IN SITU POROSITY FROM CORES: THE ROCK MECHANICS APPROACH TO OVERBURDEN CORRECTION

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ABSTRACT

Improved reliability of porosity derived from core measurements leads to improved reliability of reserve estimates. This work presents a method to derive *in situ* porosity from core measurements by performing an appropriate *in situ* stress (so-called overburden) correction. The method is based on the fundamentals of poroelasticity, and builds on controlled laboratory and numerical simulations which show that the porosity correction can be obtained by loading isotropically to the *in situ* mean effective stress (effective stress = total stress - pore pressure). This is further justified by a set of tests on field sandstone cores, where different stress paths were employed.

INTRODUCTION

Assessing *in situ* porosity as correctly as possible is a key issue in estimating reserve volumes. Consider for example a 300 m thick reservoir of areal extent 10 km^2. The average porosity of the reservoir rock is estimated to be 15 %. An uncertainty of 0.1 p.u. in this estimate corresponds to a pore volume of $0.45 \cdot 10^6$ m^3. The impact on reserve booking or field development can be considerable. In economic terms it may represent a few 10's M$.

Porosity is normally measured in petrophysical laboratories at ambient conditions, and then corrected for overburden by a few screening tests under hydrostatic stress. Normally, no pore pressure is applied in these screening tests, and the external stress is increased to the value of the effective overburden stress. The change in pore volume is measured by expelled fluid volume, and the resulting pore strain is corrected to account for the fact that the *in situ* stress state is not isotropic. The way this correction is done may vary between and within the practices of each company. Currently applied overburden correction routines do not however have a profound scientific basis.

Following Juhasz (1986) and Nieto *et al.* (1994)

$$j_{corr} = \frac{1 - s\frac{\Delta V_p}{V_p}}{\frac{1}{j_{atm}} - s\frac{\Delta V_p}{V_p}} \quad (1)$$

Here j_{corr} is the overburden corrected porosity, and j_{atm} is the porosity at ambient (atmospheric) conditions. The correction factor s is by Juhasz (1986) set to 0.62, while

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Nieto *et al.* (1994) correctly point out that this factor instead should be based on the actual stress state. We will return to this discussion in the next Section.
Overburden corrections typically fall in the range 0.5 to 1 p.u.; depending on the initial porosity and on the stress state. Considering that the experimental uncertainty in core as well as log derived porosity typically amounts to 0.5 - 1 p.u., one may first think that there is no point improving the overburden correction by 0.1-0.2 p.u. or so. On the other hand, since an erroneous overburden correction represents a *systematic* rather than a random error, it still has an impact on reserve estimates and equity discussions.

The main objective of this work is to improve the reliability of *in situ* porosity estimation from cores. This is done by establishing new correction procedures, including improved test technology, and better procedures for interpretation of old test data.

POROSITY CHANGES FROM LINEAR POROELASTICITY

In this Section, we will describe how porosity, based on linear poroelastic theory, changes with stress and pore pressure. We will use this to correct core-based porosity data to *in situ* conditions. Porosity is defined as the ratio of pore volume to total volume, i.e.,

$$j = \frac{V_p}{V} \qquad (2)$$

Porosity change associated with a stress change can be expressed in terms of pore and bulk strains by simple differentiation of Eq. (2):

$$\frac{\Delta j}{j} = \frac{\Delta V_p}{V_p} - \frac{\Delta V}{V} \qquad (3)$$

The reduction Dj in porosity as result of compaction is kept as a positive number, as is volumetric (pore and bulk) strains in compaction. If a drained experiment is done; i.e., external loading at constant pore pressure, then rock particles reduce in volume as a result of the increased interparticle forces and from basic Biot poroelasticity (see Biot, 1962; or e.g. Fjær *et al*, 1992),

$$\frac{\Delta V_p}{V_p} = \frac{a}{j}\frac{\Delta V}{V} \qquad (4)$$

where a is Biot's poroelastic coefficient. Inserted in Eq. (3) this yields

$$\frac{\Delta j}{j} = (1 - \frac{j}{a})\frac{\Delta V_p}{V_p}$$
$$or \qquad (5)$$
$$\frac{\Delta j}{j} = (\frac{a}{j} - 1)\frac{\Delta V}{V}$$

Thus, the porosity change as a result of external drained loading can be measured directly if both expelled pore fluid *and* bulk volume changes are recorded (according to (3)), and may be estimated from either pore volume change or bulk strain measurements

using Eq. (5), provided Biot's poroelastic coefficient a is known. This is often not the case, and a is then assumed = 1.
Let j_0 be the initial porosity. Then the final porosity j is derived from Eq. (5); here for the case when only pore volume changes are measured:

$$j = \frac{1-\frac{\Delta V_p}{V_p}}{\frac{1}{j_0}-\frac{1}{a}\frac{\Delta V_p}{V_p}} \cong j_0\left(1-(1-\frac{j_0}{a})\frac{\Delta V_p}{V_p}\right) \qquad (6)$$

The latter two expressions are equal within the limits of elastic theory (small strain). Notice the resemblance between Eq. (6) and Eq. (1): Eq. (6) does not, however, contain the correction factor *s*, since it is derived for a hydrostatic stress situation; but it does contain the Biot a which is taken = 1 in the standard approach. Eq.(6) holds for a drained, hydrostatic stress path typical for laboratory screening tests (as mentioned in the Introduction).

