CORE COMPACTION CORRECTION - A DIFFERENT APPROACH

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Abstract Core compaction correction in the North Sea is frequently assumed to be in the region of 0.95. The core compaction correction is that factor by which ambient core porosities are multiplied to correct to reservoir condition porosities. The core compaction correction is often arrived at by measuring porosity reduction under hydrostatic "effective overburden" conditions. An empirical uniaxial correction is then applied to simulate the reservoir stress conditions.

A study has been made on core samples from the Jurassic and Triassic sandstones of the Central North Sea area, so as to better evaluate the core compaction correction. Three laboratory techniques for the measurement of porosity at stress were used, and pore volume compressibility and core compaction correction were calculated.

Firstly, the samples were subjected to 'net hydrostatic' overburden pressure conditions at 1000 psi increments up to 10 000 psi, in three cycles, and pore volume reduction measured at each increment.

Secondly, the same apparatus was used in a single pressure cycle, building from ambient to simulated reservoir stress in 750 psi/day increments. The samples were then left for a minimum of three days at these reservoir stress conditions to monitor 'creep'.

Finally, samples were subjected to conditions where axial and radial stresses were varied independently on vertically cut core plugs. Simulated overburden loads were applied axially, and loads equivalent to 0.65 to 0.85 of overburden applied radially. These 'horizontal' loads are derived from in-situ stress data from hydraulic fracturing work.

Our results indicate that core compaction corrections are very sensitive to the application of simulated reservoir stress. Core compaction correction values somewhat less than 0.95 were observed, which suggests that this value may be overly optimistic in this, and perhaps other North Sea areas. Previous calculations of core compaction correction may be in error due to the use of low values of in-situ stress, to compaction tests run too quickly or to stress cycling, and/or the incorrect application of the uniaxial correction.

INTRODUCTION

This paper presents the results of a study made with the aim of gaining a clearer insight into, and better evaluation of methods of core compaction correction.

Included, is a brief overview of the current industry standard method of core compaction correction followed by a description of methods devised to correct some invalid assumptions made by previous workers. Results of different laboratory techniques to measure core compaction are compared and recommendation made for preferred compaction correction techniques for use in Petrophysical evaluations.

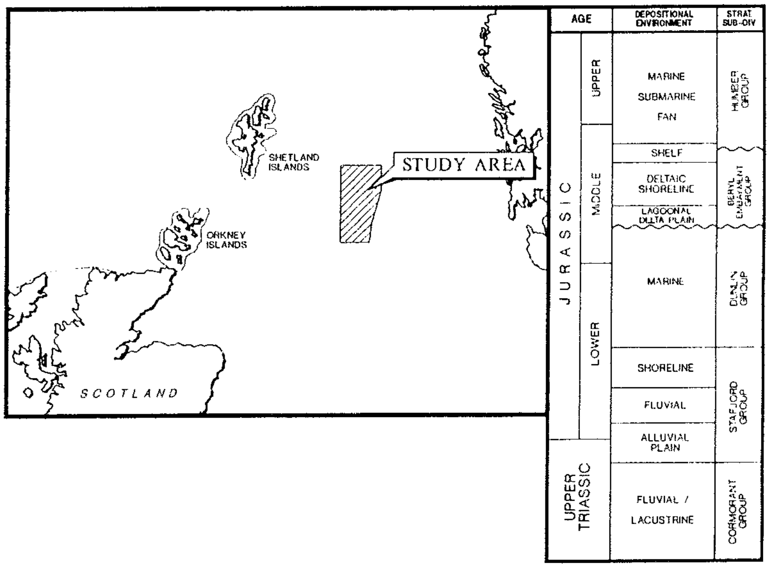

FIGURE 1 The study area showing location and generalised stratigraphy

The study area is located in the Central Graben area of the UK sector of the North Sea (Figure 1).

Commercial hydrocarbons are present in sandstone reservoir horizons ranging in age from Upper Triassic to Upper Jurassic. A generalised stratigraphic column for the area is also shown in Figure 1.

Reservoir rock properties are variable as may be expected in such a large area. Ambient core porosity values range from 10-24 porosity units, averaging 18 porosity units.

