Joint stratigraphic inversion of angle-limited stacks

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Summary

In order to provide a user guided and quantitative approach to AVA integrated processing, we propose a method to jointly invert angle-limited stacks. In a first step we use a multiwell calibration analysis to extract a single wavelet for each angle. Then, we use an inversion approach based on a formalism in which a priori information is provided for each parameter (P and S impedance). The Knott-Zoeppritz equation is used to compute the predicted synthetic data associated to a specific incidence angle. A global objective function is minimized in order to compute an optimal model for each parameter, which best explains all the angle stacks and the geological knowledge introduced through the a priori information. First results are shown on a real marine case study.

Introduction

Two approaches have appeared in recent works to estimate the elastic properties of the subsurface from PP prestack seismic data. The first one, introduced by Connoly (1999) and based on the linearization of the Knott-Zoeppritz equation consists in sequentially inverting angle-limited stacks to obtain an "Elastic impedance" volume, and then to estimate the P and S-impedances volumes by curve fitting. The second approach consists in simultaneously inverting all the angle-stacks, in order to globally estimate the P and S-impedances (Pendrel et al., 2000). This kind of method is less sensitive to local noise in the angle-stacks, and should provide more robust estimates of the elastic parameters.

Nevertheless, all these methods are limited by the fact that S-impedance is badly determined from PP data. In our approach, we introduce additional information in the inversion process in order to improve the determination of the S-impedance parameter.

In the following, we first describe our methodology and then present a first application on a real case study.

Angle stacks calibration

The first part of our methodology consists in a well-to-seismic calibration. Because NMO stretch and tuning are among the most serious factors hampering confident AVO analysis, we have decided to extract one single wavelet for each angle stack. Thus, each wavelet is able to compensate for some of the preprocessing issues.

In a first stage a multi-coherence analysis based on correlation theory permits the estimation of both signal and noise amplitude spectra, for each angle stack.

From the density and the P and S impedance logs at each well, we compute the reflection coefficient series corresponding to the mean value of the incidence angle of each angle stack, using the Knott-Zoeppritz equation. The synthetic trace at a well is then the convolution of the reflection series by a wavelet.

The second stage of the calibration methodology uses this way of computing the synthetic trace from the well logs and is divided in three steps, which are applied as described by Lucet et al. (2000), sequentially to each angle stack: the first step consists in a time shift detection, the second one is a linear phase detection, and the last one is an amplitude normalization and a detection of an optimal location for each well (in terms of correlation coefficient).

As the angle stacks are processed sequentially, a given well may have a different optimal location according to the angle. Consequently the final optimal location for each well is chosen as the one which gives the higher correlation coefficient for all the angles.

The third stage of the procedure, consists in refining each wavelet so that the synthetic traces at the optimal location of the well best fit the observed traces (least square minimization).

Joint stratigraphic inversion

The second part of our methodology consists in a joint stratigraphic inversion of all the angle-limited stacks.

We adopt a Bayesian inverse calculation to estimate elastic parameters from seismic data as thoroughly developed by A. Tarantola (1987). We assume that the seismic noise is described by a Gaussian probability with zero mathematical expectation and covariance operator C_d, and that the uncertainties on the a priori model are described by a Gaussian probability with zero mathematical expectation and covariance operator C_m. The maximum likelihood model minimizes the sum of two objective functions :

$$J = J_s + J_g$$

where J_s and J_g are respectively the seismic and " geological " objective functions.

We assume that the seismic noise is uncorrelated from one trace to another : the data covariance C_d is diagonal, with a seismic variance σ_s function of the noise level in the data. Thus J_s measures the mean square error between model-predicted and actual angle stack data :

$$J_s\left(m\right) = \sum_{\theta} \left\| R_{\theta}\left(m\right) * W_{\theta} - d_{\theta}^{obs} \right\|^2_{C_d^{-1}}$$

where $R_\theta\,(m)$ is the Knott-Zoeppritz reflection coefficient series corresponding to the current model m and to the angle θ, W_θ is the wavelet, and d_θ^{obs} is the observed seismic trace at the angle θ.