If we evaluate the situation when both external stress and pore pressure changes, as they do during coring, then the porosity change is given as

$$\frac{\Delta j}{j} = (\frac{a}{j}-1)\frac{1}{K_{fr}}(\Delta s - \Delta p_f) \qquad (7)$$

K_{fr} is the drained bulk ("framework") modulus of the rock. We notice that the effective stress governing the porosity change is different from the effective stress controlling volumetric strain, since it is merely the difference between the external stress and the pore pressure. Berryman (1992) pointed out that this does not hold if the solid rock matrix is heterogeneous, but it is a direct consequence of Biot poroelasticity for a homogeneous matrix. Notice also that particle stiffness will generally will not be the same for pore pressure change as for external stress change (Verruijt, 1982), for instance if interparticle forces lead to plastic deformation at the grain contacts (will reduce a), or to dilatant behaviour (will increase a).

We have so far neglected the fact that Earth stresses are anisotropic. We may however continue to discard that, by assuming that the rock is (isotropic and) elastic. Then, the volumetric deformation of bulk and of pore space depends only on the mean stress. This follows directly from Hooke's law and is a basic feature of linear elasticity. Thus, the porosity change during coring can be estimated by calculating the mean effective stress change (where effective stress refers to the stress minus pore pressure difference in Eq. (7)). The overburden corrected porosity needs to be evaluated by reloading the core to the effective mean *in situ* stress; i.e.

$$\overline{s'} = \frac{s'_h + s'_H + s'_v}{3} \qquad (8)$$

This illustrates the importance of knowing the *in-situ* stress state in order to perform an appropriate porosity correction. In Juhasz (1986), following Teeuw (1971), it was assumed that the *in situ* stress state is given by .

$$s_h^{'} = s_H^{'} = \frac{n}{1-n} s_v^{'} \qquad (9)$$

where n is Poisson's ratio. This yields for the correction factor

$$s = \frac{\overline{s'}}{s_v^{'}} = \frac{1+n}{3(1-n)} \qquad (10)$$

In the case n = 0.30, then *s*=0.62. In reality this factor is not related to the Poisson's ratio of the present rock, but to the mean *in situ* effective stress. Furthermore, Juhasz (1986) applied it as a correction factor to the pore volume (Eq(1)), whereas it would be equally appropriate in the case of linear elasticity, and *more* aprropriate for nonlinear elasticity to apply the correction factor directly to the applied hydrostatic stress.

We need here to remind ourselves that we have assumed linear poroelasticity. This leads directly to the porosity correction as in Eq. (6). It furthermore leads to the effective stress principle in Eq. (7), and to the conclusion that a hydrostatic stress path may be used to measure the porosity correction. We will now, first through a set of controlled experiments with synthetic rocks, and later with field cores, evaluate the validity of these assumptions and the conclusions drawn from them.

PHYSICAL AND NUMERICAL SIMULATIONS OF CORING AND CORE RELOADING

Extensive experimental work has been performed in the Formation Physics Laboratory of SINTEF Petroleum Research, forming synthetic sandstones under applied stress. This mimics the formation of a rock in the Earth, and the experiments further may simulate effects of stress changes during depletion or during coring and subsequent core testing. The work was done mainly to quantify core damage effects on compaction behaviour, but shows also core damage effects on other petrophysical quantities such as wave velocities and porosity (Holt, 1994; Holt, 1999; Holt *et al.*, 2000). Here we will present some of these data, showing stress - strain behaviour during coring simulation, as well as during core reloading.

Synthetic sandstone is manufactured by mixing sand with sodium silicate solution. After loading to a desired anisotropic stress state, representing the *in situ* effective stress, CO_2 gas is flushed through the sand plug, leading to precipitation of amorphous silica as a cementing agent. After a stabilization period, the synthetic sandstone is unloaded from its virgin stress state in a way that mimics the stress release occurring during drillout of a vertical core: First, the vertical stress is reduced as far as possible (simulating the approach of the core bit from above), and then the horizontal stress is removed (simulating the entry of the core into the coring bit area). After a relaxation period, the core is reloaded, using different stress paths. Figure 1 outlines an experiment where core reloading is done by increasing the stresses anisotropically, with perfect reinstallation of the forming ("*in situ*") stress. Tests were also performed where the reloading was done hydrostatically.

Competent (10 MPa unconfined strength; 20 % porosity) as well as very weak (2-5 MPa unconfined strength; 30 % porosity) synthetic sandstones were made. In Figure 2 we show the recorded volumetric strain as a function of mean stress during coring simulation and subsequent anisotropic and isotropic reloading for 2 cores of the competent sandstone. This rock was formed at 30 MPa axial and 15 MPa confining stress; i.e. under a mean "*in situ*" stress of 20 MPa. The data demonstrate significant nonlinear behaviour, both during coring simulation, and during core reloading. The mean stress vs. volumetric strain behaviour is however largely independent of the stress path. After reinstallation of the mean "*in situ*" stress, the sample volume is between 0 and 1 milliStrain smaller than it was prior to coring. This means that there is negligible core damage effect on porosity in this material.

