SCA2003-62: CALCULATING IN SITU STRESSES IN OVERPRESSURED SETTINGS

Terry Miller[1], and John Shafer[2]
[1]Geomechanics and Testing Analysis, 3202 Cypress Pt. Missouri City, TX, 77459, USA
[2]Reservoir Mangement Group, 15602 Winmoss Court, Houston, TX, 77068, USA

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ABSTRACT

Accurate porosity and permeability measurements and rock mechanics tests, e.g., for reservoir compressibility, depend on correct estimates of the in situ reservoir stresses. These stresses, in turn, depend on the reservoir's burial depth, its burial history, and the magnitude and history of pore pressures. This paper concentrates on the effects of the magnitude of excess pore pressures and pore pressure history on reservoir stresses.

The development of the high overpressures typically encountered in the deepwater GOM wells are either post burial or were developed during burial. These two different scenarios can result in large differences (as much as 100%) in the in situ reservoir stresses one calculates. These differences are due to the fact that rocks exhibit different stress-strain responses during burial when the stresses equal the maximum stress experienced or when they become overpressured at a constant depth. In the former, the horizontal in situ stresses will always be less that the vertical stress; and in the latter horizontal stresses can exceed the vertical stress.

Examples will be given for both pore pressure development scenarios. These examples will show that the in situ stresses for either case can be quite different even though the vertical stresses are the same. Incorrect assignment of the in situ stresses can potentially have a significant impact on the porosity-permeability data obtained during core analysis and the pore volume compressibility used for reservoir simulation obtained during rock mechanics tests.

INTRODUCTION

Routine core analysis porosity and permeability measurements are typically obtained at a hydrostatic equivalent stress of the reservoir in situ stresses. Often the core porosities are used to verify or calibrate log-derived porosities. Thus it is important when working with unconsolidated sands and high- porosity rocks (carbonates and sands) for one to accurately know the magnitude of the in situ stresses.

Rock mechanics measurements are use to determine rock strength for well bore stability and sand production studies. The type of well completion can be influenced by reservoir stresses. If, the horizontal stress exceeds the vertical stress as can occur in some overpressure environments, then fractures will be horizontal and not vertical in a frac pack completion. The magnitude of the pore volume compressibility, an essential input to reservoir simulation, can be quite sensitive to the stress path taken during pore pressure depletion; the starting point of which is the in-situ stress.

The purpose of this paper is to review simple initial stress calculations and then to review the different overpressuring mechanisms and their stress effects. Finally, we provide a procedure in overpressured rocks.

RESULTS AND DISCUSSION

Reservoir stresses are calculated on an effective stress basis as shown in equations 1 & 2. [1, 2, 3]

Effective stress (σ) = Total stress (s) – Pore pressure (p), or $\sigma = s - p$ (1)

Mean effective stress, $\sigma_m = (\sigma_v + \sigma_H + \sigma_h)/3 = (s_v + s_H + s_h)/3 - p$, (2)

The σ_H and σ_h are the major and minor horizontal (assumed to be) principal stresses, respectively.

The steps to obtain in situ stresses are as follows:

1. Assume compaction is a one-dimension process.
2. Calculate the overburden stress, s_v, by integrating a bulk density log, using seismic data, and honoring low density data for near-mudline sendiments. Typically, in offshore wells there are no density log data for the first 1000 to 2000 feet and a compaction curve from the mud line to the start of density log data is required. For cases where no density log data are available and seismic velocity data are used to estimate densities, a compaction curve from the mudline to about 1500 feet below the mudline is advisable to account for the poor resolution of density versus velocity formulations for velocities that are near that of water.
3. Determine minimum horizontal stress, s_h, from leak-off-tests (LOT's), minifrac, or lost-returns data. Typically, one assumes that minimum stress from the leak-off-test is a horizontal stress, but as will be illustrated later it may be the vertical stress.
4. Use measured or calculated pore pressure to determine σ_v and σ_h.

If no leak-off-test data are available, then s_h can be estimated using the inelastic "property" k_o, the coefficient of earth stresses at rest. When modeling sediment compaction using elastic/workhardening plastic models, this coefficient, k_o, is determined only in uniaxial strain tests with zero lateral strain and is equal to σ_h/σ_v.

$\sigma_h = ko*\sigma_v$ (3)

Typically k_o, σ_h/σ_v, is about 0.6 in sands and about 0.8 in shales. We do not consider it appropriate to use the ***elastic*** property, Poisson's ratio (ν), to calculate σ_h for an ***inelastic*** compaction process. This assumption is consistent with a sediment's irrecoverable porosity decreases during burial and the stresses estimated this way are more consistent with leak-off-test data in deepwater Gulf of Mexico wells.

Assess Overpressuring Mechanism

The examples presented here consider two principal overpressuring mechanisms, "Compaction Disequilibrium" and "Source" [2]. Figure 1 is a cartoon depicting these two mechanisms. Overpressure is any pressure in excess of the local hydrostatic pressure. In the case of compaction disequilibrium (CDE), overpressures occur when pore fluids being expelled from a compacting rock cannot escape the compacting rock mass fast enough to maintain pressure equilibrium with the hydrostatic gradient. In this mechanisme, the effective stresses arealways increasing and the vertical stress will always exceed the horizontal stress. Consequently, the current effective stresses are the maximum effective stresses experienced by the reservoir. Calculation of the effective stresses can use the same equations as for those cases where there is no overpressure, including equation #3.

