

Pore pressure prediction using an Eaton's approach for PS-waves.

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Summary

We estimate overpressure in the Columbus Basin, Trinidad W.I. using PS-waves. Shallow gas in this region reduces both seismic quality and velocity for P-waves, therefore, we use a modified Eaton's approach for pressure prediction using PS-wave moveout velocities, and we verify our findings with well data.

Introduction

Mapping overpressure prior to drilling is critical for safe and successful hydrocarbon exploration (Caricone and Helle, 2002). Lack of predictability of abnormal pressures results in cautious drilling, and this leads to slow penetration rates, excessive bit wear and increased well cost and risk while drilling (Mukerji *et al.*, 2002). The excess drilling cost in regions with abnormal pressure can amount to over \$20 million per well (Mukerji *et al.*, 2002) or \$1.08 billion per year worldwide (Dutta *et al.* 2002).

Seismic data is used to map overpressure, because of its wide areal extent and great depth of penetration, (Dutta *et al.*, 2002). Hottman and Johnson (1965), and Pennebaker (1968) use deviation of P-wave velocity from normal compaction trends to detect pore pressure and estimate pressures using empirical calibration curves. In the above, departures of the transit time from normal trends are calibrated to pore pressure gradients through empirical means. For exploration, where empirical relationships are available from well logs and drilling reports, and where information such as seismic velocity is available on a large scale, a more general, quantitative approach is desirable. In this context, the Eaton's (1969; 1975) method is found to be useful and remarkably robust (Ebrom *et al.* 2003).

The Eaton's (1969, 1975) method relates changes in pore pressure to changes in P-wave velocity. The underlying assumption of the Eaton (1969) method is that a ratio of P-wave velocity obtained from regions of normal and abnormal pressure is related to the ratio of normal and abnormal pressure for the region through an exponent that may be determined empirically. This exponential relationship is found to be general for the Gulf of Mexico, and it is found extend to other basins (Eaton, 1997). Currently, this approach is the most widely used algorithm for pore-pressure mapping (Ebrom *et al.*, 2003).

Reliance on Eaton's (1969) method may breakdown in overpressured regions associated with high porosity and high gas content. In some areas of the North Sea for example, where pockets of shallow gas are present, severe deterioration of P-wave reflections is evident (Stewart *et al.*, 2003).

Eaton's (1969) method is restricted to P-wave analysis; in gas saturated media, Ebrom *et al.* (2003) predict pore pressure using S-waves acquired from multicomponent surveys. S-wave velocity is independent of bulk modulus, so gas saturation does not attenuate S-wave energy, and scattering is reduced where the porous rock-matrix is otherwise homogeneous (Tatham and McCormack, 1991).

With acquisition of PS-wave data, there is an obvious extension of the Eaton's method to include PS-wave and S-wave velocities. Ebrom *et al.* (2003) recognize in areas where gas clouds obscure P-wave reflections. PS-wave velocities provide independent data, which increase confidence of pressure predictions. S-wave velocities are much less sensitive to gas saturation, hence more suitable for pore pressure predictions in gas prone areas (Ebrom *et al.*, 2003).

In this paper, we estimate overpressure in cross-section along a 12km traverse associated with a 2D/4C OBC line trending northwest in the Columbus Basin, Trinidad, West Indies. Extensive, non-economical gas, between 100 to 1000 meters depth (shallow gas) reduces both seismic quality and velocity for P-waves. Shallow gas affects P-waves; therefore, we explore the use of PS-waves for improved prediction of overpressure in this region. We use P-wave and PS-wave velocity analysis in an Eaton's approach for pressure prediction, and verify our findings with well data.

Theory

The extension of the Eaton's method to S-waves and PS-waves is 'natural' because of the increased acquisition of PS-wave data, and the increased use of PS-wave data because of the advantages over P-waves. We presume PS-wave velocities will decrease upon interaction with overpressure as it is composed of a P-wave and an S-wave, both of which decelerate as they enter overpressured zones.