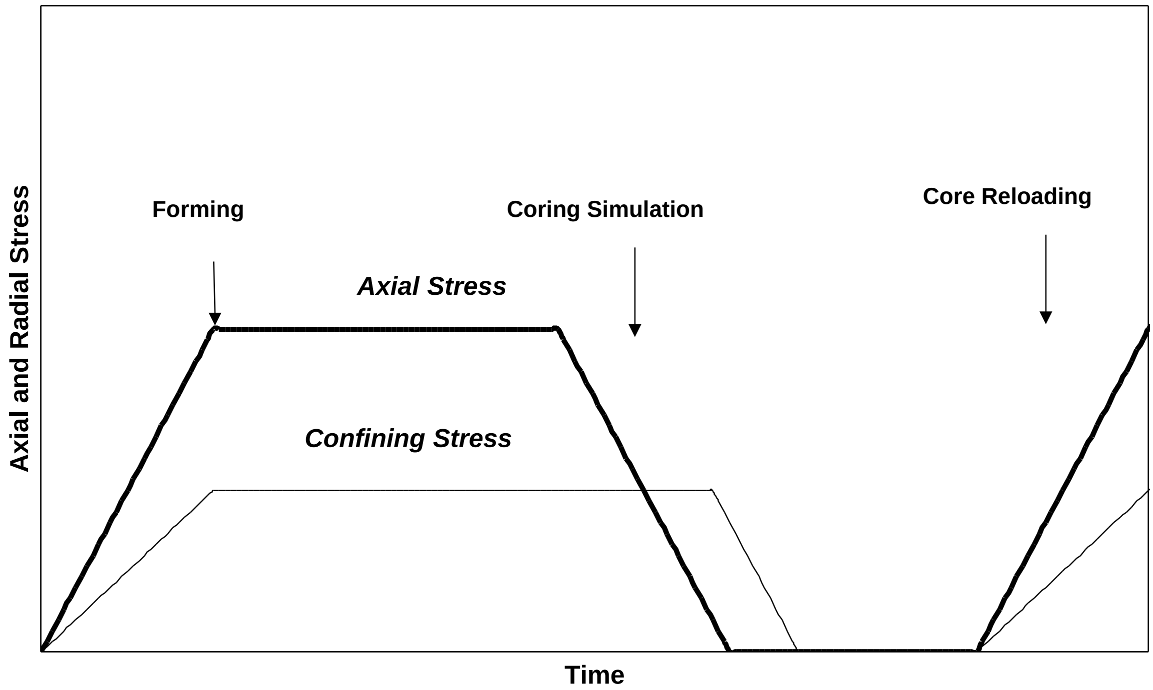

Figure 1: Sketch of stresses during experiment with forming, simulated coring, and subsequent anisotropic reloading of a synthetic sandstone.