In the "Source" mechanism, the pore volume increases either due to expansion of the pore fluid or from active flow of fluid into the rock pores, Figure 1. The effective stresses decrease in this case; thus the current effective stress is less than the maximum stress experience by the sands. The calculation of the effective stresses in overpressure regimes can use equations #1 & #2 as for those cases where there is no overpressure. However, for the "Source" regime, measurement of the horizontal stress is more difficult and one may need to estimate it. In addition, equation #3 that was appropriate for the CDE regime cannot be used. The estimation of the horizontal stress for this case is discussed later in this paper. [2]

To illustrate the differences between these two overpressureing mechanisms, we have generated a "conceptual" reservoir model. It is located offshore with a water depth of 5,000 ft, and the reservoir sands of interest are at 22,000 ft TVD. A plot of effective stress versus depth for both cases is provided in Figure 2. The pressure and stresses at 22,000 ft in Figure 2 for the two cases are also summarized in Table 1. Overpressure begins just below the mud line for compaction disequilibrium (CDE), while for the "source" over pressure begins at maximum burial depth. The effective stresses for CDE are always increasing, while for the "source" the effective stresses increase to maximum burial depth and then decrease with the onset of overpressure. The vertical effective stress is always greater than the horizontal effective stresses for the CDE case, but during overpressure generation in the "source" case the horizontal effective stress can eventually exceed the vertical effective stress.

Although the vertical effective stresses and the pore pressures are the same in both overpressure cases, the horizontal stresses are different. These different horizontal effective stresses result in a significant difference in the mean effective stress, 1153 psi in the CDE case versus 2156 psi for the Source case.

In Situ Stresses in Regimes Overpressured by Source Mechanisms

The overburden and vertical effective stress are as described earlier (s_v and σ_v) except one needs to identify maximum previous effective stresses (σ_{vmax} and σ_{hmax} = ko * σ_{vmax}) based on burial history models or geologic reasoning. [1, 2 ,3] The following two equations, 4 & 5, account for the change in effective stress due to the "unloading" of the reservoir due generation of overpressure. In this case, elastic models of sediment behavior are justified. It then follows for one-dimensional strain

$$\Delta\sigma_v = \sigma_{vmax} - \sigma_v; \qquad (4)$$
$$\sigma_h = \sigma_{hmax} - (\nu/(1-\nu))\,\Delta\sigma_v \qquad (5)$$

The "source" overpressure causes the effective stresses to decline, thus the rock is "unloaded" and will likely behave elastically. Thus the ***elastic*** property, Poisson's ratio (ν) is used to calculate the magnitude of horizontal stress change during unloading.

To understand the impact of the two overpressure mechanisms on subsequent reservoir pore pressure depletion one can compare the shear stress parameter, Q, σ_v - σ_h, versus mean stress, σ_m, in a stress path plot, Figure 3A. The curved lines are the boundary between elastic behavior to the left of the line and plastic or non-elastic behavior to the right of line. Rock that has experienced CDE overpressure is at its maximum effective stress, thus any pore pressure depletion will result in a stress path to the right of the current yield surface and inelastic compaction (the upper arrow in Figure 3A). The pore volume compressibilities versus mean effective stress are depicted as dotted arrow in Figure 3B.

The reservoir rock for the "source" overpressure regime, lies below the horizontal axis, σ_m, since the shear stress, σ_v - σ_h, is negative because the horizontal effective stress exceeds the vertical effective stress. The yield surface for the "source" regime is the curve line furthermost from the origin since this rock has experienced larger effective stresses than the CDE regime, Figure 2 and Table 1. The stress path for these rocks with reservoir depletion is shown as the solid arrow in Figure 3A. The pore volume compressibility for this regime would be lower initially since the rock starts to the left or elastic side of the yield surface and increases after it crosses the yield surfaces, Figure 3B.

CONCLUSIONS

To correctly calculate in situ stresses in an overpressure regime one needs to determine which of the two possible overpressured environments are involved, compaction disequilibrium or "source". These two overpressure regimes affect stress conditions differently and we have provided ways to estimate in situ effective stresses for both.

These two overpressure regimes, while they have the same pore pressure and burial depth, can have very different resulting pore compressibilities.

REFERENCES

1. Miller, T. W., “New Insights on Natural Hydrauliuc Fractures Induced by Abnormally High Pore Pressures”. AAPG Bulletin, **79** (7): p 1005-1018 (1995).

2. Miller, T.W., Luk, C. H., and Olgaard, D. L., The Interrelationships between Overpressure Mechanisms and In-Situ Stresses”, in *Pressure Regimes in Sedimentary Basins and Their Prediction*, 2002, AAPG Memoir 76, edited by Huffman, A. R. and Bowers, G. L. Chapter 2. p. 13-20.

