A Novel Method for Estimating in-situ Seismic Velocities for Porous Rocks Containing Hydrocarbons, including an Application of the Method to Correcting Sonic Log Velocities

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Summary:

A novel modeling approach is developed for obtaining reasonable in-situ estimates for the bulk and shear moduli of porous rocks by inverting the Biot-Geertsma-Gassmann and shear-wave equations and integrating with the inversion the Batzle-Wang formulation (1992) and available velocity and porosity data from borehole logs for water/brine saturated rocks. These data are then used to predict in-situ values for compressional- and shear-wave velocities of rocks partially saturated with hydrocarbons.

Introduction

Compressional and shear wave velocities are essential parameters for understanding the behavior of porous, fluid-saturated rocks in geophysical exploration. The "Gassmann" equation (Gassmann, 1951) is one of the most complete, practical equations used to determine compressional-wave velocities in porous rocks. Since Biot (1956) and Geertsma (1961) extended Gassmann's initial analysis, the "Gassmann" equation is sometimes referred to as the "Biot-Geertsma-Gassmann" (BGG) equation. Although no complete, exact theory for porous rock velocities has yet been developed, the BGG equation is still considered to be the most correct for partial hydrocarbon saturations (Domenico, 1984; Clark, 1992; Murphy et al., 1993; Benson and Wu, 1999).

Compressional and Shear Velocities

The BGG equation takes the following form for compressional wave velocities (V_p) in different media (Geertsma, 1961):

$$V_p = \{[K_{eff} + (4/3)\mu]/\rho_b\}^{1/2} , \qquad (1)$$

where

$$K_{eff} = K_b + K_s^{-2}(K_s - K_b)^2 / \{K_s^{-2}[K_s - K_b] + \phi[(1/K_f) - (1/K_s)]\}, \qquad (2)$$

and

$$\rho_b = \phi\rho_f + (1-\phi)\rho_s, \qquad (3)$$

and K_s is the bulk modulus of the matrix material; K_b is the bulk modulus of the empty reservoir bulk material; μ is the shear modulus of the reservoir bulk material; K_f is the bulk modulus of the fluid; ρ_b is the bulk density; ϕ is the rock porosity; ρ_f is the density of the fluid; and ρ_s is the density of the matrix grains. It is particularly difficult to obtain reasonable in-situ values for K_b and μ.

The BGG equation governs to first-order the fluid saturation effects on compressional velocities in geological materials as a function of mineralogy and porosity. In the past, it has typically been used in a forward modeling mode by a priori specifying values of K_b and μ (Domenico, 1984, 1977). In this paper a new approach is taken by inverting the BGG equation to predict K_b, inverting the shear-wave equation to predict μ, and generating reasonable input estimates of in-situ rock-matrix and fluid properties as a function of depth from the Batzle-Wang formulation (1992) to predict compressional and shear-wave velocities for in-situ porous rock systems containing hydrocarbons.

Shear-wave velocities (V_s) are determined from the following equation (Domenico, 1977):

$$V_s = (\mu/\rho_b)^{1/2} . \qquad (4)$$

Because the shear modulus of a fluid is zero, the shear modulus of the saturated rock is assumed to be the same as that of the empty, porous rock. This conclusion leads to a useful expression for the relationship between K_b and μ (Domenico, 1977, 1984):

$$\mu = K_b\,[3(1-2\sigma_b)]/[2(1+\sigma_b)] , \qquad (5)$$

where σ_b is Poisson's ratio for dry rocks.

Modeling Procedure

Equation (1) can be inverted to predict values of K_b from available field data for water/brine-saturated rocks by using compiled well-log data, such as Gregory's (1977) for Gulf Coast sands. Similarly, μ can be predicted from equation (4) and/or (5). The choice of beginning with equation (1) or equation (4) depends on the velocity data available for water-saturated rocks in the study area. If shear-wave velocities are available for water/brine-saturated rocks, they become the first choice of input since they are less sensitive to the effects of fluid saturation.

After inverting equation (1) for K_b (Benson and Wu, 1999), input values for fluid densities and compressibilities as a function of composition, pressure and temperature can be determined from the Batzle-Wang formulation (1992).