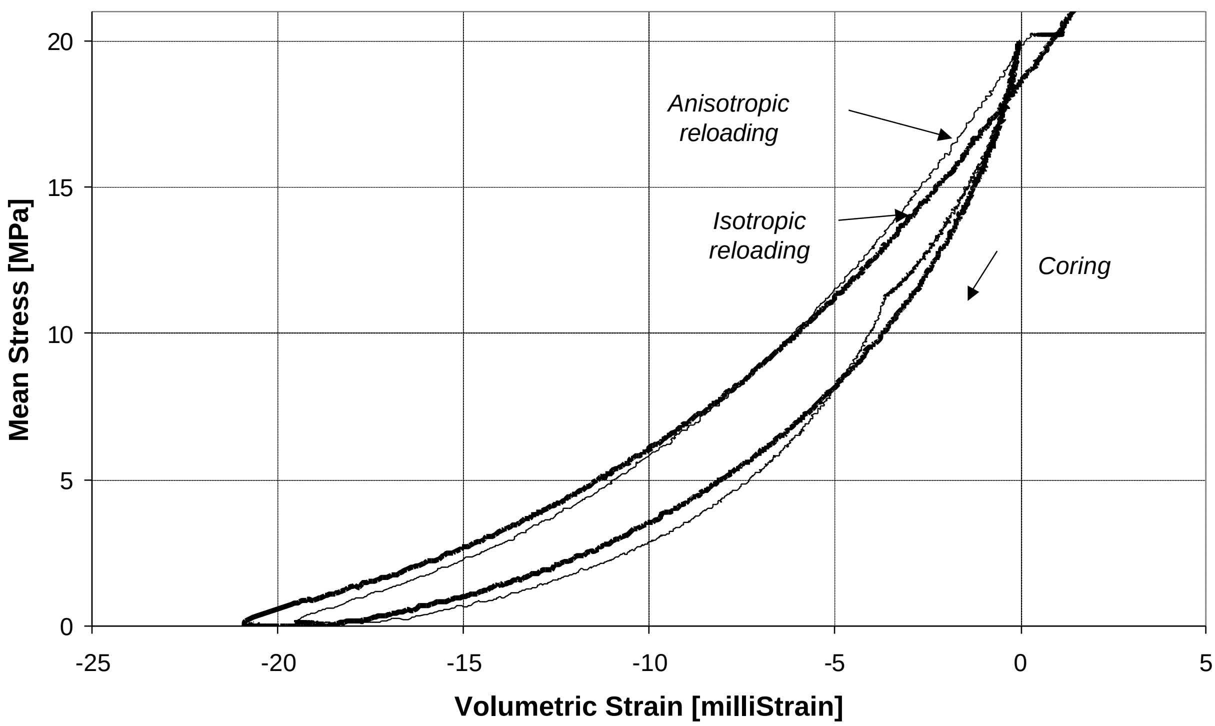

Figure 2: Mean stress vs. volumetric strain for a coring simulation + core reloading test with competent synthetic sandstone. The core reloading was in one case done along an anisotropic stress path (as shown in Figure 1), and in the other case along an isotropic stress path.

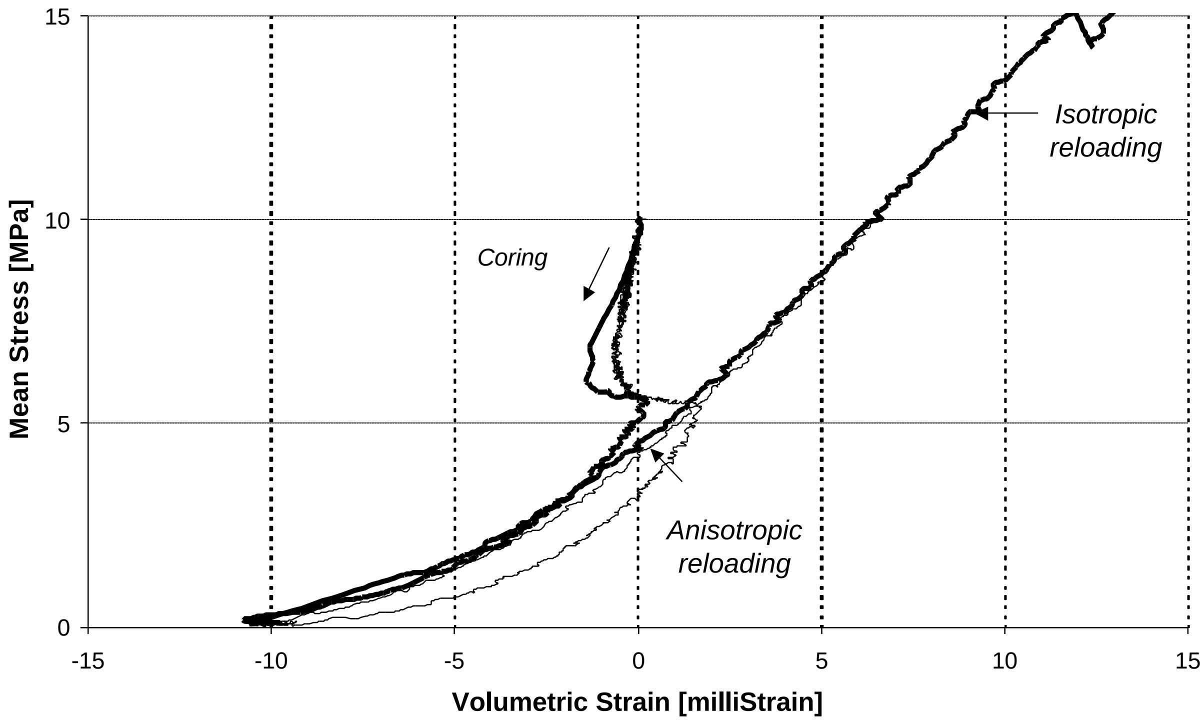

Figure 3: Mean stress vs. volumetric strain for 2 coring simulation + core reloading tests with weak synthetic sandstone. The core reloading was in one case done along an anisotropic stress path (as shown in Figure 1), and in the other case along an isotropic stress path.

Figure 3 shows the mean stress vs. volumetric strain response, for two different reloading paths, in a weak synthetic core. The forming stress was 15 MPa (axial) and 7.5 MPa (confining); i.e. the mean "*in situ*" stress was 10 MPa. When coring starts, the samples first expand slightly (negative volumetric strain), but then compact by a few milliStrains. This compaction during unloading is a result of high confining and very low axial stress, and is an inverse phenomenon to dilatancy in triaxial loading, indicating creation of damage in the material. Physically it means that the pore structure is altered by grain rearrangement. When the confining stress is removed at last, the sample again expands. In this case, the net expansion of both cores was 11 milliStrain.
During core reloading, we notice that:

i) The stress - strain behaviour is non-linear.
ii) The volumetric strains are stress path independent when plotted against mean stress.
iii) When reaching the "*in situ*" mean stress, both samples have permanently reduced their volumes by approximately 7 milliStrain.

These observations clearly violate some of the basic assumptions made in the end of the preceding Section. Nonlinearity and large strains are observed, as is also the case for competent synthetic sandstone. In this case (weak, high porosity sandstone), the porosity determined after reloading is permanently reduced (here by approximately 0.5 p.u.); i.e., there is a core damage effect on porosity that was not observed in the competent sandstone. Stress path insensitivity of volumetric strains is however still observed.

