STOCHASTIC FLUID MODULUS INVERSION USING SEISMIC REFLECTION COEFFICIENTS

Luther W. White, John P. Castagna, William Lamb, and Isabel Varela, Institute for Exploration and Development Geosciences University of Oklahoma, Norman, Oklahoma 73019*

Summary

We have developed a probabilistic method to invert reflectivity quotients for fluid modulus given imperfect data and incomplete information. The method does not require perfect amplitude calibration and outputs a fluid modulus probability density function. Numerical tests indicate that the results are most accurate when shear-wave reflectivities are utilized and when rock parameters are well known. However, even with imperfect measurements and knowledge, the inversion may yield distributions that are sufficiently narrow to distinguish gas from brine saturated porous sandstones, and provides a means to synthesize all known information and summarize this knowledge in terms of implied fluid modulus.

Introduction

The fluid modulus inversion problem seeks to deduce information concerning the identity of a fluid saturating a particular rock by comparing seismic response of the rock to that obtained when the rock is saturated with some other fluid. White and Castagna (2000) investigated the fluid modulus inversion problem given rock elastic moduli. In Mavko and Mukerji (1998) a formulation is presented for the inclusion of uncertainties in the determination of anomalous fluid modulus using velocity data given a known reference modulus-velocity combination. Their theory may be viewed as a special case of a general probabilistic inversion theory given by Tarantola (1987) applied in White and Castagna (2000). In this paper we extend the work in White and Castagna (2000) to the determination of the fluid modulus from reflection seismic data. In particular, we study the probabilistic estimation of fluid modulus from the observed ratios of reflectivities between a shale seal layer above a sandstone reservoir rock layer saturated with different fluids one of which is a known or assumed reference (brine) while the other is an unknown test containing gas, oil, or brine. While various amounts of information concerning the identity of the brine is assumed, it is always assumed there is no prior knowledge as to the identity of the second fluid. Only ratios of the reflectivities are taken as data. We present a study using R_p and R_s data on a 2D line across a known field. A 3D case study is presented in Chen et al (2002).

Our approach is to construct a multivariate pdf defined on the sample space of eleven rock and fluid parameters consisting of V_{pshale} (P-velocity of the shale), K_o (grain bulk modulus), ρ_o(grain density), ϕ_c (critical porosity), r (exponent in the critical porosity model), ϕ_{ref} (porosity for reference), $\delta\rho_{ref}$ (deviation of density from K_f –trend curve for reference), K_{fref} (fluid modulus for reference), ϕ_{test} (porosity for test), $\delta\rho_{test}$ (deviation of density from K_f –trend curve for test), and K_{ftest} (fluid modulus for test). The pdf is constructed by comparing synthetically derived reflectivity ratios from those constructed from reflectivity data. This joint pdf may be viewed as carrying the information available on the parameters from measurements and models, as well as the uncertainty. We then calculate marginal distributions enabling us to deduce probabilities on K_{ftest}.

Probabilistic formulation:

We view the parameters above as a vector $q=(V_{pshale}, K_o, \rho_o, \phi_c, r, \phi_{ref}, \delta\rho_{ref}, K_{fref}, \phi_{test}, \delta\rho_{test}, K_{ftest})$ as an element of a sample space Ω. A synthetic reflectivity quotient $Q_{syn}(q)$ is obtained using assumed models: Gassmann's equation, (Gassmann; 1951), critical porosity, and trend density-fluid modulus information (Castagna, Batzle, and Kan ; 1995). It is compared with a corresponding quantity obtained from reflectivity data values Q_{data}. A multivariate prior distribution $\pi(q)$ is defined on the sample space Ω as the product of the prior distributions that are defined from prior bounds on individual parameters. The multivariate pdf f(q) is then

$$\mathbf{f}(q) = C \exp\{-.5((Q_{syn}(q) - Q_{data})/\sigma_Q)^2\}\pi(q)$$

where C is a normalization constant and σ_Q is the standard deviation of Q_{data} . From this joint pdf we obtain the marginal pdf for K_{ftest} by integration. Fluid modulus estimates may be obtained, for example, by choosing the maximum or expected value from this marginal pdf.

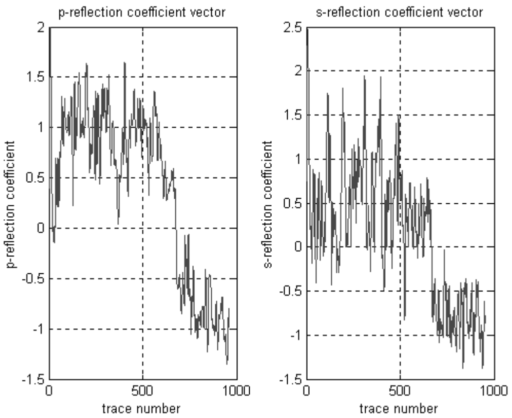
Numerical Example

We consider the estimation of fluid modulus for tests cases that may be gas or brine. We assume bounds on the parameters: V_{pshale} between 1.5 and 5.0 km/s, K_o between 34 and 44 Gpa, ρ_o between 2.55 and 2.75 gm/cc, ϕ_c between 32% and 44%, r between 1.5 and 2.5, ϕ_{ref} and ϕ_{test} between 15% and 35%, $\delta\rho_{ref}$ and $\delta\rho_{test}$ between –0.1 and 0.1 gm/cc, K_{fref} between 2.2 and 4.4 GPa, and K_{ftest} between 0 and 4.4 GPa. We construct examples by specifying these parameters and then forward calculating reflectivity quotients using Gassmann's equation, an assumed porosity-frame modulus relationship, shale velocity trends models, and density-fluid modulus trend models.

Example

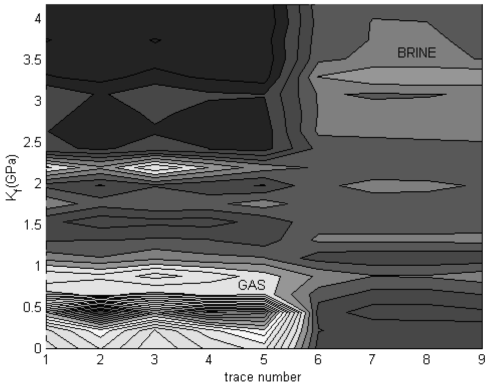
We consider data vectors consisting of R_p and R_s values indicated in Figure 1 in a region known to contain gas and brine sandstones.

Figure 1: Reflection data vectors



We perform stochastic fluid modulus inversion to obtain pdfs for nine locations the first 5 of which contain gas and the last 4 contain brine. Viewing the results as a function of K_f and location, we portray the level curves in Figure 2.

Figure 2: Contour map of the estimated K_f probability density functions



We see that our method distinguishes gas regions from brine for this example. We observe a strong gas indication in trace numbers 1-5. In the brine regions the pdfs are not as sharp indicating a larger uncertainty.

Conclusions

(1) We have formulated a means of fluid modulus inversion from seismic reflection data that provides a probabilistic estimate for fluid modulus given uncertain observations and a priori information of varying degrees.
(2) By introducing the reflectivity quotients we can operate on uncalibrated seismic data. However, as observations at different points in space are included in the quotients, seismic amplitudes must be laterally consistent or appropriately balanced.

References

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