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Insights into converted-wave AVO and its use in inversion

Carl Reine *Canadian Discovery Ltd.*
Rob Tilson *Absolute Imaging Inc.*

Summary

This presentation is a tutorial, and a series of examples, on the use of converted-wave data for AVO analysis, with the goal of improving inversion results. We discuss some of the processing considerations for converted-wave AVO, and also show examples of how changes in S-impedance and density influence PP- and PS-amplitudes differently.

Introduction

Using prestack seismic amplitudes to invert models of P-impedance (I_P), S-impedance (I_S), and density, has become the cornerstone of quantitative seismic interpretation. Determining these models allows geological relationships to be applied to seismic data using detailed well analysis, or rock-physics modelling. The limitation to how useful this application is depends on the accuracy of the model estimates, which is why additional information available from converted waves can be useful.

The underpinnings of converted-wave (PS) amplitude variation with offset (AVO) have been known for decades, however its common usage is much more recent. In this presentation, we review the principles of PS-AVO, discuss the processing considerations for the data, and show specific examples of how PS-AVO can be used to estimate I_S and density either on its own, or in conjunction with PP-AVO.

Theory

Figure 1 shows examples of a prestack gather of PP- and PS-data. The amplitude of the indicated reflection, determined by the reflectivity at the interface, varies with the incidence angle considered. This is the basic premise of the AVO method, where the behaviour of the amplitude change can be used to determine contrasts in I_P, I_S, and density. Through inversion, these contrasts are turned into models of the associated property.

The change in reflection amplitude with incidence angle is given by the Knott-Zoeppritz equations, which are most commonly used in an approximate form as given by Aki and Richards (2002), describing both PP- and PS-amplitudes (among others).

Depending on the available information, and the desired use of the equation, numerous ways of rearranging the equations are used. The Aki-Richards equations are expressed in terms of contrasts in P-wave velocity, S-wave velocity, and density. For AVO analysis, PP-amplitudes can be expressed in terms of intercept, gradient, and curvature, where the angle range of significance for each is increasing (Shuey, 1985). Similar rearrangements have been done for PS reflectivity, with the intention of finding intercept- and gradient-like terms as an analogy (Zaengle & Fasier, 1993; Donati & Martin, 1998; Ramos & Castagna, 2001).

For inversion of the AVO attributes into impedance and density, it is useful to express the equations in terms of contrasts in P-impedance, S-impedance, and density, referred to as P-reflectivity (R_P), S-reflectivity (R_S), and density reflectivity (R_d). This arrangement is desirable for inversion purposes, and for PP-data, is shown by Fatti et al. (1994). Following a similar process, the Aki-Richards equation for PS-reflectivity can also be rearranged in terms of impedance and density contrasts, either as a function of the reflected S-wave angle (Larson, 1999) or of the incident P-wave angle.

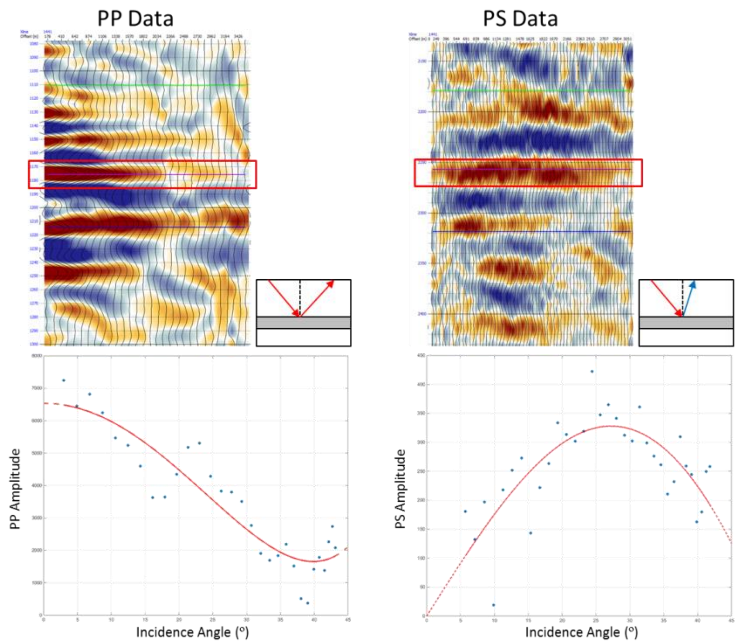

Figure 1. Prestack amplitudes versus incidence angle for PP- and PS-data. Note that at 0º, the PS amplitude is expected to always be zero, as there is no wave conversion.

Implications

Two significant differences exist between the PP- and PS-amplitude equations. Firstly, while PP-amplitudes are a function of R_P, R_S, and R_d, PS-amplitudes are only a function of the latter two. Secondly, PS-amplitudes have no intercept term, that is, at a zero degree incidence angle, there is no conversion of P-wave to S-wave energy, and the amplitude is zero.

