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PORE PRESSURE ESTIMATION FOR SHALY SAND FORMATIONS USING ROCK PHYSICS MODELS FOR COMPRESSIONAL AND SHEAR VELOCITIES: A 1D GEOMECHANICAL APPROACH

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ABSTRACT. Pore pressure estimation in sedimentary basins has been made exclusively through the compressional velocity data since the 1960s, using the normal compaction trend and lithostatic pressure profile derived from wireline logs. Considering that seismic velocity is highly dependent on petrophysical parameters such as porosity and clay volume, pore pressure estimation is commonly associated with a high degree of uncertainty due to simplistic assumptions that neglect those dependencies. To improve this issue, we propose two empirical velocity models based on compressional and shear rock physics relations for pore pressure prediction in shaly sand formations. These formulations extend Bowers and Doyen formulae, linking compressional and shear velocities to effective stress and petrophysical parameters. Finally, we used a non-linear multidimensional inversion approach to calibrate the proposed models and apply them in the context of a 1D geomechanics and pore pressure prediction study of an upper Cretaceous overpressured shaly sand oil reservoir. The results show good agreement with pore pressure data and pressure predictions from the traditional Eaton method. The advantage of the proposed approach is its consistency throughout the entire well-log petrophysical interpretation workflow, especially concerning porosity, clay volume and saturation.

Keywords: compaction; overpressure; prediction.

INTRODUCTION

Knowledge of abnormal pore pressure is a key requirement for optimal field development and well design decisions, with an impact on safety during drilling operations. Pore pressure estimation has a great value for the oil industry, since it helps drilling and oil recovery optimization. Compressional velocity plays a central role, considering it is directly affected by effective stresses. Therefore, continuous efforts have been made to obtain reliable compressional velocity and the development of comprehensive modeling formulations.

Pore pressure estimates are performed using seismic velocity and sonic log data, following a workflow consisting of two main steps: 1) obtaining the compressional velocities (V_P) on the formation, which is done through adequate seismic and processing and/or sonic acquisition (Kan and Swan, 2001; Dutta, 2002; Sayers et al., 2002; Malinverno et al., 2004); 2) a posterior transformation of these velocities into pore pressure with quality control checks to adjust ideal input variables. Traditionally, pore pressure calculation formulae have been proposed to be used on a set of wireline logs and downhole measurements. If reliable velocity data are available, the pore pressure transformation is done using one of the available methods. Essentially, all methods rely on the principle of compaction disequilibrium and require the definition of a normal compaction trend profile, which represents the gradual decrease in porosity with increasing lithostatic pressure under normal depositional conditions. Deviations from the normal compaction trend indicate abnormal pore pressure due to some overpressure generation mechanism. Thus, pore pressure estimation methods rely on the observation that pore pressure affects compaction-dependent shale properties such as porosity, density, sonic velocity, and resistivity. This observation became the foundation of two different approaches to pore pressure prediction, which are the direct method (Hottman and Johnson, 1965; Pennebaker, 1968), and the effective stress methods, based on Terzaghi's principle (Foster and Whalen, 1966; Eaton, 1975; Lane and Macpherson, 1976; Bowers, 1995). Bowers (1999) refers to any geophysical data sensitive to pore pressure as a pore pressure indicator. Terzaghi's effective stress principle (Terzaghi, 1939) states that the differential pressure (i.e., the difference between confining and pore pressures) controls the compaction trend. Lane and Macpherson (1976) proposed separating the effective stress approaches into two classes, classified respectively as vertical and horizontal methods (Bowers, 1999).

However, the above relations have often been indiscriminately applied for all formation types, including reservoir sands. It was not until a decade later that a few authors, led by Carcione et al. (2003), Sayers et al. (2003), and Doyen et al. (2004), proposed new models for pore pressure estimation in reservoir rocks to address the ambiguity involved in pore pressure estimation using conventional effective stress methods based on the presence of shale formations. These new developments represent an advance for the pore pressure studies.