To further test if the observations made from the synthetic rock experiments are valid, numerical simulations were performed with a discrete particle model (PFC^{3D} - Particle Flow Code; developed by Itasca Consulting Group in Minneapolis, USA). The basic principles of such modelling are given by Cundall & Strack (1979). A sample consisting of 4025 spherical particles (5x2.5x2.5mm) was generated with particle size distribution and porosity similar to the competent synthetic sandstone studied experimentally. Once the unbonded particle assembly was loaded to the "*in situ"* stress (here: 30 MPa vertical; 20 and 15 MPa horizontal; giving a mean stress of 21.7 MPa), the particles were cemented to each other through installation of so-called parallel bonds, defining bond shear and tensile strengths, plus bond shear and normal stiffnesses. From that stage on, coring simulation and core reloading were performed exactly as in the laboratory tests. Figure 4 shows the simulated stress - strain curves during unloading + reloading for 2 different reloading stress paths. Again, nonlinear but stress path independent behaviour is seen, and as for the competent synthetic sandstones tested in the laboratory, no core damage effect on porosity was observed. Interestingly; PFC^{3D} simulations with weaker and more porous particle aggregates did show permanent porosity reduction as a result of core damage; just like the laboratory tests.

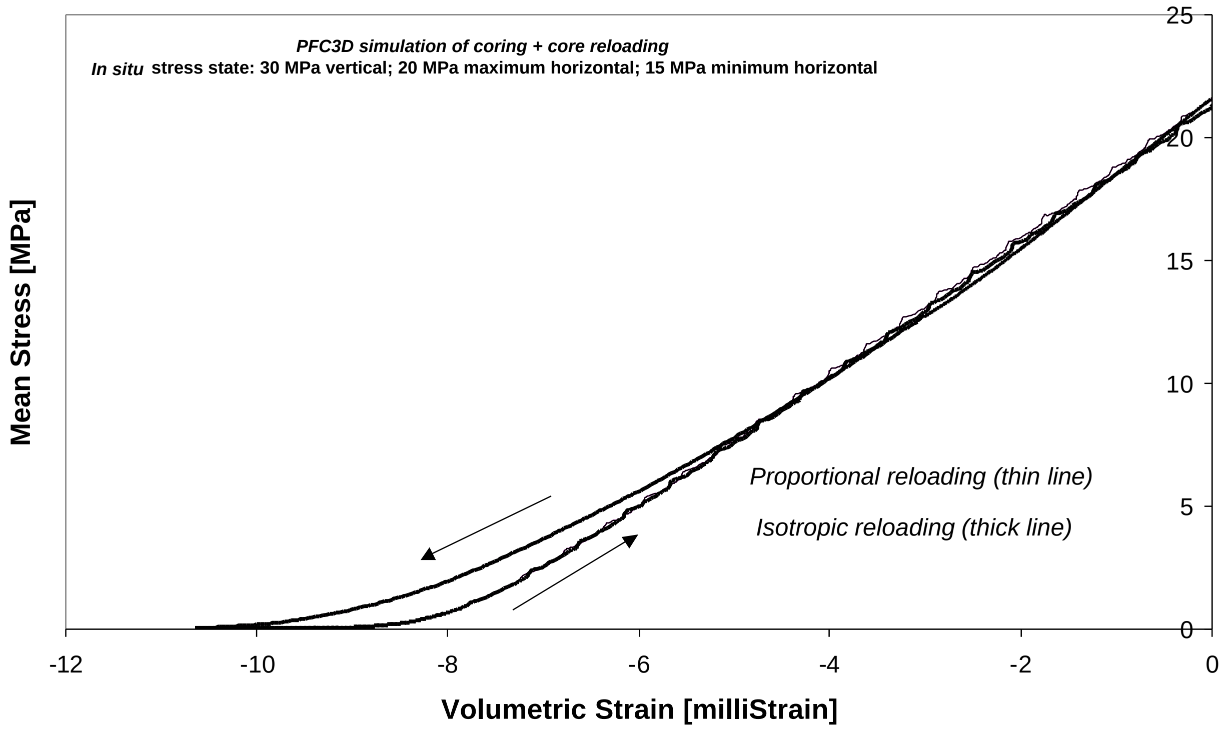

Figure 4: Mean stress vs. volumetric strain for a coring simulation (downwards arrow) + core reloading (upwards arrow) performed with a discrete particle model (PFC^{3D}), mimicing competent synthetic sandstone. Core reloading was done along an anisotropic (as shown in Figure 1) as well as an isotropic stress path. The measured curves are practically identical, during unloading as well as reloading, and are therefore not easily distinguished in the Figure.

In conclusion, the findings from the controlled laboratory and numerical experiments indicate that for reasonably competent sandstones with porosities below 20 - 30%, *in situ* porosity may be estimated by loading the core isotropically to the mean (effective) *in situ* stress. For high porosity, weak rock cores, a permanently reduced porosity may be expected as a result of core damage.

