Amplitude vs. Angle - Influence of petrophysical parameters in porous media

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Summary

The availability and use of seismic data in reservoir development is increasing. This paper describes the analysis of reflections, for elastic and porous medium considering variations in the petrophysical parameters of porosity, permeability and viscosity. Three types of seismic waves are analyzed: P_{fast} , P_{slow} and S for frequencies common to surface seismic (60 Hz) and crosswell seismic (2000 Hz) surveys. We use a system of equations derived for porous media by Chen and Quan (1995) which are analogous to Zoeppritz (1919) equations for a pure elastic solid media. We also use an elastic biphase finite-difference modeling program to compare and match the results. Final conclusions indicate a greater sensitivity of the seismic reflection response to porosity variations. Also, variations in the value of the critical angle can be a diagnosis of porosity in reservoir analysis. This effect was called "critical angle migration". S waves are more sensitive than P_{fast} waves. Reflections are less sentive to variations with permeability and viscosity; and, the two have inverse dependence and are indistinct. P_{slow} waves carry more information concerning to the petrophysical parameters but those waves can not be recorded in conventional seismic surveys.

Introduction

The consideration of subsurface media as biphase (rock + fluid) allows analysis of reflectivity with variations in several petrophysical parameters like porosity, permeability, viscosity, saturation, etc. The condition under which the seismic reflectivity response can provide valid information were analyzed in all three types of waves assumed to exist in biphase media: two compressional - P_{fast} and P_{slow} - and one shear - S (Biot, 1956). P_{slow} waves are probably impossible to be recorded with conventional arrays and frequencies used on actual seismic surveys (Klimentos and McCann, 1988); nevertheless, we discuss these slow waves because they carry a lot of information. S waves have more information than P_{fast} waves in relation to porosity, even at low frequencies. Both are sensitive to permeability only at the higher frequencies, e.g., kilohertz, encountered only in logs, crosswell seismic surveys and shallow and ultra-shallow seismic reflection profiles. Some results were confirmed by finite-difference modeling program.

Theoretical Basis

We use the basic system of equations which mathematically describes wave partitioning occurring at the interface between elastic biphase porous and saturated media. The complex system of equations was explicitly and exactly solved by Chen and Quan (1995). They applied the boundary conditions proposed by Lovera (1987) which consider continuity of: a) stress tensors; b) fluid pressure in the pores; c) solid displacement vector (normal and shear components); and d) normal displacement of relative components. These six proposed boundary conditions allow the solution of system for six emergent waves from the interface, three reflected and three transmitted waves. The resultant system describes partial differential equations that govern the continuity conditions.

The theory of wave propagation on a biphase media was given by Biot (1956). Biot considers 3D vectorial displacements of solid (**u**) and fluid (**U**) through a coupled system of differential equations:

$$\begin{pmatrix} \rho_{11} & \rho_{12} \\ \rho_{12} & \rho_{22} \end{pmatrix} \begin{pmatrix} \ddot{u} \\ \ddot{U} \end{pmatrix} + b \begin{pmatrix} \dot{u} - \dot{U} \\ \dot{U} - \dot{u} \end{pmatrix} = \begin{pmatrix} N\nabla^2 u \\ 0 \end{pmatrix} + \begin{pmatrix} A+N & Q \\ Q & R \end{pmatrix} \nabla\nabla\cdot \begin{pmatrix} u \\ U \end{pmatrix} \qquad (1)$$

were ρ_{ij} are inertial densities, N, A, Q and R are elastical constants, dots indicates temporal differentiates, ∇ , $\nabla\cdot$ and ∇^2 are space differential operators. The constant b determines the system attenuation and depends upon the differences of solid and fluid vector velocities $(\mathbf{u} - \mathbf{U})$. It is influenced by porosity, viscosity and permeability. The porosity influences inertial densities as well as elastic constants.

Results

Reflections generated by variations in porous rock, i.e., the reservoir, filled with fluids were calculated for various conditions of porosity and permeability. The behavior of the reflection coefficients were thoroughly investigated in the thesis by Roque (1996).

