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From convolutional to waveform AVO: accounting for multiples and mode conversions

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Summary

Seismic reservoir characterization in geologic settings with coals, anhydrites and gas clouds is known to be challenging due to transmission effects and non-primary energy introduced by these strong velocity contrasts. In the Cygnus field, the problem of coals and anhydrite masking the amplitude response of underlying reservoirs is well known and understood to be difficult to overcome in AVO inversion workflows. In this study, we compare a standard AVO inversion workflow, which relies on standard convolutional modelling, to a new workflow that uses 1D tau-p domain wave equation as the forward model to more accurately model the input seismic data, thereby improving the AVO inversion results. In the North Sea example shown, we observe that the inclusion of mode conversions in the forward model provides a better match to the observed seismic at the reservoir level. The updated AVO inversion, which includes mode conversions and multiples, improves the predictability of the Vp/Vs ratio.

Introduction

AVO analysis in the presence of strong velocity contrasts is a challenging problem in quantitative interpretation. These high reflectivity events introduce layers of complexity to the seismic data that are not accurately modelled by the standard convolutional model. In particular, the convolutional model assumes that the seismic signal contains primaries only. Non-primary energy, including both multiples and mode-conversions break this assumption and may result in inaccuracies being propagated into inversion results. The convolutional AVO inversion itself can filter non-primary energy by rejecting this energy into the residuals, but for many complex effects, such as shallow dipping multiples or mode conversions, this may not be realistic. One method to improve AVO inversion results is to condition the seismic data to filter out the non-primary energy. Common workflows include radon transform multiple removal or internal multiple prediction algorithms, but to remove shallow dipping multiples, these methods can significantly impact primary energy. It is desired to have a workflow or algorithm that instead of attempting to filter this energy, can model it and potentially use it to improve standard convolution AVO inversion results. In this study, we present an algorithm for 1D tau-p domain wave-equation inversion that can account for multiples and mode-conversions thereby improving inversion results in contexts where this type of noise is negatively impacting standard convolution inversion results.

Method and/or Theory

Conventional AVO inversion is based on the 1D vertical convolutional model combined with a single interface reflection coefficient model such as Zoeppritz or Aki & Richards. As such, it is assumed that the issues of multiple reflections, converted waves, and scattering have been removed or suppressed sufficiently in the pre-processing. However, short period multiples or mode conversions are very complex to remove from the observed seismic without significantly damaging primary energy. It is therefore proposed to replace the convolution model in the AVO inversion loop with a more accurate forward seismic model that accounts for these effects. Ideally, the forward seismic model would be the full 3D wave-equation resulting in what is generally known as elastic 3D Full Waveform Inversion (FWI). However, due to the elevated computational cost of elastic 3D FWI its outputs tend to be band-limited, lacking the level of resolution needed for reservoir characterization purposes.

Here, we propose to use the 1D tau-p domain wave-equation (Rasmussen, 2024) as the forward seismic model in the inversion loop. This formulation assumes that the subsurface is slowly varying horizontally, but accurately models multiples, mode conversions, and can incorporate velocity dispersion. The advantages of such an approach are that it can be fitted into conventional seismic processing and inversion, including one that uses conventional 3D FWI and that it is many orders of magnitude less computationally expensive compared to 3D FWI. To reduce the number of forward and backward tau-p transformations, the comparison of synthetic and observed seismic in the inversion loop is performed entirely in the tau-p domain by transforming the observed seismic to the tau-p domain.

Results

The results for this study include an example from the North Sea in the Cygnus field, where there are sand reservoirs below an anhydrite and surrounded by coals. First, we compare forward modelled seismic to observed, gradually increasing the complexity of the forward modelled response from standard convolution primaries only to primaries plus multiples and finally including mode conversions. The results of this comparison are shown in Figure 1. In the observed seismic, at the reservoir levels we notice a sharp decrease in far angle amplitudes as well as strong polarity reversals and distortions that are not observed in standard primaries only (PP) convolution seismic. Adding multiples does not dramatically alter the forward modelled seismic, but by adding mode conversions (PP + PSP) we begin to better model the complex polarity reversals and distortions that characterize the far angles of the input seismic. The interpretation is that the overlying high reflectivity layers are not only producing short period multiples, but more significantly a converted shear wave that significantly alters the acquired waveform.

