

P-S Converted-Wave AVO

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ABSTRACT

The advent of new tools for the acquisition and processing of multicomponent seismic data has made substantial improvements in the quality of modern shear-wave measurements. With this improved quality comes the opportunity to assess the information that the amplitudes of these seismic records impart. Aki and Richards (2002) derived a theory that describes the contribution of different rock properties to the P-S seismic amplitude response. In particular, they show that the amplitudes recorded in the P-S converted-wave gathers are related only to the density and shear reflectivities. The significance of this result is that it is viable to estimate the density of the rock in a reservoir directly from amplitude preserved P-S seismic gathers using the P-S Amplitude Versus Offset (AVO) technique. The advantage of this approach over the P-wave AVO method is that the density effect is measurable at much shorter shot-receiver offsets because the converted S-wave is reflected at a much sharper angle than the corresponding P-wave. In fact, the required P-S shot-receiver offsets are typically less than two-thirds of the corresponding P-wave offsets.

This presentation shows the results of applying the P-S AVO method to both real and synthetic P-S seismic gathers. It shows that reliable estimates of the density and shear reflectivities can be derived from modern P-S converted-wave data shot in the Western Canadian Basin by comparing the results of the P-S AVO analysis to density and dipole shear logs acquired at the same location.

Introduction

The means of doing P-S AVO has been around since 1980 when Aki and Richards published an approximation to the Zoeppritz (1919) equations. This was done for P-S data as well as for the more familiar P-P approximation and for all other combinations of P, S_V and S_H waves. A major change in recent years has been the improvement in the data quality observed in P- S_V or 3C (Three-Component) seismic data. These changes have come about due to vast improvements in acquisition technology (e.g. VectorSeis™ phones) and in processing algorithms for these data. The result of these advances is that 3C data is now of such quality that we can consider extracting amplitude information from it. To do this, Aki and Richards' equation can be inverted for the parameters contained in it, which are the reflectivities of shear-wave velocity (β), and density (ρ) or any combination thereof. In this presentation, this is done for both synthetic seismic data and seismic data acquired over the Long Lake Project, a Nexen/OPTI synthetic oil joint venture in North-Eastern Alberta. The P-S AVO results from the synthetic data show that the equations, as

implemented generate the correct response. The P-S AVO results from the Long Lake Project indicate that they might provide a solution to one of the most significant problems in this heavy oil reservoir: the detection of shale plugs that interfere with the SAGD (Steam-Assisted Gravity Drainage) production method being used here.

Theory

Aki and Richards (2002) show AVO approximations for the Zoeppritz (1919) equations, which are derived based on the assumptions of small contrasts in elastic properties between two similar half-spaces. The more familiar is the P-P approximation, but approximations were also derived for all combinations of down-going and up-going P, S_V and S_H waves. This paper examines what can be done using the P-S_V approximation, which is appropriate for modern 3C methods that produce P-S_V “converted-waves”. This equation takes the following form, using Aki and Richards' (2002) notation,

$$\frac{\Delta S}{P} = \frac{-p\alpha}{2\cos j} \left[\left(1 - 2\beta^2 p^2 + 2\beta^2 \frac{\cos i \cos j}{\alpha \beta} \right) \frac{\Delta\rho}{\rho} - 4\beta^2 \left(p^2 - \frac{\cos i \cos j}{\alpha \beta} \right) \frac{\Delta\beta}{\beta} \right] \quad (1)$$

Thus, the converted wave response depends only on the contrasts in shear velocity and density. This is substantially different and simpler than the P-P case; where the response depends upon contrasts in the compressional velocity, shear velocity and density. Using, for example, Wang and Nur's (1992) relationships between common elastic parameters, the P-S_V “converted-wave” response can be related to the reflectivity of the density ($\Delta\rho/\rho$) and the reflectivity of one of the shear velocity ($\Delta\beta/\beta$), the shear impedance ($\Delta\beta/\beta + \Delta\rho/\rho$) (Ursenbach and Stewart, 2002) or the shear rigidity ($\Delta\mu/\mu$). Contrary to the current practice in P-P AVO (e.g. Verm and Hilterman, 1995), these equations are simple enough to be implemented “as is” without any further approximations, although approximations have been proposed (e.g. Donati and Martin, 1998).