Despite that, the traditional methods are still widely used for shaly rocks and reservoir intervals. In a few words, a simple relation between Vp and pore pressure (actually, Vp vs. effective pressure, for a given lithostatic pressure) is locally calibrated using pore pressure measurements to yield proper pore pressure estimates over the target intervals. As the elastic properties in sand-shale rocks may vary significantly with porosity and lithology, as has been widely demonstrated in many studies, such as those by Castagna et al. (1985), Han et al. (1986), and Eberhart-Phillips et al. (1989), the estimated pore pressure becomes subject to this potential source of error. Another critical effect not generally considered arises due to the pore fluid. Fluid content (water, oil or gas) significantly affects the P-wave velocity in reservoir rocks.

Here we follow on this path by proposing and testing extended forms of Bowers (1995) and Doyen et al. (2004) formulae, by exploring pore pressure dependence of both compressional and shear velocity allowing us to derive two separate pore pressure expressions: one expressed in terms of compressional velocity, effective stress, porosity, shale volume, and fluid volumes, to compensate fluid uncertainties, and the other represented as a function of shear velocity, effective stress, porosity, and shale volume.

Finally, to validate our pore pressure study, we make comparative estimations using the Eaton method in the context of a 1D geomechanics modeling that only considers estimations in shales with extrapolation and calibration in sands of an upper Cretaceous overpressured shaly sand oil reservoir. The proposed velocity equations for pore pressure estimation follow a non-linear multidimensional inversion approach to calibrate the proposed models and apply them in the context of a 1D geomechanics pore pressure prediction. Results showed good concordance with the Eaton method and direct pore pressure measures confirming this approach as an alternative way for integrated well-log interpretation applications and pore pressure estimation workflow.

METHODOLOGY

Pore pressure proposed equations

Following Sayers et al. (2003) as well as Doyen et al. (2004), we start from an extended empirical expression of P-wave velocity as a function of pore pressure, P_P; overburden pressure, P_o; porosity, $\emptyset$; clay volume, C, adding the oil saturation variable in volume units (V_{oil}) to obtain

$$V_P = a_1 - a_2\emptyset - a_3C - a_4V_{oil} + a_5(P_o - P_P)^{a_6}. \tag{1}$$

One can also think of an empirical analog Doyen expression of S-wave velocity as a function of pore pressure P_P; overburden pressure P_o; porosity $\emptyset$; and clay volume C in the form of

$$V_s = b_1 - b_2\emptyset - b_3C + b_4(P_o - P_P)^{b_5}, \tag{2}$$

where a_i, $i = 1,\dots,6$ and b_i, $i = 1,\dots,5$ are the model coefficients, whose values are determined by calibration using well-log data. In the above equations, the velocity dependence on differential (or effective) pressure, given by the $P_o - P_P$, is equivalent to that proposed by

Bowers (1995), with the terms $a_1 - a_2\emptyset - a_3C - a_4V_{oil}$ in equation 1, compactly represented by a constant value called the zero-stress mudline velocity, V_o, in his model (Bowers method was based only on compressional velocity). In analogy with Bowers, the term $b_1 - b_2\emptyset - b_3C$ in equation 2 would also represent the constant value called the zero-stress mudline velocity, V_o. By introducing these terms in our model, we can account for variations in porosity, clay content, and oil saturation in volume units (V_{oil}), when using the first expression in compressional velocities, and account for variations in porosity and clay content, when using the second expression in the function of shear velocities. These developments are also related to models presented by Han et al. (1986) and Eberhart-Phillips et al. (1989) in terms of lithology effect studies. Taking equations 1 and 2, we can rewrite them to obtain expressions for the pore pressure transformation, given by

$$P_P = P_o - \left[\frac{1}{a_5}\left(V_p - a_1 + a_2\emptyset + a_3C + a_4V_{oil}\right)\right]^{\frac{1}{a_6}} \quad (3)$$

and

$$P_P = P_o - \left[\frac{1}{b_4}\left(V_s - b_1 + b_2\emptyset + b_3C\right)\right]^{\frac{1}{b_5}} \quad (4)$$

