LARGE PRESSURE DEPLETIONS IN ULTRA DEEPWATER GOM RESERVOIRS CAN SIGNIFICANTLY REDUCE NEAR WELL BORE PERMEABILITY AND PORE VOLUME

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This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Aberdeen, Scotland, UK, 27-30 August, 2012

ABSTRACT

The ultra deepwater Gulf of Mexico (GoM) Miocene and Lower Tertiary sandstone fields have pore pressures that often exceed 17,000 psi and may even exceed 25,000 psi. These conditions of high initial pore pressures allow for the potential of large pore pressure depletions to increase well productivity; however they can result in significant reduction in pore volume and permeability. Decreasing reservoir pore pressure results in a decreased oil viscosity which off sets, to some extent the reduction in rock permeability.

Laboratory measurements at true reservoir conditions including high pore pressures and large pore pressure depletions are often available for pore volume compressibility. However these test conditions are very difficult to meet when measuring transverse permeability on vertical core plugs. To mimic reservoir conditions, the uniaxial rock mechanics tests with flow are commonly performed at reduced external stresses by keeping the pore pressure low and employing the concept of effective stress. However, the effective stress path cannot duplicate the pore pressure depletion stress path for a number of reasons. Thus, one can not directly convert permeability reduction obtained in an effective stress test to reduction in permeability in a pore pressure depletion test.

The focus of this paper is to illustrate how to best predict permeability and pore volume when optimal measurement conditions of transverse permeability on vertical core plugs measurements are not available at true reservoir conditions of stress, pore pressure, and temperature. Creep data are provided to indicate that one may also need to account for the fact that laboratory measurements are completed on time scales ranging from a few hours to a few days whereas reservoir field time scales are in terms of decades.

INTRODUCTION

For the Miocene and Lower Tertiary (LT) plays in the ultra deep water (water depths > 5,000 feet) Gulf of Mexico (GoM), wells are drilled to depths in excess of 25,000 feet (7620m) and some have set depth records of about 35,000ft True Vertical Depth (TVD). Reservoir engineering challenges include pore pressures that typically exceed 17,000 psia (117 MPa) and may approach 25,000 psi. Appraisal and development wells are very expensive to drill and complete with costs well in excess of $100 million. Maximizing well productivity will require large pore pressure depletions and competent rock. Thus quantifying rock strength, pore compressibility, and permeability at reservoir conditions of pore pressure depletion are very important.

The high initial pore pressures allow for the potential of large pore pressure depletions and thus the potential for relatively significant changes in pore volume and permeability during reservoir pore pressure depletion. These very high pore pressures in the ultra deep water Gulf of Mexico cause unique challenges for rock and fluid property measurements. Pore pressure depletion/drawdown reduces permeability due to compaction from increase in net confining stress, and to increases in pore lining/throat grain volume (differential swelling) [1, 2]. Previous data indicates that the magnitudes of these two effects are potentially similar in the GoM LT rocks [3-6].

The intent of this paper is to draw reader's attention to the potential impact of very high pore pressures on pore volume and permeability measurements based on the authors' recent experience. This is supported by prior literature. Our intent is also to draw attention to the limitations in the capabilities of commercial testing laboratories that impact reservoir characterization and modeling efforts in these cases.

The literature on the effect of pore pressure on permeability is limited but has been addressed in a number of studies, with the earliest about 35 years ago.[4] Most of the prior literature involves measurements made under hydrostatic stress [1, 2, 5, 6, 7, 8]. The effect of pore pressure on GoM LT rocks were first reported five years ago [6] with hydrostatic measurements and three years ago with both hydrostatic and uniaxial measurements [3, 4]. However, due to limitations in experimental technique, these uniaxial measurements were conducted with vertical flow on vertical plugs as opposed to the desired horizontal or transverse flow on a vertical plug which would better simulate the reservoir flow direction with respect to stress.