Fig. 1 shows how the information is distributed between the parameters for each of these variations on Aki and Richards' equation. This indicates what information each of these equations contains for a given incident angle range. For example, the P-S Impedance AVO equation shows that P-S data only contains information about the shear impedance contrast to incident angles of 25°. At larger incident angles, the density information becomes increasingly important. Thus incident angles greater than 25° are required to derive independent density information.

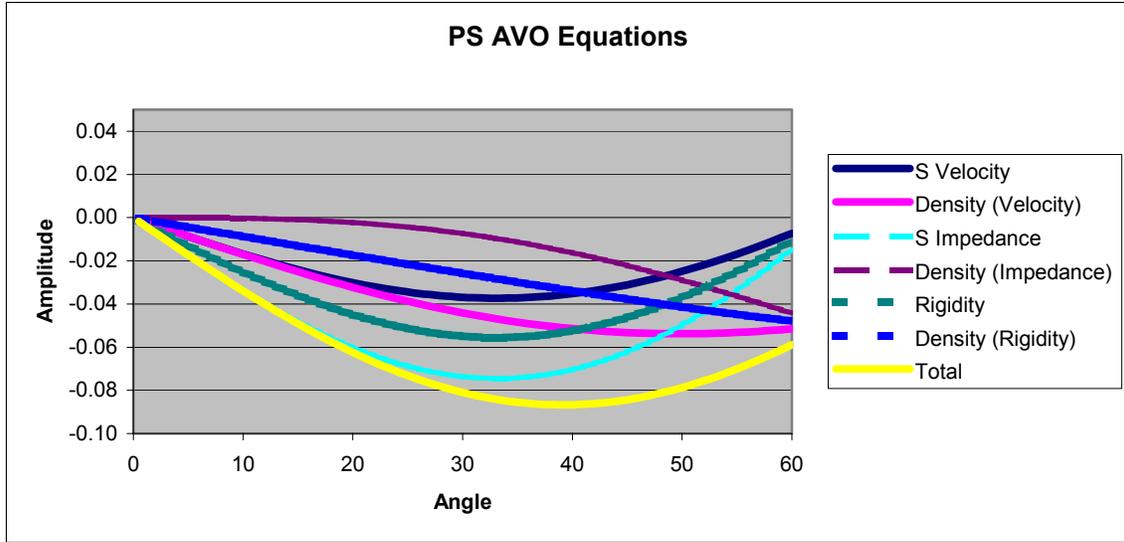


Fig. 1: Constituents of the various P-S AVO equations for $\Delta\beta/\beta = \Delta\rho/\rho = 0.1$

Synthetic Results

Fig. 2 shows noise-free synthetic data generated using Aki and Richards' equation. These show perfect results for the P-S AVO inversion indicating that the P-S AVO equations are consistent with Aki and Richards' approximation.

Fig. 3 shows synthetic data derived using ATRAK software (Guest and Kendall, 1993), which uses the full stress-strain tensors. P-S AVO results from these synthetic data are shown in Fig. 4. These results show good correlations to the values of mu reflectivity (calculated from the model Vs and density) and density reflectivity (Table 1). There are some small differences, particularly on the density reflectivity. There are several possible causes for them, including non-vertical incidence on the receivers, component leakage and small errors in Aki and Richards' approximation compared to the full stress-strain tensor result.

