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Stress path dependence of matrix permeability of North Sea sandstone reservoir rock

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ABSTRACT: Matrix permeability and pore volume compressibility are fundamentally important characteristics of hydrocarbon reservoirs because they provide measures of reservoir volume and reservoir producibility. In most laboratories these quantities are measured under hydrostatic (isotropic) loads that do not truly reflect the deviatoric stress state that exists in most reservoirs and do not adequately simulate the evolution of stresses in the reservoir as the reservoir is produced. Compression tests on a North Sea sandstone reservoir rock show that both compressibility and matrix permeability vary markedly with stress path (defined as the change in effective horizontal stress/change in effective overburden stress from initial reservoir conditions). Hence, it appears likely that in many reservoirs the direction and magnitude of matrix permeability will be largely controlled by the orientation of the maximum horizontal stress and by the magnitude of the horizontal stress difference at any given stage in the production history of the reservoir. Similarly, accurate measurements of compressibility should be obtained under loading conditions similar to those imposed on the reservoir during production. Optimum reservoir management may require that reservoir stress path be determined by measuring in-situ stresses early in the production history of the reservoir and periodically thereafter as the pore pressure is reduced.

1 INTRODUCTION

Due to their fundamental importance in reservoir evaluation and management, matrix permeabilities and compressibilities of reservoir rocks are routinely measured in the laboratory using procedures intended to simulate the reservoir environment. The most commonly used procedure is to compress the specimen in a hydrostatic test, in which the sample is subjected to an isotropic stress state (i.e., horizontal stresses equal the overburden stress) by a confining fluid. As the effective confining fluid pressure is increased, changes in the rock pore volume are measured and are used to calculate pore volume compressibility. Similarly, specific permeability is measured at incremental confining pressures by flowing a fluid of known viscosity through the specimen at a known rate and stabilized pressure difference. Matrix permeabilities are then calculated from measured values of specific permeability.

Although simple and convenient to run, the hydrostatic test has a major drawback; hydrostatic (isotropic) loading conditions are rarely encountered in real reservoirs. For example, Warpinski, Branagan, and Wilmer (1985) measured in-situ stresses in a sequence of marine sandstones and shales typical of many hydrocarbon reservoirs. Their measurements show that stresses in the sandstones are distinctly anisotropic, and that minimum horizontal stresses can be predicted from the rock material properties in some cases but not others.

Jaeger and Cook (1979) present theoretical arguments showing that the volumetric response of an elastic material to application of three dissimilar principal stresses is similar to that produced by an isotropic stress that is nominally identical to the mean of the three stresses. Users of data obtained from hydrostatic tests are cautioned to "correct" the test results to "equivalent uniaxial strain loading conditions" on the assumption that strain (or compaction) in the reservoir is uniaxial (i.e., all strain is vertical and horizontal strain is essentially zero). Teeuw (1981) and Anderson and Jones (1985) describe procedures for recalculating hydrostatic test results of elastic rocks to obtain equivalent uniaxial strain results. "Correcting" hydrostatic results to equivalent uniaxial strain loadings may approximate the volumetric changes in the rock under

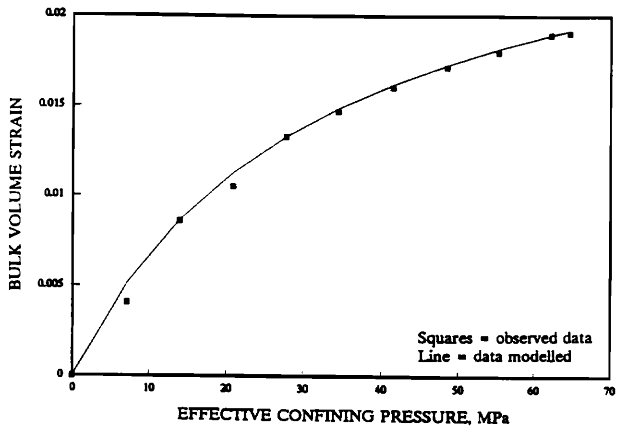

Figure 1. Plot of bulk volume strain versus effective confining pressure for hydrostatic (isotropic) loading to 65 MPa (9,425 psi).