Densities and compressibilities vary substantially, but analytical expressions can be estimated for the pressure and temperature conditions typically found in hydrocarbon exploration (Benson, 1995).

The major steps in our modeling procedure for predicting compressional and shear-wave velocities in-situ are the following:

(1) Input rock matrix parameters and fluid parameters. It is essential to input rock-matrix and fluid parameters that reflect in-situ conditions. Using our modeling program and the Batzle-Wang formulation (1992), densities and compressibilities are calculated as a function of depth for gases, oils, and brines.

(2) Input compressional or shear-wave velocities of water/brine-saturated porous rocks. Existing velocity data for water/brine-saturated rocks, particularly from well log data, are needed in our modeling program in order to predict the dry reservoir rock bulk modulus, K_b, and the reservoir rock shear modulus, μ. The well log data compiled by Gregory (1977) for Gulf Coast brine-saturated sandstones and by Kithas (1976) for brine-saturated New Mexico limestones are useful sources for typical reservoir rocks.

(3) The output predicts the following parameters:

(a) The dry reservoir bulk modulus K_b and the bulk shear modulus μ are predicted as a function of depth by inverting equations (1) and (4).

(b) Using equations (1), (5), and values of K_b and μ determined in (a), the predicted compressional- and shear-wave velocities are calculated for oil-saturated rocks, gas-saturated rocks, or partially-saturated rocks as a function of depth or porosity for a given water saturation, and as a function of water saturation for a given porosity.

(c) Using the results from (b), compressional and shear-wave impedances and reflection coefficients are predicted as a function of depth and/or water saturation for different rock-fluid boundaries. Reflection coefficients at these boundaries are involved in building realistic models of the subsurface geology and in identifying depth to bedrock, faults, fluid contacts, lithology, "bright spots" (high amplitude reflections), and "flat events" (reflections from fluid contacts).

Predicted values of the bulk modulus from equation (1) and shear modulus from equation (4) were computed by our modeling procedure as a function of depth for typical Gulf Coast sandstones. The moduli increase nonlinearly as the depth increases, with the shear modulus curve slightly above the bulk modulus curve (Figure 1). Using the values of the moduli, compressional and shear-wave velocities were predicted for a variety of reservoir conditions for typical Gulf Coast sandstones as a function of depth. As expected, the compressional-wave velocities in brine-saturated rocks are higher than in oil-saturated rocks, and the velocities in gas-saturated rocks are the lowest. However, for the case of shear waves, the gas-saturated rocks have the highest velocities and the brine-saturated rocks have the lowest velocities. This reversal anomaly can help identify oil versus gas reservoirs.

Testing the Algorithm with Laboratory Data

Ultrasonic compressional and shear velocities measured in the laboratory under controlled conditions as a function of pressure in a water-saturated state (Han, et al., 1986) were used to test the accuracy and applicability of our modeling program. Compressional and shear-wave velocities were measured for 75 sandstone samples which were obtained from either well cores or quarries. The porosities of the samples ranged from 2% to 30%, while the clay content by volume fraction ranged from 0 to 50%. The percentage error of the velocities predicted from our modeling routine compared to the measured laboratory values at a pressure of 40 MPa is usually less than 10%, with half of the samples showing an error of less than 5% (Figure 2). Similar results (Benson and Wu, 1999) were obtained for limestone samples evaluated in the laboratory by Kithas (1976).

Sonic and/or Velocity Log Predictions

In addition to its use in modeling and interpreting seismic data, another important application of our modeling routine is to predict the effect of hydrocarbons on sonic logs due to borehole invasion effects. Using the above described modeling algorithm, acoustic travel times or velocities can be estimated for the uninvaded zone containing porous reservoir rocks saturated or partially-saturated with hydrocarbons by using the sonic log data from the invaded zone to predict values for K_b and μ. The estimated velocities can be used to predict impedance and reflectivity changes corresponding to in situ reservoir fluid change, which in turn can be translated into seismic responses on a seismic section.

