Petrophysical AVO

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Abstract

Geoscientists looking at seismic amplitudes should also be considering petrophysics, particularly when performing Amplitude versus Offset (AVO) analysis. Recent developments in AVO have made the connection between the AVO amplitudes and petrophysical parameters much more clear. Through the use of examples, this paper shows how these newer AVO equations can be used in conjunction with petrophysics to produce direct measurements of the important petrophysical parameters derivable from seismic.

Introduction

For years, the most common AVO methods have been near and far offset or angle stacks and the intercept and gradient, most commonly derived using Shuey's (1985) equation. Numerous approximations to the Zoeppritz equations (1919) have been published over the years. The popular versions are due to Bortfeld (1961), Aki and Richards (1980), Shuey (1985), Gidlow et al (1992 – frequently attributed to Fatti et al, 1994), Verm and Hilterman (1994) and Gray et al (1999). Of these, all except Bortfeld's are re-workings of the Aki and Richards equation using more advantageous petrophysical measurements. The most commonly used, Shuey's equation, gives a good visual QC, allowing the AVO analyst to compare directly the results to the gathers. However, its connection to petrophysical parameters is confusing. Since the mid-1990's, most of the other equations listed have been available and they lead directly to petrophysical parameters of interest to geoscientists.

Method

Using the table of relationships between elastic parameters listed in Wang and Nur (1992), the equation of Aki and Richards (1980) can be converted into any three parameters in Wang and Nur's table: P-velocity, α, S-velocity, β, density, ρ, Poisson's ratio, σ, bulk modulus, K, shear modulus, μ, and Lamé's modulus, λ. Thus, an AVO equation can be formulated to estimate the change in any petrophysical parameter that can be derived from seismic data. The common AVO equations are listed in Table 1, where θ is the angle of incidence of the P-wave. In practice, a petrophysical analysis on the reservoir or an analogue should be done simultaneously with the seismic data processing. The petrophysical analysis determines the optimal petrophysical parameters, obtainable from seismic, that can be used to delineate the reservoir. When the processing is complete, an AVO analysis can then be done using an appropriate AVO equation that derives an estimate of this parameter from the seismic data. If desired, these parameters can then be inverted using post-stack amplitude inversion software to generate a volume of the petrophysical parameter of interest, rather than its reflectivity (e.g. Gray, 2002).

Examples

In order to illustrate this concept, very clear cases showing the difference in AVO responses for different petrophysical parameters will be shown. In the first case, the AVO response at the water bottom will be examined. In the second case, the AVO response of a low-impedance gas sand will be explored.

At the water bottom, there will always be a huge decrease in the Vp/Vs ratio, which is infinite in seawater and typically has values on the order of 5-10 just below the seafloor. Thus the reflection coefficient for the Vp/Vs ratio at the seafloor should be on the order of -1. At the same time, the Poisson's ratio in seawater is its maximum of 0.5, while at the sea bottom it will be on the order of 0.44. Thus, the Poisson's reflectivity contrast at the seafloor is only -0.06 (Table 2). Therefore, AVO that reflects the Vp/Vs ratio, like the Fluid Factor (Gidlow et al, 1992), should produce large values and AVO that reflects Poisson's ratio should produce

small values. Figure 2 clearly shows a much better water-bottom reflection in the Fluid Factor than in the Poisson's Reflectivity as predicted by the petrophysical analysis shown in Table 3.

A second case is a gas sand with petrophysical properties similar to the analogue listed in Table 3 (Goodway et al, 1997). In this case, the reflectivity of Poisson's ratio is about double that of the Vp/Vs ratio. Therefore, Poisson Reflectivity should delineate the reservoir better than Fluid Factor. Figure 3 shows that Poisson Reflectivity does indeed detect a thin gas sand (right arrow) just above the Carbonate unconformity (U/C) that the Fluid Factor does not. Goodway et al (1997) show that $\lambda\rho$ gives a still better estimate of this reflection, which is consistent with the observations here ($\lambda\rho$ reflectivity of -0.38) and is the best petrophysical measurement for this gas sand.