Equations 3 and 4 may be applied point-by-point in a 3-D MEM or 1-D MEM, assuming that a velocity is available from seismic inversion or interpolated using data from nearby wells, including sonic logs, porosity, clay volume and oil saturation in volume units. Fluids do not influence the S-wave formulation. The overburden pressure P_o, required in the calculation of P_P, can be obtained by integration of the density function, given by

$$P_o(z) = g\int_0^z \rho(z)dz \quad (5)$$

where $\boldsymbol{z}$ is the vertical depth; g is the acceleration of gravity; and ρ is the bulk density. In practice, the integral is calculated from a density cube, either from elastic inversion or well-log data, from the surface to depth $\boldsymbol{z}$, as commonly done during 1-D MEM building. The velocity and overburden pressure (obtained by integrating the density) as well as porosity, shale fraction, volume of fluids and coefficients of calibration are then input to a formula that computes a predicted pore-pressure profile (Figure 1).

Pore pressure estimation workflow

The pore pressure estimation can be described, in more detail, by the following steps (see also Figure 1):

1. Construct the best velocity $V_p(z)$ or $V_s(z)$, and density $\rho(z)$ depth profiles.
2. Use the density $\rho(z)$ to estimate the total vertical stress or overburden pressure P_o (equation 5).
3. Petrophysical interpretation – Compute clay volumes, effective porosity and effective saturation using wireline or LWD data and perform lithologic interpretation discriminating the shales and cleaner formations.
4. Model coefficient calibration – Use the results of the previous step, together with pore pressure data, to obtain coefficients a_i or b_i, as in Equations 1 and 2 using a preferred regression algorithm (for our survey it was used a multidimensional non-linear inversion approach).
5. Compute the predicted pore pressure P_P for sand and shaly sand sections, using equation 3 or 4 with inputs from the previous steps, and compare the predicted and measured pore pressure values using mud weight for quality control purposes. The prediction was also evaluated with a root mean square error (*rmse*) in order to compare the measured compressional and shear velocities with the modeled results through equations 1 and 2 using the following expression

$$rmse = \left(\frac{1}{N}\sum_{1}^{N}(V_M - V_E)^2\right)^{1/2} \quad (6)$$

where N is the total number of data; V_M is the measured compressional or shear velocity; and V_E is the estimated compressional or shear velocity through equation 1 and 2, respectively. Table 1 shows the RMSE with low values, giving us good confidence for the non-linear inversion results.

Table 1: RMSE (in unit values) obtained through the measured velocities and the modeled velocities using the non-linear inverted coefficients in equations 1 and 2.

