Well-constrained seismic estimation of pore pressure with uncertainty

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Summary

A quantitative predrill prediction of formation pore pressure with uncertainty is needed for safe, cost effective drilling in overpressured areas. This paper describes the use of a 3D probabilistic Mechanical Earth Model (MEM) that combines well data with seismic velocities to predict pore pressure and uncertainty. Application is made to an overpressured area in the Gulf of Mexico. Parameters in the velocity-to-pore-pressure transform are estimated using seismic velocities plus density logs, pressure data, and well velocities obtained by inverting time-depth pairs from checkshots in the area. A prediction of pore pressure and uncertainty is made by sampling the region of parameter space consistent with available well data.

Introduction

To safely drill a deep well for hydrocarbon exploration or production, it is important to maintain the wellbore pressure between the formation pore pressure and the maximum pressure that the formation can withstand without fracturing (Bourgoyne et al., 1986). This task is made more difficult when drilling in overpressured areas, which require a quantitative predrill prediction of pore pressure with uncertainty to be made (Sayers et al. 2002, Doyen et al. 2003, Malinverno et al. 2004). A predrill estimate of pore pressure can be obtained from seismic velocities using a velocity-to-pore-pressure transform calibrated with offset well data. However, the uncertainty in pore pressure is often not quantified. In this example from the Gulf of Mexico, seismic velocities with uncertainty, derived by den Boer et al. (2006) by combining seismic velocities with well data, are used. Parameters in the velocity-to-pore-pressure transform are estimated by using seismic velocities together with density logs, pressure information, and well velocities obtained by inverting time-depth pairs from checkshots in the area. Pore pressure and associated uncertainty are then predicted by sampling the region of parameter space consistent with available well data.

Seismic pore pressure prediction

Elastic wave velocities in rocks increase during loading due to porosity reduction and increased grain contact. However, if the rate of sedimentation exceeds that of pressure equalization in the pore space, or if dewatering is inhibited by the formation of seals during burial, the pore fluid becomes overpressured and thus supports part of the overburden load. Since any increase in pore pressure above the normal hydrostatic gradient reduces the amount of compaction that can occur, elastic wave velocities can be used to predict pore pressure. This was first demonstrated by Hottman and Johnson (1965) using sonic velocities, and by Pennebaker (1970) using seismic velocities. In this paper, it is assumed that elastic wave velocity is a function only of the vertical effective stress $\sigma$, defined by:

$$\sigma = S - p.$$  \hspace{1cm} (1)

Here, $p$ is pore pressure and $S$ is total vertical stress, which is assumed to be given by the combined weight of the rock matrix and the fluids in the pore space overlying the interval of interest:

$$S(z) = g \int_{z_0}^z \rho(z)dz.$$ \hspace{1cm} (2)

Here, $\rho(z)$ is the density at depth $z$ below the surface, and $g$ is the acceleration due to gravity.

If the relation between elastic wave velocity and vertical effective stress is known, pore pressure, $p$, may be calculated from equation (1), using equation (2) to calculate the total vertical stress. In this paper, the approach of Eaton (1975) is employed. This method is widely used in the industry and estimates the vertical component of the effective stress $\sigma$ from the seismic velocity $v$, via the relation:

$$\sigma = \sigma_{\text{Normal}} \left( \frac{v}{v_{\text{Normal}}} \right)^n.$$ \hspace{1cm} (3)

$\sigma_{\text{Normal}}$ and $v_{\text{Normal}}$ in equation (3) are the vertical effective stress and seismic velocity expected if the sediment is normally pressured, while $n$ is an exponent that describes the sensitivity of velocity to effective stress. The pore pressure is then obtained from equations (1) and (3) as:

$$p = S - \left( S - p_{\text{Normal}} \right) \left( \frac{v}{v_{\text{Normal}}} \right)^n \hspace{1cm} (4)$$

To use Eaton's method, the deviation of the measured velocity from that of normally pressured sediments, $v_{\text{Normal}}$, must be estimated. Here, we assume a linear variation with depth, given by:

$$v_{\text{Normal}}(z) = v_0 + kz \hspace{1cm} (5)$$
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where \( z \) is depth measured from the seafloor and \( v_0 \) is the velocity of sediments at the seafloor. Typical values of the vertical velocity gradient \( k \) lie in the range \( 0.6 \) to \( 1 \) \( \text{s}^{-1} \) (Xu et al. 1993).

To determine pore pressure from seismic velocities, the velocity-to-pore-pressure transform must be calibrated using available pressure measurements, and the density data must be integrated to determine the variation in vertical stress versus depth. In the example described below, pressure measurements from permeable layers in the area of interest are used to calibrate the velocity to pore pressure transform.

**Calibration of the velocity-to-pore-pressure transform**

The dataset described in this paper is located in an overpressured region of the Gulf of Mexico. Figure 1 shows the wells in the area for which data were available, together with a seismic-constrained velocity field (den Boer et al., 2006), derived by trend kriging inverted time-depth pairs from checkshots in the area, using a seismic velocity cube as a 3D trend. The resulting trend-kriged velocity estimate honors the check-shot velocities at the wells, and reverts smoothly to the tomographic seismic velocity as distance from the wells increases beyond the assumed spatial correlation range.

![Figure 1. Wells for which mud weights are available in the area of interest, together with a 3D velocity model obtained by trend kriging the inverted check-shots using the seismic velocity cube as a 3D trend. Scale bar is in ft/s.](image)

Pressure information in the area was obtained from mud weights and from direct measurements of formation pressure in permeable zones. Figure 2 shows the available mud weight data together with the best estimate of velocity at the mud weight data locations.

