A new model for pore pressure prediction

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Summary

Eaton's equation is the most popularly used model for pore pressure prediction, but it is based on over-simplified stress velocity relation. A new model for pore prediction was brought up based on stress effect modeling of lab core measurement. The new model requires exactly the same inputs and should have better performance in pore pressure prediction. Then performances of pore pressure prediction by using differential pressure and effective pressure respectively are compared. Due to delicacy in estimating the effective stress coefficient and complexity of in-situ fluid properties, introduction of effective pressure might not improve pore pressure prediction results. Our new model has been successfully applied to field data.

Introduction

Pore pressure prediction is very important to drilling engineers for prevention of drilling disasters. For geologists, the information is very helpful for study of the migration and trapping of oil and gas. Traditionally, pore pressures prediction is either based on basin modeling or velocity data derived from seismic data processing (Helset, et. al., 2010). The former usually has less accuracy. The later is intrinsically based on stress effect on seismic velocity.

For pore pressure prediction using seismic data, first we need to set up an empirical relation regarding the stress effect on velocity. The most popularly used relation is Eaton's equation (1975):

$$\frac{P_P}{D} = \frac{P_c}{D} - \left(\frac{P_c}{D} - \frac{P_p}{D_n}\right)\left(\frac{V_{obs}}{V_n}\right)^E \qquad (1)$$

where D is depth, P_p/D_n is normal hydrostatic pressure gradient, V_n is the velocity trend of normal compaction and V_{obs} is the observed velocity. E is Eaton's coefficient. Eaton's formula can be rewritten in a simpler form that is easier to be understood by geophysicists:

$$\frac{V_P}{V_{Pn}} = \left(\frac{P_d}{P_{dn}}\right)^{\frac{1}{E}} \qquad (2)$$

where V_{Pn} is the velocity trend of normal compaction (pore pressure equals to hydrostatic pressure), P_{dn} is the normal differential pressure, i.e., the difference between confining pressure and hydrostatic pressure.

For a certain reservoir rock, it is well known that the stress effect on velocity is determined by effective pressure instead of the differential pressure. It is logic to deduce that if we substitute the differential pressure in equation (2) by effective pressure, we should improve the pore prediction result.

Sarker and Batzle (2008) have discussed the applicability of stress effect coefficient (n) on pore pressure prediction. They compared the case when n=1 and E=3 and the case when n=0.7 and E=1, and found that the predicted result by the latter case has better correlation with mud pressure data, and thus concluded that n=0.7 is better approximation and should improve pore pressure prediction. This conclusion is not solid since n and E are changed simultaneously and E=1 means linear relation between the normalized differential pressure and normalized velocity, which is irrational for common reservoir conditions. Thus another goal of this paper is to use lab estimated n to test its applicability on pore pressure prediction.

Bringing up of the new model

Yan and Han's study (2009) on Han's data (Han, 1986) shows that the following velocity model is sufficient to describe the stress effect on velocity when the differential pressure is not too high (e.g., less than 60MPa):

$$V_P = V_{Pa}\left(1 - c \cdot e^{-\frac{P_d}{b}}\right) \qquad (3)$$

There are three fitting parameters in the above model: V_{Pa}, c and b. Fig. 1 shows a typical velocity-stress relation observed from lab measurement. Both exponential relation and power relation are used to fit the lab measured data. Obviously the exponential formula fit much better with the data. At higher differential pressure, the model of power relation deviated severely from the data trend.

Since the exponential relation is a much better model to describe the stress effect on velocity than the power relation used by Eaton's method, it might be possible that we can construct a better pore pressure prediction model using the exponential velocity-stress relation. First, we construct the following equation by slight rearrangement and change of notation from equation (3):

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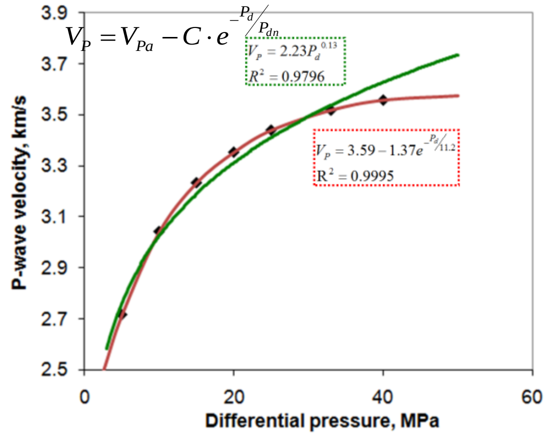

Figure 1: Typical stress effect on P-wave velocity from lab measurement.