Parameters	AVO Equations	Reference	#
α,β,ρ	$R(\theta) \approx \frac{1}{2}\left(\sec^2\theta\right)\frac{\Delta\alpha}{\alpha} - 4\frac{\beta^2}{\alpha^2}\left(\sin^2\theta\right)\frac{\Delta\beta}{\beta} + \frac{1}{2}\left(1 - 4\frac{\beta^2}{\alpha^2}\sin^2\theta\right)\frac{\Delta\rho}{\rho}$	Aki and Richards (1980)	1
$\rho\alpha,\mu,\alpha$	$R(\theta) \approx \frac{1}{2}\frac{\Delta(\rho\alpha)}{\rho\alpha} + \left(\frac{1}{2}\frac{\Delta\alpha}{\alpha} - 2\frac{\beta^2}{\alpha^2}\frac{\Delta\mu}{\mu}\right)\tan^2\theta + 2\frac{\beta^2}{\alpha^2}\frac{\Delta\mu}{\mu}\left(\tan^2\theta\sin^2\theta\right)$	Bortfeld (1961)[1]	2
$\rho\alpha,\sigma,\alpha$	$R(\theta) \approx \frac{1}{2}\frac{\Delta(\rho\alpha)}{\rho\alpha} + \left[\frac{1}{2}\frac{\Delta\alpha}{\alpha} - \left(2\frac{\Delta\alpha}{\alpha} + \frac{\Delta\rho}{\rho}\right)\frac{1-2\sigma}{1-\sigma} + \frac{\Delta\sigma}{(1-\sigma)^2}\right]\sin^2\theta + \frac{1}{2}\frac{\Delta\alpha}{\alpha}\left(\tan^2\theta - \sin^2\theta\right)$	Shuey (1985)	3
α,β,ρ	$R(\theta) \approx \frac{1}{2}\frac{\Delta(\rho\alpha)}{\rho\alpha} + \left(\frac{1}{2}\frac{\Delta\alpha}{\alpha} - 4\frac{\beta^2}{\alpha^2}\frac{\Delta\beta}{\beta} - 2\frac{\beta^2}{\alpha^2}\frac{\Delta\rho}{\rho}\right)\sin^2\theta + \frac{1}{2}\frac{\Delta\alpha}{\alpha}\left(\tan^2\theta - \sin^2\theta\right)$	Shuey using β	4
$\rho\alpha,\rho\beta,\rho$	$R(\theta) \approx \left(\frac{1}{2} + \frac{1}{2}\tan^2\theta\right)\frac{\Delta(\rho\alpha)}{\rho\alpha} - 4\frac{\beta^2}{\alpha^2}\frac{\Delta(\rho\beta)}{\rho\beta}\sin^2\theta + \left[2\frac{\beta^2}{\alpha^2}\sin^2\theta - \frac{1}{2}\tan^2\theta\right]\frac{\Delta\rho}{\rho}$	Gidlow et al (1992)	5
$\rho\alpha,\sigma$	$R(\theta) \approx \frac{1}{2}\frac{\Delta(\rho\alpha)}{\rho\alpha}\cos^2\theta + \frac{\Delta\sigma}{(1-\sigma)^2}\sin^2\theta$	Verm and Hilterman[2] (1994)	6
K,μ,ρ	$R(\theta) \approx \frac{1}{2}\left(1 - \frac{1}{2}\sec^2\theta\right)\frac{\Delta\rho}{\rho} + \frac{1}{4}\left(1 - \frac{4}{3}\frac{\beta^2}{\alpha^2}\right)\left(\sec^2\theta\right)\frac{\Delta K}{K} + \left(\frac{\beta^2}{\alpha^2}\right)\left(\frac{1}{3}\sec^2\theta - 2\sin^2\theta\right)\frac{\Delta\mu}{\mu}$	Gray et al (1999)	7
λ,μ,ρ	$R(\theta) \approx \frac{1}{2}\left(1 - \frac{1}{2}\sec^2\theta\right)\frac{\Delta\rho}{\rho} + \frac{1}{4}\left(1 - 2\frac{\beta^2}{\alpha^2}\right)\left(\sec^2\theta\right)\frac{\Delta\lambda}{\lambda} + \frac{1}{2}\left(\frac{\beta^2}{\alpha^2}\right)\left(\sec^2\theta - 4\sin^2\theta\right)\frac{\Delta\mu}{\mu}$	Gray et al (1999)	8

Table 1: Common AVO equations expressed using a consistent parameter set.

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[1] This is Bortfeld's (1961) equation number 9. Also commonly used is his equation number 18, which can be expressed in these

terms as $R(\theta) = \frac{1}{2}\ln\left(\frac{\rho_2\alpha_s\cos\theta_1}{\rho_1\alpha_1\cos\theta_2}\right) + \frac{\beta^2}{\alpha^2}\sin^2\theta\left(1 - \frac{\alpha_2^2}{\alpha_1^2}\right)\left(2 + \frac{\ln\left(\frac{\rho_2}{\rho_1}\right)}{\ln\left(\frac{\alpha_2}{\alpha_1}\right) - \ln\left(\frac{\alpha_2\beta_1}{\beta_2\alpha_1}\right)}\right)$, where the subscripts 1 and 2 represent the upper

and lower media, respectively. Equation 18 requires the additional assumption that the relative change in ρ is proportional to the relative change in β. Equation 9 does not require this assumption and is similar to modern AVO equations and so it is presented here.

[2] Verm and Hilterman (1994) make additional assumptions $\alpha/\beta=2$ and $\sin\theta=\tan\theta$ to simplify their equation to two terms.

