# Pre-stack stratigraphic inversion and attribute analysis for optimal reservoir characterisation

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## Summary

To optimise the information that one can retrieve from pre-stack seismic data, we propose a 3-step scheme. First, angle sub-stacks are inverted into elastic parameters: acoustic and shear impedances and densities. Angle sub-stacks are initially carefully calibrated to supply for each of them the wavelet that best explains the seismic traces around the wells from the available well log data. A priory knowledge of the medium geometry as well as the well log data are then used to build an elastic a priori model in acoustic and shear impedances and density. Both elastic a priori model and wavelets are then used to invert jointly the angle sub-stacks via a pre-stack stratigraphic inversion. In a second step we apply Generalised Principal Component Analysis to optimise the information brought by the inverted elastic parameter values: new attributes are proposed for an improved and more realistic geological interpretation of the data. In the last step these attributes are interpreted in terms of lithofacies.

## Introduction

A standard interpretation workflow to make pre-stack seismic data interpretable volumes in a geological or petrophysical sense involves a preliminary preserved amplitude processing of the data in order to generate several angle sub-stacks. These sub-stacks are then analysed, e.g. using the Zoeppritz equations, to retrieve a set of elastic parameters that explains best the amplitude variation with angle. Finally these elastic parameters can be either qualitatively or quantitatively interpreted, mainly on the basis of well information.

In this workflow one has to be extremely careful on the choice of the method applied at each step, as it may dramatically affect the quality and quantity of the resulting information. For instance, if we analyse the information content of the linearized forward modelling, it appears that P-wave AVO data contains only information on acoustic and shear impedances and density. Moreover Nicolao et al., (1993) demonstrated that from P-wave AVO data solely, P-wave related parameters were usually accurately estimated, S-wave related parameter estimation depended strongly on the noise level and the angle range, and density-related information was very difficult to retrieve. Therefore with an AVO inversion technique one can estimate an optimal elastic model in acoustic and shear impedances and, with much less confidence, in density. Finally, this set of elastic parameters can be interpreted in terms of lithofacies for example. This interpretation step has to be carried out using optimal attributes derived from inversion results. Indeed, the elastic parameters provided by AVO may not be as clearly related to lithofacies variations as other attributes such as the difference between acoustic and shear impedances, Lamé's parameters or any combination of the elastic parameters obtained by inversion.

In the present paper a three-step process is considered to optimise the information that can be retrieved from pre-stack data. A joint stratigraphic pre-stack inversion scheme (Tonellot et al., 2001) is run on angle sub-stacks previously calibrated using a multi-well and multi-angle analysis (Lucet et al., 2000). Then Generalised Principal Component Analysis (Voutay et al., 2002) is the method applied to extract new attributes from the estimated ones to better explain facies variations. Finally these attributes are geologically interpreted through seismic facies analysis with a supervised pattern recognition algorithm (Bertrand et al., 2002). We first expose briefly the methods, we then apply them to a real case study.

## Pre-stack stratigraphic inversion

The available angle sub-stacks are jointly inverted using a 3D stratigraphic inversion methodology (Tonellot et al., 2001). This methodology, which is based on the Zoeppritz equations, allows the direct estimation of an optimal elastic model in acoustic and shear impedances and density, under the constraint of geological and petrophysical a priori information.

Preliminary to the inversion, each angle sub-stack is calibrated with the well information using an extension of the multi-well to seismic calibration procedure proposed by Lucet et al. (2000). This procedure results in the computation of one angle seismic wavelet per angle sub-stack. Through the use of Zoeppritz equations, each wavelet ensures an optimal consistency between the well and the angle seismic information. Moreover, the computation of one wavelet per angle allows to partly correct for preprocessing issues due to wavelet variation with angle.