J_g measures the error between a priori and predicted model parameters according to the norm associated to C_m^{-1}. The choice of C_m is derived from the one used in the INTERWELL software for the 3D poststack stratigraphic inversion option (Brac et al., 1988). This exponential covariance operator is described by Tonellot et al. (1999), and permits the introduction of an a priori geometry derived from interpreted horizons and stratigraphic knowledge.

Using this geometry and the well logs, an a priori model for each elastic parameter is built by filling the inter-well volume using a standard interpolation technique. The confidence on this a priori model is incorporated by means of a priori user defined parameters : a variance for each elastic parameter uncertainty, a correlation coefficient of the interparameter uncertainties, and a correlation length which tunes the confidence in the a priori geometry.

Once the a priori information is defined, the objective function is minimized using a standard conjugate gradient technique.

Example

We apply our inversion methodology on a 3D marine data set. Five angle-limited stacks are provided, corresponding respectively to the stack of angles 0-6, 6-12, 12-18, 18-24, and 24-30 degrees. Each angle cube contains 601 lines with 701 traces by line. Log data (P and S-impedances and density) were available at 3 wells. An interpretation of the near offset reflections is also available.

We first run the calibration procedure, in order to extract the five wavelets corresponding to the five seismic cubes. The analysis is done on mini-cubes of 21x21 traces around the theorical position of each well. The phase analysis has shown that, for all the angles the optimal phase in term of correlation coefficient is around -20 degrees. The wavelets extracted by this procedure are shown in Figure 1. As expected, the frequency bandwidth of the largest angles are lower than the nearest one. At the optimal well location, the fit between the observed and the synthetic angle gathers is illustrated in Figure 2 for two wells. These results are very good, especially for well B.

Although we plan to apply our inversion methodology on the full 3D cubes, we present here a first inversion result on a 2D line which includes a well. We compute an a priori model for each elastic parameter. This is achieved using the well logs and two horizons which delineate the reservoir zone. We define three geological units, and build an a priori model in P and S-impedance, by interpolating the well logs information along correlation lines defined by stratigraphic knowledge (Fig. 3). A priori parameters were set within each of the three defined geological units, according to some information about the lateral heterogeneity.

We finally jointly invert the five available angle-limited stacks. Inversion results are shown on Figure 4. In Figure 5 and 6 we show respectively the near and far angle residuals : the main events of the seismic data have been explained by our optimal model, as the residuals mainly contain incoherent noise. Thus this optimal model correctly explain the amplitude variation of the seismic with angle. The P-impedance result shows the complexity of the reservoir zone. The S-impedance result provides a somehow different image that should be useful for a better reservoir characterization.

Conclusion

We introduce a new methodology for AVA analysis based, on one hand on the joint inversion of angle-limited stacks, and on the other hand on the use of a formalism which permits the introduction of geological knowledge in the inversion process. We have shown a first result on a seismic line. We will present the inversion results of the full 3D cubes.

Aknowledgments

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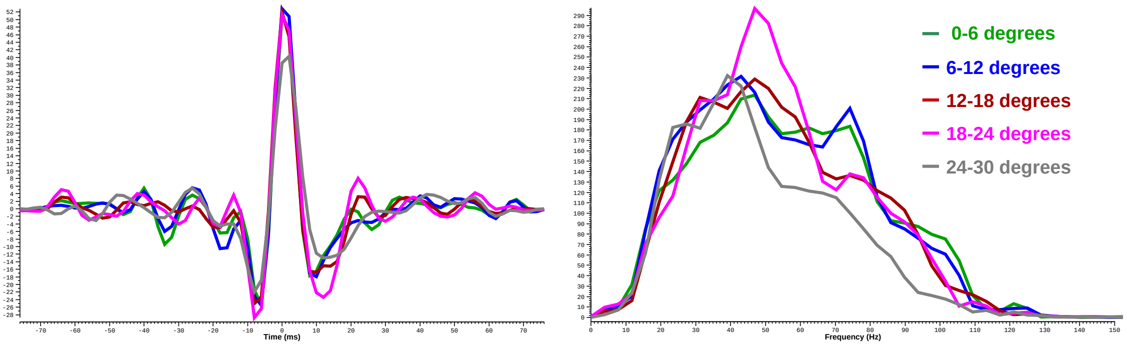


Fig. 1: Optimal angle wavelets extracted for each angle stack.