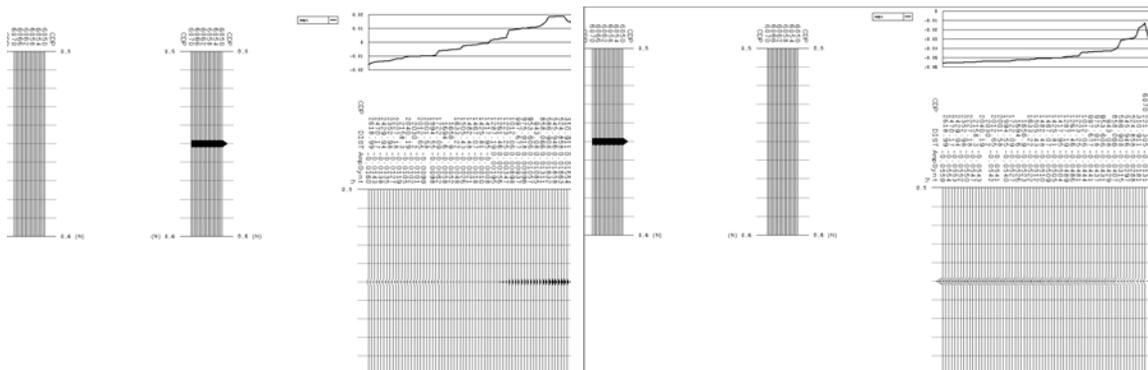


Fig. 2: The left side of the figure shows a synthetic derived using changes only in shear rigidity with the corresponding P-S AVO responses to its left with density reflectivity on the left and rigidity reflectivity on the right. The right side of the figure shows the results using changes only in density.

Formation	Depth	P-S Time	α	β	ρ	α/β	$\rho\beta$	μ	$\Delta\alpha/\alpha$	$\Delta\beta/\beta$	$\Delta\rho/\rho$	$\Delta(\rho\alpha)/\rho\alpha$	$\Delta\mu/\mu$
Shallow	0	0.0	1500	300	2000	5.00	600.0	0.18					
Grand Rapids	69	276.0	1943	511	2105	3.80	1075.7	0.55	0.129	0.260	0.026	0.284	0.507
Clearwater	87	320.5	2006	589	2127	3.41	1252.8	0.74	0.016	0.071	0.005	0.076	0.146
B	127.2	408.8	1972	497	2124	3.97	1055.6	0.52	-0.009	-0.085	-0.001	-0.085	-0.169
C	136.2	431.5	2109	709	2177	2.97	1543.5	1.09	0.034	0.176	0.012	0.188	0.352
Wabiska	157.9	472.3	2048	617	2169	3.32	1338.3	0.83	-0.015	-0.069	-0.002	-0.071	-0.140
McMurray	171	500.0	2360	864	2124	2.73	1835.1	1.59	0.071	0.167	-0.010	0.157	0.315
Channel	184.9	522.0	2258	806	2264	2.80	1824.8	1.47	-0.022	-0.035	0.032	-0.003	-0.038
Pay	205	555.8	2425	999	2093	2.43	2090.9	2.09	0.036	0.107	-0.039	0.068	0.174
Devonian	238	602.4	4660	2483	2568	1.88	6376.3	15.83	0.315	0.426	0.102	0.506	0.767

Table 1: Elastic parameters for the ATRAK isotropic model.