Since during drilling, drilling fluid invades the porous zones of the borehole and moves existing hydrocarbons away from the borehole wall, and since the sonic log operates only within a few inches of the borehole wall, the recorded travel times, or velocities, will be determined for the porous native rock filled primarily with drilling fluid versus in-situ fluids, particularly hydrocarbons. Knowing the properties of the drilling fluid and using available well logs to help provide rock parameters in the invaded zone, the dry rock bulk modulus, K_b, of the native rock is predicted by inverting equation (1), and the shear modulus, μ, by inverting equation (4). Using these valuess fors K_b and μ, along with reasonable estimates of matrix and fluid properties from the Batzle-Wang formulation, the predicted reservoir travel time, or velocity, can be determined (Figure 3).

Conclusions

By inverting the BGG and shear-wave velocity equations, using available velocity data for water/brine saturated rocks to determine K_b and μ, coupled with generating in-situ estimates of rock-matrix and fluid parameters as a function of depth from the Batzle-Wang (1992) formulation, a new solution is provided for predicting reasonable estimates of in-situ velocities, impedances, and reflection coefficients for porous, fluid-filled rocks systems. Applications of our modeling solution include predicting sonic travel times and/or velocities of porous, hydrocarbon-saturated rocks in the uninvaded zone, which can be used in modeling seismic data and for correcting sonic well log data.

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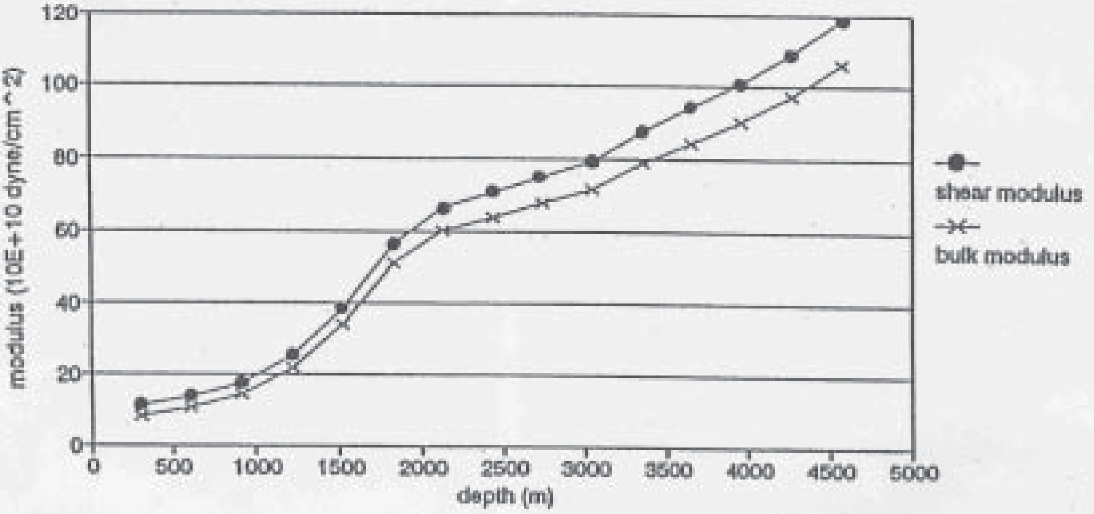

Figure 1: The bulk and shear moduli of empty reservoir rock as a function of depth for average Gulf Coast sandstones generated from our modeling algorithm. Fluid and matrix parameters were generated from the Batzle-Wang formulation (1992). Brine-saturated P-wave velocities for average Gulf Coast sandstones were obtained from well log data compiled by Gregory (1977).