This exercise demonstrates that the most significant noise in the observed seismic that we were able to model comes in the form of converted PP-PS-PP energy. In other geologic contexts, it is possible that multiple contamination would be more significant, but the ability to model these different sources of non-primary energy separately give valuable insight into the nature of the signal we observe. We can use this information to inform seismic processing or pre-conditioning, but in this case the proposed solution is to invert the data using a 1D tau-p wave equation. The results of the inversion at the same well location as in Figure 1 are shown in Figure 2. This figure compares AVO inversion results for acoustic impedance (AI), Vp/Vs ratio and density using a standard convolutional forward model to those using a 1D tau-p wave equation. In the standard convolutional results, we see the impact of the inability to model the complexity in the observed seismic manifest as a poor correlation between inverted Vp/Vs ratio (in blue) ad observed Vp/Vs (in red). At the level of the target sands, the Vp/Vs ratio appears nearly anti-correlated. In the results using the Tau-P domain inversion, we observe a significant uplift in the Vp/Vs results as the low Vp/Vs of the sand is clearly resolved. The results for AI are of good quality and largely unchanged, while the results for density are consistently poor with both methods.

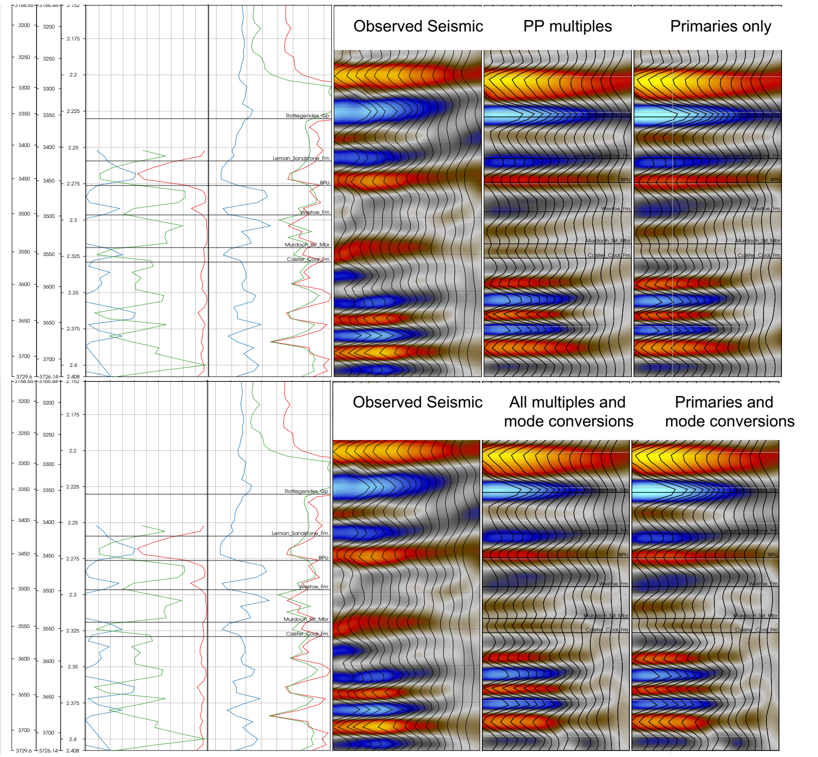

Figure 1: Forward modelled vs observed seismic comparison at a well location. Comparison includes PP only modelling (top) and PP and PSP modelling (bottom).