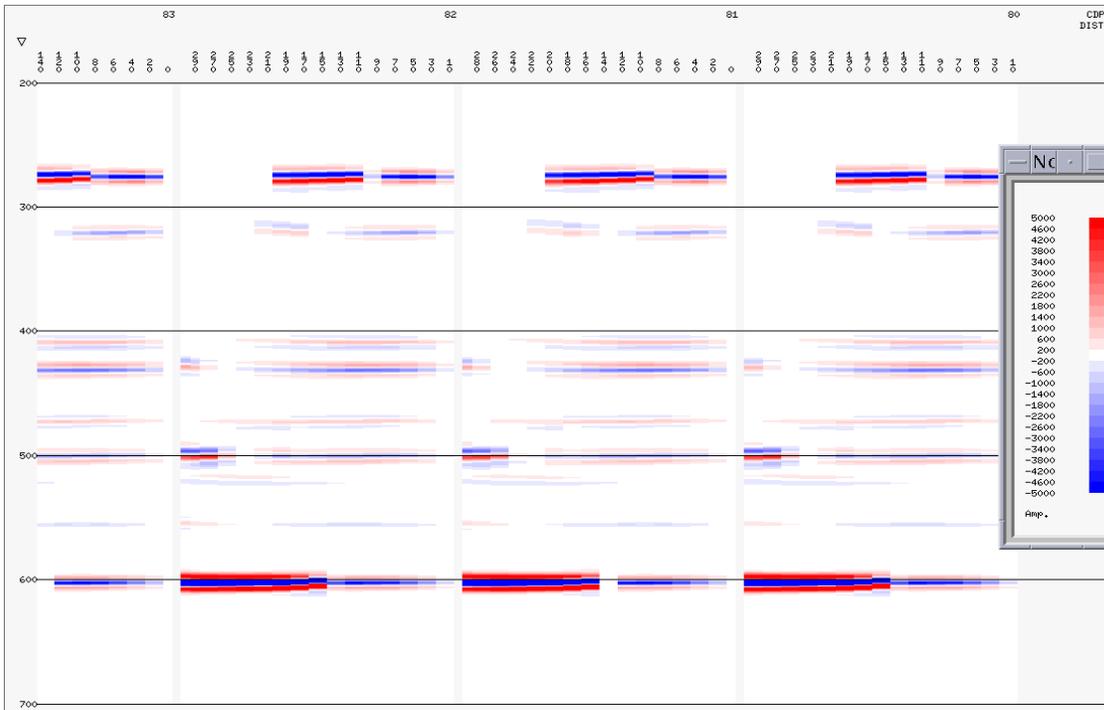


Fig. 3: Synthetic P-S_v gathers generated by ATRAK.

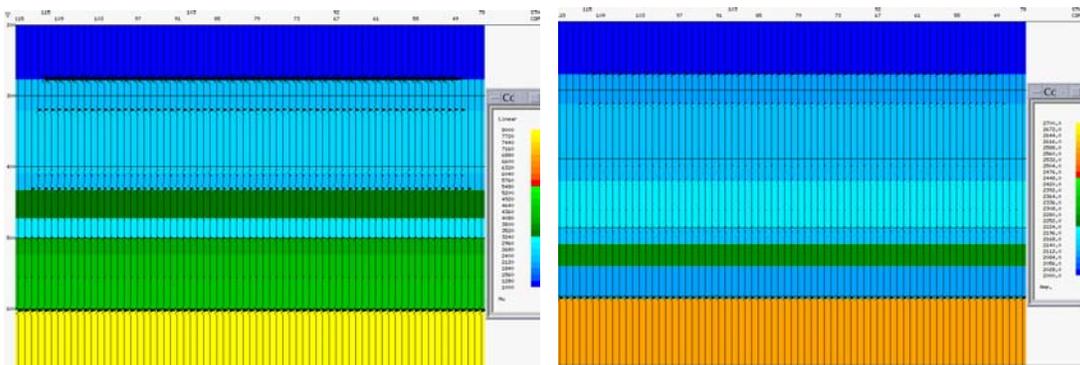


Fig. 4: P-S AVO results for the synthetic gathers in Figure 3 showing shear rigidity (μ) reflectivity with μ values from the model in color in the background on the left and density reflectivity with density values from the model in color in the background on the right.

Seismic Data Results

The first item of note is the remarkable data quality of modern P-S converted-wave seismic acquisition and processing (*Fig. 5*). These results allow for the use of AVO on these data. In the past, P-S seismic data has been so noisy that the only information derivable from it was structural components from the stack. Now that clear events can be seen in the pre-stack gathers, the possibility of extracting petrophysical information from these data presents itself.