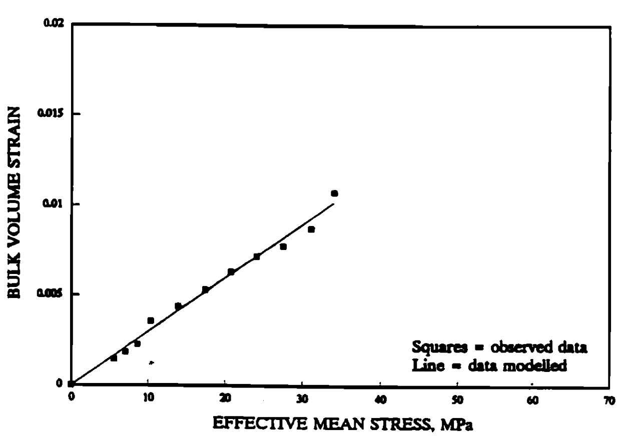

Figure 2. Plot of bulk volume strain versus effective mean stress for uniaxial strain loading (K_o is approximately 0.25) to 69 MPa (10,000 psi) effective axial stress.

uniaxial strain loading but it does not account for the distortional effects of stress anisotropy, i.e., the deviatoric component of the stress field, which cannot be duplicated by the isotropic stress state.

Bruno, Bovberg, and Nakagawa (1991) showed the importance of stress anisotropy on matrix permeability in a series of flow-through experiments in which they compared matrix permeabilities measured under increasing axial loads with permeabilities measured under increasing radial loads. Their results show matrix permeabilities were much larger parallel to the maximum stress direction than perpendicular to it.

Teufel and Rhett, 1991, compiled in-situ stress measurements obtained from shut-in pressures from 32 hydraulic fractures conducted over a period of 20 years in the Ekofisk Field, North Sea. Following 20 years of production and a 21-24 MPa (3,000-3,500 psi) reduction in reservoir pore pressure, the ratio of the change in effective minimum horizontal stress to the change in effective overburden stress, or the reservoir stress path, K, is approximately 0.20. This value is highly significant, because values of K ranging from 0.4 for Tor Formation chalks to 0.5-0.6 for Lower Ekofisk Formation chalks were measured in many uniaxial strain compression tests, which were conducted on the assumption that compaction in the Ekofisk reservoir is essentially uniaxial strain in nature. The disparity between K obtained from hydraulic fracture data and values of K measured in laboratory tests indicates that reservoir stress path cannot currently be determined solely from the material properties of a rock. Rather, the stress path followed by a reservoir must be determined from in-situ stress measurements made over a range of reservoir pressures. Furthermore, the low value of K measured in the field indicates that shear stresses in the reservoir have increased much more rapidly with drawdown than had been thought based on K values measured in uniaxial strain compression tests of the reservoir chalks.

The purpose of this paper is to determine the effects of stress path loading on measurements of matrix permeability and compressibilities in reservoir sandstones. Anelastic Strain Recovery measurements were conducted to estimate initial in-situ stress ratios prior to production in a sandstone reservoir rock from the North Sea. Measurements show that the relative magnitudes of effective overburden stress:maximum horizontal effective stress:minimum horizontal effective stress are 1.0:1.2:0.8. Hence, in this reservoir the stress anisotropy in the horizontal plane is very

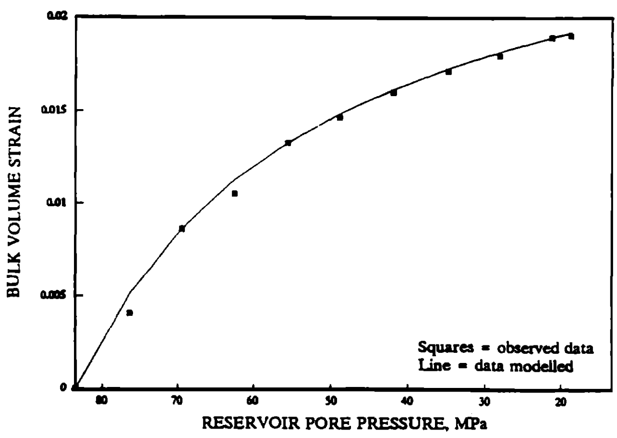

Figure 3. Plot of bulk volume strain versus reservoir pore pressure for hydrostatic (isotropic) loading to 65 MPa (9,425 psi) effective confining pressure.