(4)

Here the normal velocity trend (V_{Pn}) equivalent to that of Eaton's formula is not explicit and but it can be calculated by equation (4) if we set $P_d = P_{dn}$:

$$V_{pn} = V_{Pa} - C \cdot e^{-1} \tag{5}$$

So that equation (4) can be rewritten in a more practical form:

$$V_P = V_{Pn} + C\left(e^{-1} - e^{-P_d/P_{dn}}\right) \tag{6}$$

Comparing with equation (2), equation (6) looks a bit more complicated, but basically the inputs are same, they need a velocity trend of normal compaction and different constants E and C respectively.

Comparing of P_p prediction models

To compare these models, we first use log data with pore pressure profile interpolated and smoothed from MDT (modular dynamic formation tester) measurements to calibrate these two models. The blue curve in the right panel of Fig. 2 is the pressure profile and two dashed curves are confining pressure and hydrostatic pressure respectively. The blue curve in the left panel is the sonic velocity data. It can be seen that there is a big section of formations (more than 2000 meters) that are over-pressured. We are told that pore pressure above 3000 m is basically normal.

Here calibration means that we use given pressure profile and the two models to fit the sonic velocity data respectively to find the normal compaction trend (V_{pn}) and the coefficients (E for Eaton's equation and C for the new model). The calibration results are shown in left panel of Fig. 2. We can see that the new pore pressure prediction model (equation (6)) fit better with the sonic log than Eaton's equation. The dashed straight curves in the left panel are the calibrated V_P trends of normal compaction for Eaton's formula (green) and the new model (red) respectively. The calibrated constants E and C are 2.92 and 3.87 respectively. Correspondingly when the calibrated models are used to predict pore pressure, the new model performs better in pore pressure prediction, as shown in the right panel of Fig. 2.

For using Eaton's equation to predict pressure, an important step is to determine the velocity of normal compaction trend from the shallower section. We have just got the normal velocity trends by calibration with given pressure data. Thus we can extrapolate the velocity trends to shallower section and compare them with the sonic log. As shown in the left panel of Fig.3, there is a low velocity

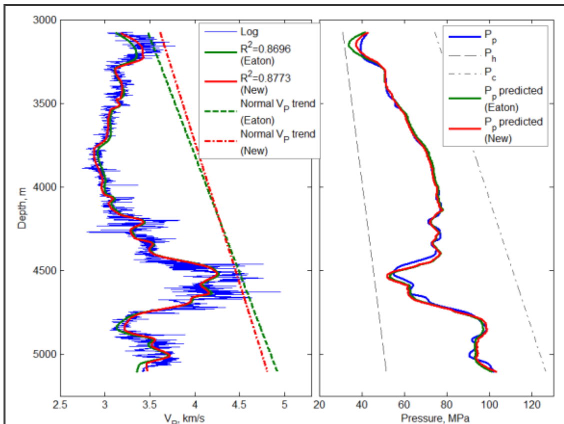

Figure 2: Calibration of the P_p prediction models

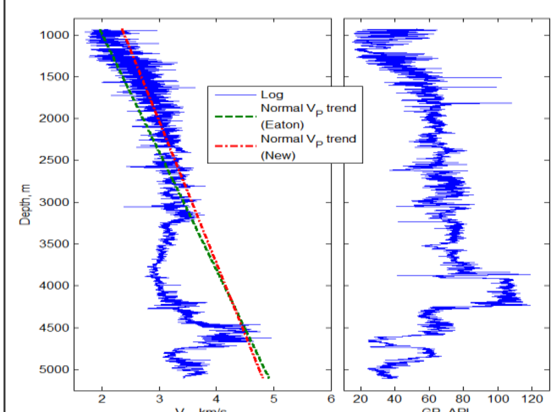

Figure 3: Extrapolation and comparing of the normal compaction trends from calibration.