The Eaton's approach predicts pore pressure with P-wave velocities using

Eaton's Approach for PS-waves

$$\frac{\sigma_{eff.o}}{\sigma_{eff.n}} = \left(\frac{V_{po}}{V_{pn}} \right)^{E_p} \quad (1)$$

(Eaton, 1969), and with the S-wave velocities using

$$\frac{\sigma_{eff.o}}{\sigma_{eff.n}} = \left(\frac{V_{so}}{V_{sn}} \right)^{E_s} \quad (2)$$

(Ebrom *et al.*, 2003), where $\sigma_{eff.o}$ is the observed effective stress, $\sigma_{eff.n}$ is the effective stress under 'normal' conditions, V_n is the interval velocities under 'normal' conditions, V_o is the observed interval velocities and E is the Eaton's exponent. The nature of PS-waves allows for extension of the Eaton's approach. Though interval velocities may be calculated for pure P-waves and S-waves directly using Dix's equation, interval velocity from PS-waves provides neither V_p nor V_s uniquely. PS-wave interval velocity is the product of the V_p and V_s according to

$$V_{PS} = \sqrt{V_p V_s} \quad (3)$$

(Tessmer and Behle, 1988), where this square-root relationship allows for overpressure estimation using PS-waves. By substituting V_{PS} for V_s in Equation 2

$$\left(\frac{V_{PS.obs}}{V_{PS.n}} \right)^{E_{PS}} = \left(\frac{\sigma_{obs}}{\sigma_n} \right), \quad (4)$$

where E_{PS} is an empirical constant for PS-waves. Equation (4) allows for prediction of overpressure using PS-wave interval velocities deduced from velocity analysis. The value of E_{PS} , and therefore the sensitivity of the Eaton's approach for PS-wave velocities, should be between the values acquired for P-wave and S-wave.

Field Testing

Stacking velocities for P-wave and PS-wave gathers are deduced from semblance plots. It is significantly easier to pick velocities using the PS-wave gathers than the P-wave gathers especially in areas with shallow gas. Figure 1 shows the comparison of the gathers and semblance plots in areas with and without shallow gas. The semblance "bright spot" are clearer and more defined in PS-wave data than in P-wave data particularly in shallow gas areas. PS-waves are less affected by shallow gas as the quality of the semblance in and out of shallow gas is quite similar.

Interval velocities are determined from stacking velocities via the Dix's equation. We compare P-wave and PS-wave interval velocities derived from seismic with normally pressured regional velocity trends. We interpret negative

deviations from the regional trend as overpressure. The magnitude and areal extent of the deviations should be the same for both P-waves and PS-waves, but in the Columbus Basin, we find that they differ. Specifically, the areal extent of P-wave deviation is much larger than the PS-wave deviation. We conclude P-wave interaction with the laterally extensive area of shallow gas results in an erroneously wide area of velocity deviation from the regional trend (Figure 2). This strong P-wave deviation directly affects our ability to predict pore pressure with spatial accuracy. We find that the areal extent of PS-wave velocity deviation is much reduced when compared to the P-wave deviation. We expect the discrepancies to occur because PS-waves are less affected by shallow gas as the velocity of the up-going S-waves is not affected by fluids. Therefore, we conclude PS-waves show a more accurate areal extent of velocity deviation due to overpressure than the P-wave.

We estimate pore pressure for the region by converting P-wave and PS-wave interval velocities to pore pressures using an Eaton's approach. For PS-waves, we use the method of Ebrom *et al.* (2003). Consistent with analysis of the velocity deviations in Figure 2, we find that shallow gas causes discrepancies between the predicted magnitudes and areal extents of abnormal pressures derived from P-waves and PS-waves. P-wave analysis shows that overpressure extends over a large region, where PS-wave analysis indicates a much smaller region of overpressure.

We verify our derived velocities and predicted-pressure values using formation test and sonic log data from 5 wells proximal to the line. Direct comparison between the sonic-derived velocities and the seismically derived velocities shows that shallow gas decelerates P-wave velocities, and that PS-wave velocities are less affected. Figure 3 shows the comparison of well sonic, and calculated sonic velocities to the velocities derived from seismic. The PS-wave velocities from seismic are more consistent than P-wave velocity when compared with the sonic data. The variations in intensity and location can be account for by lateral variations of overpressure in the basin and geological structures between the seismic line and the well.

