Joint pre-stack stratigraphic inversion and facies analysis on a Brazilian deep offshore field

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Abstract

We present in this paper an integrated workflow to extract key parameters from seismic angle sub-stacks in a reservoir characterization purpose. The workflow consists in three main steps. First, from seismic angle sub-stacks and well log data, we use a multi-well and multi-angle calibration technique to extract one wavelet per angle sub-stack. Second, we use a joint stratigraphic inversion method to retrieve elastic parameters (density, P- and S-impedances) from the seismic angle sub-stacks. This method is a model-based inversion, which allows to integrate a priori geological knowledge in the impedance retrieving process. To compute synthetic angle sub-stacks from the elastic parameter model in the inversion process, we use the Aki-Richards equations, which are linear approximations of the Knott-Zoeppritz full-wave equations. Finally, we present the methodology for a qualitative interpretation of the P- and S-impedances into seismic facies. This integrated workflow is applied to a real case-study: the interpretation of pre-stack seismic data from a Brazilian deep offshore field.

Introduction

Reservoir characterization in complex geological environments, such as turbiditic systems recorded in a deep-offshore marine context, has become one of the central issues for the recent years. This task requires the integration of a huge amount of data from different sources (well-log data or core data, and pre-stack seismic angle sub-stacks). Apart from checking the quality of each of these sources of information, interpretation methods have also to care about their differences in scale and in resolution.

A standard reservoir characterization workflow generally begins with an inversion step, which allows to retrieve elastic parameters from seismic angle sub-stacks, on the basis of Knott-Zoeppritz equations, or one of their linear approximations, such as the Aki-Richards equations. These elastic parameters can then be interpreted qualitatively and/or quantitatively on the basis of the well data.

However, the use of such workflows has also risen new issues that have to be carefully tackled at each step. First, we deal with data from different origins, and with different resolutions. A calibration step is therefore necessary to ensure the consistency between well log data and seismic data. Second, the use of pre-stack seismic data allows a more complete reservoir characterization, but also rise new issues such as how to deal with the NMO errors and the tuning issues. The proposed workflow should be able to account for these issues, or at least to characterize them. Finally, we have to keep in mind that the inversion of PP-reflection wave seismic data does not allow to have the same confidence on the three retrieved elastic parameters: The P-impedance model is generally well determined, whereas the reliability of the S-impedance model depends greatly on the noise level of the seismic data; and the density model is usually not well determined (Lebrun *et al.*, 2000). Finally, in the interpretation of the inversion results, we have determine which attributes are the most relevant for reservoir characterization.

In this paper, we present an application of such a workflow on a deep offshore field. The first task is to retrieve P- and S-impedances from seismic angle sub-stacks. This task is achieved by using the joint inversion scheme presented in Tonellot *et al*. (2001). Prior to the inversion step itself, we have to extract one wavelet for each angle-substack. The adopted methodology is an adaptation of the well log to seismic angle sub-stack calibration developed for post-stack-data (Lucet *et al.*, 2000), and is a multi-well and multi-angle technique. Finally, the P-and S-impedance are interpreted with a seismic facies analysis technique (Bertrand *et al*., 2002).

Well log to seismic angle sub-stack calibration

Well log to seismic angle sub-stack calibration is a preliminary step to the inversion method. In order to account for a mean NMO stretch and tuning, we extract one wavelet for each angle sub-stack. The differences between these signals compensate for some of the preprocessing issues. As a by-product, the calibration step also searches for an optimal location for each well (in line, CDP and time origin), in the vicinity of its initial location.

This calibration step begins with a multi-coherency analysis based on the correlation theory. It allows to compute from each seismic angle-stack a zero-phase signal of both signal and noise, as well as their amplitude spectra.