EXPERIMENTS WITH FIELD SANDSTONE CORES

A triplet of sandstone cores from a well in The Netherlands was selected for experimental work at SEPTAR's compaction laboratory in Rijswijk. The main purpose of these experiments has been to see if the stress path insensitivity of volumetric strain vs. mean effective stress holds for real core material. The experimental set-up permits simultaneous bulk volume and pore volume measurements throughout the test. By measuring the volume of fluid required to saturate the sample, an estimate of the initial porosity can be obtained with the core inside the cell, reducing uncertainties relating to the handling and mounting of the core.

By visual inspection, the core plugs were found to be heterogeneous, with coarse-grained highly porous layers in between a matrix of fine-grained lower porosity material. The measured porosity at ambient conditions was 13.2% as an average, and the cores may be regarded as competent sandstone. The mean effective *in situ* stress was estimated to be 25.5 MPa. Because of the heterogeneity, this is not an ideal core for checking the overburden correction procedure. On the other hand, if the basic principles also are found valid for this material, then there is good reason to expect that they are also valid in less complex cores.

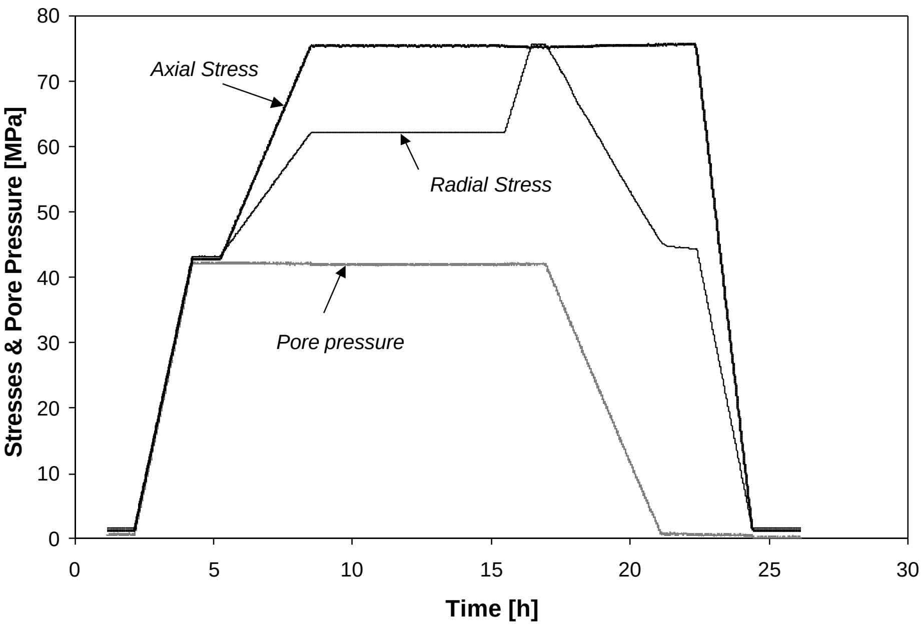

Figure 5: Axial & confining (radial) stress, and pore pressure during Test # 1B with field sandstone core.

The cores (75 mm long; 37.7 mm in diameter) were placed inside the triaxial cell and saturated with brine. The initial porosity was estimated from the injected brine volume at 1 MPa effective confinement (0.5 MPa pore pressure). After equilibration, the pore pressure was increased to the *in situ* level (42 MPa), with the axial and radial stresses equal so that the effective stress was constant = 1 MPa. After a 1-hour creep period at this stress level, drained loading tests (keeping the *in situ* pore pressure) were performed along 3 different stress paths: Isotropic (Test # 1A) until the axial and confining stresses are equal to the *in situ* vertical stress (76 MPa); proportional (Test # 1B) until the assumed *in situ* stress is reached (using $(\sigma_H + \sigma_h)/2$ for the confining pressure), and uniaxial strain (K_0) (Test # 1C) until the vertical *in situ* stress is reached. The only difference between the tests was the development of confining (radial) stress. In the K_0 test this was very low, reaching merely 46 MPa at the end of loading. In the proportional test, it reached 62.2 MPa. Figure 5 shows how stresses and pore pressure are applied throughout the test # 1B (anisotropic core loading). After the drained loading, the samples were left for a period of 7 hours to check for creep. Then the pore pressure was depleted. Finally the confining stress was removed and the samples were taken out.

Figure 6 shows the bulk volumetric and the pore strains in the three tests, plotted vs. mean effective stress. Although slight differences are seen, one may, considering the heterogeneous nature of this rock, conclude that the results do not depend strongly on stress path. Notice also that the creep strains are quite small, in contrast to what was observed by Nieto *et al.* (1994) with somewhat higher porosity sandstones.