We verify our pressure prediction using mudweights and formation tests from well logs and drilling reports. We find pressure predictions associated with P-waves, especially in areas of shallow gas, are less reliable (Figure 4) than for PS-waves. Figure 5 shows predicted mudweights are reliable using PS-wave velocities up to approximately 4,500 m while the P-waves (Figure 4) do not respond to changes in pressure favorably.

From the above, we conclude that PS-wave velocity provides a superior map of overpressure in the region.

Eaton's Approach for PS-waves

Since S-wave velocities are unaffected by the presence of shallow gas and P-waves are impeded by overlying shallow gas, using PS-waves is currently the most effective method to map overpressured regions.

Conclusions

Eaton's (1969) method can be modified successfully for PS-waves. As PS-wave velocities are related to P-wave and S-wave velocities via their product, the Eaton's coefficient for the modified Eaton's equation for PS-wave, is a function of the P-wave and S-wave Eaton's exponents. The value of the exponent is between that of the exponents for P-wave and S-wave velocities hence the sensitivity is between the two. The modified Eaton's equation for PS-wave was tested and determined to be more reliable for predicting pore pressures especially in area of shallow gas.

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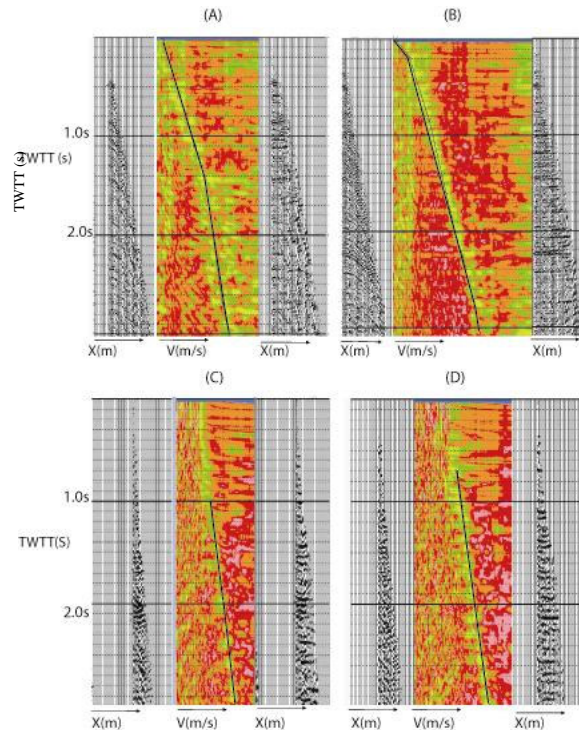


Figure 1: The raw gathers (left), semblance (center) and corrected gathers (right) for P-waves and PS-waves in and out of shallow gas areas. A) The P-wave gathers and semblance in the shallow gas area. The area of semblance is not well defined. B) The P-wave gathers away from the shallow gas area, the semblance is well defined velocity analysis is fairly easy. C) PS-wave gathers in the shallow gas region, the semblance is well defined more than the P-wave data. D) PS-wave gathers outside the gas zone, has similarly defined semblance as the P-wave gathers.

Eaton's Approach for PS-waves

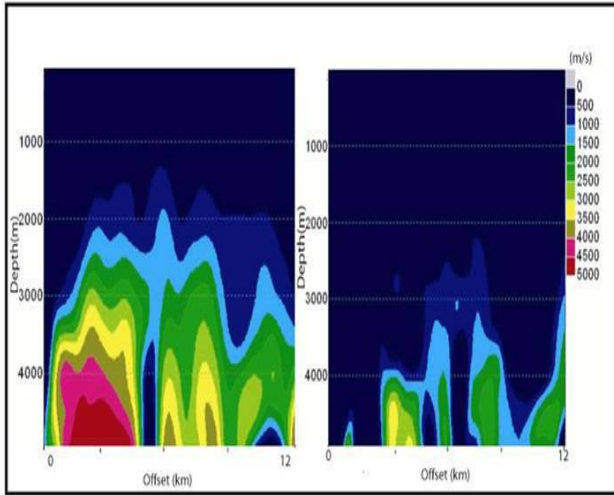


Figure 2: The figure on the left shows the P-wave velocity deviation from the P-wave regional velocity trend and the right the PS-wave velocity deviation from the PS-wave regional velocity trend. The extent of the P-wave deviation is larger than the PS-wave area.