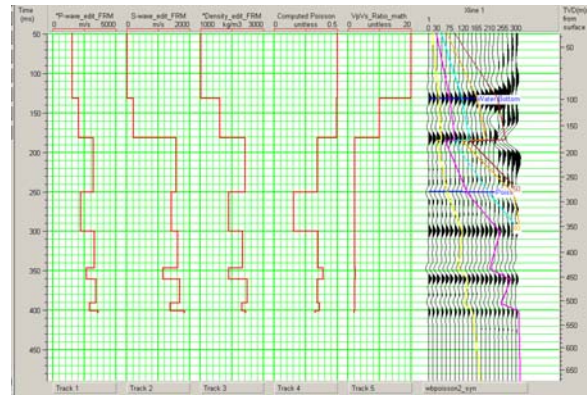|	Water	Seabed	Refl.
α	1500	2000	0.14
β	0.1	200	1.00
ρ	1.00	1.75	0.27
α/β	∞	10	-1.00
σ	0.50	0.44	-0.06
μ	0.00	0.07	1.00
κ	2.25	6.31	0.47
λ	2.25	6.86	0.51

Table 2: Parameters for a water-bottom reflection

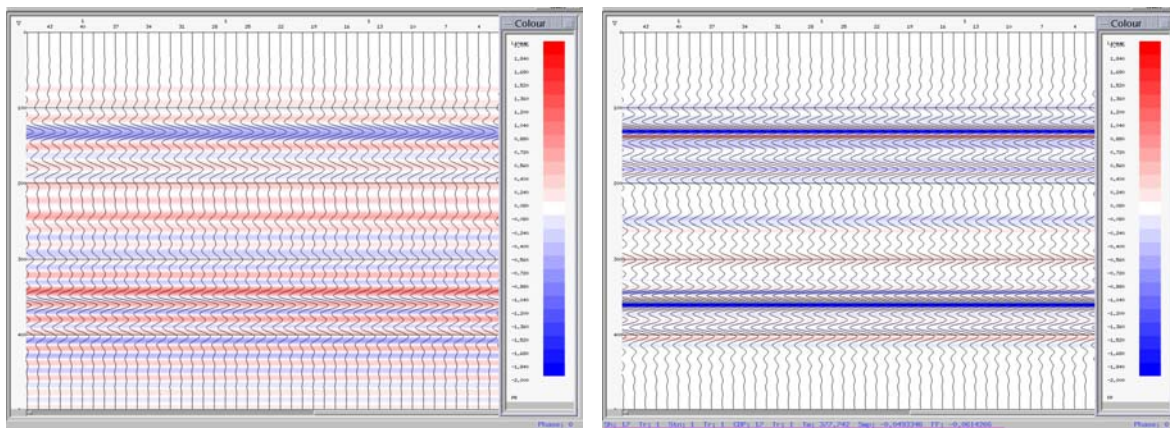Figure 1: Synthetic used to generate water-bottom model.

Figure 2: On the left is Poisson Reflectivity (Verm and Hilterman, 1994); on the right is Fluid Factor (Gidlow et al, 1992). The reflection at 0.13s is the water bottom

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	Shale	Gas Sand	Refl.
α	2898	2857	-0.01
β	1290	1666	0.13
ρ	2.43	2.28	-0.03
α/β	2.25	1.71	-0.13
σ	0.38	0.24	-0.22
μ	4.04	6.31	0.22
K	14.99	10.15	-0.19
λ	12.30	5.94	-0.35

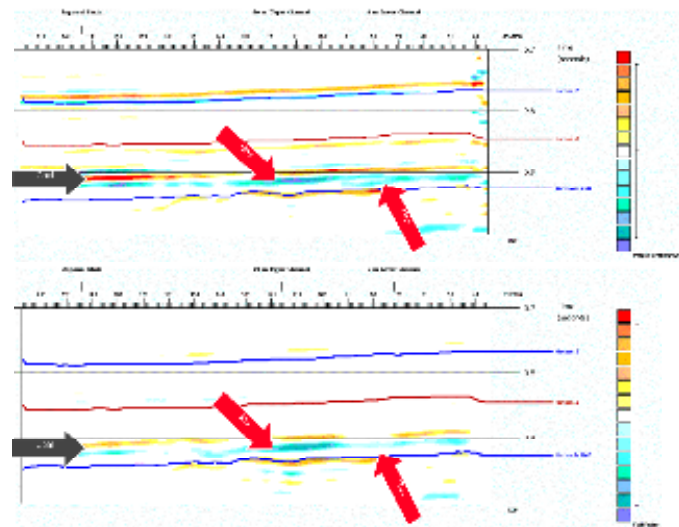Table 3: Petrophysical properties for a Cretaceous gas sand with a shale caprock.

Figure 3: Poisson's Reflectivity (top) from Equation 6 and Fluid Factor (bottom) from Equation 5, after Gray (1999).

Conclusions

An AVO equation producing petrophysical parameters that delineate the reservoir type of interest should be used in every AVO analysis. For optimal turnaround, petrophysical analysis to determine these parameters should be done while the seismic data is in pre-processing. The AVO gradient and far stack are mixtures of three petrophysical parameters and are confusing as a result. They are best used for amplitude QC in the gathers since they don't have any clear petrophysical meaning.

There are many AVO equations available that use petrophysical parameters like P-Impedance, S-Impedance, Bulk Modulus, Shear Modulus, Lamé's Modulus and Poisson's Ratio. Using the best parameterization, based on the petrophysics of the reservoir, simplifies AVO interpretation.

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