THEORETICAL CORE COMPACTION METHODS

Traditionally, ambient core porosities are corrected to reservoir stress condition porosities by measuring porosity of a few core plugs at "effective overburden stress" conditions as part of a Formation Factor SCAL programme. The change in porosity from ambient conditions is determined, and then a "uniaxial correction factor" is applied to this change to calculate a core compaction correction factor which can be applied to all ambient porosity measurements. Frequently, this 'Uniaxially' corrected compaction correction varies between 0.93 and 0.97, and a value of 0.95 is often assumed.

The "effective overburden stress", $\bar{s}_v$, is generally calculated as:

$$\bar{s}_v = S_v - P \tag{1}$$

where S_v (Total overburden stress) = depth* overburden gradient
P = initial reservoir pressure

$$\phi_u = (\phi_a - U_c * \Delta PV)/(1 - U_c * \Delta PV) \tag{2}$$

where ΔPV = change in pore volume
ϕ_a = Ambient porosity
ϕ_u = Uniaxially corrected porosity

The uniaxial compaction correction, U_c, is assumed to be 0.62 after Teeuw (1971). It is our contention that this 0.62 factor is incorrect because it has been arrived at by extrapolating linear elasticity into regions where it does not apply, and because it does not account for tectonic stress.

Both Keelan (1985) and Juhasz (1988) and others (personal communication) have derived the 0.62 factor and equation 2 from Teeuw's (1971) expression:

$$e_z = (1 - \nu)/[3*(1 + \nu)]*e \qquad (3)$$

where e_z = uniaxial strain
e = hydrostatic strain at hydrostatic pressure equal to uniaxial pressure.
ν = Poissons ratio

If ν=0.3 then e_z=0.62*e, that is U_c=0.62.

However, Teeuw (1971), Nelson (1981), and Geertsma (1957) all point out that equation 3 holds under linear elastic strain conditions only. The shape of the porosity versus stress curves (figures 5 to 8) clearly show that porosity is not linear and therefore linear elasticity does not hold over the range of ambient to overburden stress conditions.

Rather than measuring the porosity at effective overburden stress and then correcting for uniaxial compaction, we suggest that it is better to calculate the true in-situ stress state in the reservoir and measure the porosity at that stress or a hydrostatic stress equivalent to it. The "effective total stress" on the reservoir can be defined as (Geertsma (1956), Jaeger & Cook (1976), Nur & Byerlee 1981):

$$\bar{s} = [(S_{h1} + S_{h2} + S_v)/3] - \alpha P \qquad (4)$$

where S_{h1} = Minimum horizontal stress
S_{h2} = Maximum horizontal stress
S_v = Overburden or effective stress
α = Biot alpha parameter

Teeuw's (1971) calculations are based on the assumptions that the horizontal stresses in the reservoir are equal to one another, that there are no tectonic stresses on the reservoir, that the Biot alpha parameter is 1, and that the horizontal stresses are controlled by the present day Poisson's ratio of the reservoir rock. The authors and Nelson (1981) claim that Teeuw's assumptions yield horizontal stresses which are only a lower limit of those that may truly exist in the reservoir.

It is generally accepted that the minimum horizontal stress, S_{h1}, is equal to the fracture gradient, Fg, times the depth. The overburden stress is overburden gradient (1 psi/foot) times depth with the maximum horizontal stress being somewhere in between the other two stresses for most reservoirs.

In the North Sea, it is the authors experience from extensive hydraulic fracturing work, that the fracture gradient is commonly 0.7 to 0.8 psi per foot. Teufel (1985) has similar experience of the minimum stress, from strain relaxation tests in the Central North Sea. Assuming a fracture gradient of 0.75 with a maximum horizontal stress halfway between minimum stress and overburden stress, with a Biot parameter of 0.9 (Hall 1953, Nur and Byerlee 1981), yields an effective total stress of:

$$\bar{s} = .875*S_v - .9*P \qquad (5)$$

or if $P = 0.43*S_v$ (Hydrostatic gradient is 0.43 psi/ft)

$$\bar{s} = .49*S_v \qquad (6)$$

or

$$\bar{s} = .856*\bar{s}_v \quad \text{(from equation 1)} \qquad (7)$$

Equation 7 suggests that if a plot of porosity versus effective stress is made, then the porosity at a pressure of 0.856 times effective overburden stress better estimates the true in-situ porosity than the methods used by Keelan (1985) and Juhasz (1988). If, however, fracture gradient data is not available then Teeuw's (1971) method yields the following for a rock with a Poisson ratio of 0.3:

$$\bar{s} = 0.62*\bar{s}_v \qquad (8)$$

This leads to (see Appendix 1):

$$\bar{s} = .77*S_v - .9*P \qquad (9)$$

If we assume that the two horizontal stresses are equal then equation 9 translates into a fracture gradient of 0.65 psi/foot. If the maximum horizontal stress is intermediate to the other two stresses then equation 9 translates to a fracture gradient of 0.54 psi/foot. Both cases are too low to explain observed fracture gradients and demonstrate our contention that Teeuw's assumptions offer a lower limit on minimum horizontal stresses.

The application of all three theoretical methods to hydrostatically and biaxially measured porosity changes are discussed further under results (See Figures 7 and 8).

LABORATORY TEST PROCEDURES EMPLOYED

Sample Preparation

Plug samples were drilled at ninety degrees to the bedding using synthetic formation brine as a core bit coolant. The samples were 1.5 inches in diameter and at least 1.5 inches in length. Geological data did not indicate any potential problems during core cleaning and therefore Soxhlet extraction was performed. The plugs were cleaned of hydrocarbons and brine using a series of solvents. In all, the samples took approximately two weeks to clean. The plugs were then dried to a constant weight using a vacuum oven at 40°C.

In order to characterise the plugs and select those horizons that exhibited minimum heterogeneities the permeability to nitrogen and helium porosity were measured. Using these data a suite of twenty-four samples representing six geological units were selected for testing.

All of the plugs were then saturated using synthetic formation brine.

Quality Control

Electrical resistivity measurements

Whilst the primary aim of the testing was to generate compressibility data the study also afforded the opportunity to study the alteration in Formation Resistivity Factor (FRF) under varying stress regimes. This allows the use of FRF as a guide to plug mechanical competence and a comparison of FRF prior to and after the compressibility test was used as a quantitative indication of plug elasticity. Room condition FRF's were determined using the two (silver) electrode method.

Pore volume compressibility measurements

Repeat cycling and duplicate plugs were used to assess plug integrity and reality of measurement differences. Porosity values before and after compressibility testing were also noted as a guide to plug elasticity.

Hydrostatic Loading System

These tests were undertaken to provide information on the effects of cycling the overburden pressure, the rate of pressure application, and to test sensitivity to small changes in permeability and porosity.

Each sample was loaded into a rubber overburden sleeve and confined by two silver electrodes and stainless steel platten enclosures. In order to prevent the ingress of air this process was undertaken with the plug immersed in synthetic formation brine. The samples were then loaded into a hydrostatic core holder that facilitated the measurement of core resistance and reduction in pore volume (Figure 2).

As a result of this loading procedure an unquantified volume of brine was initially present in the system between the sample and the confining sleeve. Before real pore volume reduction and resistivity values could be accurately measured, the excess brine had to be removed from the system. This is discussed further under results.

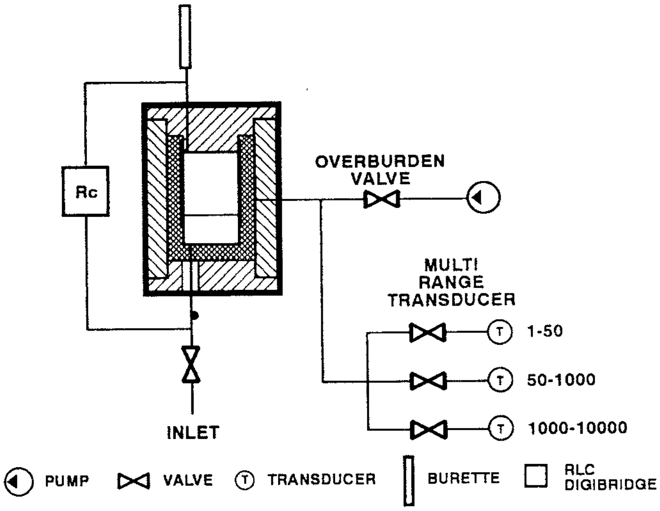

FIGURE 2 Schematic diagram of the 'hydrostatic' testing rig

Two methods of applying the hydrostatic stress were employed. In method one the effective stress was increased up to a maximum of 3000 psi, the pressure was then reduced to 200 psi. Pore volume change and resistance were monitored at several intermediate pressures. This cycle was repeated, and then a third loading cycle was undertaken. The third cycle was continued up from 200 psi to the maximum stress of 10 000 psi, in 8 hours.