Through the process of fitting AVO curves to amplitude data, estimates of R_P (PP data only), R_S, and R_d (PP- and PS-data) are obtained. Therefore, by having both PP- and PS-data, two independent estimates of R_S and R_d are available. However, it is commonly known that the influence of R_d on the PP-amplitude is minimal, and only takes effect at higher incidence angles. In that case, what are the relative contributions of each component to the total reflectivity for both types of data?

Figure 2 shows the relative contributions to the reflection amplitudes for a hypothetical interface between the layers described in Table 1. In this example, R_S never contributes more than 35% of the total reflection strength for PP reflection, and this doesn't occur until the incidence angle reaches approximately 45º. For the PS reflection however, R_S is almost entirely responsible for the reflection amplitude.

That R_S is more significant for the PS-reflectivity than the PP-reflectivity is not surprising, but what is potentially more interesting is the contribution of R_d. For the PP-reflection in this example, R_d makes almost no contribution to the amplitude until around 35º, and its total contribution remains below 5% even at 50º. For the PS-amplitude, R_d becomes more significant earlier on, around 20º, and reaches almost a 20% contribution by 50º incidence. Clearly this is a source of density information that could be exploited.

Property	Layer 1	Layer 2
v_P	3900 m/s	4900 m/s
v_S	2150 m/s	2650 m/s
Density	2525 kg/m³	2650 kg/m³

Table 1. Layer properties for example shown in Figure 2.

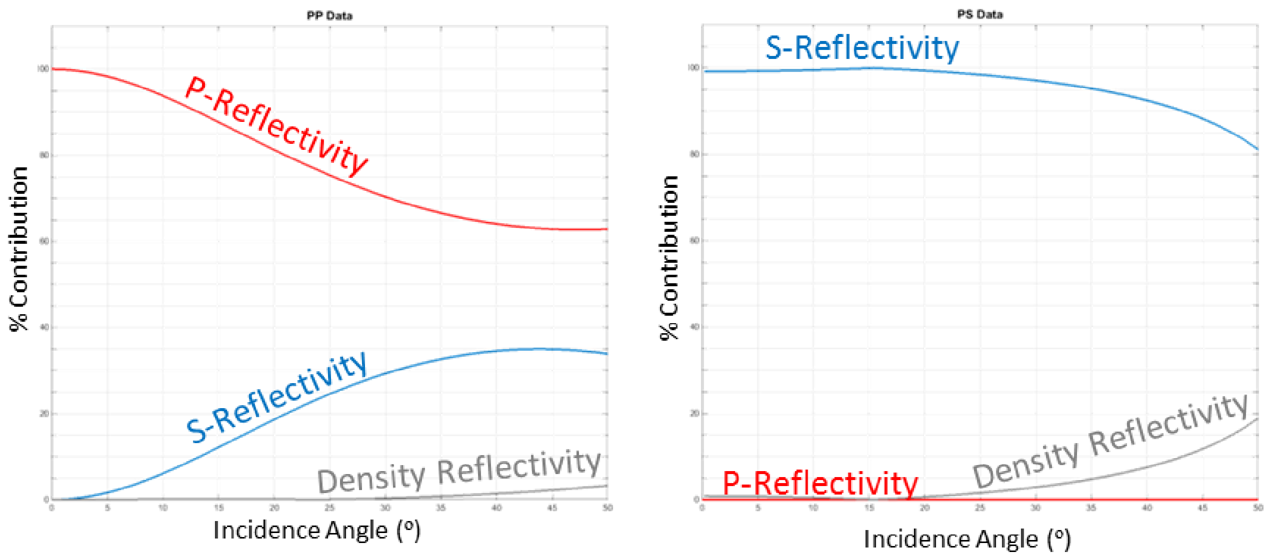

Figure 2. Relative contributions of P-reflectivity, S-reflectivity, and density reflectivity to the AVO curves of PP- and PS-data. For PS-data, the contribution of S-reflectivity and density reflectivity are more significant than for PP-data. Model parameters are shown in Table 1.

Stewart (1990) and Larsen et al. (1998) were some of the first to investigate converted wave data for inversion analysis. In each case, R_d is converted into R_P using Gardner's equation as outlined by Smith and Gidlow (1987), and the data are inverted jointly for R_P and R_S. This is just one approach to inverting the data. The main benefit of the joint inversion done in this manner is that the two most robust attributes, R_P and R_S, are inverted to create a single model.

However, density is a critical parameter in many plays, for example the oil sands in the McMurray Formation (Weston Bellman, 2007). Rather than absorbing it into the well-behaved R_P term, it is possible to leave it in its native form, and further constrain the more elusive density model. Because R_d has more influence at lower incidence angles, this makes converted-wave data a valuable part of the inversion

Processing

As with PP-data, processing of PS-data for AVO requires attention to preserve the amplitude response, and minimize prestack noise. Figure 3 shows the processed PS-data used for additional AVO and inversion examples presented.