In a second step, the calibration integrates the P-and S-impedance and density well logs: These well logs allow to compute synthetic traces $Synth_{[\theta]}$ for any angle range [θ], on the basis of the Equation 1:

$$Synth_{[\theta]} = \int_{\theta} R_{\theta}\left(I_P, I_S, \rho\right) * W_{[\theta]}\, d\theta \qquad (1)$$

where R_θ is the reflection coefficient series computed from the well log data at a given incidence angle θ, using the Aki-Richards equation, and $W_{[\theta]}$, the estimated wavelet for the angle range $[\theta]$. This second step is an adaptation of the multi-well calibration technique described in Lucet *et al*. (2000). It consists in successively estimating for each angle sub-stack the characteristics of a linear phase wavelet (time shift, constant phase shift and normalization coefficient), which will be representative of the available wells. With these parameters, we obtain a maximal correlation between the observed seismic gather extracted in the vicinity of the initial well position and the synthetic gather computed from Equation 1. Finally, each well can be optimally moved to the position (inline, CDP and time) where the local correlation coefficient between synthetic and observed data is the greatest.

However, if this methodology were applied sequentially on each angle-substack, one "optimal" position would be computed for each well and each angle sub-stack. This result is in contradiction with the requirements of the next steps of the interpretation, such as inversion or quantitative and qualitative interpretations. Consequently, the final optimal position for each well has to be chosen as the one, which gives the maximal average correlation coefficient over all the angle sub-stacks.

The third step of the calibration consists in refining each wavelet, so that the synthetic traces at the optimal position of each well best fit the observed traces. This step involves a least square minimization of the misfits between synthetic and observed traces.

As a final remark, this calibration is a step-by-step procedure, which allows to make a strong quality control of the seismic angle sub-stacks in the vicinity of the well positions. As it is a multi-angle procedure, it also allows to check the angle consistency of the seismic data.

Joint stratigraphic inversion

The second part of the methodology consists in a joint stratigraphic inversion of all the angle sub-stacks. The joint inversion methodology has been preferred to other methods, because it permits to retrieve more reliably the S-impedance model, in the presence of noise on the data (Tonellot et al., 2002).

The adopted methodology is based on a Bayesian formalism presented in Tarantola (1987). This formalism allows to integrate in the optimization process a geological a priori model $\mathbf{m}_{\mathbf{prior}}=(\mathbf{I}_{\mathbf{P\ prior}}; \mathbf{I}_{\mathbf{S\ prior}}; \rho_{\mathbf{prior}})$, which is computed by interpolation of the well log data along correlation (stratigraphic) surfaces. To achieve the inversion, we assume that the uncertainties on the seismic data are described by a gaussian probability density function, with a zero mean, and a covariance operator C_d. This covariance operator reflects the confidence in the seismic angle sub-stacks. We also assume that the uncertainties on the differences to the a priori model are described by a gaussian probability density function, with a zero mean, and a covariance operator C_m, which reflects the confidence in the a priori geometry and elastic parameters. In this context, the maximum likelihood model **m** is the one that minimizes the two-term objective function:

$$J(\mathbf{m}) = J_S(\mathbf{m}) + J_g(\mathbf{m}) \qquad (2)$$

where $J_S(\mathbf{m})$ is the seismic term defined by:

$$J_S(\mathbf{m}) = \sum_{[\theta]} \left\| \int_{[\theta]} R_\theta(\mathbf{m}) * \mathbf{W}_{[\theta]} d\theta - \mathbf{d}^{obs}_{[\theta]} \right\|^2_{\mathbf{C}_\mathbf{d}^{-1}} , \qquad (3)$$

and $J_g(\mathbf{m})$ is the geological seismic term, defined by

$$J_g(\mathbf{m}) = \left\| \mathbf{m} - \mathbf{m}_{\mathbf{prior}} \right\|^2_{\mathbf{C}_m^{-1}} \qquad (4)$$

The reflection coefficients for a given incidence angle are computed on the basis of the Aki-Richards equations.

This joint inversion approach results in a robust quantitative estimation of the P- and S-impedances. Note that the retrieved density model is not reliable enough (*Lebrun et al., 2000*) to be accounted for in the next interpretation steps.