Laboratory measurement of brine permeability as a function of confining stress and pore pressures indicate that for these LT rocks, the routine core permeability measurements at close to zero pore pressure may underestimate the in-situ rock permeability by 10% to 40% at maximum reservoir stress and pore pressure [3, 4, 5]. Also, the rate of permeability decline is observed to be greater with pore pressure depletion as compared to when pore pressure is kept constant (Figure 1 which is a replot of Figure #13 in [3]).

Data Input To Reservoir Simulators

Reservoir simulators require a table/plot of pore volume (PV) and permeability (perm) [reduction] factors versus reservoir pore pressure. Over the past half dozen years, the co-authors have been involved in obtaining PV and permeability versus stress for reservoirs in the ultradeep GoM, Miocene and LT sands. These stiff rocks displayed uniaxial pore volume compressibilities (PVC) typically between 1 and 4 microsips (1/1E06psi) and displayed a permeability reduction of about 10% to 60% for an increase in effective axial stress of 12,000 psi Typically the stiffer the rocks the less the percent of permeability reduction, but not always. Also the pore volume compressibility was relatively constant with increasing axial stress for at least the first 6,000 psi of effective drawdown, but for the second 6,000 psi there sometimes was a marked increase in compressibility (e.g. pore collapse) with further loading.

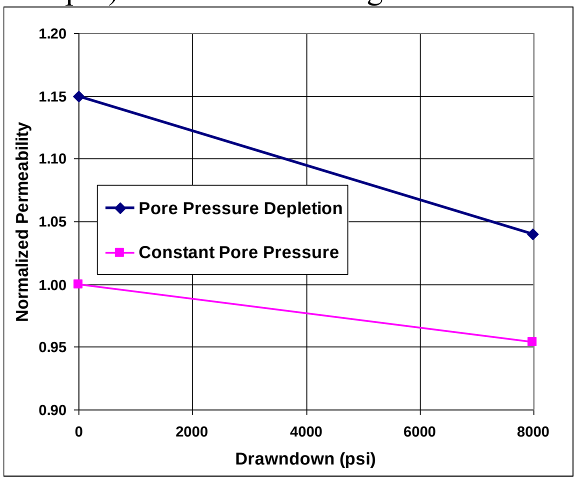

Figure 1: Stress path affects permeability response

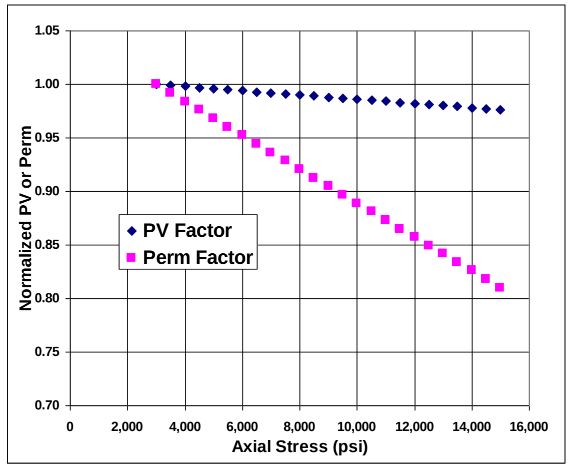

Figure 2: Pore Volume and Perm Factor versus axial Stress

Pore volume and permeability factor versus axial stress obtained from a uniaxial effective stress (low pore pressure) compaction test for rock displaying PVC (2 microsips) and permeability reduction of about 20% for 12,000 psi increase in axial stress is depicted in Figure 2. For an effective stress (ES) test to simulate the reservoir pore pressure depletion (PPD) one needs to assume that changes in axial stress can be equated to change in pore pressure. This is not the case for stiff rocks as we will explain.

The data in Figure 2 were obtained simultaneously during an “effective stress” uniaxial compaction test (low and constant pore pressure, with increasing axial stress). The use of low pore pressure for the tests was required because of limitations in experimental capabilities of Commercial Testing Laboratories. Due to a number of experimental challenges, transverse permeability measurements during a pore pressure depletion uniaxial compaction test at reservoir conditions of stresses, pore pressure, and temperature is not routinely available and attempts to this point have been considered developmental. While it is generally possible to obtain pore pressure depletion uniaxial pore volume compressibilities at reservoir stresses, pore pressure, and temperature, without flow measurements, set-ups for the addition of horizontal permeability measurements are not established at this time.

