Inversion of frequency-dependent AVO data for fluid properties

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Summary

A number of methods to estimate the frequency-dependence of reflectivity have been published recently. Application to field data has shown promise, but the information content of the images is poorly understood and no means to quantitatively interpret the results is available. We present a method to quantitatively invert frequency-dependent reflectivity for fluid properties. The method is model dependent, and relies on good knowledge of the relationship between dispersion and rock and fluid properties. Specializing the method to the case of gas-water mixtures, we show the potential to estimate fractional gas saturation from frequency-dependent AVO data.

Introduction

Laboratory measurements of the frequency-dependence of velocities (Batzle et al. 2006) demonstrate that dispersion is related to fluid saturation. This suggests that velocity dispersion may be a useful tool for seismic fluid characterization, but unfortunately direct estimates of dispersion are difficult to obtain. One promising strategy is based on attempting to estimate the frequency-dependence of the reflection coefficient (Chapman et al. 2005; Ren, 2009; Innanen, 2009).

Wu (2010), Zhang (2011) and Xu (2011) produced images of the frequency-dependence of reflectivity, and noted correlations with rock properties of interest. Although the technique is clearly promising, the information content of the images is still poorly understood and no method for quantitatively interpreting the results is available.

In this paper we present a new method for inferring rock and fluid properties from frequency-dependent AVO data. We use a rock physics model to apply the method to the case of gas-water mixtures, where the gas saturation is allowed to vary. The method allows us to derive attributes which measure both the "low frequency" reflectivity and the frequency-dependence of reflectivity. We derive a rock physics template which suggests that crossplotting these attributes may allow us to separate the cases of low gas saturation, full water saturation and full gas saturation. This has proved problematic in the past with traditional, frequency-independent, AVO analysis.

Method

Standard AVO interpretation relies on associating a measured seismic amplitude with the plane wave reflection coefficient. Wilson et al. (2009) extended this analysis to the case where velocity dispersion was present and reflectivity was frequency-dependent. His method involved the spectral decomposition and balancing of pre-stack seismic data and the application of a linearized equation relating the reflection coefficient to angle of incidence and frequency. He showed how to invert the pre-stack data to obtain an estimate of dispersion properties. The method produces images of frequency-dependence of reflectivity which often correlate with fluid properties (Wu, 2010). Clearly, it would be advantageous to be able to quantitatively relate such images to rock properties of interest.

In this paper we consider reflections from the interface between a layer having frequency-independent properties and a layer whose properties are frequency-dependent. This is to simulate the case of reflection from the top of a reservoir which exhibits strong fluid-related dispersion.

Our attention is focussed on a particular rock property of interest X, and we consider p different values of this property. We assume that we know velocity and attenuation as a function of frequency in the dispersive layer, either from use of an appropriate rock physics model or through direct measurement in the laboratory, in which case we may calculate the reflection coefficient as a function of frequency and offset by standard means.

Considering m angles of incidence θ, n frequencies f and p rock properties we arrange our computed reflection coefficients in a matrix R of the following form:

$$
\underbrace{\begin{matrix} R_{\theta_1}^{f_1} & \cdots & R_{\theta_1}^{f_n} \\ R_{\theta_2}^{f_1} & & R_{\theta_2}^{f_n} \\ \vdots & & \vdots \\ R_{\theta_m}^{f_1} & \cdots & R_{\theta_m}^{f_n} \end{matrix}}_{X_1} \;\cdots\cdots\; \underbrace{\begin{matrix} R_{\theta_1}^{f_1} & \cdots & R_{\theta_1}^{f_n} \\ R_{\theta 2}^{f_1} & & R_{\theta_2}^{f_n} \\ \vdots & & \vdots \\ R_{\theta_m}^{f_1} & \cdots & R_{\theta_m}^{f_n} \end{matrix}}_{X_2} \;\cdots\cdots\cdots\; \underbrace{\begin{matrix} R_{\theta_1}^{f_1} & \cdots & R_{\theta_1}^{f_n} \\ R_{\theta_2}^{f_1} & & R_{\theta_2}^{f_n} \\ \vdots & & \vdots \\ R_{\theta_m}^{f_1} & \cdots & R_{\theta_m}^{f_n} \end{matrix}}_{X_p}
$$

Following the method of Causse et al. (2007), we perform spectral decomposition on the matrix R, allowing us to approximate the reflection coefficients as a series of weights, C, which are a function of rock properties and frequency ,and basis functions h which are a function of angle of incidence:

$$R_{X_k}^{f_l}(\theta) \approx C_1(f_j, X_k)h_1(\theta) + \cdots + C_i(f_j, X_k)h_i(\theta)$$

The dependence of the weight functions C on frequency can often be approximated by a linear relationship, which allows us to carry out intercept-gradient analysis for the frequency-dependence. In such an analysis, the intercept will give the low frequency limit of reflectivity, which should correspond to that predicted by the Gassmann equation, while the gradient will give a measure of the frequency-dependence of reflectivity.

Examples

We apply this method to the model considered by Rutherford and Williams (1989), where we introduce dispersion into the lower layer following the technique introduced by Chapman et al. (2006). The lower layer is considered to be saturated with a mixture of gas and water, modelled as an effective fluid. In such a case, it is predicted that strong dispersion and attenuation occurs for small values amounts of gas, with a peak value typically around 10% saturation, while smaller values of attenuation are seen for the cases of full saturation with either water or gas. An example of the attenuation versus gas saturation relation is shown in Figure 1. Similar behaviour has been seen many times in the laboratory.

