Estimation of gas saturation changes from frequency-dependent AVO analysis

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Seismic attenuation is believed to be sensitive to many reservoir parameters of interest, but its routine application is inhibited by the lack of reliable quantitative relationships which can relate observed behaviour directly to rock and fluid properties. This paper calibrates a frequency-dependent rock physics model for a gas field in Austria, through analysis of well log-data and frequency-dependent AVO analysis of seismic reflection data. Analysis of the model reveals the potential to estimate changes in gas saturation which cannot be detected with the standard, single frequency approximation.

Introduction

Seismic attenuation measurements can in principle enhance reservoir characterization efforts, since attenuation is known to be more sensitive to certain petrophysical parameters, particularly saturation, than is seismic velocity. While significant strides have been made recently in techniques for the estimation of attenuation (Reine et al., 2009), the lack of reliable quantitative relationships which can relate the attenuation directly to the rock properties of interest prevents the routine use of attenuation based methods. Such quantitative relationships will ultimately have to be calibrated and tested in-situ.

In this paper we consider the frequency-dependence of the amplitude-versus-offset (AVO) response, which is closely related to variations in attenuation. While many theories exist for the elastic properties of rocks saturated with multiple fluids, we outline a rather pragmatic approach which has the merit of being readily applicable to field data. We calibrate our model with well-log and seismic data from a gas field, and explore the potential of the method to image gas saturation and porosity variations. An advantage of our work is that the method is in principle predictive, opening the way to further testing and calibration with field data. We believe that such work should guide and augment more theoretical studies of seismic attenuation.

Theory

The theory for wave propagation in rocks saturated with multiple fluids is an active current research area (Muller et al., 2010). White (1975) produced a remarkably robust model for the effect of gas bubbles on attenuation, while Gist (1994) argued from an analysis of laboratory data that it was necessary to combine the effect of such bubbles or "gas pockets" with the "squirt-flow" effect. There is still no truly satisfactory model which achieves this. Broadhead (2012) emphasised the importance of the contact angle between films of different fluids, and this appears to be a promising direction.

Nevertheless, predictions of the various approaches are typically rather similar from a qualitative standpoint. For mixtures of gas and water, low attenuation is typically predicted for full saturation by either fluid, with a maximum of attenuation occurring for an intermediate saturation. The location of this maximum is model dependent, but usually occurs for gas saturations between 10% and 50%, with a bias towards low gas satuations. In Figure 1 we show representative curves drawn using the theory of Chapman et al. (2002) with an effective fluid. The bulk modulus of the effective fluid was calculated using Wood's equation while viscosity was averaged volumetrically. Theoretically, the absolute value of the maximum of attenuation is sensitive to a "crack density" parameter-similar parameters exist in other theories. In practice, this parameter will be chosen to calibrate the model.

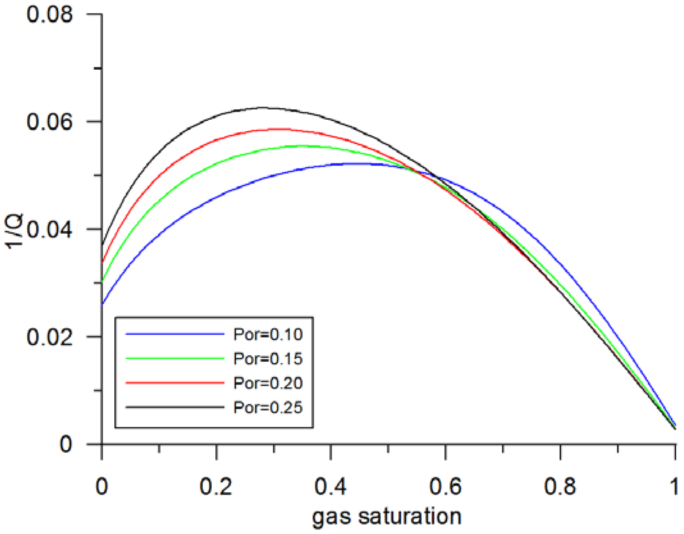


Figure 1 *Attenuation (1/Q) varying with gas saturation under different porosity using the theory of Chapman et al. (2002).*

Frequency-dependent AVO inversion (Wilson et al., 2009), attempts to estimate the frequency-dependence of P- and S-wave impedance from pre-stack reflection data. The method begins by performing spectral decomposition, followed by a spectral balancing procedure which removes the overprint of the wavelet and allows the resulting derivative of P-wave impedance to be associated with fluid induced seismic dispersion (Wu et al, 2012).