Given that the PV/Perm factors versus axial stress or inferred pore pressure data shown in Figure 2 are not obtained at reservoir conditions, both measurements need to be converted to such. Rock property measurements of PVC, permeability, velocities, etc are stress path dependent. Constant pore pressure tests are not equivalent to pore pressure depletion as grain compressibility effects cause different loading trajectories that cannot be described by a simple effective stress model. One can only mathematically convert from one stress path to another if one assumes isotropic linear elastic behavior [3, 5], but cannot predict the effect of the stress path differences on physical properties such as velocity, permeability or porosity.

Effective Stress Law

To mimic reservoir conditions uniaxial rock mechanics tests with flow are performed at low pore pressure and converted to reservoir stresses using the concept of effective stress. An effective stress law is a means to convert two variables, confining stress and pore pressure, into one equivalent variable. One such expression would be:

Rock property = f(pore pressure, confining stress) = f(Effective Stress) (1)

Effective stress = confining stress - effective stress coefficient*pore pressure (2)

Every rock property; e.g. permeability, compressibility, sonic velocities, etc., has its own effective stress coefficient (ESC) [9, 10]. This coefficient is less than 1.0 for most rock properties, but has been observed to be greater than 1.0 in some cases for permeability. From linear poroelasticity, the magnitude of ESC for bulk volume is dependent on the relative magnitude of the bulk modulus (or bulk compressibility) of the rock and grains. Rocks that have a lower bulk modulus or higher bulk compressibility tend to be characterized by ESC closer to a value of 1.0 for a wide range of properties [3,5].

Throughout this paper effective stress (low and constant pore pressure) uniaxial (radial strain is held constant) pore or bulk compressibility are defined in Table 1. The external stress (a tensor), is denoted by σ and the subscript will indicate a type or directional component (e.g. "a" for axial or vertical and "m" for average of axial and radial). Pp denotes pore pressure and Vb is bulk volume & Vp is pore volume.

Table 1: Compressibility (microsips) and Resulting ESC

C_{pca}	C_{bcm}	ESC_{bv}	C_{pcm}	ESC_{pv}
1	0.6	0.67	2	0.90
4	2.1	0.90	8	0.98

Note: Assumes $C_g = 0.20$
$C_{pca} = (1/Vp)[\partial Vp/\partial \sigma a]$
$C_{bcm} = (1/Vb)[\partial Vb/\partial \sigma m]$
$C_{pcm} = (1/Vp)[\partial Vp/\partial \sigma m]$

Biot's effective stress coefficient, "Alpha", is the ESC for total volume change (bulk compressibility) where:

Alpha or ESC_{bv} = 1- [grain compressibility (C_g)/bulk compressibility (C_{bcm})]. (3)

Carroll's [11] effective stress law for pore volume is where:

ESC_{pv} =1- [grain compressibility (C_g)/pore compressibility (C_{pcm})]. (4)

For example using typical values for the lower compressibility (C_{pca}) samples (about 1.0 microsips) in our data base, if matrix or grain compressibility is 2.0E-07 (1/psi) and the bulk compressibility to mean stress (C_{bcm}) is 6.0E-07 (1/psi), then Biot's alpha or ESC_{bv} using equation #3 would be 1-(0.2/0.6) = 0.67 (Table 1).

To better illustrate the impact of ESC's on effective stress PVC tests we have assumed a set of stresses and pore pressures. Thus, Table 2 would indicate that a ESC_{bv} of 0.67 would imply that the equivalent stresses for an effective stress test (low pore pressure) to match reservoir stresses would increase the mean effective stress from 2,400 psi (ESC_{bv} =1.0) to 9,600 psi (ESC_{bv} = 0.67). Thus to simulate 12,000 psi depletion, the axial stress would increase from 9,600 psi to 21,600 psi.