Careful application of statics, honouring PP and PS information, was applied to optimally align the prestack traces. To preserve AVO behaviour, both deconvolution and scaling were applied on the PS-data in a surface-consistent manner using the standard methods developed for the processing of PP-data. For scaling, individual trace amplitudes were estimated from the filtered radial data, and then decomposed into shot, receiver, offset, and CDP components. The shot and receiver components were then applied to both the radial and transverse data. Polarization analysis and layer stripping further ensured that the amplitudes were not adversely affected by differences in shear-wave splitting and source-receiver azimuth.

Because prestack time migration is desired prior to AVO analysis (Mosher et al., 1996), 5D interpolation was carried out to fill in the offset/azimuth distribution, and prevent migration artifacts. For PP data, 5D interpolation is usually done on supergathers. This choice reduces structural smearing and ensures that the data are suitably modelled by a superposition of plane waves. In the PS case, the equivalent gathers must be generated using an asymptotic conversion point, or a deterministic conversion point suitable for the zone of interest. By using the deterministic conversion point for the reservoir, the reflections of most significance, and those above, are binned more appropriately.

For this data, we created conversion point gathers where the conversion point was calculated at a depth of 1500 m, using a gamma of 2.2. In this case, the location of the conversion point could differ by over 100 m between the asymptotic and deterministic binning. The data were then interpolated using a minimum weighted norm interpolation (MWNI). This allowed for more complete sampling of the data when sorted into common-offset vectors (COV). Prestack time migration was done using a Kirchhoff algorithm on the COV data, and the results show significant improvements compared to gathers migrated without using the MWNI interpolation (Figure 3).

Conclusions

As with conventional PP-wave data, PS-data contains information regarding the S-impedance and density of the subsurface. Because these parameters are often difficult to obtain reliably, the use of PS-wave data provides an additional, and independent, means of estimating these useful elastic parameters. These estimates can be made as a standalone process, or as a joint inversion between the two data sets.

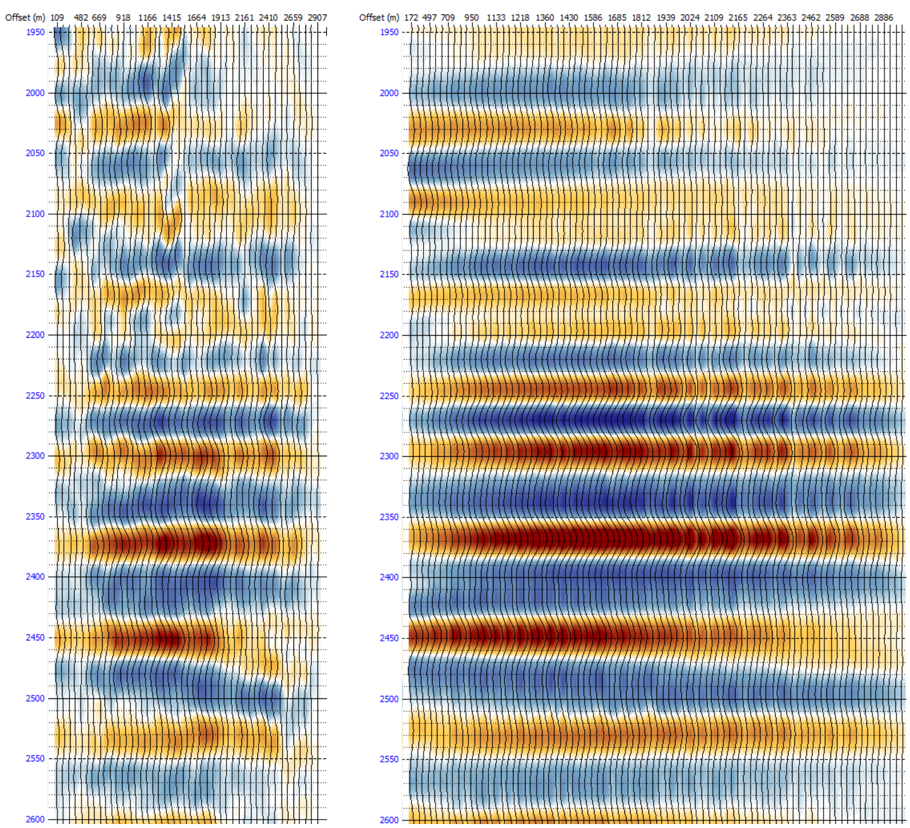

Figure 3. PS gathers after prestack time migration: Left, without 5D interpolation; Right, with 5D interpolation. The 5D interpolation reduces the effects of noise and incomplete sampling on the migration operation. This is particularly evident in the weaker reflections above 2200 ms.

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