In this work, we assume that a starting background model is known for both upper and lower layers. This includes representative values of *Vp* and *Vs*, or distributions of values, associated with given petrophysical parameters such as porosity and saturation. The rock physics model will then allow us to calculate attenuation and frequency-dependent velocity for each realisation of the petrophysical parameters, together with a complex, frequency-dependent, reflection coefficient. Comparing these computed reflection coefficients with the spectrally decomposed and balanced seismic amplitudes provides a basis for an inversion of the data in terms of petrophysical parameters.

Boston (2011) performed a numerical study which applied principal component analysis to frequency-dependent reflectivities computed from reasonable rock physics models, with a particular emphasis on determining gas saturation. He showed how to derive two parameters from the frequency-dependent reflectivity, one which had a sense of “low-frequency reflectivity” and the other representing the “frequency-dependence of reflectivity”. Crossplotting these parameters was able to separate the three cases of full water saturation, low gas saturation and full gas saturation. This was in contrast to the traditional AVO technique which has difficulty in discriminating low and full gas saturation. The example which follows illustrates this result within the context of a practical example.

Example

Our study area is a gas field in Austria. Logs from a producing well were available, and are reproduced in Figure 2 with the top of the reservoir marked. Compared with the overlying shales, the reservoir exhibits lower Gamma Ray (80 API), higher resistivity (5 Ohm), lower density (2.35 g/cm^3) and lower P-wave velocity (3100 m/s). The producing interval is a sandstone with a porosity of 16% and a water saturation of around 59%. In addition we have pre-stack seismic data which has been tied to the well. The AVO behaviour of the well follows a typical class III pattern.

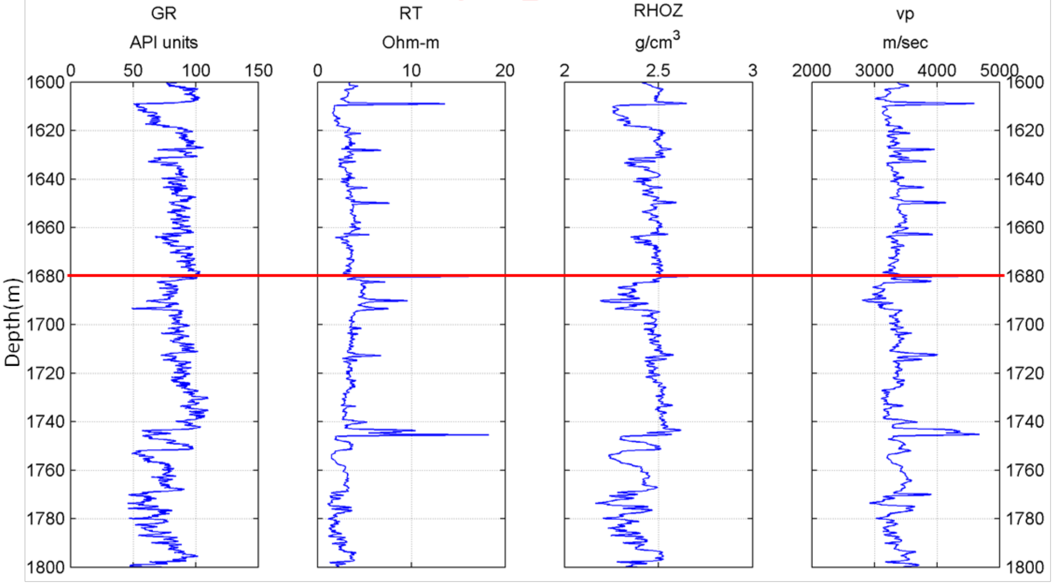


Figure 2 *Well logs from a gas field in Austria. The red line indicates the top of the reservoir.*

The first step is to calibrate our frequency-dependent rock physics model, but to do so we require to take account of the attenuation. This involves choosing an appropriate value of the crack density parameter which controls the peak value of attenuation in Figure 1. Table 1 displays the parameters used for the calculation of frequency dependent-reflectivities at the interface of a two-layer model. We argue that the porosity and saturation is known at the well location, so that if we also have an estimate of the corresponding attenuation then we will be able to choose an optimal value of crack density to match the model to the data.

Table 1 *The material parameters for the two-layer model with shales overlying sandstone reservoir.*

Layers	Vp(km/s)	Vs(km/s)	Vp/Vs	Den(g/cm^3)	Porosity	Crack density	Water saturation
Upper	3.200	1.600	2.0	2.50			
Lower	3.100	1.865	1.66	2.35	0.16	0.15	0.60

We achieve this through application of frequency-dependent AVO analysis to the pre-stack data. For each value of the crack density, we can calculate a set of frequency-dependent reflection coefficient curves as shown in Figure 3. The field data meanwhile can be spectrally decomposed and balanced following the Wilson et al. (2009) method to give a set of amplitudes for each angle of incidence and frequency which we can compare to the computed reflection coefficient curves. The crack density which gives the best fit to the seismic data is selected to calibrate the model.