In order to evaluate the sensitivity of this test to variations in permeability and porosity two samples from each horizon were tested in this manner.

In method two the intention was to determine the effect of the rate of load application, and the samples tested were subjected to a single cycle of increasing load with a controlled application of pressure at a rate of 750 psi/day. Initial procedures adopted were identical to method 1.

Bi-Axial Loading System

These tests were undertaken in an attempt to simulate more accurately, the effective reservoir stress, by introducing an average horizontal stress determined from fracture gradients in the reservoir, described by equation 4.

The cell assembly used for the tests with Bi-axial loading is shown in figure 3. Each sample was loaded into a rubber overburden sleeve and fixed into position using silver electrodes and stainless steel plattens. This assembly is mounted in a frame that allows the application of axial and radial load independently. Initially loads of 50 psi were applied hydrostatically and brine was flowed through the system to remove any gas that may have been introduced during the loading procedures.

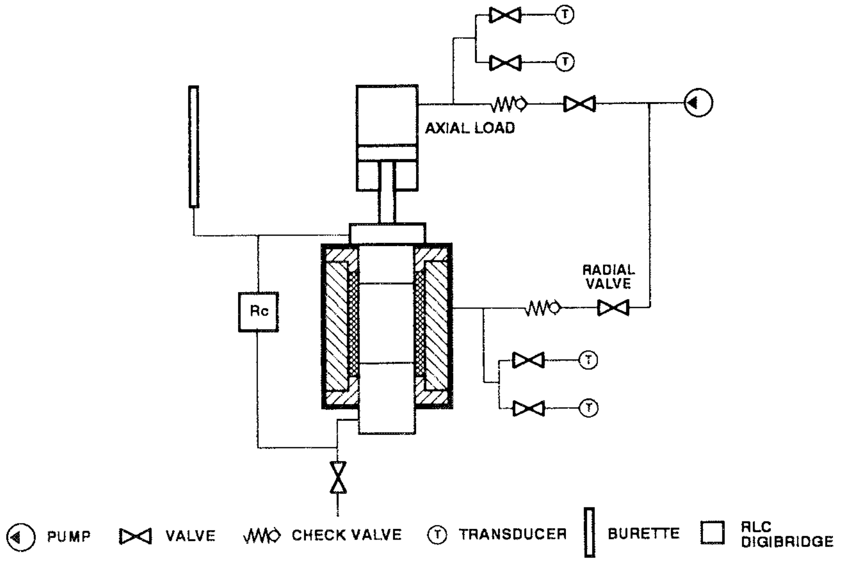

Figure 3 Schematic Diagram of the 'Biaxial' Testing Rig

The axial and radial pressures were then increased independently in increments in the ratio of 1:0.85. For each pressure step, brine volume expelled and core resistance were noted. The radial load was then reduced to simulate a load ratio of 1:0.65, core resistance and brine volume expelled were again recorded. The radial load was then returned to 1:0.85 prior to increasing pressures to the next salient point. Measurements were made up to the maximum stress ratio of 6000:3900. At this point, the radial load was increased to 6000 to create an equivalent hydrostatic pressure and to provide a comparison point for the samples tested only under hydrostatic load.

Upon completion of the analysis the samples were allowed to imbibe brine as the pressure was gradually reduced. The plugs were then unloaded and the FRF was measured. Each sample was then submerged in synthetic formation brine and FRF was monitored for several days.

RESULTS OF LABORATORY TESTS

For the purposes of comparison of laboratory test data, an "effective overburden stress", $\bar{s}_v$, (equation 1) was assumed to be 6000 psi.

Hydrostatic Loading - 3 Cycles

This method is very common for laboratory determination of porosity reduction, and potentially has several problems which can affect the value of the end measurement used by petrophysicists and reservoir engineers.