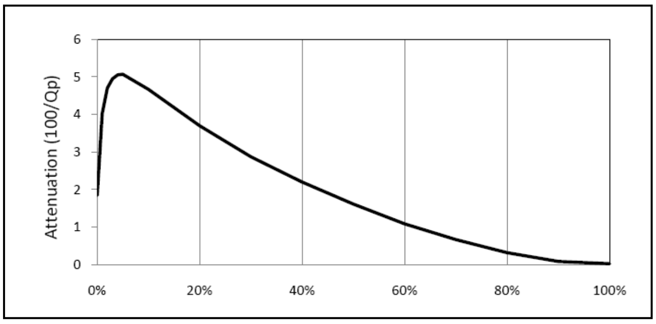

Figure 1: Predicted values of attenuation versus gas saturation for the modeling.

Corresponding to this Figure, we can calculate reflection coefficients for each value of the saturation as a function of both angle of incidence and frequency. Figure 2 shows an example of such curves. When we have little dispersion, the reflection coefficients for different frequencies overlie each other, but when we have larger dispersion the curves are clearly separated.

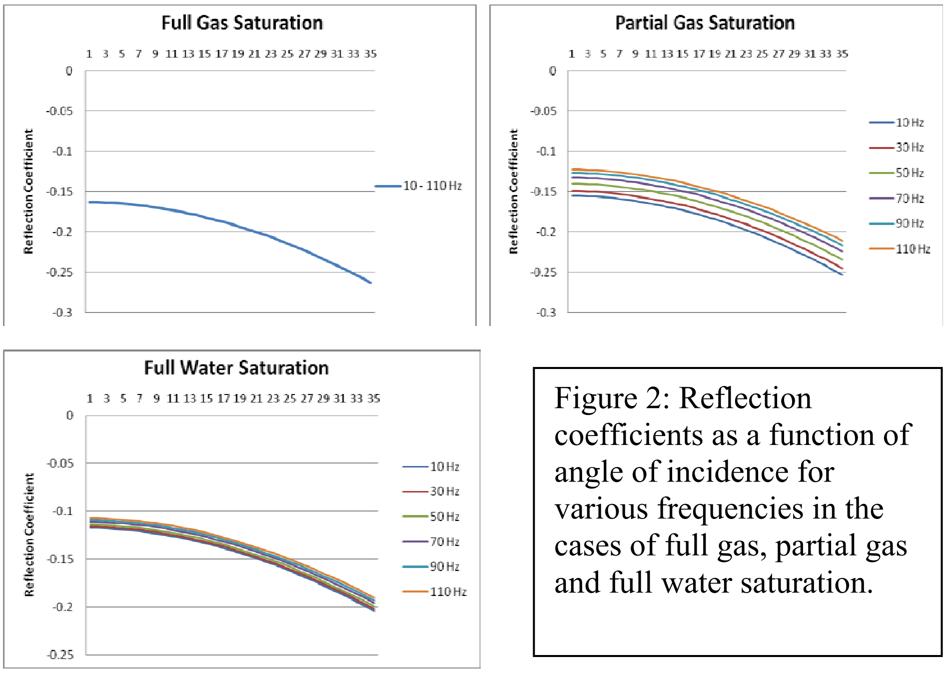

Figure 2: Reflection coefficients as a function of angle of incidence for various frequencies in the cases of full gas, partial gas and full water saturation.

Constructing our reflection matrix and following the method described above, we find that the reflection coefficients can be described accurately using only one basis function and weight. Additionally, the variation of the weights with frequency for each saturation is approximately linear, allowing us to associate each saturation with a gradient and intercept. Crossplotting these attributes results in Figure 3. Full gas saturation, partial gas saturation and full water saturation are clearly separated in this crossplot.

Conclusions

This paper has presented a method which in principle can estimate fractional gas saturation from seismic data. The method is model dependent, and relies on a good knowledge of the link between fluid saturation and dispersion properties. The procedure further assumes that it is possible to estimate the frequency-dependence of the reflection coefficient from seismic data through the application of spectral decomposition procedures. We show how to estimate both a low-frequency (or Gassmann) reflectivity as well as an attribute which measures the frequency-dependence of reflectivity. Analysis of a typical example reveals that crossplotting these attributes is able to separate three cases of interest- full gas saturation, low gas saturation and full water saturation- whereas this was not possible using traditional AVO methods. Future work will involve testing this method on field data.

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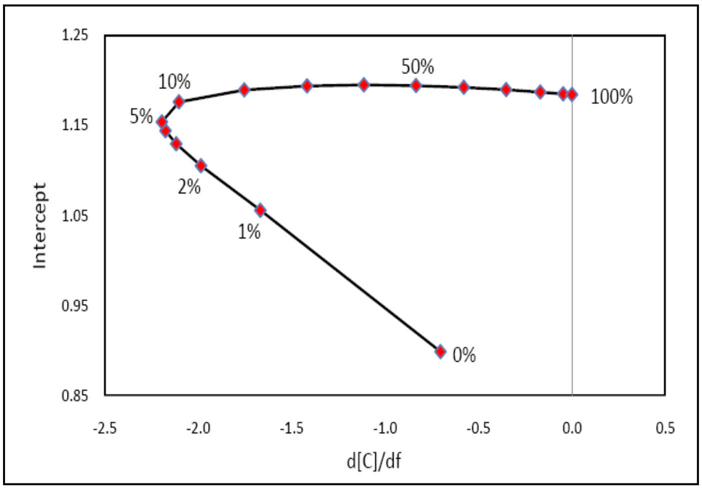

Figure 3: Crossplot of low-frequency-reflectivity against frequency-dependence of reflectivity.