Seismic facies analysis

The next step of our methodology consists in interpreting the inverted P- and S-impedance volumes into geological or petrophysical parameters. In this paper, we focus on a qualitative interpretation of the inversion results in terms of seismic facies. This task is achieved by applying a pattern recognition approach similar to the one described in Bertrand *et al*. (2002). The proposed approach is based on discriminant analysis, and allows to compute a geologically interpreted facies map. This interpretation is divided into four steps.

In the first step, we work with well log and core data. This database has first to be completed, because wells are generally incompletely cored. This operation is achieved with an electrofacies analysis of the available well logs, and also lies on discriminant analysis. Because logs are recorded at a very detailed scale, this facies interpretation at logs has to be upscaled to the seismic scale. The upscaling of the detailed electrofacies series is done by first finding the most frequent electrofacies in a moving time-window, and then resampling it at the seismic time step. This interpretation, which is available at each well, represents the geological interpretation of well data at the seismic scale. As a last step, we define for each well a global "seismic facies" C_i, which is representative of a given time interval (for example a constant time interval from the top marker of the reservoir).

In the second step, we extract attributes from the P- and S- impedance optimal volumes. These attributes may be the series of P- and S-impedances $\mathbf{m}(\mathbf{x})$ in the studied time interval, extracted at a given seismic bin position $\mathbf{x}$; or any attribute computed thereof.

Then, we calibrate a classification function between the considered attributes $\mathbf{m}(\mathbf{x})$ and the facies C_i defined at the well positions. This calibration is done on the basis of a training sample database, which is composed of the seismic bins in the vicinity of the well positions, where attribute extraction has been completed, and where a facies C_i has been a priori assigned. This calibration step allows to assess the discrimination power of the considered attributes with the facies database.

If the discrimination is judged satisfactory enough, the calibrated classification function is applied to assign all the seismic bins in the studied area.

One of the advantages of this methodology is that it is based on a Bayesian formalism, and thus, it allows a characterization of the uncertainties at each step of the process, by computing probabilities to assign each seismic bin to the different facies. In conclusion, this qualitative interpretation step allows to translate attributes extracted after inversion into geological facies.

Data and application

A 3D dataset in a deep offshore turbiditic environment is considered. It is made of 4 angle sub-stacks ([0°-10°]; [10°-20°]; [20°-30°] and [25°-35°]). Each angle sub-stack has 791 lines and 2361 crosslines, and covers about 600 km^2. In the inversion process, we focus on a constant 500-ms time window (125 time samples) centered on a regional picked horizon. This analysis window includes the most important reservoirs in the studied field. This operation allows to concentrate on a zone where the data are less corrupted by noise, attenuation… Log data, P- and S- impedances, as well as density are available from 16 wells, ten of which have been accounted for in the calibration and a priori model building phases.

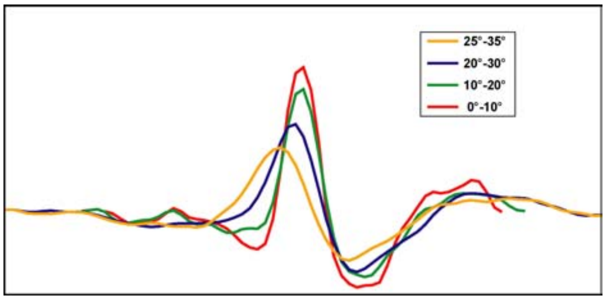

Figure 1- Variations of the estimated multi-well wavelets with the angle

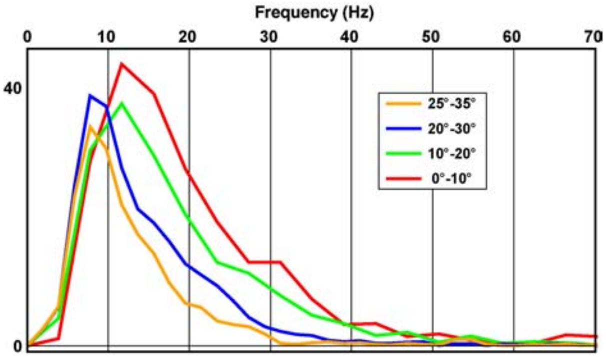

Figure 2-Variation of the power spectra of the estimated multi-well wavelets with the angle