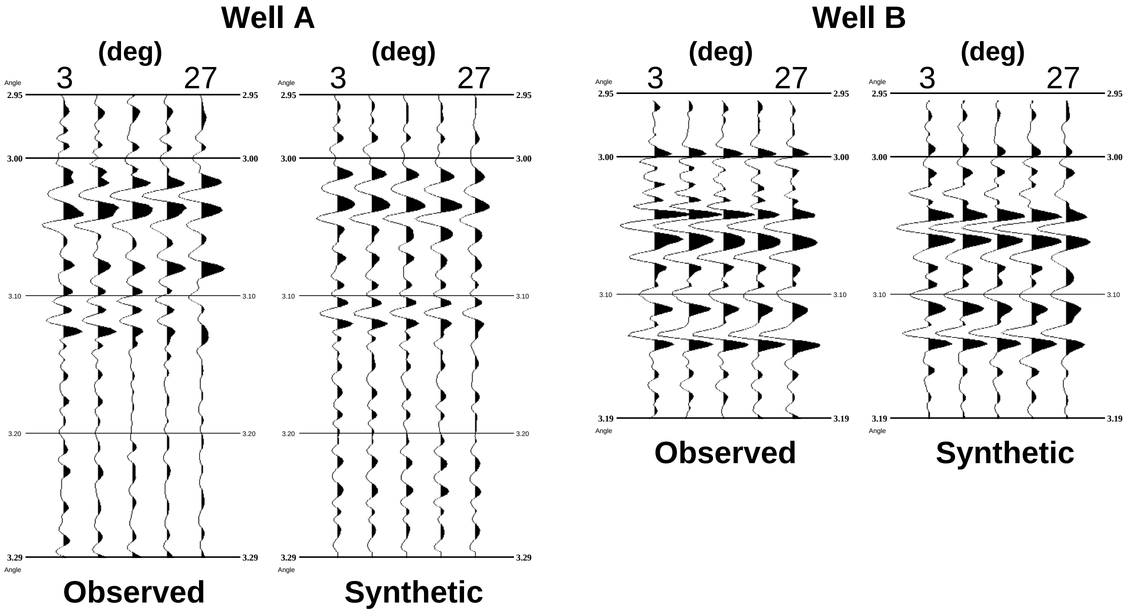


Fig. 2: Angle gathers at optimal well location A and B : observed (left) and synthetic corresponding to the optimal angle wavelets (right).

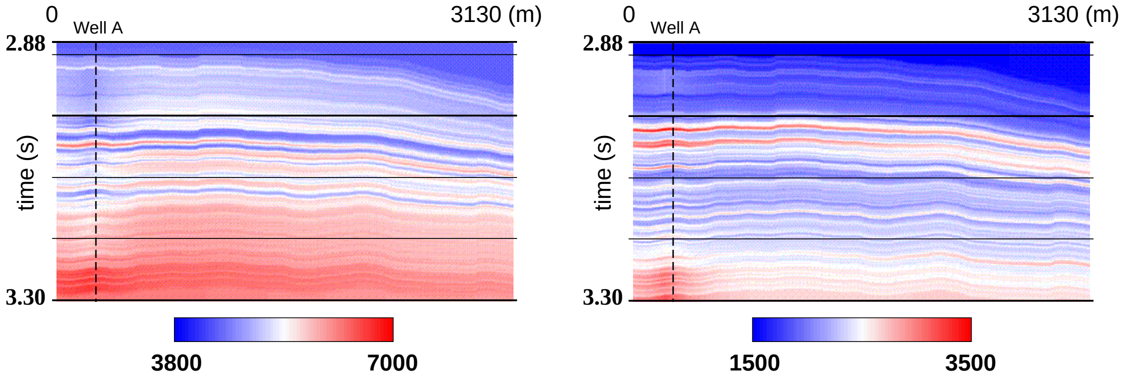


Fig. 3: A priori model in P-impedance (left) and S-impedance (right).