To analyze the influence of frequency, the results were calculated at various frequencies for surface seismic (60 Hz) and crosswell seismic (2000 Hz). The frequency comparisons allow us to examine the potential sensitivities of different types of seismic surveys as a function of the petrophysical parameters in the reservoir to be imaged. The three types of seismic waves were analyzed in the presence of three types of fluids normally founded in the subsurface:

oil: viscosity = 180cp., density=0.88 g/cm^3 and compressional velocity=1450 m/s

water: viscosity = 1cp, density = 1.0g/cm^3 and compressional velocity = 1500 m/s gas: viscosity = 0.022cp, density=0.14 g/cm^3 and compressional velocity = 630 m/s

The results for P_{fast} waves are presented in Figure 1 for the variation in permeability, and Figure 2 for a variation of porosity. The sensitivity of P_{slow} waves are presented in Figure 3 for permeability and Figure 4 for porosity. The *S* waves sensitivity is shown in Figures 5 (permeability) and 6 (porosity).

Conclusions

Reflected P_{fast} and *S* waves have low sensitivity to permeability variations in oil or water bearing reservoirs, as verified by the insensitivity of the reflection coefficients with respect to permeability variations (Figures 1 and 5). Even in a gas filled reservoir, permeability can only be distinguished with the use of higher frequencies, present only in crosswell reflection seismic surveys (same figures). The reflection coefficient at the critical angle grows with permeability in a reservoir with gas and it becomes a diagnosis in the case of a wide angle seismic imaging. This effect is also minor at low frequencies as used in surface seismic. An important theoretical result is the absence of necessity of increasing frequencies to better discrimination of different permeabilities using P_{slow} waves (Figure 3). The responses attained sing low (60 Hz) and high (2000 Hz) frequencies are very similar. Such evidence have no practical importance in actuality because P_{slow} waves have not be recorded if field seismic surveys.

All three types of analyzed seismic waves (P_{fast}, P_{slow} and *S)* showed higher sensitivity to porosity variations, indicating that this parameter can be more easily estimated from seismic data. A remarkable result is that the variation of critical angle value presented by *S* and P_{fast} waves are due to a change of porosity in reservoirs with oil or water (Figures 2 and 6). This effect is called "*critical angle migration*" and becomes the best diagnosis of porosity by its potentially easy observation in AVA analysis. Reservoirs with gas cape doesn't present this type of effect. For this kind of reservoir analysis it is necessary to have a complete angular sampling and the analysis for comparative examination. The variations for the P_{slow} waves reaffirm that they carry a lot of information, as attested by strong variability in the calculated curves for all types of fluids or frequencies (Figures 3 and 4).

As a final result, it can be pointed out that reflectivity analysis based on this model can never provide inverse solutions for permeability and viscosity separately because the two parameters are indistinct in the Biot system and thus, are impossible to distinguish. Moreover, these conclusions are based on the Biot model of waves in poroelastic media. Their applicability to field data analysis depends on the appropriateness of the Biot model.