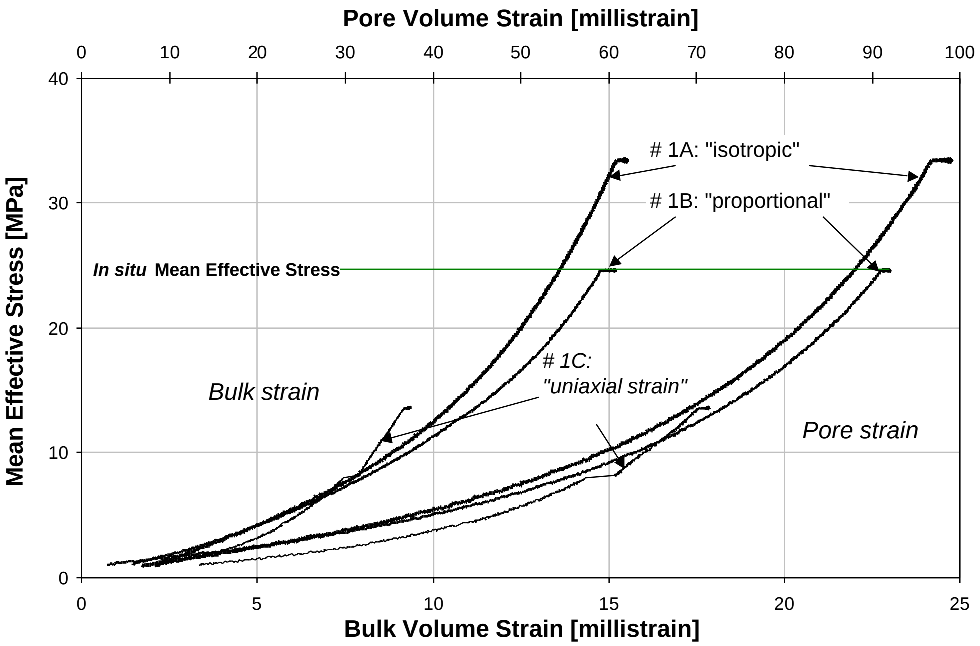

Figure 6: Pore and bulk volumetric strains vs. mean effective stress for the 3 tests performed with field sandstone cores. The data shown are from the drained loading and subsequent (7 h) creep period.

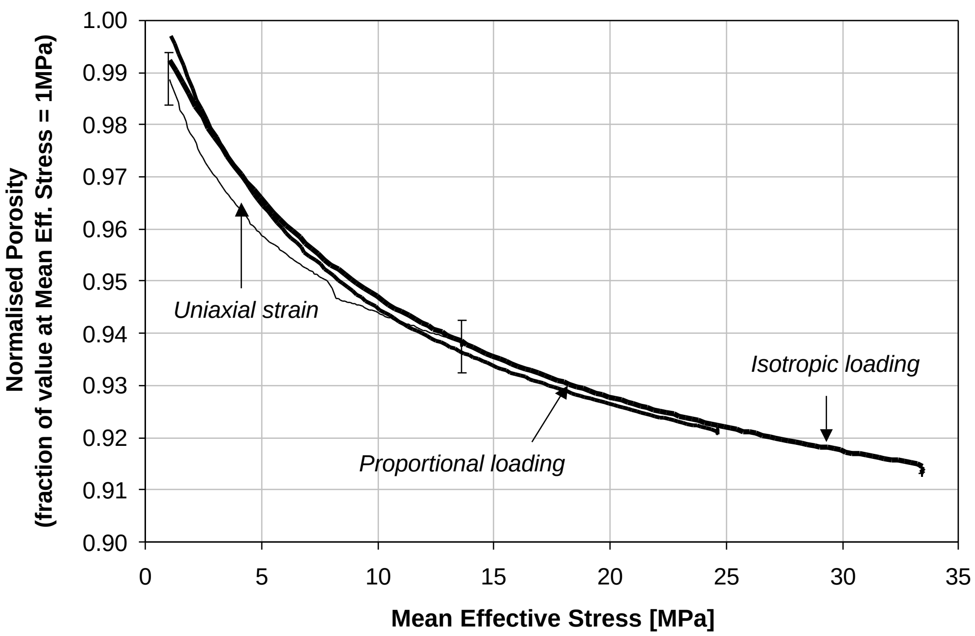

Figure 7: Porosity correction factor vs. mean effective stress for the 3 different stress paths employed. Porosity values are normalised with respect to measurements at 1.5 MPa confining and 0.5 MPa pore pressure.

In Figure 7, the relative porosity reduction is shown, computed directly from the observed strains, i.e.,

$$\frac{\varphi_{corr}}{\varphi_0} = \frac{1-\dfrac{\Delta V_p}{V_p}}{1-\dfrac{\Delta V}{V}} \tag{11}$$

The stress path insensitivity is nicely demonstrated. We may thus conclude from these experiments that isotropic loading to mean effective *in-situ* stress seems to be sufficient in order to establish the overburden correction factor. Here, the reduction factor at the mean effective *in situ* stress was 0.922; implying an *in situ* porosity of 12.2 %.

DISCUSSION

The estimated porosity reduction factor depends on the mean effective *in situ* stress. An error of ± 5 MPa in the stress state, would lead to (from Figure 7) an error of ± 0.005 in the correction factor, or ± 0.07 p.u. This may appear as an insignificant correction, but, as mentioned in the Introduction, it may represent significant reserves, and it is a systematic error. This points to the necessity of determining *in situ* stress as accurately as possible.

If an industry standard routine, such as described by Eq. (1) was used; the porosity correction factor would be 0.946. This indicates that the reserve estimate based on the standard method is too optimistic. This is largely because in this case the *ad hoc* stress correction factor s=0.62 is too low compared with the true stress correction factor; $s = \overline{\sigma'}/\sigma'_v$ =0.76. If the correction factor 0.62 was applied to the stress instead of the strain, then a porosity correction factor would be 0.927. This is closer to the best estimate (0.922) from the method introduced here. For this particular case, and in many cases of passive compressional basins, s is likely to be larger than 0.62. In extensional regimes, however, s could be smaller, leading to larger reserves than estimated with a conventional approach.