In our joint inversion approach, the optimal elastic model in acoustic and shear impedances and density minimizes the objective function:

$$\mathbf{J}(\mathbf{m}) = \sum_{\theta} \left\| \mathbf{R}_{\theta}(\mathbf{m}) * \mathbf{W}_{\theta} - \mathbf{d}_{\theta}^{\mathbf{obs}} \right\|^{2}_{\mathbf{C}_{\mathbf{d}}^{-1}} + \left\| \mathbf{m} - \mathbf{m}^{\mathbf{prior}} \right\|^{2}_{\mathbf{C}_{\mathbf{m}}^{-1}} \qquad (1)$$

For a given incidence angle $\theta$, $\mathbf{R}_{\theta}$, $\mathbf{W}_{\theta}$ and $\mathbf{d}_{\theta}^{\mathbf{obs}}$ are respectively the Zoeppritz reflection coefficient series corresponding to the current model **m**, the angle seismic wavelet and the observed angle stack; $\mathbf{m}^{\mathbf{prior}}$ is an elastic a priori P- and S- impedance and density model; $\mathbf{C}_{\mathbf{d}}$ and

$\mathbf{C_m}$ are covariance operators which describe the uncertainties on respectively the data and the model. The choice of $\mathbf{C_m}$ is of particular interest as it enables first to adjust the confidence in each a priori model parameters, and second, to take into account a 3D a priori geometry derived from interpreted horizons and stratigraphic knowledge in the inversion. In this joint inversion scheme, the optimal elastic model explains simultaneously the amplitude of all available angle stacks according to the Zoeppritz equations, and the a priori information, which acts as a 3D stratigraphic filter in the model space. Moreover, the S-impedance determination is improved, thanks to the use of S-impedance a priori information.

This joint inversion approach results in a robust quantitative estimation of the P- and S-impedance and density, although this last parameter is much less reliable.

## Generalised Principal Component Analysis

Generalised Principal Component Analysis (GPCA) is a multivariate statistical method. It analyses the relationships between given group of attributes but also considers separately each group. GPCA reduces the number of variables for a more reliable and realistic geological interpretation. The method has been developed and exposed by Voutay et al. (2002). Its main advantage is to allow the description of similarities between groups of variables while summarising each group. Note that GPCA and Principal Component Analysis yield similar results only if the number of groups is one.

Applying GPCA on the pre-stack stratigraphic inversion results allows to propose new attributes which are easily related to elastic parameters; thus they keep a physical meaning. Moreover the number of attributes necessary to explain most of the inversion results is reduced compared with the initial number of parameter samples.

## Seismic facies analysis

Using the new attributes proposed by GPCA, seismic facies are detected with a supervised pattern recognition approach similar to the one applied by Bertrand et al. (2002). This supervised approach, which is based on discriminant analysis, enables the introduction of a priori geological information through training traces in the vicinity of typical wells for guiding the facies determination.

## Data and application

A 3D dataset in a deep-offshore turbiditic environment is considered. It is made of 6 angle sub-stacks (0°-6°,6°-12°,12°-18°,18°-24°,24°-30° and 30°-36°). Each angle sub-stack has 251 inlines and 501 crosslines. Log data, acoustic and shear impedances as well as density, are available from two wells.

The 6 angle sub-stacks are calibrated using 15*15 trace cubes around each well actual position. We found a constant -20° phase-shift for all wavelets. Figure 1 illustrates the 6 estimated wavelets. As expected, the high frequency content tends to decrease with an increasing stack angle, because of the NMO stretch. Then, three geological units are defined by two interpreted horizons: the top and the base of the reservoir. The elastic a priori model is obtained by interpolating the well log information in accordance to the stratigraphic patterns chosen within each geological unit.

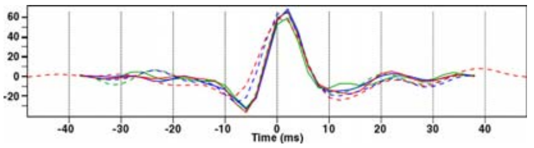

Figure 1: Wavelets from the multi-well analysis: for the 0°-6° (solid green line), 6°-12° (solid blue line), 12°-18° (solid red line), 18°-24° (dashed green line), 24°-30° (dashed blue line) and 30°-36° (dashed red line) angle sub-stacks.

