

Amplitude versus angle full waveform inversion (AVA-FWI): application in an OBN data set

Introduction

The routines used for elastic seismic inversion in E&P industry today still rely on the simplified primary-only convolutional model based on approximations of the Zoeppritz equation. These approximations allow the inverse problem in question to be linearized, thus facilitating the computation and implementation. Although these methods have proven capable of producing reliable results, particularly for P-impedance (I_p), it cannot be ignored that the aforementioned approximations are strictly valid for weak contrasts between the elastic properties of the layers and break down after the critical angle. Because of this, they should be used with caution when the seismic data contains reflection with angles above thirty degrees. An alternative and more rigorous method is elastic full waveform inversion (E-FWI), however, the complexity and high demand for computational resources associated with this type of inversion ultimately make its costs unfeasible for conventional reservoir characterization projects.

A midway option between E-FWI and linearized AVO inversion, consists in methods that consider the subsurface as locally 1-D, but do not use approximate formulas to solve the Zoeppritz equation, and also take into account all events generated in the layered medium such as multiples and converted waves. Note that this increases the chance of better explaining the reflection amplitudes, especially for far and ultra-far angles; (Mallick, 2007), (Simmons and Backus, 1994), what is very important for V_s and Density estimation. Examples of such inversion method can be found in Liu et al. (2016), Oliveira et al. (2018) and Haffinger et al. (2025). These nonlinear methods have a higher computational cost than conventional AVO inversion; however, this cost is much lower compared to E-FWI. This is due to the use of analytical solutions to solve the problem of wave propagation in layered media. This category of method shows superior results in comparison with conventional linearized AVO inversion, however there aren't many examples of its application in the literature; see, e.g., Mallick and Adhkari (2015), Oliveira et al. (2019) and Contreras et al. (2020), this must certainly be one of the reasons why they haven't yet gained more ground in the E&P industry, despite their potential. In this work we present an elastic inversion case study using a 1-D wave-equation-based method, named AVA-FWI, to invert a deep water OBN marine seismic data, which was acquired with the aim of studying carbonate rock formations that occur just below a thick salt layer in the Santos Basin, Brazil.

Method

AVA-FWI is a deterministic inversion based on the reflectivity method (Muller, 1985), which consists of a mathematical solution to elastic wave propagation in horizontally stratified isotropic media, capable of handling all propagation effects, including internal multiples, mode conversion and attenuation. Because of that, it can handle high elastic property contrasts between layers and accurately predicts the amplitude of reflections with high angles of incidence (Oliveira et al., 2018). It input migrated prestack gathers in time domain, sorted by incidence angle. Once the data has been migrated, the subsurface can be represented as a 1D geological medium divided into elemental layers with constant thickness. The parameters to be determined (for each elemental layer) are V_p (P wave velocity), V_s (S wave velocity), I_p (P wave impedance), I_s (S wave impedance) and density. The inversion solution can be expressed by considering a vector $\mathbf{m}$ representing this set of elastic properties of the layered medium, which minimizes an error function that measures the L2 distance between the observed and calculated angle gathers:

$$E(\mathbf{m}) = \sum_{i=1}^{na} [S_o(\phi_i, \mathbf{m}) - S(\phi_i, \mathbf{m})]^2, \quad (1)$$

where ϕ is incidence angle, na is the number of angles and S_o is the observed angle gather. AVA-FWI implements a robust nonlinear, optimization based inversion algorithm (Oliveira, 2025) based on

efficient routines to calculate full waveform angle gathers $S(\phi, \mathbf{m})$ and differential angle gather $\partial S(\phi, \mathbf{m})/\partial \mathbf{m}$. The workflow for AVA-FWI is similar to that of conventional linearized AVO inversion; it requires smooth initial models for the elastic parameters and an estimated seismic wavelet. A parameterization stage is necessary to set up appropriate values for the stabilization factor and the number of iterations of the optimization algorithm in order to minimize $E(\mathbf{m})$. The inversion of each angle gather is done independently; that is, no regularization is used to impose lateral continuity.