The 4 angle sub-stacks are calibrated using 15*31 (375*375 m) trace cubes around each well initial location. Figure 1 illustrates the 4 estimated wavelets. Figure 2 shows their associated amplitude spectra. As it could be expected, the frequency content tends to decrease with the angle because of the NMO stretch. The computed correlation coefficients between synthetic and observed data are very high, indicating a local good consistency between seismic and well log data. Figure 3 illustrates this good fit, by comparing the observed data extracted at the optimal well "W-A" position (on the left) with the synthetic data computed from well log data (on the right).

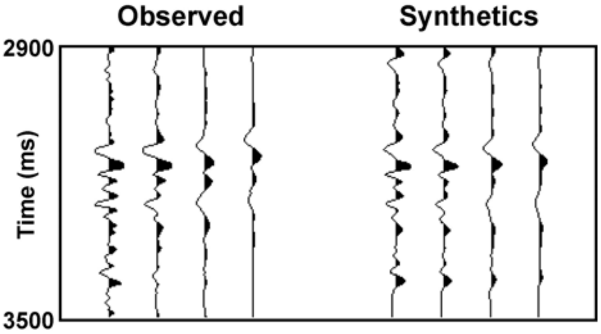

Figure 3- Comparison between the observed seismic gather extracted at well "W-A" optimal location (left), and the synthetic gather computed from the well log data (right)

Then, four geological units are defined by three interpreted regional horizons. The elastic a priori model is obtained by interpolating the well log information in accordance to the stratigraphic patterns chosen within each geological unit.

The 4 angle sub-stacks are inverted jointly into P- and S-impedance (and density) volumes using the elastic a priori model and the 4 wavelets. At the bottom of Figure 4, we have represented the estimated P-impedance volume on a section where well "W-A" is located. This section can be compared with the corresponding P-impedance a priori model (top). The right part of Figure 4 is representing real low-pass filtered P-impedance log data and the extracted optimal P-impedance trace at well "W-A" position. Figure 5 is composed of the same views, in S-impedances. On both figures, the fit between well log data and inversion results is very good. Moreover, in comparison to the a priori model, which is very smooth, the optimal impedance models display a high resolution. As a first quality control of the inversion, Figure 6 compares the observed gather at well "W-A" optimal position with the residual gather extracted at the same location. The residuals have a low energy, and are not correlated through the angle dimension, which indicates that the inversion process has worked correctly at this position. Figure 7 and 8 compare the residual amplitude sub-stacks with the corresponding observed angle sub-stacks for the [0°-10°] (Near) and the [25°-35°] (Far) angle sub-stacks. The residual amplitudes have a very low energy. Moreover, they are less spatially correlated than the observed sub-tacks. It results that the joint inversion has explained most of the signal, leaving mostly noise. The only high-energy event, observed in the zone A of the far angle sub-stack corresponds to a data anomaly, which is neither consistent geometrically with the surrounding amplitudes, nor through the angle dimension. In this case, the inversion process has therefore correctly rejected it. A second example of noise rejection for the same reasons can be highlighted in zone

B of the nearest angle sub-stack. This noise corresponds certainly to migration errors.

On the basis of these results, a seismic facies analysis will then be applied as described above.

Conclusions

We have presented an integrated scheme to optimize the information that can be retrieved from 3D pre-stack seismic data. We have first extracted for each angle-sub-stack a wavelet, by using a multi-well and multi-angle wavelet calibration technique. The calibration has also allowed to find an optimal location for each well. We have then used a joint inversion methodology to retrieve optimal 3D P- and S-impedance volumes, from the pre-stack seismic data. The applied formalism allows to integrate a priori geological knowledge in the inversion process, which helps a lot in rejecting spatially coherent noises. The methodology has then been applied to a real case study. We will present the results from the seismic facies analysis.