Table 2. Conversion of Reservoir Stress to Effective Stresses

Reservoir Pressures & Stresses (psi)					Effective Stresses (psi)		
Pore pres.	Total Vert.	Total horiz.	Total mean	ESC	Vertical	Horiz.	Mean
20,000	23,000	22,100	22,400	1.00	3,000	2,100	2,400
20,000	23,000	22,100	22,400	0.98	3,500	2,600	2,900
20,000	23,000	22,100	22,400	0.90	5,000	4,100	4,400
20,000	23,000	22,100	22,400	0.67	9,600	8,700	9,000

The corresponding pore volume compressibility (C_{pcm}) for the 1 microsip C_{pca} samples is about is 2.0E-06 (1/psi), thus ESC_{pv} using equation #4 is 1-(0.2/2.0) = 0.90. As we can see from Table 2, this would imply that the equivalent stresses for an effective stress test (low pore pressure) to match reservoir stresses would increase the mean effective stress from 2,400 psi (ESC_{pv} =1.0) to 4,400 psi (ESC_{pv} = 0.90). Thus to simulate 12,000 psi depletion the axial stress would increase from 5,000 psi to 17,000 psi. Tables #1 & #2 provides similar information for pore volume compressibility (C_{pca}) for the higher end range of our samples, 4.0E-06 (1/psi).

The "standard" procedure for measuring Biot's α or ESC_{bv} at the beginning of a PPD test leads to unrealistically high values. Biot's α varies during a test – assuming incrementally linear response, as shown in Figure 3A for a PPD PVC test on a rock sample with a pore volume compressibility of about 1.5 microsips. The high values of bulk compressibility and thus Biot's Alpha are at stresses significantly below reservoir stress where core plug sleeve conformance and strain calibration can be an issue. Thus at stresses above reservoir stress the average bulk compressibility is about 0.55 microsips and the average value of Biot's Alpha is about 0.65 assuming that the grain compressibility is 0.20 microsips. According to Zimmerman [12] a more direct approach to obtain Biot's Alpha is given in the equation $(\varepsilon a)/\partial\ (-Pp) = \alpha\ [(\varepsilon a)/\partial\ (\sigma a)]$. The slope of axial strain (εa) versus pore pressure as measured during pore pressure depletion PVC test or inferred during an effective stress PVC test are presented in Figure 3B. The value of Biot's Alpha obtained from the ratio of these slopes is 2.08/2.94 or 0.7 that agrees well with that calculated from the average value of the bulk compressibility in the PPD PVC test.

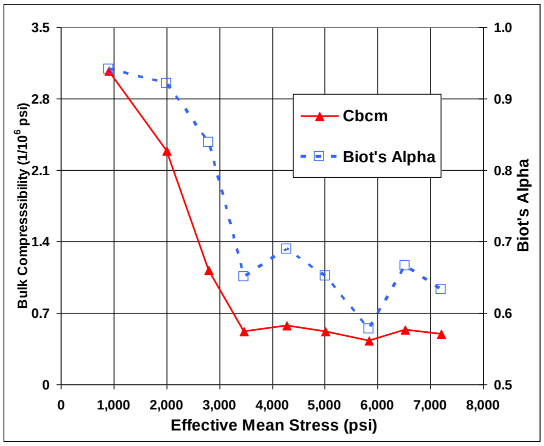

Figure 3A: Bulk compressibility and Biot's Alpha versus mean stress

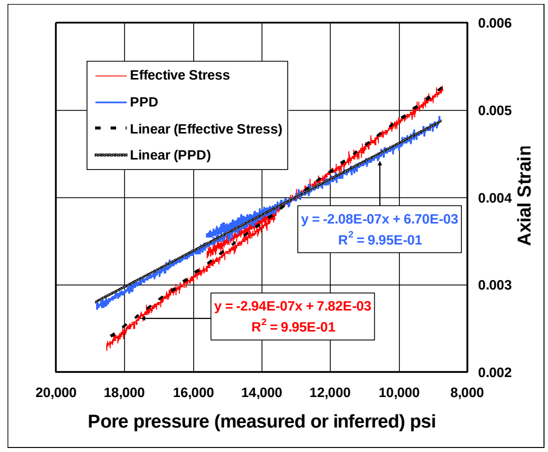

Figure 3B: Calculation of Biot's Alpha from slopes of axial strain versus pore pressure

