Anisotropic direct probabilistic inversion of AVO seismic data

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Summary

The challenges presented by unconventional tight reservoirs often require the use of more complex approximations to model AVO responses. In addition to this, moving from deterministic inversion methods towards probabilistic frameworks allows for better vertical resolution and a more comprehensive statistical analysis of possible solutions.

Here, we extend the isotropic direct probabilistic inversion (DPI) presented by Hansen et al (2018), Jakobsen and Hansen (2019) and, Jakobsen and Hansen (2020) to accommodate VTI anisotropy. They introduce DPI as a single-step inversion process which inverts pre-stack seismic data directly for geologic facies. It is based on the Bayesian probabilistic framework developed by Jullum and Kolbjørnsen (2016).

We use Ruger's AVO approximation for VTI media as the forward modeling operator to compute the likelihood function in DPI. The benefits of this approach are two-fold. First, the model space is expanded from three (AI, Vp/Vs, density) to five elastic parameters which now includes the two weak anisotropy Thomsen parameters ε and δ. This provides an opportunity for resolving elastic ambiguities that might not be resolved by using only three isotropic parameters. Secondly, the use of a more complex AVO approximation that accounts for common anisotropic effects helps to avoid the misinterpretation of hydrocarbon-related AVO signatures, which might result from the false positive effect of overlaying anisotropic shales above water-saturated sands. The same idea can be extended to unconventional reservoirs in which case the same incorrect signature can be misinterpreted as a false positive increase in brittleness if the anisotropy of the overlaying shale is not accounted for during the inversion process.

DPI addresses both of these challenges under a probabilistic framework that provides higher vertical resolution than deterministic AVO inversions. Moreover, DPI integrates a priori geological information, like average thicknesses and/or stratigraphic ordering rules which reduces the solution space to only the stratigraphic relationships that can be supported by the geological deposition expected in the area. Well log data from the Montney formation was used to build a 1D model to illustrate and test these ideas. In this case, understanding the vertical heterogeneities within the Montney formation is a key factor in the design of horizontal well completions. Our results show, that even in the case of very thin, almost indistinguishable litho-facies but with slightly different anisotropic parameters, DPI is able to predict the spatial distribution of these facies with relatively high confidence levels.

Facies model

Figure 1a shows the facies model used to test the direct probabilistic inversion. A facies log derived from the interpretation of petrophysical and core data was used to build this model. Notice how the upper half of the model is dominated by the interlayering of dolomitic siltstones and dolosandstones, with the dolomitic siltstones showing larger thicknesses. The bottom half of the model shows a series of argillaceous dolosiltstones interlayered with dolomitic siltstones. In contrast to the upper half the proportion/thicknesses of the dolomitic siltstones are smaller in the bottom half.