large indeed, and it may strongly influence the direction and magnitude of maximum permeability in the reservoir. However, unlike the Ekofisk Field, there is currently insufficient pressure drawdown to determine the reservoir stress path. As a result, it was decided to measure material properties, compressibilities, and matrix permeability of the reservoir in a series of compression tests representing a range of possible stress paths the reservoir might follow as reservoir pressure is drawn down during production.

2 RESERVOIR ROCK LITHOLOGY

The reservoir rock is a poorly-sorted, conglomeratic, quartz pebble, sandstone. Matrix grains are angular monocrystalline and polycrystalline quartz. Secondary porosity resulting from likely dissolution of feldspar is common. Booklets of euhedral kaolinite commonly occur as probable alteration products of pre-existing feldspar grains. Quartz is the principal cement and well-terminated quartz overgrowths are commonly developed on numerous quartz grains. A black, insoluble bituminous phase, which partially fills some pores, is evidence of a likely earlier phase of hydrocarbon accumulation.

Examination of cores shows the rock is extensively fractured by steeply dipping, subplanar, "healed" shear fractures, which typically show obvious shear displacement.

3 TEST PROCEDURES AND RESULTS

A variety of compression tests were run on samples of the reservoir rock to measure its material properties under reservoir conditions and to simulate the range of possible stress paths the reservoir may follow during production. Test specimens were 2.54 cm (1 inch) diameter by approximately 5 cm (2 inch) long, cylindrical plugs that were free of fractures and obvious defects. Samples were prepared with an immobile brine saturation of approximately 20%, then heated to the reservoir temperature of 150° C (300° F), and brought to a stress state simulating the effective in-situ stresses under initial reservoir conditions. The initial effective mean stress in the reservoir is nominally equal to the initial effective overburden stress of 11 MPa (1,600 psi), so initial reservoir

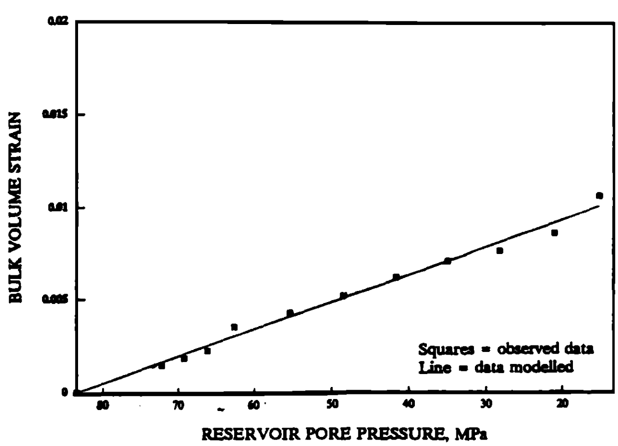

Figure 4. Plot of bulk volume strain versus reservoir pore pressure for uniaxial strain loading (K_o is about 0.25) to 69 MPa (10,000 psi) effective overburden stress.

conditions were approximated by applying an effective confining pressure of 11 MPa (1,600 psi) to each sample. Effective stresses were increased by decreasing pore pressure in increments of 6.9 MPa (1,000 psi) at a stress rate of -3.45 MPa/hour (-500 psi/hour). Following each 6.9 MPa increase in stress the sample was allowed to stabilize at constant stress for 22 hours in order to identify the onset of time-dependent strain (or "creep"), which signifies the begining of ductile behavior in the rock.