(i) The pore volume reduction measurement of the initial cycle has a large effect on the final calculation of porosity reduction. The volume of brine expelled over the first 200 psi effective stress was greater than for the remainder of the test. It was important to differentiate how much of the brine was excess, from the annulus between the core plug and the confining sleeve. This was performed graphically, with a plot of effective stress in 10 psi increments against volume of brine expelled. Where excess brine removal is complete there is a sharp inflexion, which when extrapolated along the main curve trend to zero pressure, gives true pore volume reduction (Figure 4). Clearly, if this excercise was not performed, any porosity reduction calculated would be too high.

(ii) Multiple stress cycling of the core plug is ostensibly bad practice, as it cannot be representative of in-situ stress conditions, and may induce both fracturing and grain damage in the rock. Our findings were that, for the Jurassic and Triassic sandstones tested, cycling gave a good indication of plug elasticity and integrity. In all but one of the tests, the rocks behaved elastically, cycles 2 and 3 overlaying exactly. Given this elastic behaviour, porosity reduction data could be used with some confidence from the 3rd cycle measurements (Figure 5).

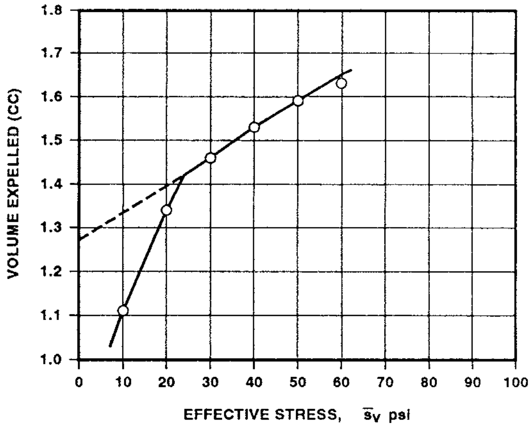

FIGURE 4 Determination of excess brine in 1st cycle

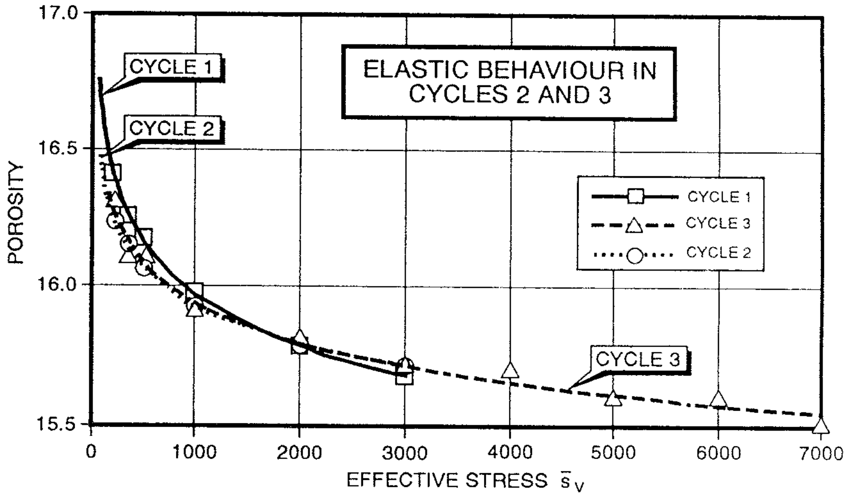

FIGURE 5 Typical 3 cycle data - elasticity in cycles 2 and 3

(iii) Time is an important factor in this measurement. Our results show that the cycled hydrostatic data does not reach equilibrium because of the rapidity of the measurements. This is evident when a comparison is made with the 10 day hydrostatic data (Table 1). Results from the three cycle test typically indicate a good degree of agreement between porosity reduction and formation factor measurements on duplicate samples (Figure 6). This indicates the lack of sensitivity to small changes in porosity and permeability.