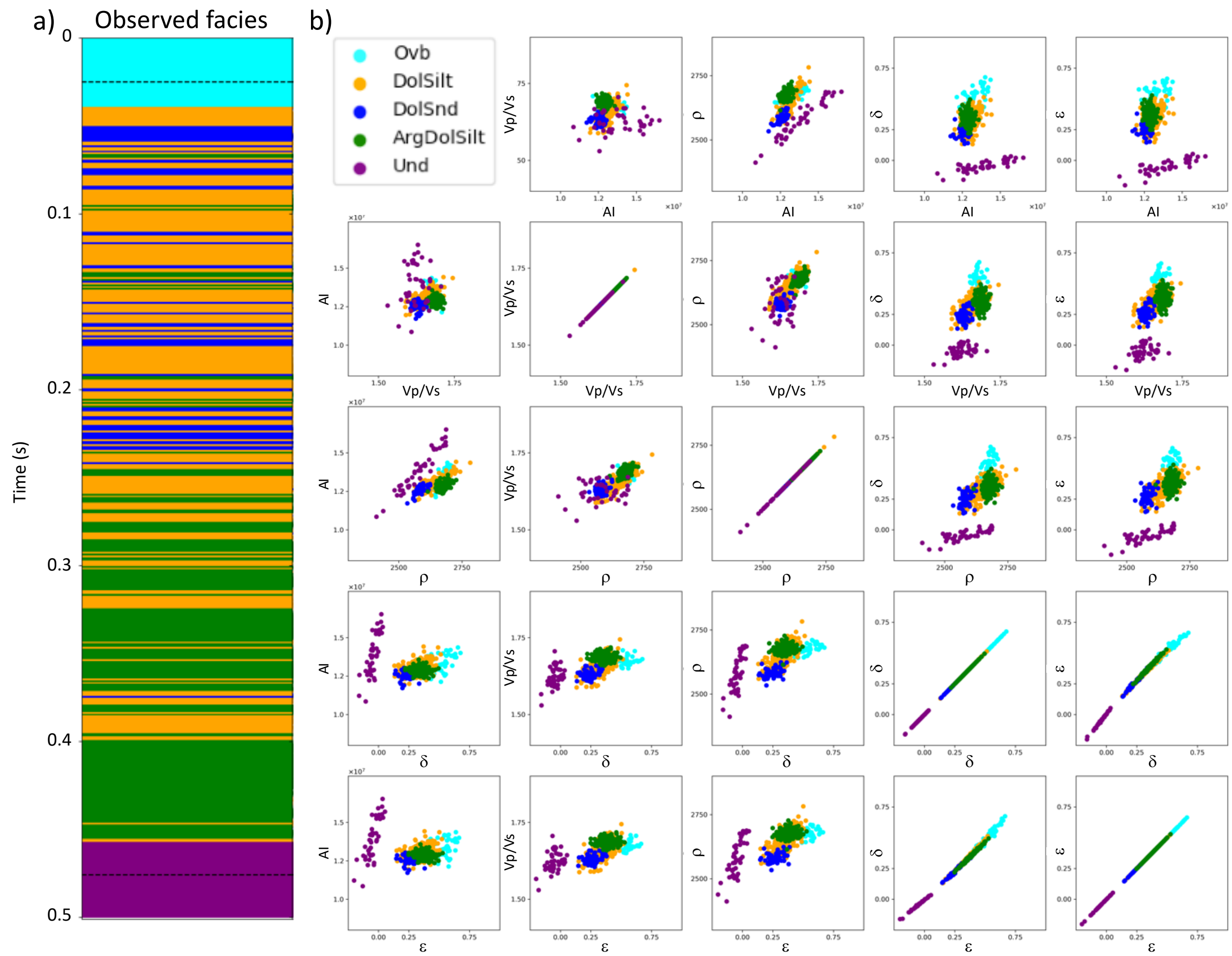

Figure 1. a) 1D facies model from Montney well. b) Cross-plots of isotropic elastic parameters (AI, Vp/Vs, ρ) and weak anisotropic Thomsen parameters (ε and δ) from each facies.

Figure 1b shows the distribution of the elastic properties for each facies in all the possible combinations of the five elastic parameters used in the probabilistic inversion. All the elastic properties values, including the anisotropy parameters were measured/modelled by well logs. Notice how in the AI, Vp/Vs space all the facies seem to occupy a similar space. Only when the weak anisotropy parameters are considered, does a clear separation between the underburden facies and the rest of the facies become evident. Additionally, combining Vp/Vs and either ε or δ seems to provide a better separation of the dolosandstones and the argillaceous dolosiltstones. Notice that the dolomitic siltstone remains undifferentiated regardless of the space used for the analysis.

Inversion results

Figure 2 shows the inputs and results of the probabilistic inversion. Five angle-stacked traces between 5° and 36° are computed using Ruger's VTI approximation and the well log data available. Colored random noise was also added to the traces to simulate more realistic data. The prior probabilities for each facies are shown in the middle panel (colour coded for facies). Notice that the probabilities for the dolomitic siltstone and the argillaceous dolosiltstones are the same with a value of 0.45. The prior probability for the dolosandstones was fixed at 0.1. These probabilities approximate the proportion of each of those facies within the target window and are tapered down as they approach the expected location of the transition from the overburden and to the underburden.