To correctly apply an effective stress law, it is commonly assumed that one needs to design the experiments to simulate true reservoir stress conditions for the desired property. If one is most interested in PVC then ESC_{PV} would be $1-(C_g/C_{pcm})$. For higher compressibility samples (C_{pca} ~ 4 microsip), ESCpv is expected to be close to 1, while for lower compressibility samples (C_{pca} ~ 1 microsip), ESCpv can be significantly less than 1. Thus only for the lower compressibility samples (C_{pca} approaching 1 microsip) is there a clear reason to apply effective stress coefficients in calculation of what stresses to use in conducting a PVC test. For a new field, both bulk and pore volume compressibility would not be known at the start of a rock mechanics program, thus one needs results from several tests to correctly design remaining tests. Obviously if one simulates reservoir behavior with uniaxial pore pressure depletion tests, then the uncertainties introduced by application of effective stress laws do not come into play.

A few words of caution about attempting to predict a compressibility for one protocol (e.g. pore pressure depletion) based on test results from another (effective stress, low pore pressure). To do so requires adopting a model allowing one to predict deformations for the loading path of interest. If one wants to assume that the elastic constants are isotropic and independent of the loading path, then the poro-elasticity equations should be fine if used properly. Our experience with consolidated sandstones is that the linear elastic model typically does a good job of representing measured data provided stresses do not approach the yield surface for the material [3, 5]. However, if you find for example that the elastic constants measured using pore pressure depletion are systematically different from the elastic constants measured during constant pore pressure testing (and/or if there is anisotropy in elastic constants), the analysis needs to be done differently.

Pore Volume Compressibility

When flow and PVC are combined together in a single test, it is not possible to directly measure the change in pore volume to directly calculate pore volume compressibility. In such cases, pore volume strain and pore volume compressibility are commonly calculated based on the bulk strain measurements subject to corrections to account for the effects of grain compressibility (e.g. Zimmerman [12]). For the effective stress test converting measured bulk compressibility to effective stress pore volume compressibility does not provide the pore pressure depletion equivalent PVC which requires a separate conversion that is also documented by Zimmerman [12].

Time Dependent Compaction (Creep)

During the past seven years on several projects, the authors [6] have utilized PVC testing protocol such that at the end of the effective stress or pore pressure depletion PVC test, representing about 12,000 psi depletion, the stresses and pore pressure were held constant for up to 48 hours to record the strain. The measured change in pore volume during this creep portion of the PVC test, while small, is still a significant fraction of the total non-creep PV change. As shown in Figure 4, the total volumetric strain from the start of the PVC test increased by about 32% in one day of creep. In 30 years of reservoir life total volumetric strain would be extrapolated to increase by about 190%, thus nearly tripling the delta PV observed during the non creep portion of the laboratory test. Thus we found that accounting for creep at maximum depletion could increase the total volumetric strain by about 50% (C_{pca} ~ 1E-06 psi^{-1}) to 200% (C_{pca} ~ 4E-06 psi^{-1}) and in some cases the samples even crept into failure. The two parameter creep model [13] used to fit the creep data shown in Figure 4 is given in equation #5.

$$100(\text{creep } \Delta PV/\text{total non creep } \Delta PV) = \text{constant}*\text{Log10}(1+\text{creep duration}/\text{time constant}) \qquad (5)$$

Thus accounting for creep may potentially triple the PV factor at large pore pressure depletions (12,000 psi) in terms of reservoir time scale and because of the link between PV and perm, this time dependent strain has potentially to significantly impact the permeability reduction. While this model does an excellent job of fitting the observed creep data for up to 48 hours, there is no guarantee that it will be accurate out to 11,000 days or about 30 years.