Core analysis laboratories most often do not perform both bulk and pore strain measurements. If only one of the two strain parameters is recorded, then the resulting correction depends on the Biot coefficient α (see Eqs. (5)). The pore strain based estimate is then more reliable, because it is less sensitive to α than the bulk strain based estimate.

An interesting side result of our laboratory tests presented above was that they permitted (through Eq. (4), assuming piecewise linear elasticity) estimation of α vs. applied stress. We found that the Biot coefficient decreased with increasing stress and reached a value of ~ 0.7 at high stress. Notice that these tests were done at constant pore pressure and changing external load. Therefore the Biot α measured here is representative for a more irregular, sometimes dilatant volume change of particles resulting from increase of interparticle forces rather than a more regular volume change resulting from change of pore pressure. In practice, the Biot constant should be measured under field representative conditions, e.g. in compaction analysis it should be measured during pore pressure depletion.

CONCLUSIONS AND GUIDELINES FOR PRACTICAL USE

The scientific results obtained in this work can be summarised as follows:

From poroelastic theory it is seen that porosity (for rocks with a homogeneous framework) depends on an effective stress that is equal to total stress minus pore pressure and is not dependent on Biot α. The applicability of linear poroelasticity is however limited, as the stress - strain behaviour of a core is always non-linear. Using synthetic sandstones manufactured under stress, the stress release during coring, and the subsequent reloading of the core in a laboratory test, could be simulated. Similar studies were also performed numerically, using a discrete particle model. In the case of very high porosity sandstone, the stress release during coring is likely to introduce a permanent core damage, which then may yield a significant permanent porosity reduction in the reloaded core compared to the same material *in situ*. In lower porosity (say below 25 %) cores, such core damage effects appear to be insignificant. Both the experimental and the numerical (discrete particle) approach demonstrated that the porosity change during core loading depends mainly on the mean stress.

Three field sandstone cores with 13 % porosity were tested in the laboratory. The volume of injected pore fluid was used to estimate the initial porosity within the measurement cell. The volume of expelled pore fluid and the bulk volumetric strain were used to determine the stress dependent porosity change. The cores were loaded along different stress paths, applying external stresses and *in situ* pore pressure. The experiments confirmed within measurement accuracy the absence of stress path sensitivity seen with synthetic rocks and in discrete particle simulations. Thus, from this work isotropic loading seems to be sufficient in order to assess *in situ* porosity. More experiments are necessary to see if the findings above are generally confirmed. Care should be taken not to bring the cores close to yielding conditions.

A set of practical guidelines for overburden correction was established from this work. The described procedure should be applied to a set of screening tests, which then form the basis for deriving a correction factor for a majority of porosity measurements. The key is to measure the porosity change by loading the core to its mean effective *in situ* stress. This implies that good knowledge of the *in situ* stress state is necessary. Vertical stress is obtained by integration of the density log, or based on previously established stress gradients in the region. Pore pressure should be obtained from a direct formation test. Minimum horizontal stress should be based on fracture closure stress in mini-frac or extended leak-off tests. Maximum (and in principle also minimum) horizontal stress could be based on a newly developed technique utilising acoustic emission measurements on cores (Kenter *et al.*, 1998; Pestman *et al.*, 2001; Holt *et al.*, 2001). Initial porosity may be taken from routine ambient porosity* (e.g. He-porosity) measurements, but is preferably determined from the injected pore fluid volume in the same cell as stress dependent porosity is measured. Ideally, pore volumetric and bulk volumetric strains should both be recorded throughout the loading tests, and porosity calculated

* Consider here our discussion that a 'stress gap' between the ambient porosity measurement and a test in a triaxial cell can introduce a relatively large error. Porosity (He) measurements under a small confining stress, like routine permeability measurements, might be the preferred way.

from Eq. (11). If that is not feasible, better accuracy is obtained if pore strain is measured than if bulk strain is measured. Eq. (6) is then used for calculating the corrected porosity, which means that knowledge of Biot's a coefficient is required.

For high porosity sandstones (30 % or above), one may suspect permanent core damage effects on porosity. This cannot be corrected for in any straightforward manner. An alternative is to perform a study where a synthetic analogue rock is manufactured under stress, and then use data from that material to quantify the permanent porosity reduction.

NOMENCLATURE

K_{fr}	bulk modulus of drained rock framework	[milliStrain]	10^{-3}
p_f	pore pressure	a	Biot's poroelastic coefficient
V_p	pore volume	j	porosity
V	bulk volume	n	Poisson's ratio
$\frac{\Delta V}{V}$	volumetric bulk strain	s_H	maximum principal horizontal stress
$\frac{\Delta V_p}{V_p}$	volumetric pore strain	s_h	minimum principal horizontal stress
$s = \frac{\overline{s'}}{s'_v}$	stress correction factor	s_v	vertical stress
		s'	effective stress
		$\overline{s}$	mean total stress
		$\overline{s'}$	mean effective stress

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