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interval around 1200 m caused by gas-bearing sands. We can see that the normal velocity trend (sometimes peopled call it shale trend) inverted from the new model is much closer to the actual normal velocity trend than that inverted by Eaton's equation. For this well, it is logical to say that if you use the correct velocity trend of normal compaction then you will get even worse pore pressure prediction result by using Eaton's equation. Thus the new model we brought up has potential to perform better in pore pressure prediction than Eaton's equation.

Applicability of effective stress coefficient

The effective stress coefficient is introduced when it is found that the stress effect on velocities cannot be uniquely determined by the differential pressure (difference between confining pressure and pore pressure). With introducing of effective stress coefficient, the effective pressure is defined as

$$P_e = P_c - n \cdot P_p \qquad (7)$$

where P_e is effective pressure, P_c is confining pressure, n is effective stress coefficient and P_p is pore pressure.

For estimation of n from lab measurement, Todd and Simmons (1971) derived this formula to estimate the effective stress coefficient:

$$n = 1 - \frac{\left(\partial V_P / \partial P_p \right)_{P_d}}{\left(\partial V_P / \partial P_d \right)_{P_p}} \qquad (8)$$

Here n is treated as a function of both the differential pressure and pore pressure, but they are not independent variables. For practical estimation, at each value of differential pressure, V_P is assumed to change linearly with pore pressure; and at each value of pore pressure, V_P is assumed to change linearly with differential pressure. From lab observation, these assumptions are not necessarily true, especially for the latter assumption. This process is tedious and very sensitive to random measurement error. Thus it is worthwhile to find a more efficient way to estimate the effective stress coefficient.

As Todd and Simmons (1972) pointed out that there are two pressure effects of the same order: (1) the pressure dependence defined by P_c-n*P_p, and (2) the pressure effect due to fluid compressibility change. Thus the estimated n is actually apparent effective stress coefficient including saturation effect caused by fluid compressibility change.

Obviously n estimated from lab measurement should not be used directly for field application. Gassmann equation is used to make correction on effect of fluid compressibility

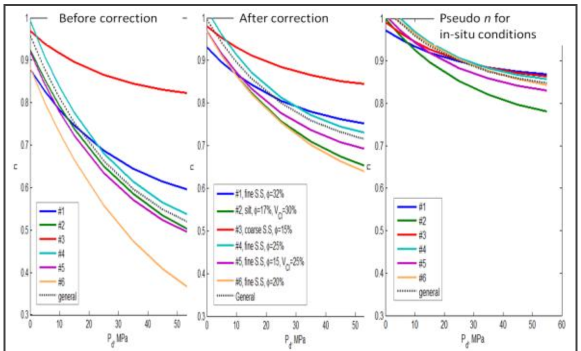

Figure 5: Effect of pore fluid on estimation and application of n

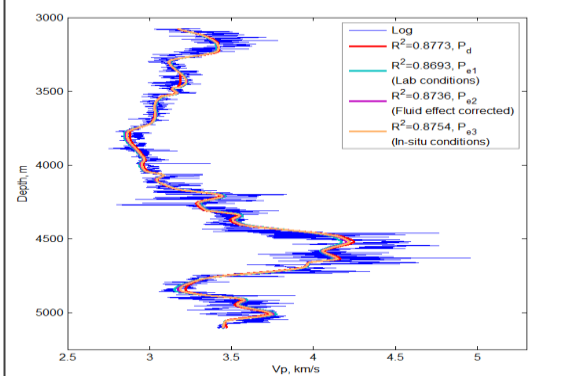

Figure 6: Correlations between P_p prediction models and sonic log using different pressure inputs

change. The results are shown in Fig. 5. We have measured six core samples including silt, fine sandstone and coarse sandstone. No clear relations between n and lithology, porosity and clay content are observed. So in application, a general trend of n indicated by the dashed curve is used.