The magnitude of creep is dependent upon the temperature, stresses, and the fluid saturations [13]. At elevated temperature and high pore pressures and stresses, these GoM stiff rocks have the potential to experience stress corrosion cracking interaction (and/or other rock-water interactions), resulting in higher PVC then 100% oil saturated samples or tests conducted at ambient temperatures whether oil or brine saturated. Previous studies by co-authors [6] has indicated that either 100% brine or connate water saturation are equally effective at introducing these chemical effects on creep. The magnitude of creep is also significantly impacted by the magnitude of the pore pressure depletion. The relative contribution of creep at 6000 psi pore pressure depletion is about a third of that at 12,000 psi pore depletion. Also it is our observation that the magnitude by which the pore volume compressibility increases (non-linear) with axial stress (ES test) or pore pressure (PPD) correlates to the magnitude of the creep at the end of the loading ramp.

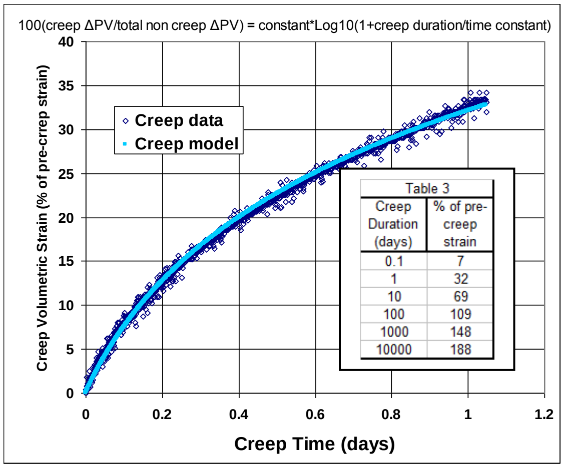

Figure 4: Creep Modeling

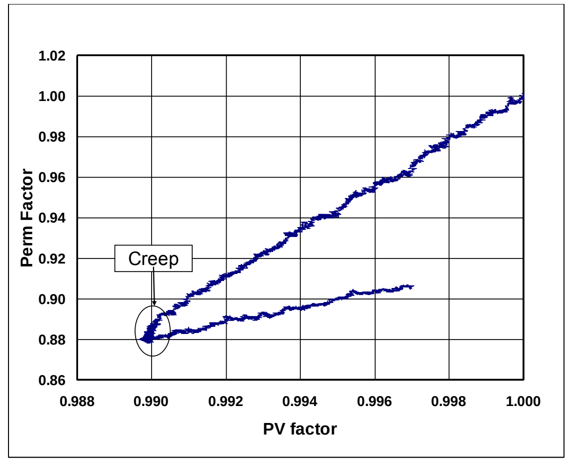

Figure 5: PV Factor versus Perm Factor

It is possible to obtain both PVC and permeability data with an effective stress uniaxial PVC test at ambient temperature. As just mentioned, the measurement of creep at the conclusion of an ambient temperature PVC test does not provide an accurate measurement of creep (time dependent compaction) at reservoir conditions. Thus the preferred and direct approach is to obtain pore pressure depletion PVC data with no flow data at reservoir conditions of stresses, pore pressures, and temperature with core sample at connate water saturation or 100% brine saturation and measure creep at the conclusion of the PVC test. If this is not possible then a reservoir temperature effective stress PVC test should be used. This approach requires effective stress PVC and permeability measurements at ambient temperature on a companion core plug to obtain relevant permeability data versus axial stress.

Permeability Factor

Because commercial testing laboratories typically can only measure permeability at low and constant pore pressure, the measurements reported here were obtained from an effective stress PVC test at constant pore pressure as illustrated in Figure 2. The main experimental difficulty in measuring transverse permeability during a PPD test is being able to port the inlet and outlet flow lines through core plug jacket in such a way to maintain a well defined geometry of the flow boundary condition that is not affected by changes in effective stress. This is not as much as an issue when the flow axis coincides with the long axial of the core plug.

PV Factor versus Permeability Factor

A nearly linear relationship is observed if normalized permeability factor is plotted against PV factor from the effective stress PVC data (Figure 5). Such a cross-plot is a good QC for detecting if the viscosity of the oil (working fluid) used in flow measurement is correctly accounting for temperature changes in the core sample. With laboratory temperature fluctuations observed of nearly +/- 2F and a 1% change in viscosity per 1°F, this small temperature driven viscosity variation has a large impact of the reported perm when the perm reduction is only 10% for a 12,000 psi increase in axial stress.