Acknowledgments

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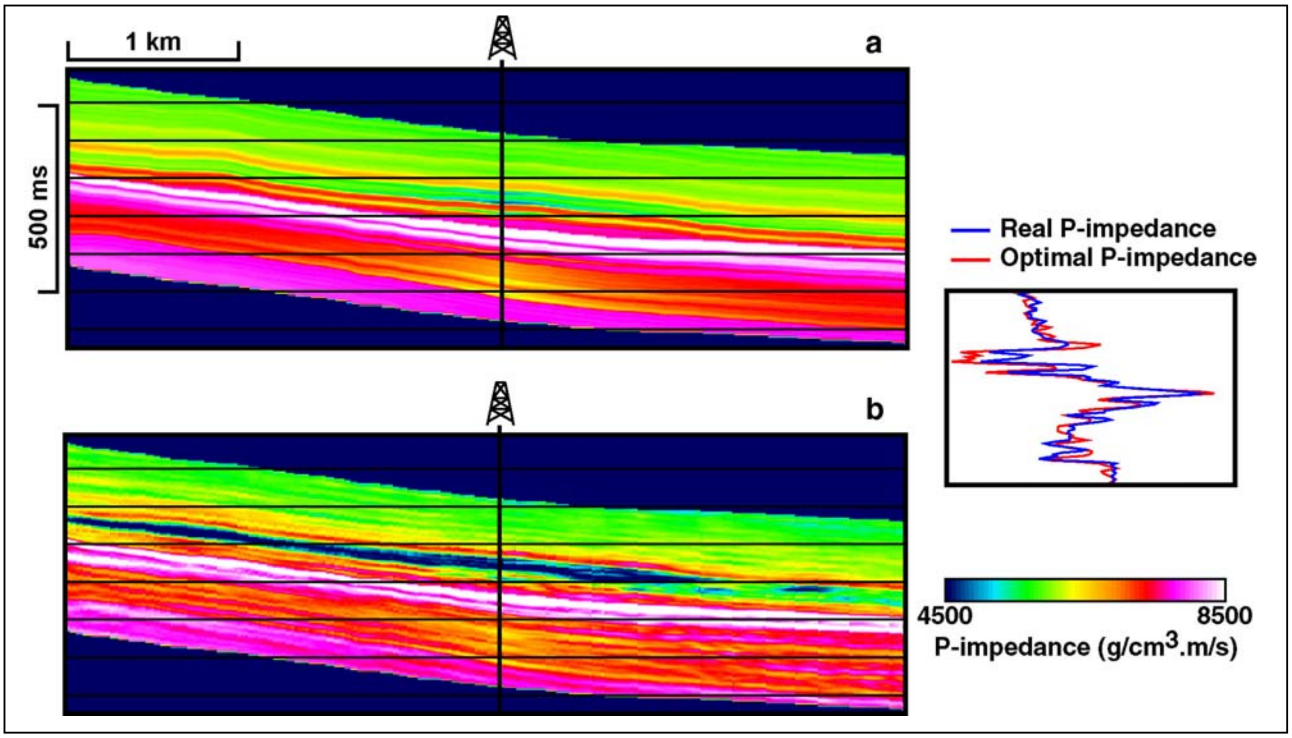

Figure 4- Optimal P-impedance section at well "W-A" optimal location (b), compared to the corresponding a priori P-impedance section (a). Logs on the right hand-side are the traces extracted in each model at the well location