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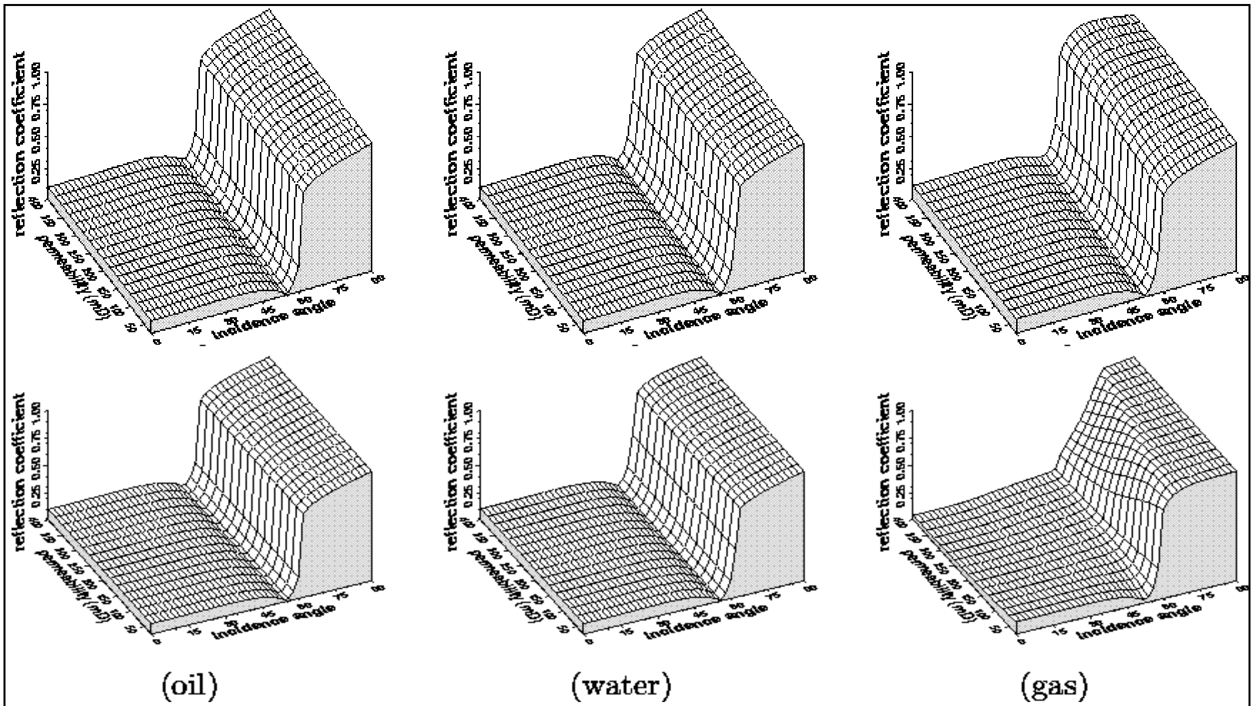


Figure 1: Sensitivity of P_{fast} waves to permeability (superior=60 Hz, inferior=2000 Hz). Horizontal axis = incidence angle, vertical = reflection coefficient and profundity = permeability).