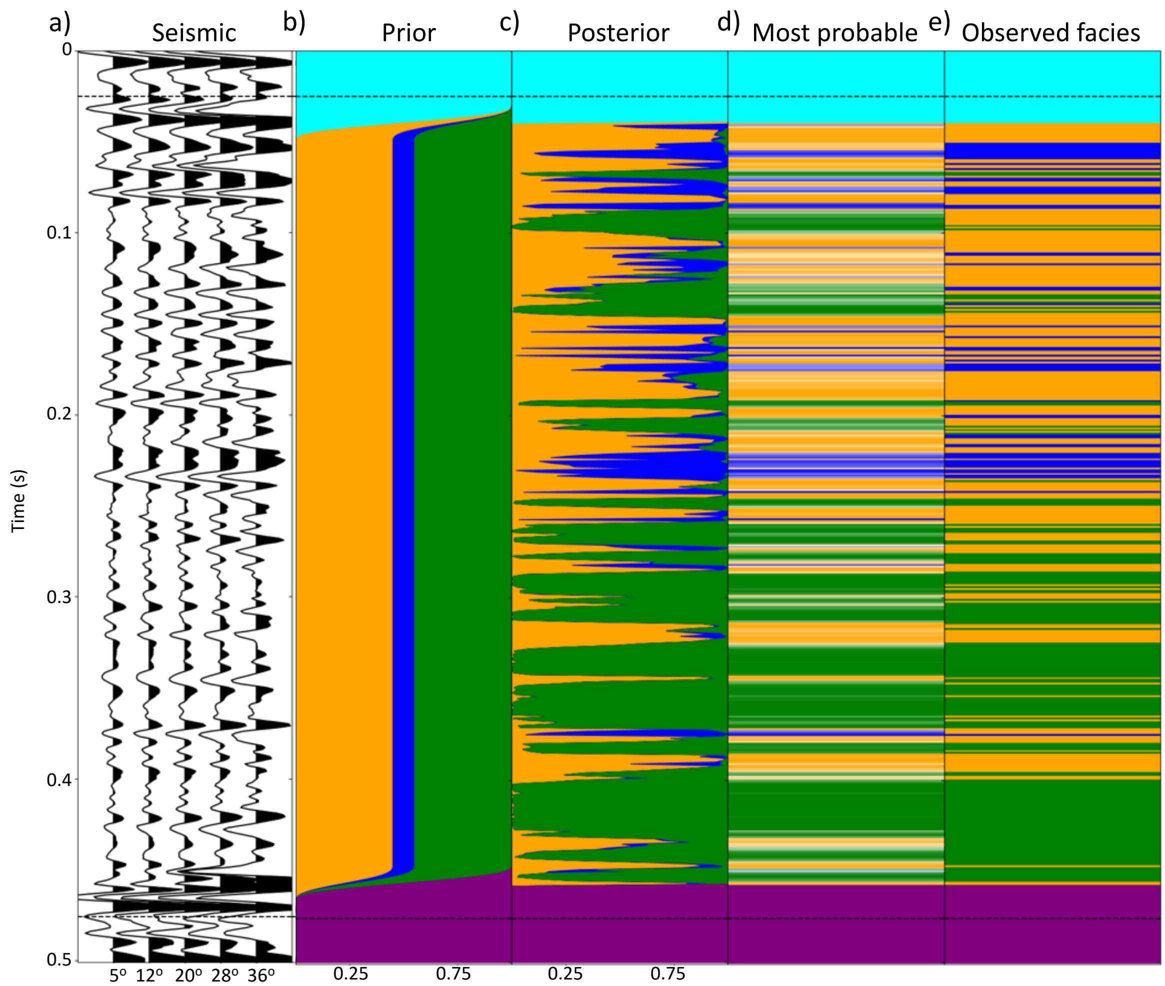

Figure 2. a) Modelled seismic data with added colored random noise. b) Prior and c) posterior probabilities. d) Most probable facies extracted from posterior probabilities. e) Observed facies. Facies color codes are the same as in Figure 1.

The inversion results are represented by the posterior probabilities. Compared to the prior probabilities the posterior probabilities contain detailed stratigraphic information. Notice that the resolution of the inversion results is well below the tuning thickness expected from the frequency content of the seismic data (mean frequency 45 Hz). The facies with the largest probability at each depth is then extracted from the posterior probabilities and plotted on the "most probable" panel. The color intensity on this panel reflects the confidence level for each estimate. The most probable facies predicted by the inversion matches in 89% of the cases with the correct facies according to the input model (observed facies in figure 2e). More importantly, the inversion results display the correct proportions expected for each facies i.e. an upper half dominated by dolomitic siltstones while the lower half is predominately made of argillaceous dolosiltstones with thicknesses increasing with depth.