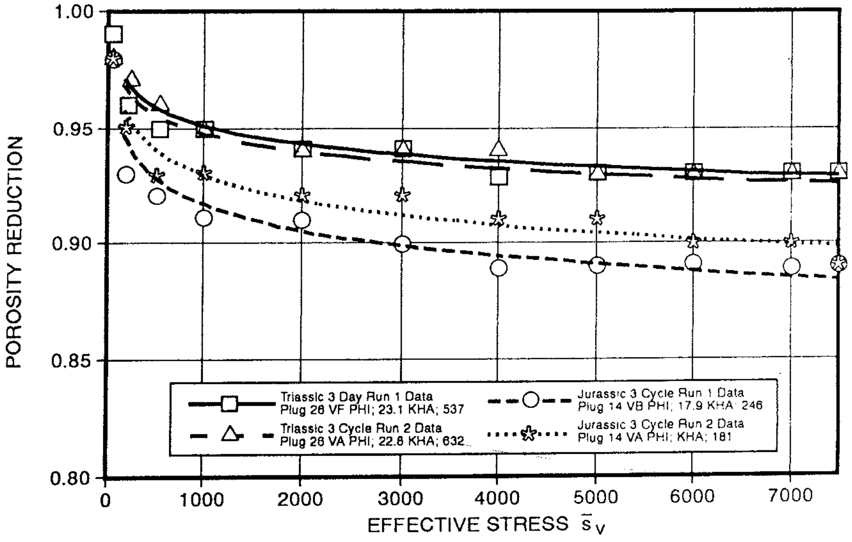

FIGURE 6 Comparison of duplicate plug samples

Hydrostatic Loading - 10 Days

This method was attempted to determine the effect of rate of stress application on porosity reduction measurements. Our experience has shown an increase in stress of 750 psi/day to be optimum in terms of data quality recorded, laboratory equipment and personnel time. Item (i) of the hydrostatic 3 cycle measurement also applies here, and has been dealt with in the same fashion. A second 10 day cycle was also performed on each sample to check plug integrity and measurement repeatability. This lends confidence to the interpretation of differences in measurements being "real".

The salient differences between this test and the 3 cycle test are clear, a single cycle, and a test span 30 times longer (240 hours compared to 8 hours). A definite pattern emerged from the data. Jurassic and Triassic samples had consistently different porosity reduction values at equivalent overburden stress values (s_v = 6000 psi). Table 1 illustrates that under 3 cycle loading a typical Jurassic sample porosity reduction value is 0.89, compared to 0.93 for a Triassic sample. Perhaps more significant is the greater porosity reduction exhibited by the 10 day loading, giving typical values of 0.87 and 0.90 for Jurassic and Triassic samples respectively (at s_v = 6000 psi). The 10 day loading is probably more effective in allowing the rock to 'creep' and more truly reversing the stresses on the plug from ambient back to in-situ conditions. The importance of creep in compression test work has been shown by De Waal (1986). Results also indicated that Formation Factor, may be sensitive to rate of stress application, being generally lower following 10 day loading. All samples were monitored for Formation Factor following compressibility testing. The elasticity of the plugs was evident from our results, however, it was interesting to note that Formation Factor values did not stabilize back to ambient values for a minimum of 6 days for Triassic samples and up to 9 days for Jurassic samples, perhaps indicative of burial depth difference.

Biaxial Loading

This method was attempted to more accurately simulate "effective reservoir stress". Results of this testing were expected to show a marked difference to the hydrostatic loading state, possibly obviating the need for any uniaxial correction.

In practice, the difference between the 3 cycle hydrostatic data and the 1:0.85 axial to radial stress at 6000 psi axial stress was very small, porosity reduction values being 1% less than, or equal to, the equivalent 3 cycle data. For the 1:0.65 axial to radial stress regime, differences were again small (Table 1).

Overall, the biaxial testing gave porosity reduction values similar to, or less than, the 3 cycle testing which may indicate that laboratory porosity reduction measurements for this set of samples, are more sensitive to rate of stress application than actual stress regime. The average time for a biaxial test, was just less than 24 hours, i.e. longer than the '3 cycle', less than the '10 day'. This similarity between 3 cycle and biaxial can be rationalised, in that the biaxial stress state at 6000 psi axial and 3900 psi radial is equivalent to 4600 psi hydrostatic stress (equation 4). With our data set all porosity versus effective stress curves are fairly flat in the region 4000 to 6000 psi. Differences here though real, are small enough as to be close to experimental accuracy.

As with the other test methods repeatability was good, and sensitivity to small changes in plug porosity and permeability low.