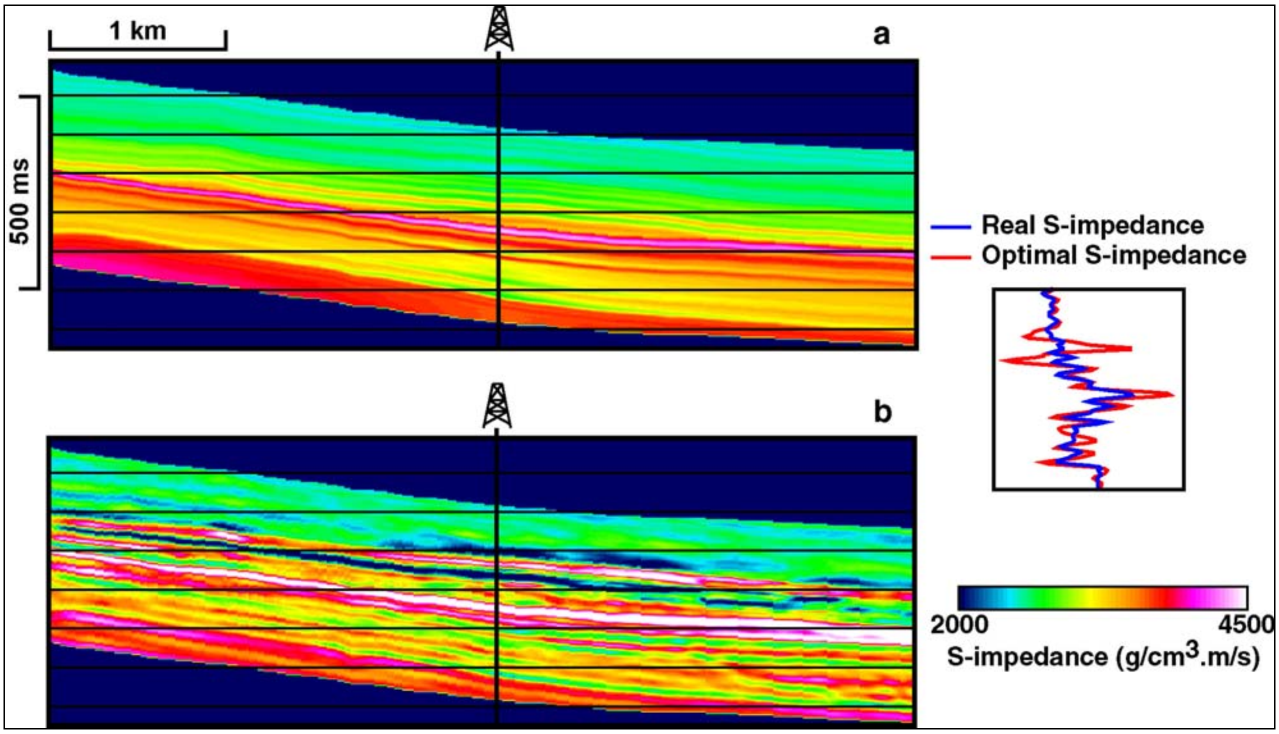

Figure 5- Optimal S-impedance section at well "W-A" optimal location (b), compared to the corresponding a priori S-impedance section (a). Logs on the right hand-side are the traces extracted in each model at the well location.

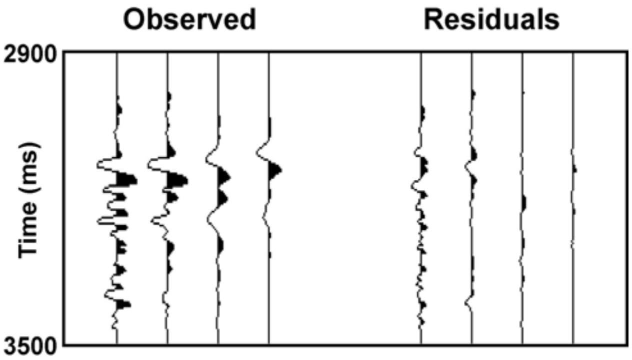

Figure 6- Comparison between the observed seismic gather extracted at well "W-A" optimal location (left), and the residual gather after inversion (right).