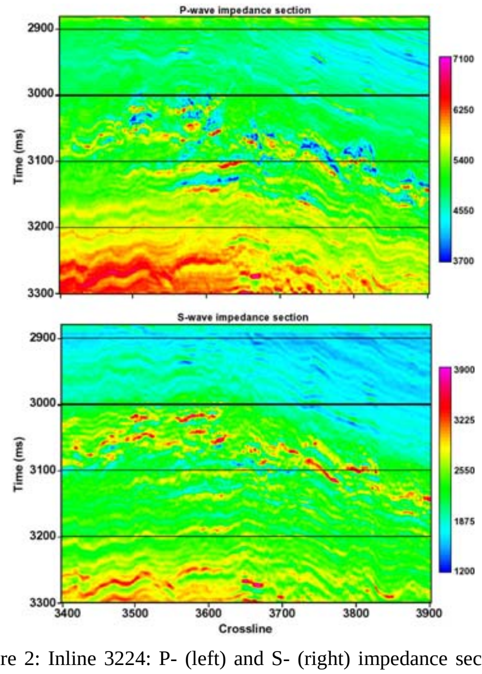

Figure 2: Inline 3224: P- (left) and S- (right) impedance sections from the joint pre-stack inversion of the 6 angle sub-stacks after 50 iterations. Impedances are in m/s*g/cm$^3$.

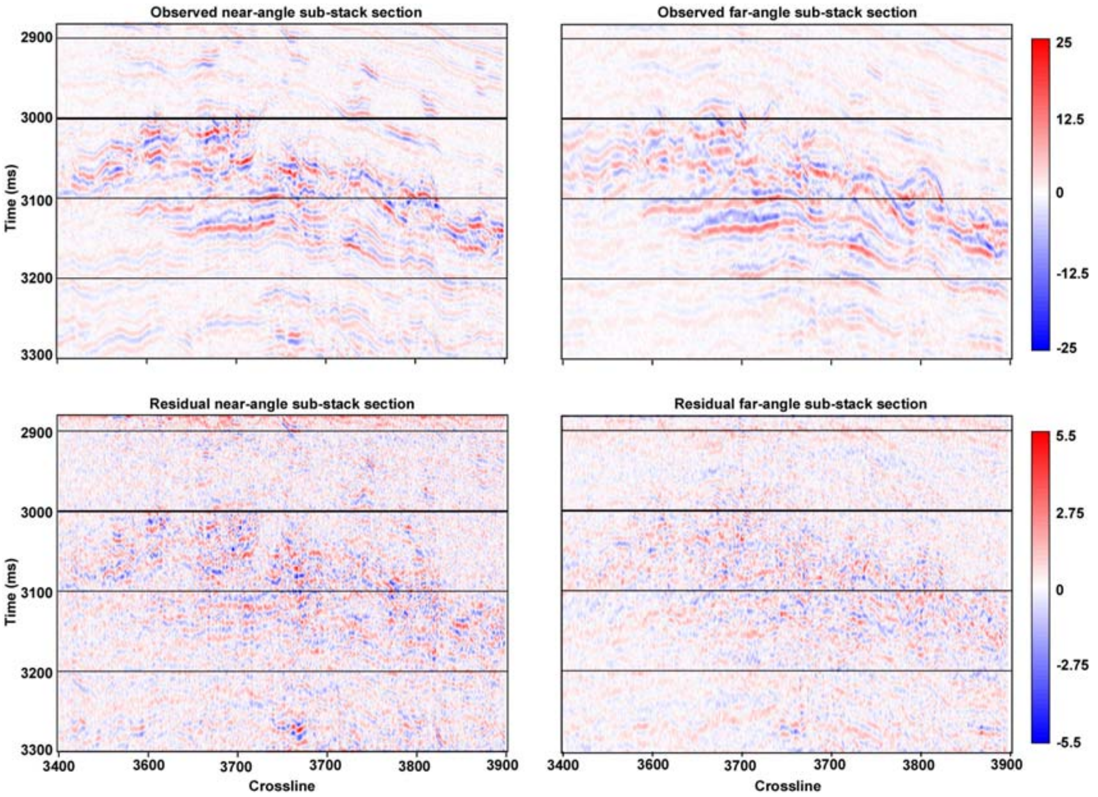

Figure 3: Inline 3224: Observed (above) and residual (below) sections after 50 iterations for the nearest (left column) and furthest (right column) angle sub-stacks.