TABLE 1 Summary of Typical Laboratory Test Results

Jurassic Samples	Ambient Conditions		Effective Stress 6000 psi	
	PHI	FF	PHI.REDUCTION	FF
Hydrostatic Run 1	17.9	21.4	0.89	30.3
Hydrostatic Run 2	17.2	24.4	0.90	34.6
Hydrostatic 10 day	17.5	22.8	0.87	33.1
Hydrostatic 10 day Run 2	17.5	22.8	0.86	33.3
Biaxial 0.85	17.3	22.3	0.88	32.9
Biaxial 0.65	17.3	22.3	0.89	31.5
Triassic Samples	**Ambient Condition**		**Effective Stress 6000 psi**	
	PHI	FF	PHI.REDUCTION	FF
Hydrostatic Run 1	21.8	13.9	0.94	17.3
Hydrostatic Run 2	21.4	15.3	0.93	18.4
Hydrostatic 10 day	21.7	15.5	0.91	19.8
Hydrostatic 10 day Run 2	21.7	15.5	0.90	18.6
Biaxial 0.85	21.8	14.3	0.93	17.4
Biaxial 0.65	21.8	14.3	0.94	17.0

APPLICATION OF THEORETICAL COMPACTION CORRECTION METHODS TO LABORATORY TEST RESULTS

Thus far, differences in porosity reduction values have been noted due to lithology (Jurassic and Triassic) or simply burial depth, and laboratory technique. All values have assumed an "effective stress" s_v of 6000 psi which necessitates correction to either 'uniaxial' conditions, equation 2, or "effective total stress" conditions, equations 4, 7 or 9, to give a compaction correction value.

All three theoretical methods have been applied to typical porosity versus effective stress curves from the data set. Figures 7 and 8 illustrate the resulting compaction correction factors. These compaction correction factors can be seen to vary with effective total stress. In Figure 7, the hydrostatic 3 cycle test, the effective total stress can be taken at 5160 psi (equation 7) or 3725 psi (Teeuw 1971, equation 8). With our data set, porosity reduction values are similar at these stresses, with values of 0.93 and 0.935 respectively. From the same figure, the Traditional method widely applied in the industry (Juhasz 1988, Keelan 1985) (equation 2) suggests a compaction factor of 0.954. This corresponds to an effective total stress of only 700 psi. This is clearly anomalous and may be due to the non-linearity of the curve, invalidating a linear strain assumption. The different effective total stress states defined, have been applied to the other data in the same fashion, to indicate variation in compaction factor.