The PV Factor versus Permeability Factor for the creep portion of the PVC test is highlighted in Figure 5. If one assumes that this PV to permeability relationship (Figure 5) is constant for the loading ramp, we can predict the Perm Factor for creep behavior to account for the difference in time scale between lab tests and reservoir drawdown. A close inspection of the plot of PV factor versus Permeability Factor shows that the slope of the creep portion has a slightly steeper slope than the depletion portion, and thus this assumption may understate permeability decline during creep.

RESULTS

Correcting PV and Permeability Factors to Reservoir Conditions

If both PV factor and Permeability factor are obtained from a single effective stress test, then the PVC calculated from the measured C_{bca} will need to be converted to the equivalent PPD PVC. This conversion typically represents about a 10 to 20% increase in PVC and thus an equal magnitude decline in PV Factor will occur. If PV factor is obtained from the preferred pore pressure depletion PVC test at reservoir temperature then no conversion is required.

The second correction and the one with the far greater impact is for time dependent portion of the compaction (creep) which has the potential to triple the predicted pore volume compressibility and, by inference, the permeability reduction. However, as already stated, creep data should come from PVC tests (either effective stress or preferably PPD) conducted at reservoir temperature using core samples at connate water saturation or 100% brine saturated. The magnitude of the creep contribution to the effective PVC is dependent on the extent of pore pressure depletion. Thus our approach has been to assume that the contribution of creep to the pore volume compressibility exponentially increases from zero at zero depletion to the measured creep at 12,000 psi depletion (Figure 4 and Table 3 within Figure 4). To be conservative we have only use the projected creep out to a reservoir life of 100 days, about 100% of the pre-creep strain, which is about 50% of the total creep for 30 years based on data presented in Table 3.

The permeability and PV factors presented in Figure 2 that were obtained from an effective stress test at ambient temperature have been corrected for reservoir conditions of temperature, stress path (PPD), and reservoir time scale. These corrections are based on the methodology presented in this paper. Figures 6A and 6B summarize these corrections. Figure 6A is a plot of inferred reservoir pressure versus PV Factors: uncorrected PV Factor is corrected for increase in PVC resulting from ES to PPD conversion, and then added to this creep correction. Figure 6B is a plot of inferred reservoir pressure versus Permeability Factors; uncorrected Permeability Factor, corrected for increase in PVC resulting from ES to PPD conversion, adding to this creep correction, and finally adding in correction for ES to PPD permeability decline. These estimates of corrections required on typical lab measurements are provided to focus attention on the importance of obtaining accurate pore volume and permeability data at reservoir conditions of temperature, stresses, and pressures and account for the difference in time scale between lab and reservoir.