The 6 angle sub-stacks are inverted jointly into acoustic and shear impedance and density volumes using the elastic a priori model and the 6 wavelets. Figure 2 shows the estimated acoustic and shear impedance volumes after 50 iterations. Figure 3 shows the observed and residual volumes for the nearest (0°-6°) and furthest (30°-36°) angle sub-stacks. The residual value smallness highlights that most of the event amplitudes have been explained in the inversion process, leaving mostly noise. Estimated acoustic and shear impedance volumes show a high resolution in both reservoir and surrounding areas. Shear impedances ($Z_S$) bring certainly added information compared with acoustic impedances ($Z_p$) as in some area, e.g. below 3200 ms, $Z_p$ values are generally high while $Z_S$ values are high only along few reflectors (e.g. between trace 50 and trace 150). That may indicate lithology change rather than fluid change since $Z_S$ values varies while $Z_p$ values remain fairly constant. At this stage a Poisson's ratio ($\sigma$) volume is computed from the inverted impedance volumes.

To optimise the analysis of the inverted parameters, GPCA is performed within the reservoir interval: a 19 time-sample, i.e. 36 ms-long, interval is extracted from the $Z_P$, $Z_S$, $\rho$ and $\sigma$ volumes obtained from inversion. As a result only 14 new variables are required to explain 100 % of the parameter variances.

The first 10 projections explain 95.0 % of the acoustic impedance variance, 97.3 % of the shear impedance variance, 92.4 % of the density variance and 95.1 % of the Poisson's ratio variance. For any further facies analysis one can use the first 10 new attributes rather than the 4*19 initial parameter samples gathered in the analysis window. The degree of proximity between the new variables and their projections in each group indicates that, for instance, the first variable is close to $Z_S$ (0.90), $\sigma$ (0.90) and $\rho$ (0.78) but further from $Z_p$ (0.44); the second variable is closer to $Z_p$ (0.76) and $Z_S$ (0.87) than $\rho$ (0.54) or $\sigma$ (0.54); the third variable is mainly a linear combination of $Z_S$ (0.80), $\rho$ (0.73) and $Z_p$ (0.66) than $\sigma$ (0.55). Figure 4 shows the first three projection sections. One channel and one fault are clearly imaged on these sections. Other lithology variations are better highlighted by some projections than other.

These new attributes will then be interpreted through seismic facies analysis with a supervised pattern recognition algorithm.

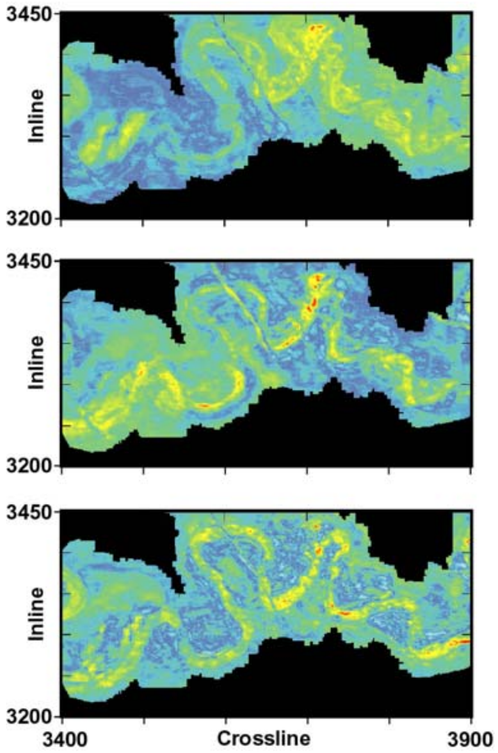

Figure 4: First (above), second (middle) and third (below) projection sections from GPCA.

## Conclusions

We have presented a 3-step scheme to optimise the information that can be extracted from 3D seismic pre-stack data. First we calibrated properly angle sub-stacks and built a priori models for acoustic and shear impedances and density. We inverted the partial stacks jointly into $Z_p$, $Z_S$ and $\rho$ volumes. Second we extracted new attributes with GPCA to optimise further facies interpretation. This step reduced the number of attributes required to explain over 90 % of the inverted parameters from 4*19 to 10 only. On the new attribute projection maps, lithologies and structures are highlighted. Finally, these new attributes will be interpreted using a supervised facies analysis.

## References

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