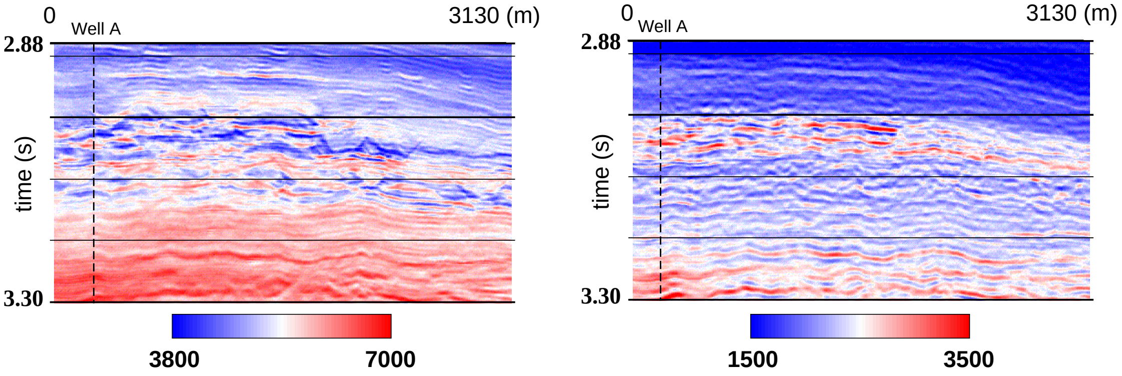
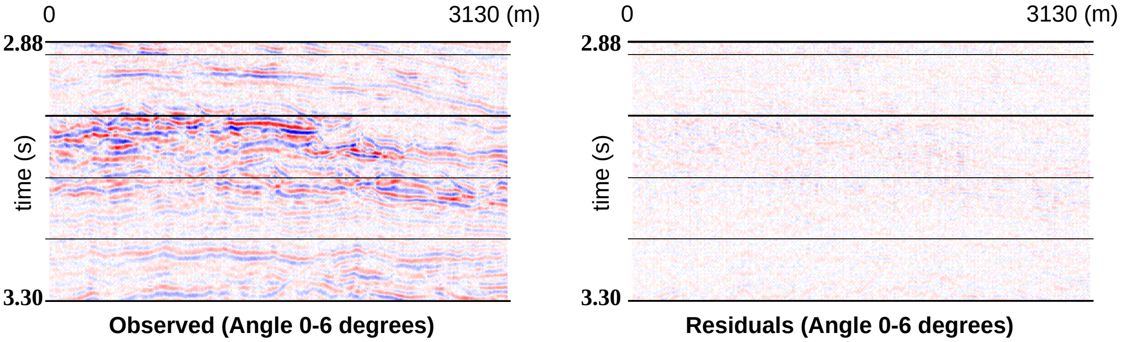


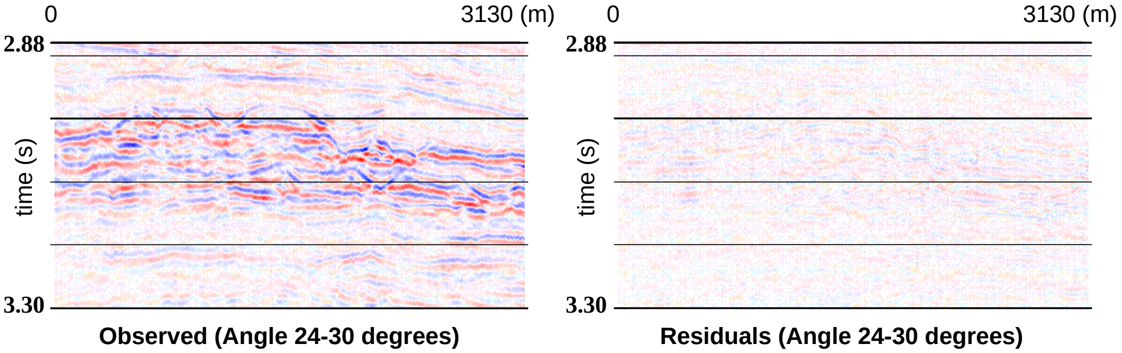
Fig. 4: Optimal model in P-impedance (left) and S-impedance (right)



Observed (Angle 0-6 degrees)

Residuals (Angle 0-6 degrees)

Fig. 5: Observed (left) and residuals (right) data corresponding to the angle 0-6 degrees.



Observed (Angle 24-30 degrees)

Residuals (Angle 24-30 degrees)

Fig. 6: Observed (left) and residuals (right) data corresponding to the angle 24-30 degrees.