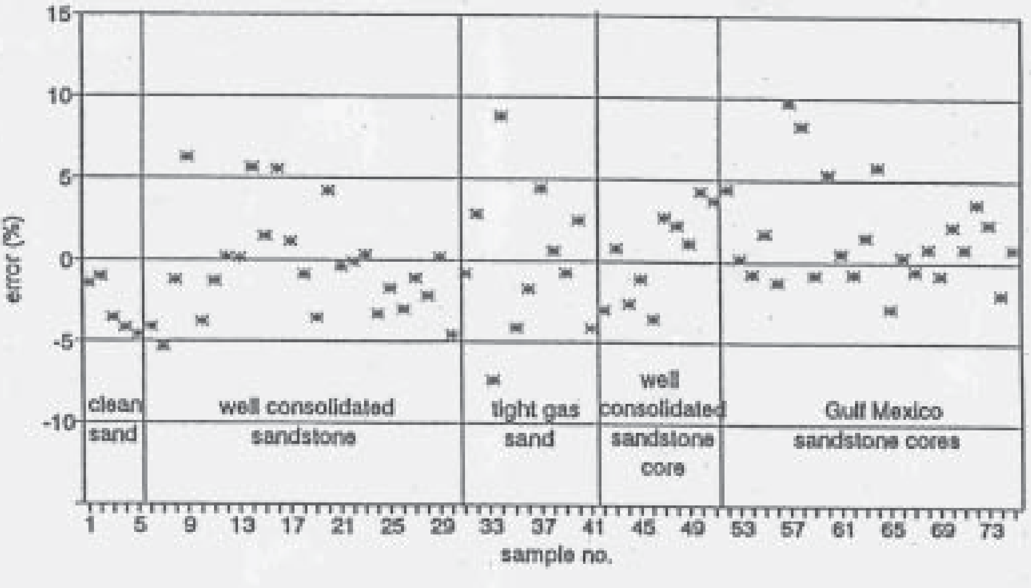

Figure 2: Percentage error between predicted velocities generated by our modeling algorithm and the measured laboratory values of 75 different sandstone samples saturated with water at a pressure of 40 MPa (Han et al., 1986).

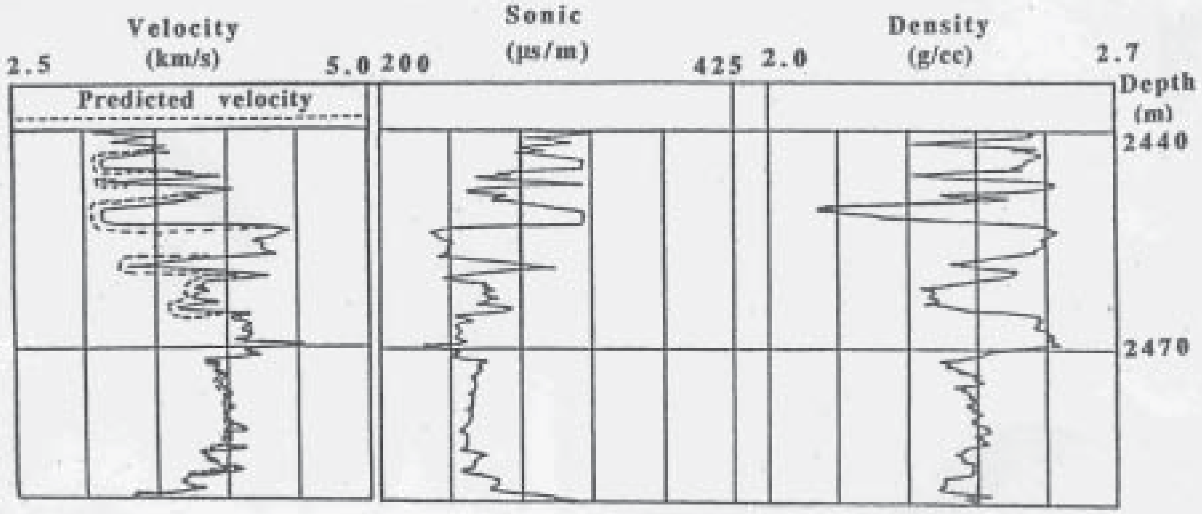

Figure 3: Gulf of Mexico well log examples shown for depths from 2440 m to 2490 m. A velocity log is in track 1, a sonic log in track 2, and a density log in track 3. In track 1, the predicted velocity log generated from our modeling algorithm is overlain on the measured velocity log. Based on the measured logs and the predicted velocity log, a gas zone is interpreted between 2444 m and 2466 m and an oil zone between 2473 m and 2487 m.