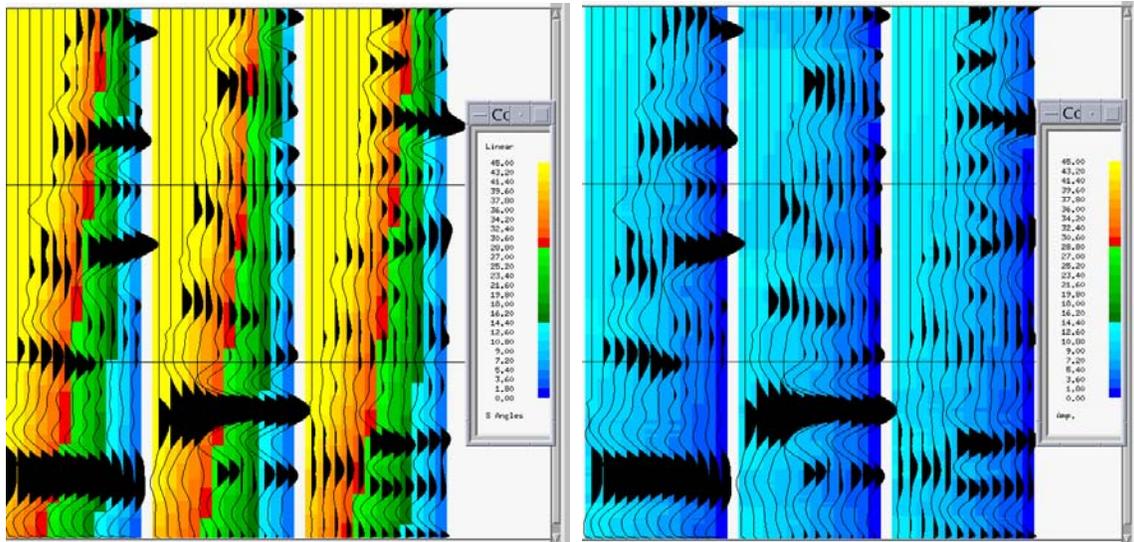


Fig. 5: P-S common offset stacks from the converted-wave seismic data shot over the Long Lake Project with inverse P-S scaling applied to balance the amplitudes across the gather. In color in the background are the estimated angles for P-S AVO; incident angle is the background for the gathers on the left and emergent angle for those on the right.

P-S AVO has been applied to the P-S data shot over the Long Lake Project, a Nexen/OPTI synthetic oil joint venture in North-Eastern Alberta. The reservoir consists of a mixture of bitumen and sand with the bitumen actually supporting the very high porosity sand. It also consists of breccias, shale plugs and a mixture of thinly bedded sands and shales. The reservoir is being produced using the SAGD process. So far, the most significant barriers to production are the shale plugs, which sometimes occur between the steam injector well and the producer, rendering the SAGD process and its two horizontal wells useless. So, it is important to be able to identify where these shale plugs exist. The estimated shear rigidity (μ) reflectivity shows a remarkable correlation to the gamma ray logs overlying it. Only hints of this correlation have been observed in the P-S stack or the P-P data. Strong reflections on the P-S AVO rigidity reflectivity section correlate very well with zones of high shale content as indicated by the gamma ray log (Dumitrescu et al, 2003). Rigidity may be a good indicator of shale in this reservoir since the shale should be more consolidated than the surrounding unconsolidated heavy-oil reservoir sands, so the observed

correlation seems to make sense physically. Therefore, the shear rigidity reflectivity derived from the P-S data in this reservoir may prove to be extremely important in deciding where and at what depth to drill future wells in this reservoir.

Density reflectivity has also been derived from these data. It shows a less marked correlation with the density logs than the shear rigidity reflectivity has with the gamma ray logs. Note, however, that there are two density logs from wells that are 150 m apart that appear significantly different. Such vast differences over such a small distance suggest either extreme heterogeneity in the reservoir or that the density logs require editing. So, as yet, the density reflectivity results are inconclusive.

Conclusions

P-S AVO appears to be applicable using modern 3C P-S_v seismic data. This is largely due to substantial improvements in both acquisition technology and multi-component processing algorithms in the last few years. P-S AVO is capable of estimating the reflectivity of the density and the reflectivity of a shear-wave component: one of shear-wave velocity, impedance or rigidity. The methodology has been tested with both synthetic seismic data and 3C seismic data from the Long Lake Project. The synthetic data shows that the P-S AVO equations produce the expected results and the application of P-S AVO to the Long Lake Project 3C data suggests that it may be very useful in identifying shale plugs that are barriers to SAGD production in this heavy oil reservoir.

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