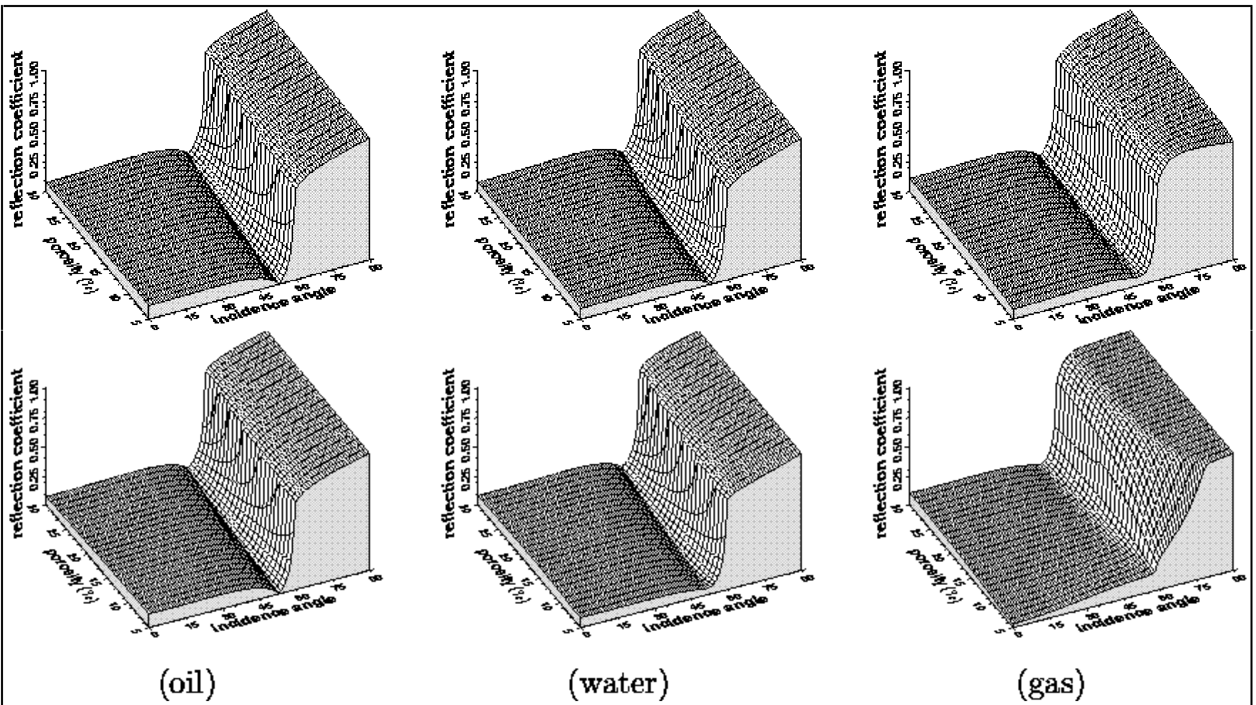


Figure 2: Sensitivity of P_{fast} waves in relation to porosity (superior=60 Hz, inferior=2000 Hz). Horizontal axis = incidence angle, vertical = reflection coefficient and profundity = porosity).

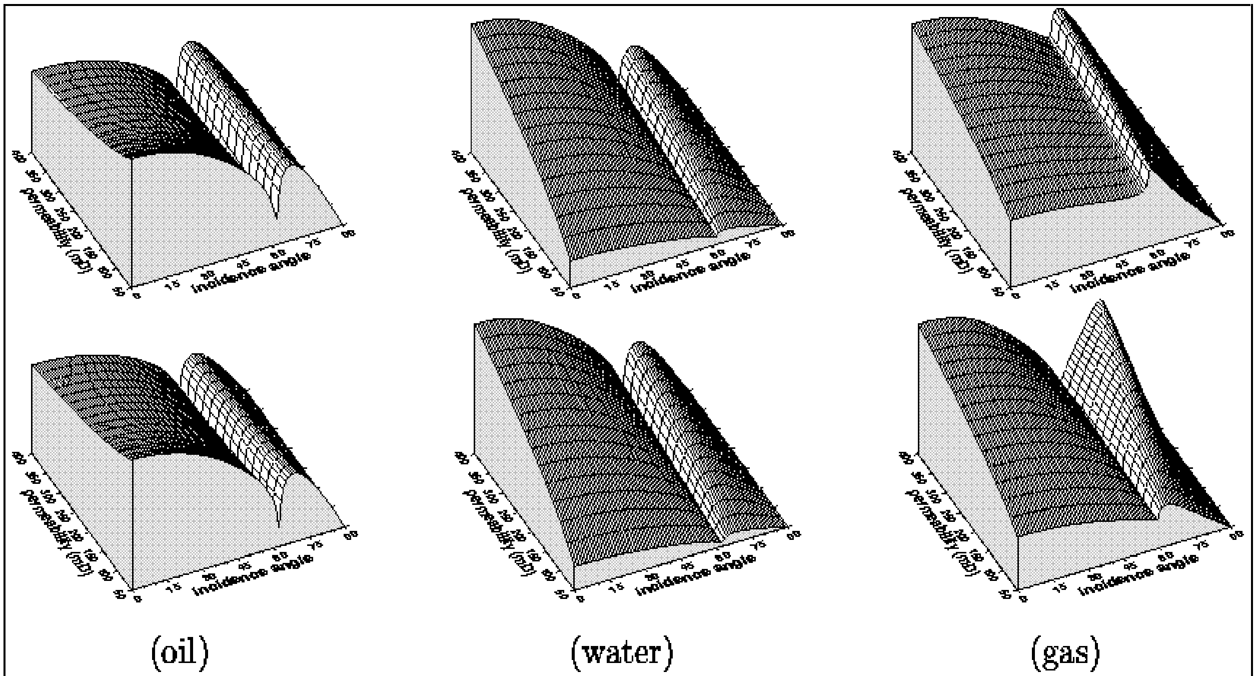


Figure 3: Sensitivity of P_{slow} waves in relation to permeability (superior=60 Hz, inferior=2000 Hz). Horizontal axis = incidence angle, vertical = reflection coefficient and profundity = permeability).