	V_p	V_s
RMSE	0.23	0.22

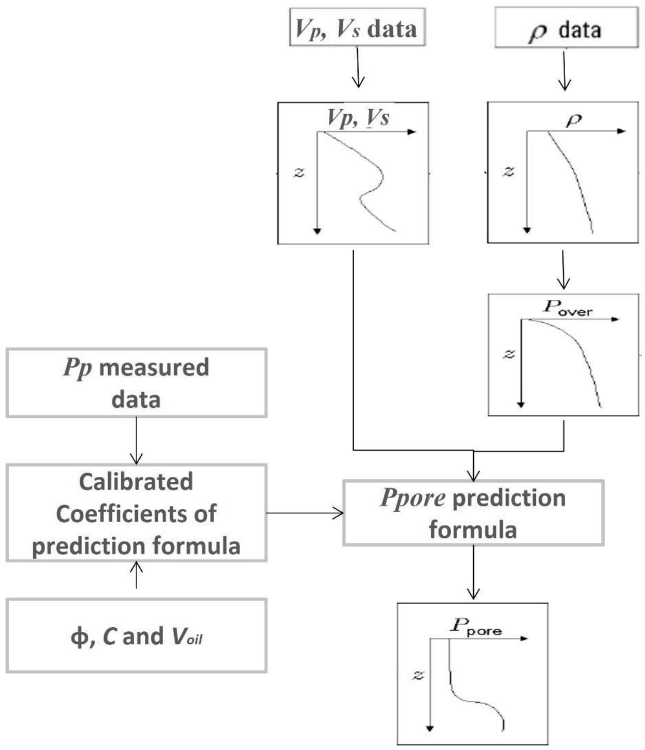

Figure 1: Basic workflow for predicting pore pressure using Equation 3 or 4, including inputs using well-log or seismic derived velocity and density data.

Considering the semi-empirical nature of the proposed formulations, it is always important to check against competing approaches, such as the ones represented by Eaton's method (Eaton, 1975).

RESULTS

Case Study

To test the workflow presented in the previous section, we use an idealized case study involving a consolidated upper Cretaceous shaly sand oil reservoir, whose data are subjected to a confidentiality agreement. The shaly sand interval analyzed shows abnormal pressures (abnormal means above local hydrostatic pressure). The data used in this study consist of clay volume, porosity, water saturation (petrophysical processed curves), compressional velocities, density logs, direct measures of pore pressure, and mud weight.

Multidimensional non-linear inversion for calibration

The multidimensional non-linear inversion results using the iterative Levenberg-Marquardt algorithm (Levenberg, 1944; Marquardt, 1963), developed through Scipy libraries - Python language, are applied to this study for calibration purposes in both proposed pore pressure methods. The term "*multidimensional*" is related to the inversion approach of coefficients representing more than 2-dimensional variables included in the formulation (equations 1 and 2). Figure 2 shows the comparative results of the proposed pore pressure estimation methods based on VP (fourth track) and VS (fifth track).

The final pore pressure composite results in Figure 2 (done using IP software for log's display and Python routines for pore pressure inversion and computations) have five tracks arranged as follows: (1) shading zones for VCL - SAND lithology and WATER – OIL fluids, and interpreted LQC petrophysical data given by PHIE (effective porosity curve), VCL (clay volume) and VUWA (volume of water in the undisturbed zone computed using Archie water saturation) in the first track; (2) Relative depths in the second track; (3) Logarithmic compressional slowness (DTCO) and shear slowness (DTSM) in the third track; (4) Hydrostatic pore pressure (PPMW_NORM), Eaton pore pressure calibrated with RFT data (PPMW_EATON), our proposed pore pressure approaches computed using a non-linear inversion method for calibration through equations 3 and 4 (PPMW_EQVP_IN and PPMW_EQVS_IN), direct pore pressure measures (RFT) and mud weight (MW) in the fourth and fifth track, respectively. All pressures are in pounds per gallon units (ppg).