3.1. MECHANICAL PROPERTIES OF THE RESERVOIR ROCK

A series of hydrostatic and uniaxial strain (the stress path, K, was approximately 0.25) compression tests were conducted on samples with porosities ranging from 13% to 20% to measure material properties and failure characteristics of the reservoir rock under simulated reservoir conditions. Values for elastic modulus, defined here as the slope of the stress-strain curve measured at some constant effective confining pressure that is greater than zero, were measured during a uniaxial strain test at increments of 6.9 MPa (1,000 psi) effective overburden stress. Values of elastic modulus were somewhat erratic but averaged about 2,760 MPa ($4*10^5$ psi) at effective confining pressures less than 6.9 MPa. At effective confining pressures from 6.9 MPa to 20.7 MPa measured values of elastic modulus were fairly constant at 13,800 MPa ($2*10^6$ psi).

Failure properties of the reservoir rock (i.e., friction angle and cohesion) also were measured in order to evaluate the likelihood that shear failure of intact rock or sliding failure along existing fractures will occur as the reservoir is produced. Consequently, many of the compression tests were terminated by intentionally failing the rock in order to determine criteria for failure. A simple, linear Mohr-Coulomb failure criterion describes brittle failure in the reservoir rock quite adequately. The friction angle, determined from Mohr envelopes, is close to 30°. A pronounced linear relationship (R^2 = 0.91) exists between cohesion, τ_o, and initial porosity, Φ_o, and is given by Equation 1:

$$\tau_o,\ MPa = -1.8\ \frac{MPa}{\%} * \Phi_o,\ \% + 43.4\ MPa. \tag{1}$$

Yield stress was never reached during the hydrostatic tests, so the intercept of a "ductile

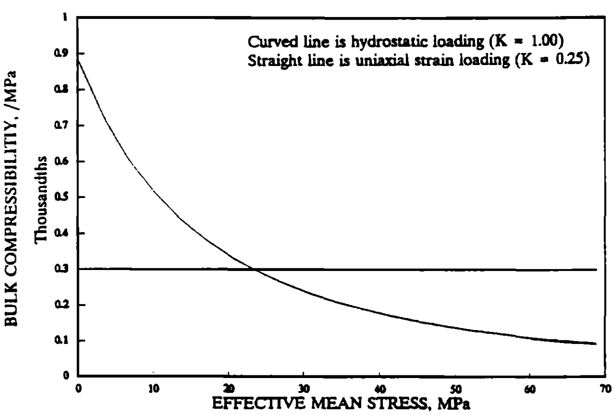

Figure 5. Plot of bulk compressibilities versus effective mean stress calculated from bulk volume strains measured during hydrostatic loading (curved line) and bulk volume strains measured during uniaxial strain loading (straight line).

end cap" with the normal stress axis occurs at effective confining pressures greater than 69 MPa. The rocks behaved elastically at loads as high as 96.6 MPa (14 kpsi) effective overburden stress in uniaxial strain tests and 69 MPa effective confining stress in hydrostatic tests.

3.2. BULK ROCK AND PORE VOLUME COMPRESSIBILITIES

Bulk rock and pore volume compressibilities were calculated from volume strains measured during hydrostatic tests, and generalized bulk and pore volume compressibilities, defined as the derivative of volume strain with respect to effective mean stress, were measured during uniaxial strain tests. Changes in the rock bulk volume are presumed due entirely to changes in the rock pore volume, and the volume of the grain matrix is assumed to remain constant. In the hydrostatic tests (K = 1.0 in isotropic loading), which were conducted to 69 MPa (10 kpsi) effective confining pressure, volume strains and compressibility showed strong non-linear dependence on effective confining pressure (Figure 1). Equation (2) relates bulk rock compressibility to effective confining pressure, Pcon', which is nominally equivalent to the mean effective stress:

$$\beta_{bulk\ rock} = \frac{8.9*10^{-4}}{(1+3.1*10^{-2}*Pcon')^2}. \tag{2}$$

Approximate values for pore volume compressibility are obtained by dividing the numerator in Equation (2) by the rock's initial porosity, expressed as a decimal fraction.