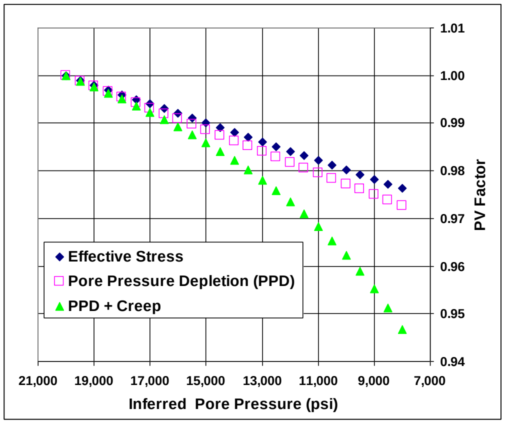

Figure 6A: PV Factor versus Pore Pressure

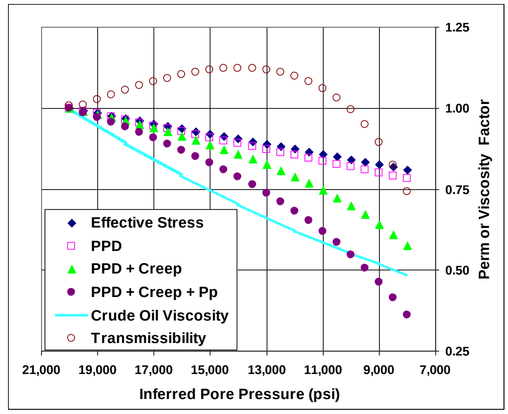

Figure 6B: Perm Factor versus Pore Pressure

Figure 6B also plots the relative viscosity response of a typical crude oil with decreasing pressure but assuming constant reservoir temperature. For the first 10,000 psi pore pressure depletion, the viscosity is decreasing faster than the permeability decline for this example and thus the transmissibility of the rock is greater than at in-situ conditions. Figure 6B also plots the relative transmissibility (permeability decline versus viscosity decline) that indicates that the relative transmissibility peaks at about 7,000 psi pore pressure depletion.

The stress path impact on permeability response correction was the subject of several papers mentioned in the introduction. In some cases, we have found that the rate of permeability decline for a pore pressure depletion tests was twice that of an effective stress test (Figure 1). The core material that was used for this permeability versus stress & pressure tests cited in these references is from the same sand unit as those for Figures 4, 6A & 6B. However, instead of doubling the rate of permeability decline we have elected to use 150% decline. Please recall as stated in the introduction that these laboratory tests had measured the change in vertical permeability during a uniaxial PVC test on a vertical plug as opposed to a transverse permeability which would more accurately represent reservoir conditions. Since non-hydrostatic changes in stress (e.g. $\Delta\sigma_a \neq \Delta\sigma_r$) will generally result in non-isotropic changes in the petrophysical properties such as permeability, we have elected to discount the correction by half to be conservative.

SUMMARY

The primary objective of this paper has been to illustrate that PV and Perm Factors obtained from an ambient temperature effective stress (low and constant pore pressure) uniaxial PVC test may greatly underestimate the PV and permeability decline during pore pressure depletion that would actually occur in the reservoir at large drawdowns that would be experience by the near-wellbore region.

We have shown that the two largest potential corrections to effective stress data that impacts permeability decline are creep and the effect of pore pressure. Both of these are likely to be influenced by rock mineralogy and location of ductile grains. Obviously reservoir temperature PPD PVC laboratory tests with simultaneous transverse flow measurements for permeability best simulate the reservoir conditions. If this is not available then at a minimum an ambient temperature ES PVC test to obtain permeability data coupled with a reservoir temperature PPD PVC lab test with creep but no flow measurements is required to obtain effective pore volume compressibility data that simulate reservoir time scale.

Given that we have very limited data on the magnitude of the ESC_{perm}, [14] and it will be rock specific, then the potential impact of pore pressure on permeability might best be treated with a sensitivity analysis until such data does become more readily available.

Future Challenges

The following items are identified as deserving attention by the Core Analysis/Rock Mechanics Service companies:

- There is a great need for transverse permeability measurements during PPD PVC tests so estimated correction factors are not required.
- There is a need to obtain creep data versus extent of pore pressure depletion to project PV factors out to reservoir time scale at all magnitudes of drawndowns.
- There is a need to extend ESC_{perm} to inelastic regime (creep, pore collapse).
- Hopefully sometime in the near future we will be able to simulate with digital rock data the impact of pore pressure on permeability that we can not conveniently measure in the lab at true reservoir conditions.

Related Issue

Rock mechanics tests to obtain data for well completion are all effective stress tests with zero pore pressure and typically assume that Biot's effective stress coefficient, alpha, is very near one, but the measured value at reservoir stress conditions are potentially significantly lower, 0.7. This could potentially impact well completions rock mechanics data interpretations. It should also impact the calibration of the log derived Poisson's ratio and Young's modulus since compressional and shear velocities have different ESC's and thus effective stress collection of static and dynamic properties will not reflect reservoir conditions of stresses and pore pressures.

ACKNOWLEDGEMENTS

The authors thank Noble Energy and NER for their support and approval to publish this paper. Shafer and Boitnott acknowledge Terry Miller's contributions during past decade.

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