Kenter, C.J., and Unander, T.E. (1994): Core damage effects on compaction behaviour. SPE/ISRM Paper 28027, pres. at *EUROCK'94*, Delft, Netherlands 29-31 August.

Krueger, R.F. (1986): An overview of formation damage and well productivity in oilfield operations. Journal of Petroleum Technology, Febr. 1986; pp.131-52.

Maury, V., Santarelli, F.J., and Henry, J.P. (1988): Core discing: A revies. In *Proc. SANGORM Symp. Rock Mechanics in Africa*, pp. 221-31.

Santarelli, F.J. and Dusseault, M.B. (1991): Core quality control in petroleum engineering. In J.C.Roegiers (ed.) *"Rock Mechanics as a Multidisciplinary Science"*, A.A.Balkema, pp. 111-20.

Teufel, L.W. (1982): Determination of in situ stress from anelastic strain recovery measurements of oriented cores. In Proc. 25th US Rock Mecanics Symposium.