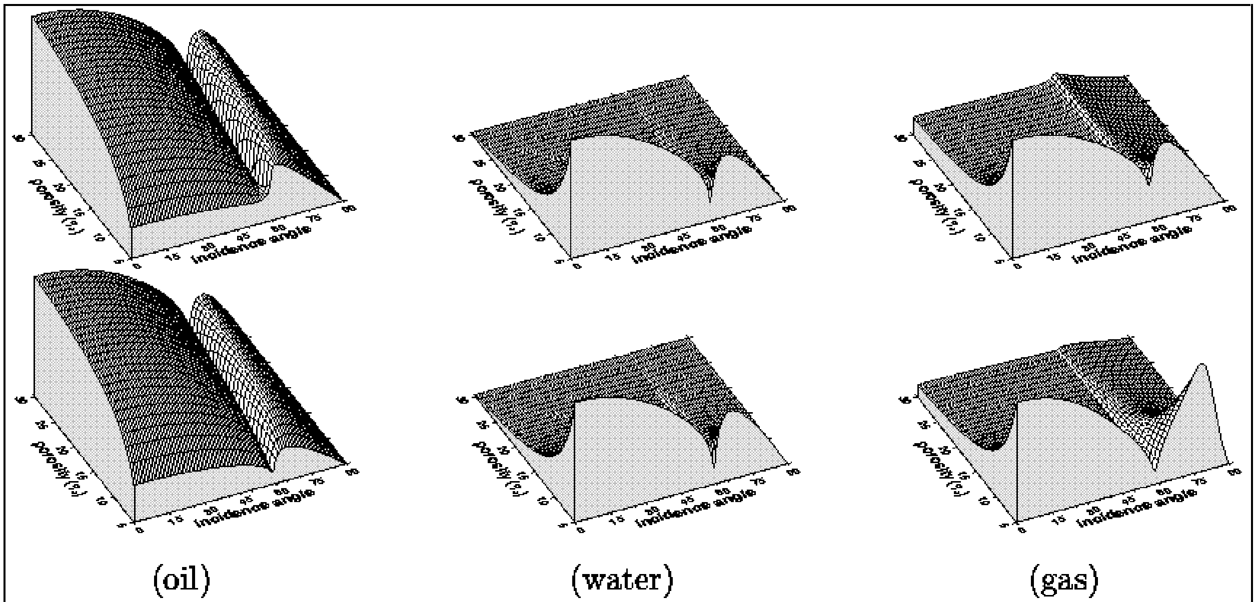


Figure 4: Sensitivity of P_{slow} waves in relation to porosity (superior=60 Hz, inferior=2000 Hz). Horizontal axis = incidence angle, vertical = reflection coefficient and profundity = porosity).