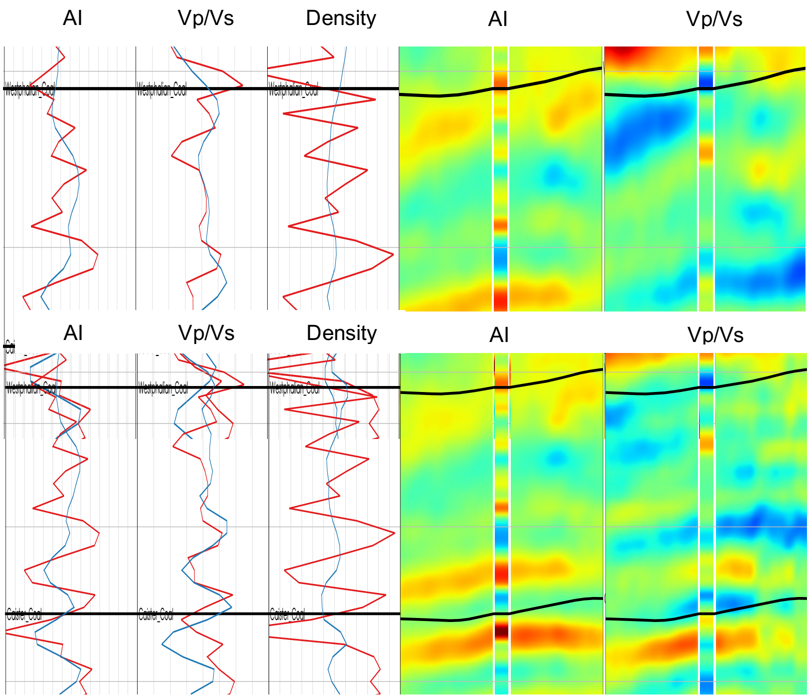

Figure 2: Inversion results (blue in log tracks) compared to de-trended well logs (red in log tracks) using a standard AVO inversion algorithm (top) and a tau-p waveform inversion accounting for mode conversions (bottom).

Discussion

The algorithm and results presented in this study provide the framework for a robust, computationally efficient modelling and inversion workflow that is a means to improve our ability to understand seismic data around high reflectivity events. The example shown suggests that the high impedance anhydrite overlying the target sand is a generator of converted shear waves, which creates complex interference that is not modelled by a simple convolutional model. Inverting the observed data with a 1D tau-p wave equation model is shown to improve our ability to characterize the Vp/Vs ratio of the target sand. There is potential for this workflow to provide similar insight in other high reflectivity settings such as in the presence of coals or gas clouds. In these settings, it is possible or perhaps desirable to extend the forward model to include for instance Q or VTI effects. In such cases, another possible use for this workflow and algorithm would be its ability to act as a means of wave equation based multiple and mode conversion filtering. As a product of the inversion process itself, a primaries only seismic volume is output that could be used for subsequent structural or conventional AVO interpretation.

It is important to note that the applicability of this workflow more broadly requires more testing and understanding across more datasets. While non-primary noise is certainly evident and present in many settings, there remains numerous other noise sources in seismic data that may not be related to these complex wave phenomena. Understanding where and to what degree these phenomena are impacting seismic interpretation is important to the correct application of this method. Similarly, a best practice for the use of this method should also consider the best practice of seismic data processing. The authors suggest that a rigorous first step to validation of the forward modelled seismic is a comparison to walkaway VSP data, where we can be more certain of the cause of the events we observe, as compared to 3D seismic data after processing, where numerous other processing steps can cause waveform alterations that may be unrelated to non-primary energy.

Conclusions

This paper introduces a method for AVO inversion that inverts the whole recorded waveform including multiples and mode conversions. The method seeks to address shortcomings of the standard convolutional model in settings such as coals, anhydrite stringers and other potential high reflectivity boundaries. In the North Sea example shown, we demonstrate first with forward modelling and subsequently with an inversion comparison how accounting for these phenomena in our seismic model can improve our understanding of the observed seismic and improve the accuracy of inverted properties.

References

Rasmussen, K. B. (2024). Comparison of tau-P domain wave-equation inversion with convolutional inversion. Third EAGE Conference on Seismic Inversion. p 1-5. https://doi.org/10.3997/2214-4609.202438022