Finally, Figure 3 compares the actual well log data in red track lines against the mean of the elastic properties realized for each facies at each depth. The dashed track lines represent two standard deviations from the mean. These results confirm that the solution space for each of the elastic properties remained within reasonable values.

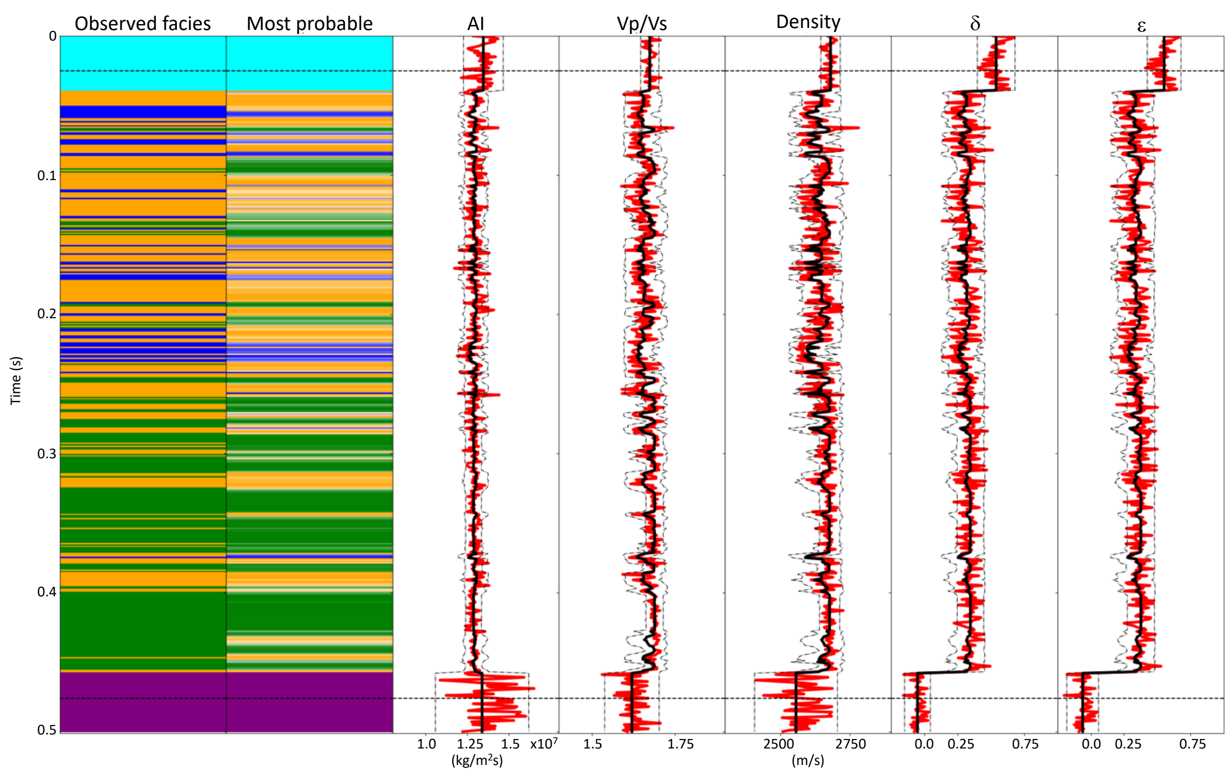

Figure 3. DPI results. The red track lines represent the log data for each property. The black track line represents the mean of the realized property values during the inversion. The dashed track lines indicate two standard deviations from the mean.

Conclusions

The direct probabilistic inversion of anisotropic AVO data provides superior vertical resolution to what could be expected from a deterministic AVO inversion. Incorporating anisotropic effects during the inversion correctly accounts for changes in the AVO gradient resulting from a change in Vp/Vs and/or changes in the Thomsen VTI anisotropy parameters ε and δ. This differentiation is not possible when using isotropic formulations in which the presence of anisotropy would result in an incorrect estimation of the gradient-related elastic parameter (Vp/Vs, shear-impedance, density, etc.).

Since the output of DPI are estimated probabilities for each facies at each depth, a more comprehensive statistical analysis can be performed. Even though this is not shown in this study P10, P50 and P90 models can be derived for a more in-depth interpretation and exploration risk analysis.

Acknowledgements

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