Use of reflection tomography to predict pore pressure in overpressured reservoir sands

Summary
A pre-drill estimate of pore pressure is important for drilling in overpressured areas. In this presentation, seismic velocities obtained using reflection tomography are used to predict pore pressure over an area which contains several distinct pressure cells with pressure differences as large as 3000 psi. The velocity to pore pressure transform used is calibrated using an extensive data set from wells in the area.

Introduction
Pore pressure can be predicted from seismic velocities using a suitable velocity to pore pressure transform. Prior to the work described below, good quality seismic data had been used to perform a pre-stack depth migration over an area containing several overpressured reservoirs, and was based on seismic velocities determined using reflection tomography. Reflection tomography (Stork, 1992; Wang et al., 1995; Woodward et al., 1998) replaces the low resolution layered medium and hyperbolic moveout assumptions of conventional velocity analysis methods with a more accurate ray-trace modeling based approach. Examples of the use of tomographic inversion for pore pressure prediction in shales include those of Lee et al. (1998) and Sayers et al. (2002). In the work described below, these velocities are used to predict pore pressure in the various reservoir units in this area.

The sensitivity of the elastic wave velocity to changes in stress and pore pressure is demonstrated by comparing logs from the same formation containing similar fluids at different depths and reservoir pressure. To perform this comparison, it is assumed that velocity is a function of the vertical effective stress, \( \sigma \), which is defined by

\[
\sigma = S - p
\]

where \( p \) is the pore pressure and \( S \) is the total vertical stress.

Pore pressure was obtained from RFT measurements. An example of the RFT data available is shown in Figure 1, which shows RFT measurements for a well with an oil/water contact.

![RFT data for a well in the study area showing an oil/water contact.](image)

Figure 1. RFT data for a well in the study area showing an oil/water contact.

The vertical component of the total stress, \( S \), at any point is assumed to be given by the combined weight of the rock

Variation of velocities with pore pressure and stress
Elastic wave velocities in rocks increase during loading due to a reduction in porosity and an increased contact at grain boundaries. Since any increase in pore pressure above the normal hydrostatic gradient reduces the amount of compaction which occurs, elastic wave velocities may be used for pore pressure prediction. This was first demonstrated by Hottman and Johnson (1965), using sonic velocities, and by Pennebaker (1970) using seismic velocities. In the following, it is assumed that the elastic wave velocity is a function only of the vertical effective stress, \( \sigma \), which is defined by

\[
\sigma = S - p
\]

where \( p \) is the pore pressure and \( S \) is the total vertical stress.

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matrix and the fluids in the pore space overlying the interval of interest. This may be calculated from an integral of density as follows:

\[ S = g \int_0^z \rho(z) \, dz \] . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . (2)

where \( \rho(z) \) is the density at depth \( z \) below the sea surface and \( g \) is the acceleration due to gravity.

In order to calculate the vertical stress \( S \) away from the calibration wells, a density cube covering the area of interest was constructed by combining available density logs in the study area with the interfaces in the seismic velocity model obtained using reflection tomography.

Figure 2. Interfaces in the tomographic velocity model.

Figure 3. The density cube obtained by combining available density logs with the interfaces in the seismic velocity model.

Figure 2 shows the interfaces in the seismic velocity model in the area of interest, while Figure 3 shows the density cube calculated by combining these interfaces with the available density logs in the area.

**Sensitivity of elastic wave velocities to effective stress**

In order to determine whether the elastic wave velocity is sensitive to changes in pore pressure and stress, velocity data from wells in the same formation, but at different depths and pore pressures were compared. An example is given in Figure 4, where the different colors correspond to different formations. Although these wells sample the same formation with the same pore fluid, the velocities in well B are significantly higher than those in well A, due to the larger effective stress in well B resulting from the same formation being about 1000 ft deeper than in well A.

![Figure 4 – Sonic log for wells A and B.](image)

For a given formation with given fluid content, the variation of velocity with porosity, \( \phi \), clay content, \( C \), and effective stress, \( \sigma \), was assumed to take the form

\[ v = a_1 - a_2 \phi - a_3 C + a_4 \sigma^{\eta} \] . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . (3)

where the porosity, \( \phi \), and clay content, \( C \), were estimated from the density and gamma-ray log. The stress
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dependence in equation (3) is the same as that assumed by Bowers (1995).

If the difference in effective stress between wells A and B is neglected, it is not possible to simultaneously fit the data from the two wells using equation (3). Figures 5 and 6 compare measured velocities in these wells with those predicted using equation (3) with coefficients determined using a least squares inversion of the data for well B, neglecting the difference in effective stress between wells A and B.

The velocities for well A are clearly overpredicted, due to the lower effective stress at shallower depths in well A.

Taking the difference in effective stress between well A and B into account gives the fit shown in Figure 7, with coefficient $a_4$ determined using a least-squares inversion. The increased agreement results from taking into account the decrease in effective stress in going from well B to well A, resulting from the approximately 1000 ft increase in depth.

Figure 7. Measured velocities in well A compared with those predicted using equation (3) with coefficients determined using a least squares inversion of the data for well B and including the difference in effective stress between wells A and B.

Figure 8 shows the upscaled velocity for the interval of interest in all wells for which suitable RFT measurements were available so that the effective stress could be calculated. The points show the mean of the upscaled sonic and effective stress in the interval of interest, while the error bars depict the standard deviation from the mean for the upscaled velocity and effective stress. The curve shown is a fit of the velocity vs effective stress points to a Bowers type relation between seismic interval velocity and effective stress of the form

$$v = v_0 + A \sigma^B \quad \text{(4)}$$

where $v_0$ is the velocity of the sediment at low stress, assumed constant, and $A$ and $B$ describe the variation in velocity with increasing effective stress. Whilst the deviations from the curve in this figure probably originate from variations in porosity and clay content, equation (4) is seen to give a reasonable fit to the data.
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Equation (1) was then used to calculate pore pressure over the entire area by subtracting the effective stress obtained by inverting the seismic velocities from the total vertical stress obtained by integrating the density cube. The predicted overpressure in one of the reservoir layers is shown in Figure 9.

![Figure 8. Upscaled velocity in the interval of interest for wells for which RFT measurements were available, together with the velocity vs effective stress curve given by equation (4) with coefficients obtained using a least squares inversion.](image)

![Figure 9. Overpressure predicted in one of the reservoir layers.](image)

**Conclusion**

In this presentation, a prediction of pore pressure in an overpressured area containing several pressure cells with pressure differences as high as 300 psi was made, based on the seismic interval velocities obtained using reflection tomography.

In order to predict pore pressure, it was assumed that velocity is a function of the vertical effective stress, defined as the difference between the total vertical stress and the pore pressure. The total vertical stress was calculated from an integral of formation density from the depth of interest to surface, while the pore pressure was estimated from RFT measurements. This required a density cube to be built, based on available density logs in the area, and the interfaces in the seismic velocity model. The sonic velocities for all wells having suitable RFT measurements were upscaled, and a relation between velocity and effective stress of the form \( v = v_0 + A\sigma^B \) (Bowers, 1995) was derived from a best fit of the data, assuming \( v_0 \) to be independent of clay content and porosity. This was then used to predict pore pressure over the entire area, using the interval velocities obtained using reflection tomography. It is expected that the pore pressure prediction could be improved by taking into account the variation in clay content and porosity as well as the uncertainty in the velocity to pore pressure transform.

**References**

Bowers, G.L., Pore pressure estimation from velocity data: Accounting for pore pressure mechanisms besides undercompaction, *SPE Drilling and Completion* (June 1995) 89-95.