Application in an OBN data set

The data in question is a 3-D deep water, P-wave ocean bottom nodes (OBN), acquired in Santos basin, Brazil, with the aim to characterize carbonates rocks formations that occurs just below a salt layer. The data was originally depth migrated, but it was converted to time in order to apply AVA-FWI elastic inversion. The angle gathers employed were generated from partial angle stacks, starting with a mean incidence angle of 10 degrees and ending at 34 degrees, with a 6-degree interval. The data underwent a preconditioning step that included an inverse Q filter and residual NMO correction. The initial low-frequency V_p , V_s , and ρ models used in the AVA-FWI inversion, were obtained from well logs. The logs were extrapolated using the interval velocity model (derived from seismic processing) to fill in regions where log data were not available. The V_p logs were directly extrapolated using the interval velocity, while the V_s and ρ logs were adjusted through linear relationships, derived from crossplots between the interval velocity and V_s and ρ curves. Once extended, the well logs data were filtered to retain only low-frequency content, limited to 8 Hz. Additionally, seismic horizons were used as guides during the interpolation process for generating low-frequency volumes for the elastic parameters. The inversion of each angle gather took, on average, seven iterations to achieve convergence. The inversion results (V_p , I_s and density) are displayed on a random line that intersects four wells (Figures 1 and 2). Three horizons are also shown: H1, H2, and H3, where H1 refers to the base of the salt layer. Note that the well intervals are available only in the zone of interest between H1 and H2. It is possible to observe good lateral continuity of the layers reconstructed by the inversion and a good consistency between the inversion results and the V_p , I_s , and ρ values present in wells A, B, C and D.

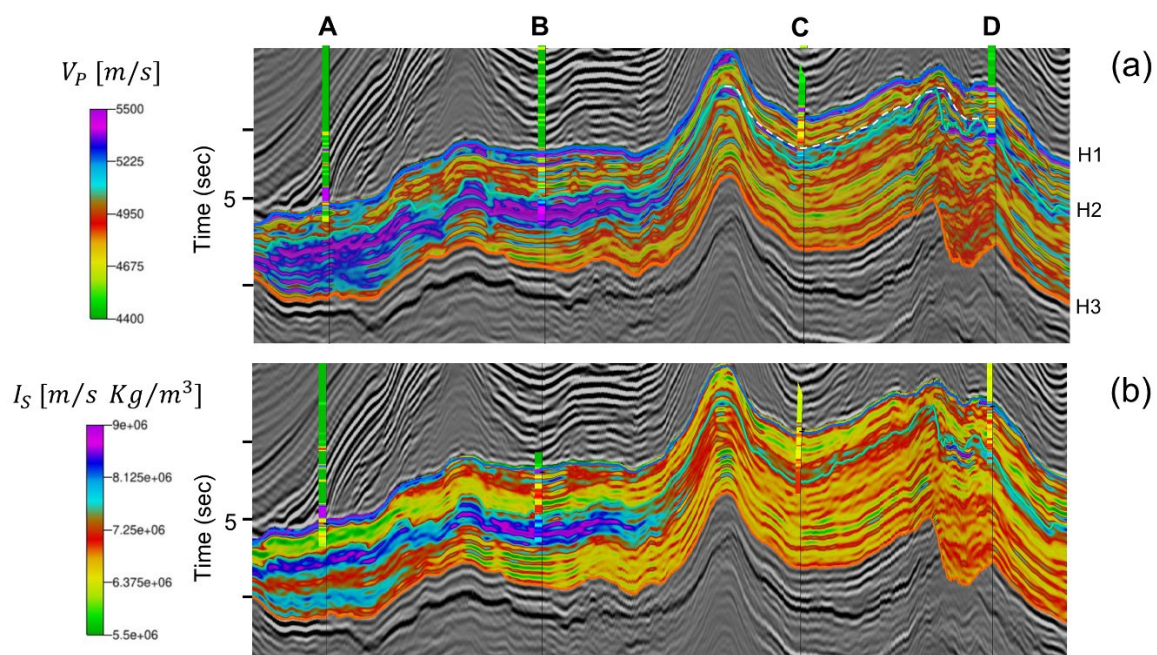


Figure 1 (a) Inverted V_p section (random line) (b) inverted I_s section. The target zone lies between horizon H1 and H2.

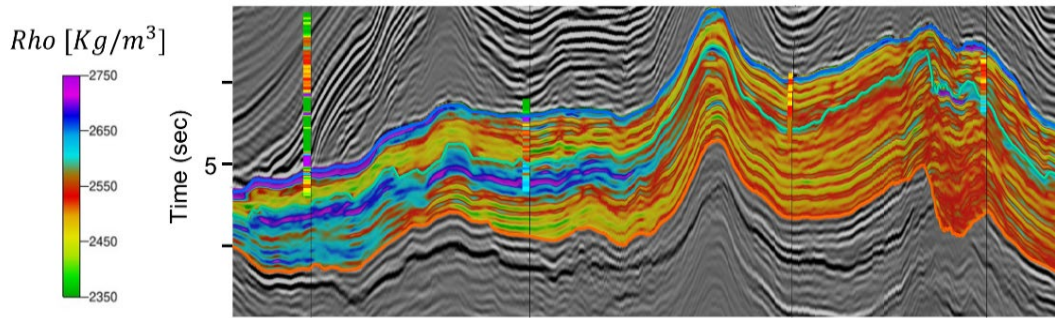


Figure 2 Inverted density section. The target zone lies between horizon H1 and H2.