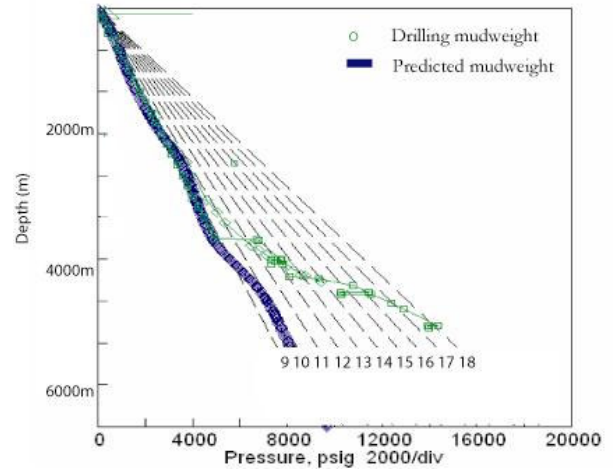


Figure 4: The blue line shows the predicted mudweight using P-wave data and compares it to well drilling mudweight. The P-wave predicted mudweight follow suitable up to ~2800m where the predicted mudweights drastically lower than actual mudweights used.

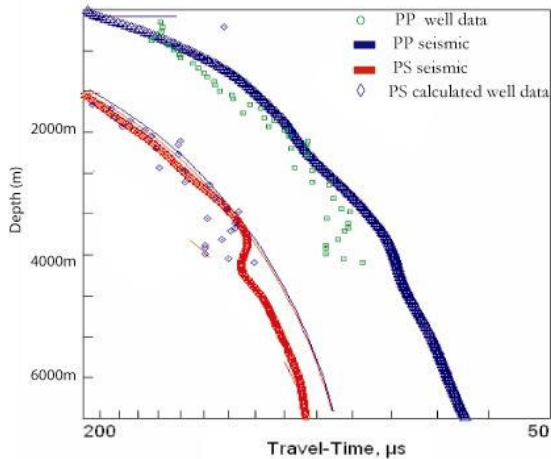


Figure 3: Comparison of well data with P-wave and PS-wave seismically derived velocities. Both the P-wave and the PS-wave seismic velocities correlated suitably with the shallow well data. At approximately 4000m, well data shows there is a rapid decrease in velocities; however the P-wave velocities show no such response. The PS-wave velocities decrease at a similar depth as the known overpressure zone. The magnitude and location of the deceleration varies from well data because of lateral variation of abnormal pressure and structural geology between the location of the well and the seismic line.

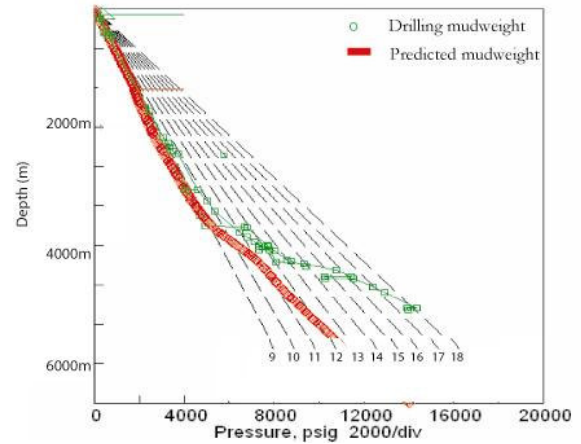


Figure 5: The red line shows the predicted mudweight using PS-wave data and compares it to well drilling mudweight. The PS-wave predicted mudweight follow suitable up to ~4000m where the predicted mudweights begins to deviate from the actual drilling mudweight gradually.