3. Bowers, G. L., “Detecting High Overpressure”. The Leading Edge. Feb., p. 174-177 (2002).

TABLE 1: Reservoir Stressess for the Two Types of Overpressure									
					Current		Maximum		
Type of Over pressure	Depth	P_p	s_v	s_h	σ_v	σ_h	σ_v	σ_h	σ_m
	(ft)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)	(psi)
CDE	22,000	17,630	19,070	18,640	1,440	1,010	1,440	1,010	1,150
Source	22,000	17,630	19,070	20,120	1,440	2,505	8,880	6,215	2,155
NOTE: These stress values are from the conceptual model whose results are displayed in Figure 2.									

FIGURES

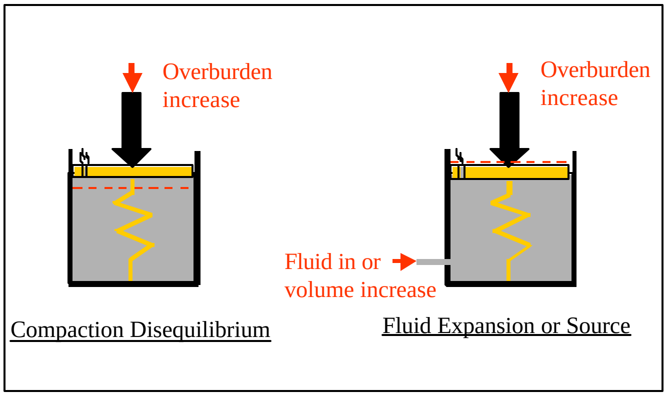

Figure 1: Overpressure Mechanisms

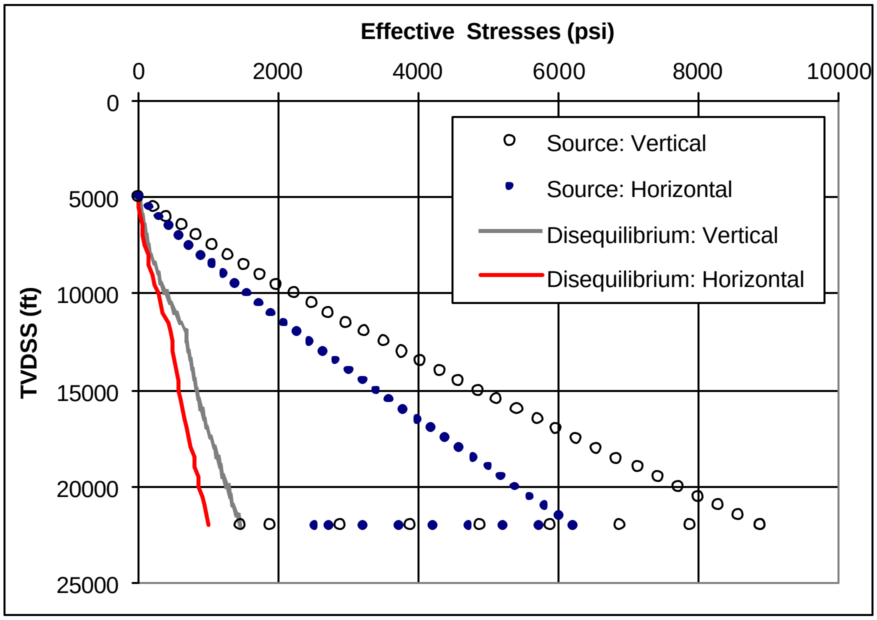

Figure 2: Effective Stress versus Depth in Different Overpressure Regimes

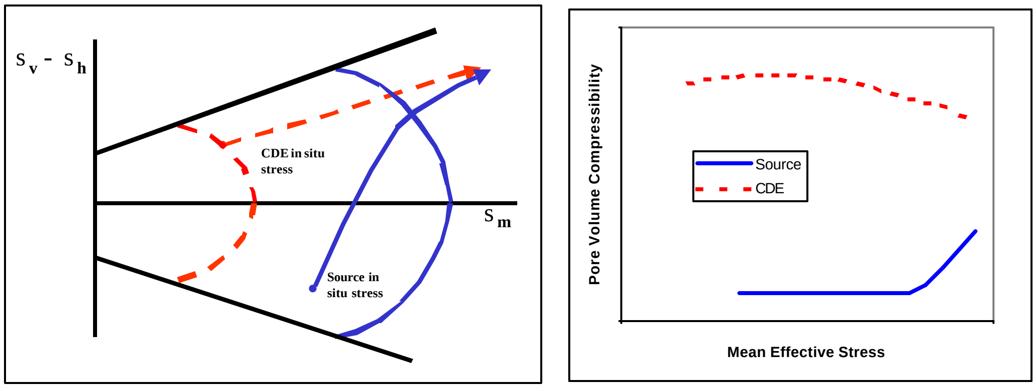

Figure 3: Stress Path Plot for Initial Reservoir Stresses and1-D Pore Volume Compressibility. Dashed line for stress path and yield surface for rock from compaction disequilibrium overpressure regime. Solid line for stress path and yield surface for rock from source overpressure regime.