The quantitative consistency of the inversion can be better assessed by directly comparing the estimated values of the elastic parameters with the values obtained from well B logging, which were filtered in the same frequency bandwidth of the seismic data (Figures 3 c,d and e). It is also possible to observe that the modeled angle gather obtained in the last iteration of the inversion algorithm (figure 3b) is very similar to the closest real angle gather to well B position (figure 3a).

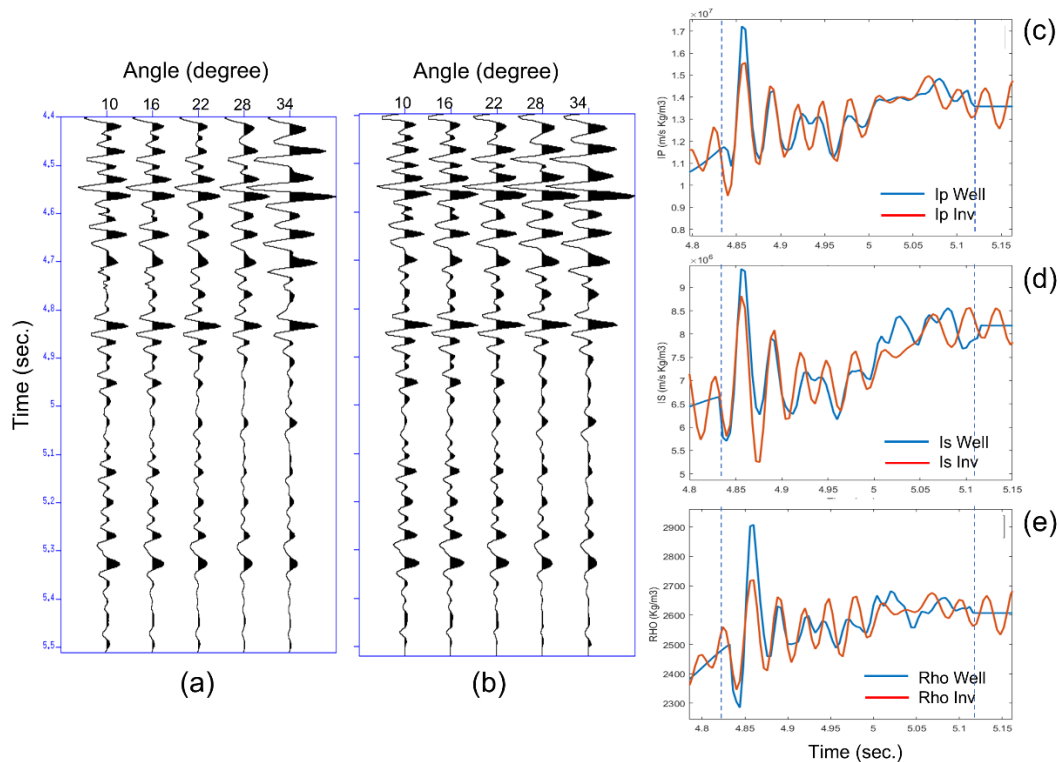


Figure 3 (a) Real angle gather in position of Well B (b) calculated angle gather obtained in the final iteration of the AVA-FWI inversion (c) inverted V_p (red) and V_p from well-log (blue) (d) inverted I_s (red) and I_s from well-log (blue) (e) inverted density (red) and density from well-log. The well log data were filtered to the same bandwidth of seismic. The dashed vertical lines delineate the interval where well log information exists.

Conclusions

The AVA-FWI inversion resulted in elastic parameter sections with good resolution and lateral continuity. The inverted data indicate substantial vertical and spatial variation in reservoir elastic properties over the field area. An interesting fact is that the increased resolution achieved by inversion

allowed for a more precise delineation of the layers. Note that the V_p , I_s and density sections strongly indicates that the H2 horizon, which was originally mapped in the amplitude data, should be repositioned between wells C and D, as shown by the dashed line in Figure 1a.

The inversion managed to arrive at a model of elastic parameters that reproduced the real data with high precision. These parameters also show high correlations with the filtered well data at the same seismic frequency, allowing higher confidence on the inversion results in this area. We draw attention to the good stability, resolution and continuity of the density section. Density inversion represents a challenge for the conventional AVO inversion, as it requires reflection amplitudes with larger angles (far and ultra far) that are difficult to explain using approximate formulas to the Zoeppritz equation.

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