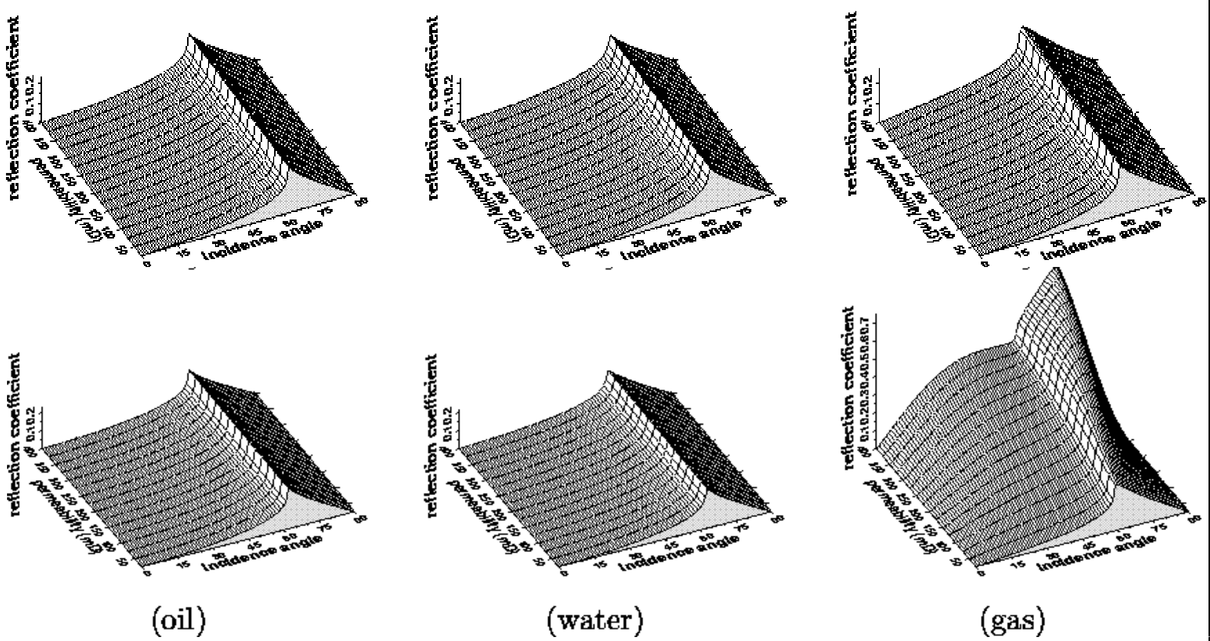
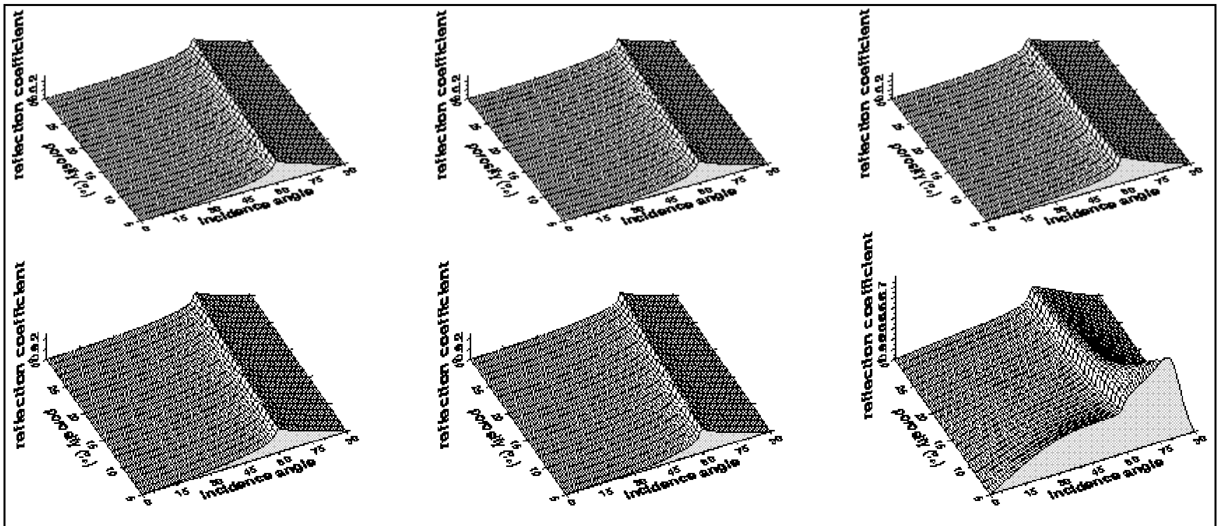


Figure 5: Sensibility of *S* waves in relation to permeability (superior=60 Hz, inferior=2000 Hz). Horizontal axis = incidence angle, vertical = reflection coefficient and profundity = permeability).



(oil) (water) (gas)

Figure 6: Sensibility of *S* waves in relation to porosity (superior=60 Hz, inferior=2000 Hz). Horizontal axis = incidence angle, vertical = reflection coefficient and profundity = porosity).