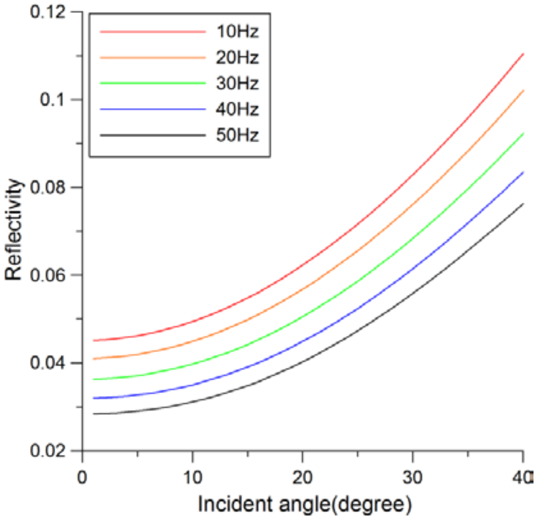
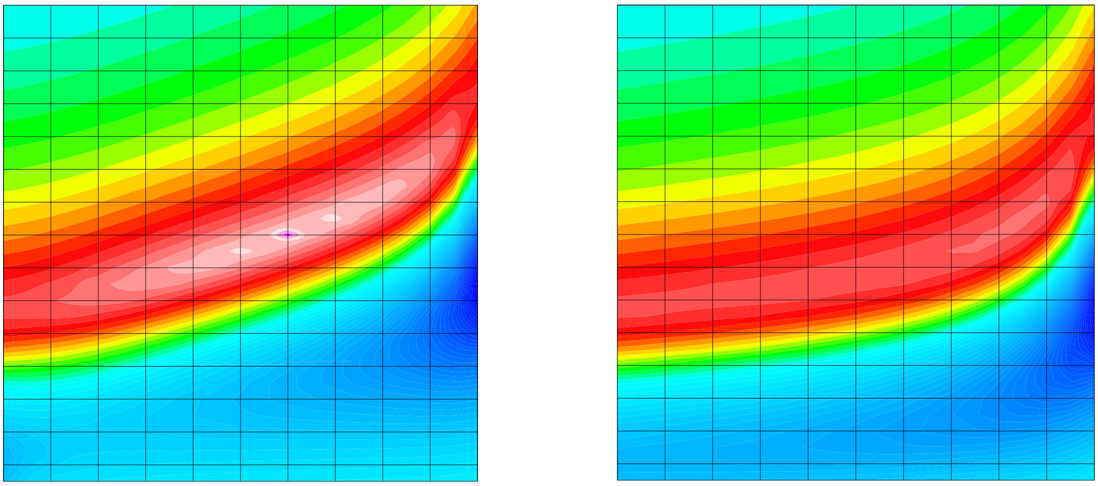


Figure 3 *Frequency-dependent reflectivities at the interface for the model with material parameters displayed in* ***Table 1****.*



(a) Frequency-dependent theory

(b) Gassmann's theory

Figure 4 *Goodness of fit between the computed reflection coefficients and the data by scanning porosity and water saturation.*

Once the model is calibrated to the data, we can study the potential resolution of the method for determining variations in porosity and saturation. We scan through different combinations of porosity and water saturation, and compute the goodness of fit between the computed reflection coefficient curves and the data. We then repeat the analysis replacing the frequency-dependent rock physics modelling with the single frequency Gassmann approach. Comparing these results in Figure 4, we recover the well known result that it is hard to distinguish between low and high gas saturations on the basis of Gassmann's theory, but the frequency-dependent theory shows more promising. The reason for this result is that while high and intermediate gas saturations show the same reflectivity for low frequencies, the frequency-dependence of the reflectivity is different because of the behaviour depicted in Figure 1.

A similar procedure was applied to seismic data for different locations. The seismic data was compared to the predicted response for different combinations of porosity and saturation. As such, the technique can be used to assess the likely changes in porosity and saturation between zones for which seismic data are available. As more well data becomes available, we expect to refine our calibration of the model and test further the potential of the method to discriminate subtle changes in saturation.

Conclusions

We have argued that the frequency-dependent AVO technique is theoretically capable of providing greater resolution of gas saturation changes than conventional AVO techniques. The overriding reason for this is the strong frequency-dependence of velocity, and high attenuation, which is observed for intermediate saturations compared to relatively frequency-independent response for full saturations. Calibrating our approach from well-log and seismic data from a producing gas field, we demonstrated the potential to estimate gas saturation and porosity variations within a known lithology. Further testing and calibration is of course necessary, but we believe that our results demonstrate the potential for the use of frequency-dependent rock physics theories to improve the interpretation of seismic data.

Acknowledgements

This work is supported by the sponsors of the Edinburgh Anisotropy Project. The authors thank OMV for providing access to the data and for permission to present the results.

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