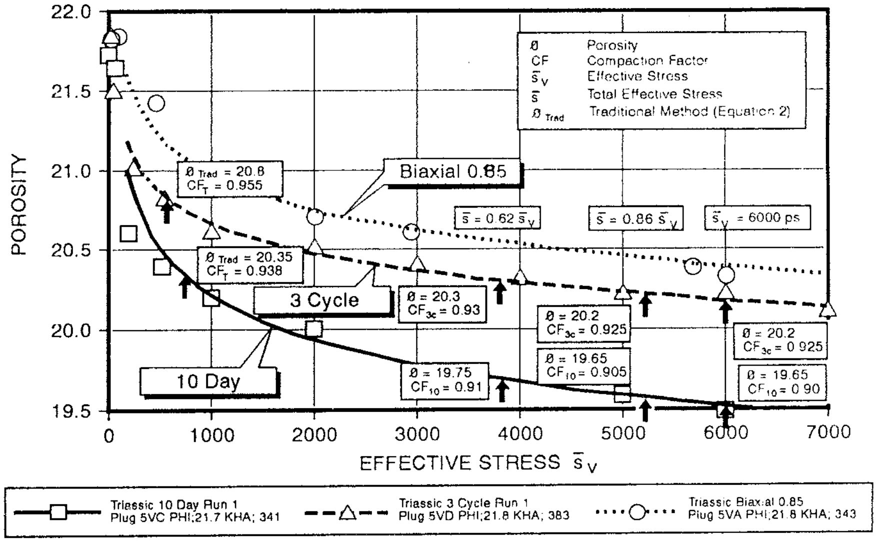

FIGURE 7 Application of theoretical methods - Triassic

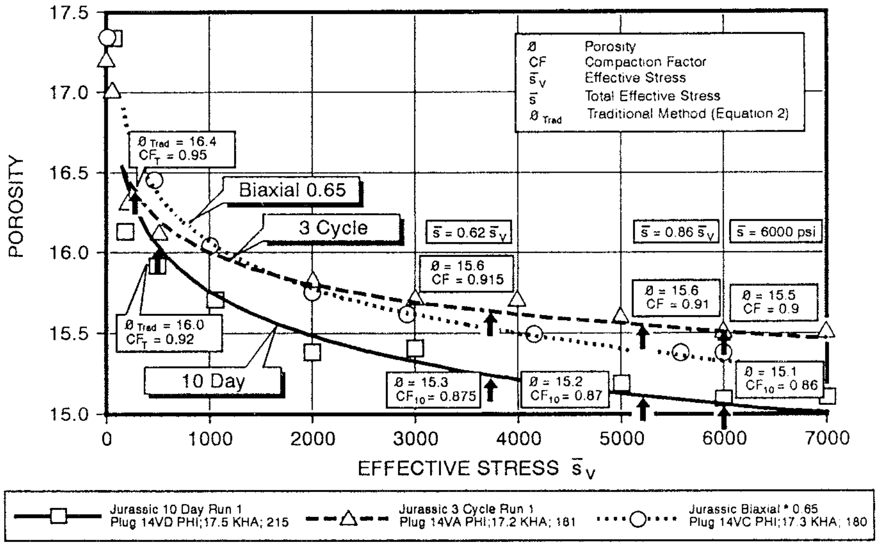

FIGURE 8 Application of theoretical methods - Jurassic

CONCLUSIONS

Based on theoretical analysis we suggest that uniaxial compaction correction not be used in calculating core compaction factors. Instead, in-situ stresses should be estimated using fracture gradient data if possible and porosity should be measured under those stresses or a hydrostatic stress equivalent to it (see equation 4). In the absence of fracture gradient data, Teeuw's equation 8 and 9 can be used to calculate a lower limit on the effective total stress.

Our results indicate that for this dataset, core compaction correction values less than 0.95 are likely. Variation in rate of stress application appears to be a significant factor in determining the end value of core compaction correction to be used to correct ambient core porosities to reservoir condition porosities. Different core compaction corrections observed in Jurassic and Triassic rocks having similar ambient porosities and permeabilities, may indicate the significance of rock fabric and/or initial burial depth.

We recommend, from our results, that a hydrostatic stress equivalent to the in-situ stress conditions be applied much more slowly than is current practice in order to allow the rock to 'creep' back to a state more representative of that in the reservoir. Given our results and dataset this would seem to be a more significant factor in porosity reduction measurement than simulating reservoir stresses in biaxial testing.

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APPENDIX 1

Teeuw's (1971) equation A-4 states:

$$\bar{s}_H/\bar{s}_v = \gamma/(1 - \gamma) \qquad (1)$$

where γ = Poisson ratio
$\bar{s}_H$ = effective horizontal stress
$\bar{s}_v$ = effective overburden stress

if $\gamma = .3$ then

$$\bar{s}_H/\bar{s}_v = .43 \qquad (2)$$

$$\text{since } \bar{s} = (\bar{s}_{H1} + \bar{s}_{H2} + \bar{s}_v)/3 = \left(\frac{S_{H1} + S_{H2} + S_V}{3}\right) - \alpha P \qquad (3)$$

$$\bar{s} = .62\ \bar{s}_v \qquad (4)$$

$$\text{since } \bar{s}_H = S_H - \alpha P \qquad (5)$$

$$\text{and } \bar{s}_v = S_V - \alpha P \qquad (6)$$

where α = Biot parameter
P = reservoir pressure
S_H = horizontal stress
S_v = overburden stress

if $\alpha = 0.9$ and $P = 0.43\ S_v$

$$\text{then } \frac{(S_H - .387S_v)}{(S_v - .387\ S_v)} = .43 \quad \text{(for equation 2)} \qquad (7)$$

$$\text{and } S_H = .65\ S_v \qquad (8)$$

using equation 3 assuming $S_{H1} = S_{H2}$

$$\bar{s} = 0.77S_v - .9P$$

GEOLOGICAL EVALUATION