![Figure 2. Velocity best estimate values and wellbore pressures at the depths of the available mud weights.](image)

Mud weights represent an imperfect estimate of pore pressure. They are most reliable when it is clear from drilling records that mud density has been increased in response to increased gas levels at a given depth. The pore pressure can then be deduced from the mud weight required to prevent gas from entering the wellbore. Mud weights are usually higher than the pore pressure, but may be lower in shale intervals if the well is drilled underbalanced with no formation fluids entering the wellbore. For these reasons, direct pressure measurements were used to calibrate the velocity-to-pore-pressure transform, even though such measurements were far fewer in number.

To calculate the total vertical stress needed for calibrating the velocity-to-pore pressure transform, a 3D model of subsurface bulk density, \( \rho \), was constructed. This assumed an empirical relation between density and depth below mud-line, specifically designed to fit representative Gulf of Mexico density data (Traugott 1997):

\[
\rho(z) = a + bze^c.
\]

Here, \( z \) is depth below the mudline, and \( a, b, \) and \( c \) were determined using the available density data. Vertical (overburden) stress was then obtained by integrating this density function from the mudline to the depth of interest and adding the vertical stress contributed by the water column. Uncertainty in vertical stress was estimated numerically by integrating multiple stochastic density simulations, assuming a constant density error of \( \pm 3\% \). The average vertical stress uncertainty is thus found to be of the order of \( \pm 1\% \). Compared to the error in seismic velocity, vertical stress uncertainty represents a relatively small proportion of the corresponding uncertainty in pore pressure (Doyen et al., 2003).
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The normal pore pressure $p_{\text{Normal}}$ was assumed to follow hydrostatic gradients of 0.455 psi/ft above the mud-line and 0.465 psi/ft below, consistent with other published Gulf of Mexico studies (Bourgoyne et al., 1986). Eaton’s exponent $n$ was assumed to lie between 3 and 5, while the velocity associated with normally compacted sediments $v_{\text{Normal}}$ was assumed to be given by equation (5). The velocity-depth gradient $k$ was assumed to take a value between 0.5 and 0.7 s$^{-1}$, while the initial velocity $v_0$ was assumed to lie between 4,800 and 5,600 ft/s.

Using a 3D grid-based optimization procedure (Sayers et al., 2002), the numeric ranges of parameters $v_0$, $k$, and $n$ were determined via root-mean-square (rms) analysis of the residuals $\Delta p = p_{\text{meas}} - p_{\text{pred}}$:

$$
\Delta p_{\text{rms}} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \Delta p_i^2},
$$

(7)

Here, $p_{\text{pred}}$ is the predicted pore pressure, $p_{\text{meas}}$ is the measured pore pressure, and $N$ is the number of pore pressure measurements. Using this procedure, a discrete list of feasible triplet combinations of $v_0$, $k$, and $n$ was determined. This list of triplets corresponds to a volume of $v_0$, $k$, and $n$ parameter space, implicitly accounting for complex intercorrelations between these parameters. Figure 3 shows a comparison of the measured pore pressure with that predicted by equation (4) in which the values of $v_0$, $k$, and $n$ that minimize equation (7) were used. Figure 4 compares the measured pore pressure with the pore pressure predicted at the location of the mud weight data. Figure 5 compares the predicted pore pressure at the location of the mud weight data with the wellbore pressures calculated using the reported mud weights. It is seen that while most of the reported mud weights are higher than the predicted pore pressure, some mud weights are lower; this suggests that the wells were being drilled underbalanced at these locations.

Prediction of pore pressure with uncertainty

Using an efficient Fast Fourier Transform Moving Average (FFT-MA) implementation of the Sequential Gaussian Simulation (SGS) technique (Le Ravalec et al. 2000), a set of 1,000 spatially correlated simulations was generated for both velocity and vertical stress. For each pair of spatially correlated simulations, a suite of pore pressure realizations was then computed from Eaton’s equation by employing every $v_0$, $k$ and $n$ triplet in the list of feasible combinations. From the resulting expanded set of pore pressure realizations, an experimental probability density function (pdf) was derived for each cell in the 3D model. Summary statistics, including the mean (best estimate), deviation (expected uncertainty) and standard percentiles ($P_{10}$, $P_{50}$, $P_{90}$), were then inferred from each pdf. Figure 6 shows the 3D pore pressure best estimate thus obtained; Figure 7 shows the corresponding uncertainty.
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Figure 6. 3D pore pressure best estimate. Scale bar is in lbm/gal.

Figure 7. 3D pore pressure uncertainty. Scale bar is in lbm/gal.

Conclusion

A predrill estimate of formation pore pressure can be obtained from seismic interval velocities by employing a velocity-to-pore-pressure transform. However, seismic velocities should be derived using a method that delivers sufficient spatial resolution for predrill well planning. By combining seismic interval velocities with well velocities, a refined velocity field with uncertainty can be obtained that honors available well velocities and thus can be used to more reliably predict pore pressure in an area of interest. The method involves identifying the region of parameter space consistent with the available data and performing stochastic simulation to estimate the local pore pressure distribution within each cell of the model. Data obtained while drilling may be used to constrain the acceptable region of parameter space, so that the best possible pore pressure prediction can be made ahead of the bit, based on drilling information and seismic velocities.

References


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EDITED REFERENCES
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