Generalized bulk rock and pore volume compressibilities were also calculated from volume strains measured in uniaxial strain compression tests (which followed a stress path of K approximately equal to 0.25) conducted to an effective overburden stress of 69 MPa. Under uniaxial strain conditions bulk volume strain was linear with effective mean stress (R^2 = 0.99) (Figure 2), so bulk rock compressibility is constant at about

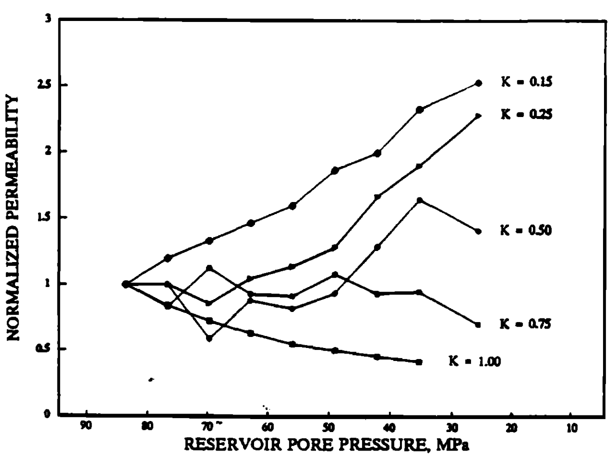

Figure 6. Diagram shows variation in normalized permeability with reservoir pore pressure for North Sea sandstone loaded along 5 different stress paths, K, where K = 1.00, 0.75, 0.50, 0.25, and 0.15.

$3.0*10^{-4}$/MPa ($2.1*10^{-6}$/psi). Hence, pore volume compressibility measured under uniaxial strain conditions also is constant at about (3.0/initial porosity)$*10^{-4}$/MPa.

Volume strains plotted against reservoir pore pressure for the hydrostatic test and the uniaxial strain test are shown in Figures 3 and 4, respectively. These two plots emphasize the influence of stress path on reservoir volume as reservoir pore pressure is reduced.

Figure 5 is a plot of bulk rock compressibility determined from hydrostatic tests (K = 1.0) and a generalized bulk rock compressibility determined from the uniaxial strain test (in which K approximately equals 0.25) versus effective mean stress. Figure 5 clearly shows that values for compressibility vary significantly depending on the stress path chosen for the measurements. Compressibilities measured under isotropic (hydrostatic) loading conditions (K = 1.0) may be very misleading if applied to a reservoir that follows a uniaxial strain stress path or a stress path having a K value less than that for uniaxial strain. Consequently, truly representative measurements of volume strain and possible variations in bulk rock and pore volume compressibility with drawdown should be measured under loading paths that duplicate the stress path followed by the reservoir during production.

4 MATRIX PERMEABILITY

A series of "stress path" compression tests were run on 5 samples of the reservoir rock to simulate the range of possible stress paths the reservoir may follow during production. From approximate initial reservoir conditions the pore pressure and confining pressure were continuously changed so the stress state applied to each sample evolved along a constant stress path of K = 1.0, 0.75, 0.50, 0.25, or 0.15, respectively, where K is the change in effective horizontal stress (i.e., effective confining pressure)/change in effective overburden (i.e., effective axial) stress from initial reservoir conditions. The tests were run with stress control to an effective overburden stress of 69 MPa. Effective stresses were applied by reducing pore pressure in increments of 6.9 MPa over a 2 hour interval while maintaining the total axial stress constant and adjusting the confining pressure to maintain the desired K. All pressures were applied by liquid filled syringe pumps that were fully controlled by computer. The control algorithm is:

$$Pcon_i = Pcon_o + (Ppore_i - Ppore_o)*(1 - K) \qquad (3)$$

where
$Pcon_i$ = confining pressure required to follow stress path, K.
$Pcon_o$ = confining pressure under initial conditions.
$Ppore_i$ = current pore pressure.
$Ppore_o$ = pore pressure under initial conditions.
K = desired stress path.
= Δ effective confining pressure/Δ effective axial stress.