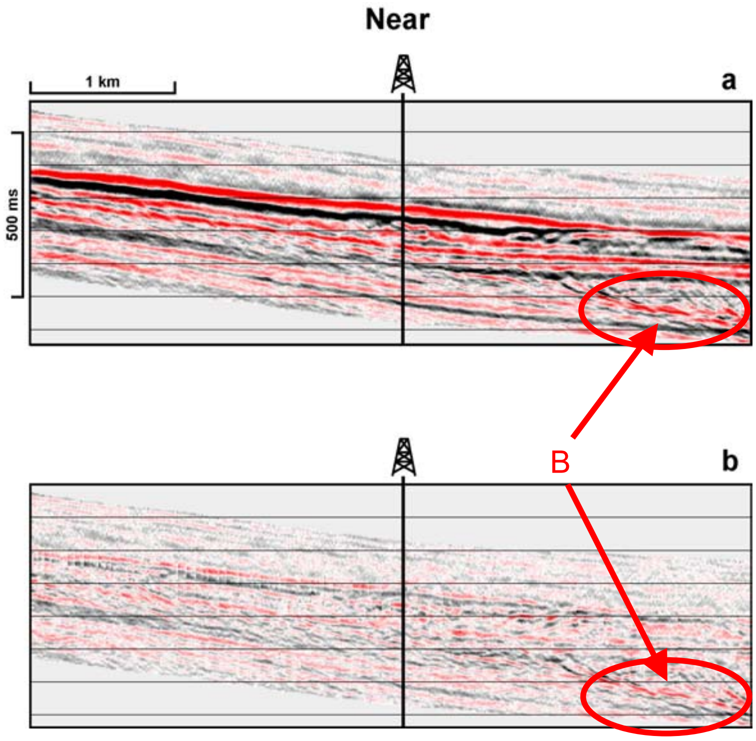

Figure 7- Near angle sub-stack observed seismic section at well "W-A" optimal location (a), compared to the corresponding residual amplitude section (a).

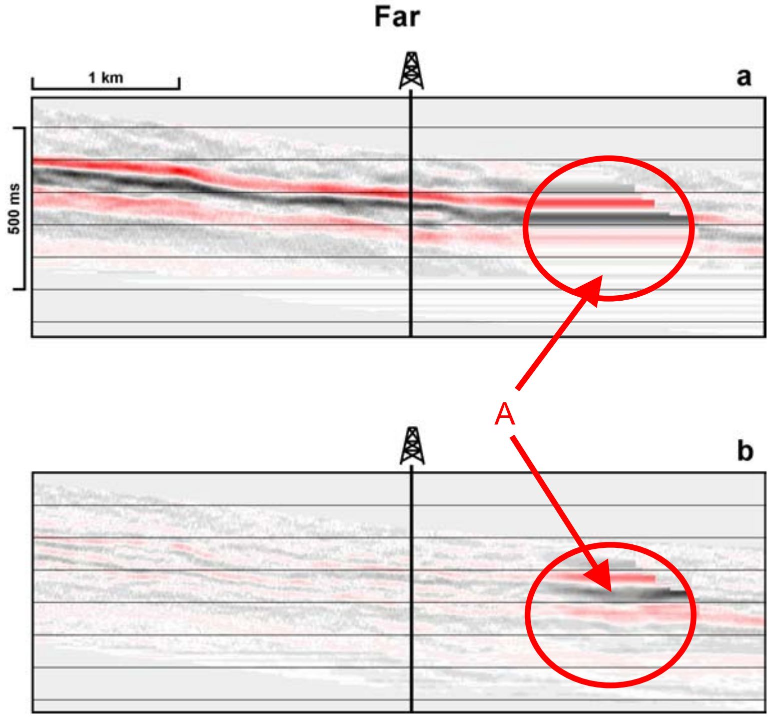

Figure 8- Far angle sub-stack observed seismic section at well "W-A" optimal location (a), compared to the corresponding residual amplitude section (a). Zone A corresponds to a data anomaly, which is rejected by the inversion.