From Fig. 5 we can see that estimation of n is very sensitive to fluid compressibility change. Then the differential pressure terms (both P_d and P_{dn}) in equation (6) are replaced by effective pressures using different n. P_{e1} is calculated using initial n estimated by regression (left panel in Fig. 5); P_{e2} is calculated using n corrected for fluid compressibility change in lab conditions (middle panel in Fig. 5) and P_{e3} is calculated using n corrected for in-situ conditions (right panel in Fig. 5). From Fig. 6, we can see that the corrections with sonic log improve slightly, but the best fitting using effective pressure is still worse than the case using differential pressure. So using effective pressure instead of differential pressure does not guarantee improvement of pressure prediction results for this well.

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Thus our study shows that introduction of effective stress coefficient might not improve pore prediction performance. This might be due to several types of factors. The first is from measurement: like reading error, hysteresis, length and density change of core samples and et al.; the second is dispersion; the third is from model errors, both the velocity-stress model and exponential *n* model are approximations; and the forth is from the uncertainty during application: the temperature, pressure, salinity and composition of in-situ pore fluids, and the effective stress coefficient also varies with lithology.

Field application example

We have applied the new model to an over-pressured reservoir using poststack seismic data. Since density has similar pressure dependence behavior, we simply change P-wave velocity in eqn. (6) into P-waved impedance. Using inverted impedance we can predict the pore pressure for the entire survey area. As shown in Fig. 7, the predicted pore pressure have good match with the pore pressure profile in the well and show comply with geological structure.

Conclusions

The new model we brought up has potential to perform better in pore pressure prediction than Eaton's equation. Introduction of effective pressure might not improve pore pressure prediction performance. Usually the effective stress coefficient estimated from lab measurement should not be applied directly for pore pressure prediction. Our new model has been successfully applied to field data.

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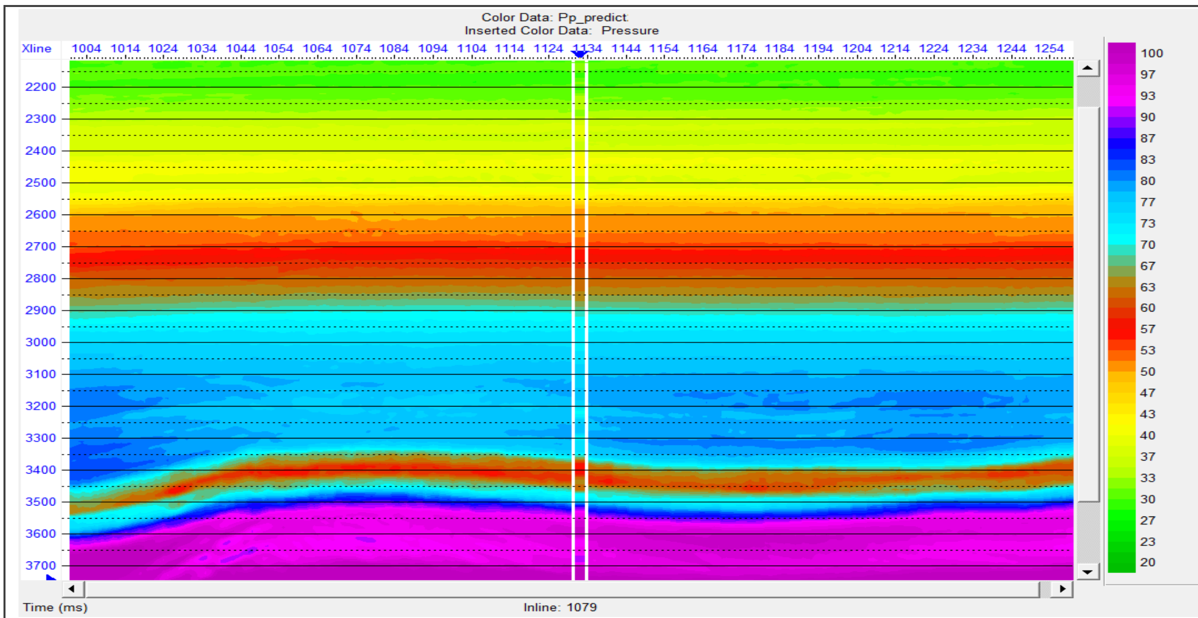

Figure 7: Pore pressure prediction from poststack seismic data

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EDITED REFERENCES

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