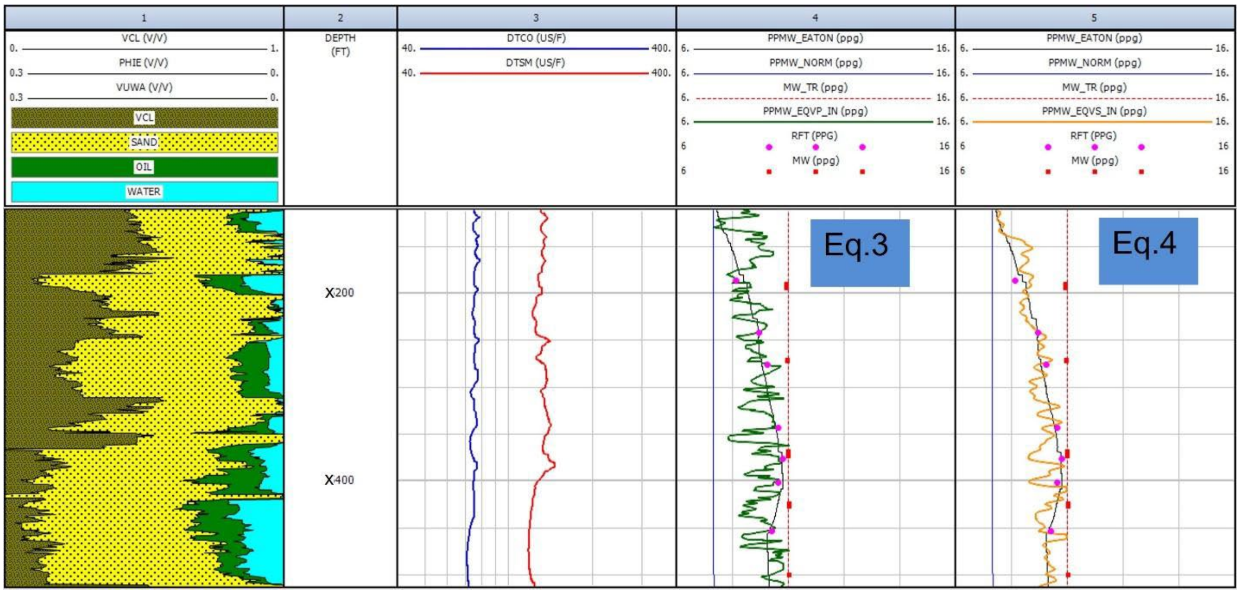

Figure 2: Final pore pressure composite results.

The calibrated results for pore pressure estimation using this inversion methodology show a good fit with the direct pore pressure measurements and are in concordance, compared with the Eaton pore pressure method. It is observed that the proposed method reflects the lithological and fluid effects in the behavior of the curves considering their respective equations. Other information related with local geo-pressures was not deeply discussed taking into account confidentiality agreements of the data.

DISCUSSION

It is known that adequate pore pressure estimation results depend on a combination of quality field velocity information and pore-pressure measurements. This requires the use of solid operational procedures, acquisition tools and reliable technologies. As a recommendation for future works, we suggest using stochastic analysis to quantify and propagate data uncertainties and prior information in the pore pressure prediction procedure using the proposed equations. The Eaton method as a common and conventional approach for pore pressure estimation is also submitted to errors and uncertainties during the 1D construction that must be quantified when possible.

The method was specifically developed for shaly-sand reservoirs following conventional or non-linear calibration procedures. Other studies must be extended for complex mineralogy.

As additional and future discussions, the local effects and behaviors of the pore pressure distribution obtained using this pore pressure estimation approach must be studied considering the heterogeneity of the lithological and petrophysical properties.

CONCLUSIONS

Our proposed effective stress methods to estimate pore pressure integrate compressional-and shear wave velocities with density (overburden), porosity, clay volume and fluid volumes (this last parameter for the case of the compressional velocity equation), as an extension of a widely used empirical formula relating velocity with effective stress, called Bowers method (1995). Our extended formulation also follows the same lines of the extension proposed by Doyen et al. (2004), except for an extra term that is saturation dependent included in the compressional velocity equation. The pore pressure relation as a function of shear velocity and lithology gives us an additional and alternative way for pore pressure prediction considering that, at low frequencies, shear velocity is not influenced by fluid uncertainties as compressional velocities.

We also used Eaton's method to predict pore pressure, to compare the results with our proposed equations. Both methods used for pore pressure estimation in this consolidated Cretaceous shaly sand oil reservoir case study show consistent agreement with direct pore pressure measurements and mud weight data (no kicks reported during drilling in this well). It is important to consider, however, that the abnormal pressure observed in this field is linked to the disequilibrium compaction as the dominant overpressure mechanism (loading mechanical mechanism dominant).

An important difference observed in this case study with our proposed method is the distribution of pore pressures along the shaly sand section interval, showing a correlated behavior in the overpressured interval in terms of petrophysical changes (porosity, shale volume and saturations).

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