Following each incremental increase in stress the samples were equilibrated for 22 hours at the new stress conditions. During each "stress path" test, specific permeability was measured at increments of 6.9 MPa effective overburden stress by flowing a light, pure mineral oil through the plug at a constant rate and adjusting the downstream pore pressure valve until the pressure difference along the length of the plug had stabilized. The matrix permeability of the sample subjected to isotropic loading was measured by flowing an inert gas through the specimen at incremental loadings of 6.9 MPa effective confining pressure. Once conditions were stable, the flow rate and the pressure difference were logged every minute for 15 minutes. Matrix permeability was calculated for each set of data using Equation (4), and the results were averaged to obtain a single average value for matrix permeability at each incremental stress.

$$k = \frac{Q\mu L}{A\Delta P} \tag{4}$$

where
k = matrix permeability, darcys
Q = flow, cm^3/sec
μ = viscosity, centipoise
L = sample length, cm
A = cross-sectional area of the sample, cm^2
ΔP = pressure difference along the sample, atm

In order to compare changes in matrix permeability observed along the 5 stress paths all permeabilities were normalized by dividing each permeability by the initial permeability measured under initial reservoir conditions of 11.0 MPa effective confining pressure.

Results of the 5 stress path-matrix permeability tests are shown in Figure 6. The specimen loaded hydrostatically (K = 1.0) clearly shows a decrease in permeability as the effective confining pressure (nominally equivalent to the effective overburden stress) increases with reduction in reservoir pore pressure. This behavior is consistent with test results commonly obtained from hydrostatic tests, in which the effective confining pressure, which simulates the effective mean stress in the reservoir, increases as the reservoir pore pressure is drawn down.

As K diminishes, however, the reduction in matrix permeability with reduction in pore pressure (i.e., with increase in effective stresses) quickly vanishes, and then permeability actually increases at values of K somewhere between 0.75 and 0.5. Under uniaxial strain loadings the matrix permeability at 69 MPa is more than double its value under initial reservoir conditions.

The mechanism responsible for increases in matrix permeability along low-K stress paths is presently unclear. Radial strains were carefully monitored during the tests for evidence of sample dilation. Radial strains remained very small, even in those tests with low K values (indicating relatively low confining pressures), so dilation was negligible. Test results suggest that matrix permeability may be related to shear stresses (Mordecai and Morris, 1971), which increase with decreasing K.

5 SUMMARY AND CONCLUSIONS

Recent in-situ stress measurements indicate that some reservoirs follow stress paths that are significantly different from either a constant stress boundary condition or a uniaxial strain boundary condition (i.e., no lateral displacement of the reservoir boundaries). Measurements made during laboratory compression tests of a North Sea reservoir sandstone, which were conducted by following prescribed stress paths, indicate that both compressibility and matrix permeability can be highly stress-path dependent; specifically, measurements of compressibility made under isotropic stress conditions differ markedly from compressibilities made under uniaxial strain conditions. Furthermore, matrix permeability may either decrease or increase depending on how the in-situ stress state evolves as the reservoir is produced. Hence, reservoir permeability may not remain constant during production but may vary significantly with changes in pore pressure and the effective state of stress imposed on the reservoir rock.

Under hydrostatic loading (the conventional test procedure followed by the petroleum industry) the permeability of the sandstone decreases with increasing effective stress. However, in sharp contrast, under non-hydrostatic loading, in which the stress path is K = 0.5 or lower, the permeability increases with increasing effective stress. Test results indicate that the increase in permeability is greater for stress paths that have lower stress ratios and correspondingly larger incremental increases in shear stress.

Variations in compressibility and matrix permeability appear to be strongly influenced by the stress path followed by the reservoir. It seems likely that in many reservoirs the direction and magnitude of maximum permeability at any given stage in the production history of the reservoir will be largely controlled by the orientation of the maximum horizontal stress and by the magnitude of the horizontal stress difference. Consequently, optimum reservoir management may necessitate measuring both magnitude and orientation of in-situ stresses under initial reservoir conditions and periodically thereafter in order to determine the reservoir stress path and the direction of maximum horizontal in-situ stress. Compressibility and matrix permeabilities of reservoir rocks should be measured in the laboratory under conditions simulating the stress path followed by the reservoir.

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