Extracting high resolution images using multiparameter elastic FWI

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Summary

We apply a multiparameter elastic FWI to estimate P-wave velocity and reflectivity in an elastic media. The algorithm used in this work comprises the scale separation of the sensitivity kernels and the elastodynamic wave-equation parameterized in terms of velocity and reflectivity. The aim is to mitigate the crosstalk between velocity and density in the computation of the P-wave velocity and reflectivity. Additionally, this provides an estimate of the relative density. Using a narrow azimuth streamer and a OBN data acquired in deep-water scenarios in offshore Brazil, we demonstrate that to the multiparameter EFWI can simultaneously improve the accuracy of the velocity model and the resolution of the reflectivity from with minimal data pre-processing. We discuss the benefits of inverting both parameters while mitigating the crosstalk between them, enabling the computation of additional attributes that can assist in quantitative interpretation.

Introduction

FWI imaging is an effective alternative to conventional imaging for improving structural interpretation in seismic exploration. The approach consists of performing high-frequency reflection FWI followed by computation of the reflectivity, represented as the derivative of the impedance field, or velocity (with constant density). This approximation improves the resolution and continuity of the reflectivity compared to the conventional model building and imaging workflow (e.g., Wang et al., 2021).

Multiparameter FWI for the joint inversion of velocity and reflectivity was introduced as an alternative for the construction of FWI images (e.g., Yang *et al*., 2021). The aim of this approach is to separate the background velocity and reflectivity effects through a scale separation in the FWI gradients, to minimize the crosstalk of such parameters during the inversion. Another important element of the approach is a wave-equation parameterized in terms of velocity and reflectivity, to overcome the difficulty in the construction of a density model (Whitmore *et al*., 2020). By applying this multiparameter FWI approach, Korsmo *et al*. (2024) computed attributes such as the relative density/impedance that are valuable in quantitative interpretation.

In scenarios with small impedance contrasts, the acoustic approximation made in the joint inversion of velocity and reflectivity appears to be sufficient to obtain reliable velocity and reflectivity images. However, in geological settings with complex overburden comprising large impedance contrasts, such as those produced by the presence of salt, carbonates and /or volcanic rocks, the enhancement of the physics assumed in the FWI approach might improve the estimation of such parameters (e.g., Liu *et al*., 2024). Hence, the multiparameter inversion was extended to an elastic case focusing on inverting P-wave velocity and reflectivity as described in detail in Huang *et al*. (2025)

Here, we discuss the advantages of applying multiparameter elastic FWI approach to OBN and narrow azimuth streamer data in deep-water scenarios both from offshore, Brazil. We show our high-resolution reflectivity inverted using unprocessed data comparing with the conventional workflow, which significantly reduce the turnaround time of VMB projects.

Theory/Methodology

Following the work of Whitmore *et al*. (2020) for the acoustic case, Huang *et al*. (2025) re-formulated the stress particle velocity scheme of the elastodynamic wave equations to use reflectivity as a proxy of density:

$$\frac{\partial \tilde{v}_i}{\partial t} = \frac{\partial \sigma_{ij}}{\partial x_i} \tag{1}$$

$$\frac{\partial \sigma_{ij}}{\partial t} = \tilde{c}_{ijkl}\frac{\partial \tilde{v}_k}{\partial x_l} - \tilde{c}_{ijkl}\left(2r_l^p - \frac{1}{V_p}\frac{\partial V_p}{\partial x_l}\right)\tilde{v}_k \tag{2}$$

where $\tilde{v}_i$ is the weighted particle velocity wavefield (v_i) along the three components, which are functions of space $\boldsymbol{x}$ and time t; σ_{ij} represent the stress tensor with six independent constants, $\tilde{c}_{ijkl}$ is the weighted stiffness tensor c_{ijkl}, which depends only on velocities and Thompsen parameters, V_p is the P-wave velocity and r_l^p is the P-wave vector reflectivity.

As in the acoustic case, the aim is to provide a practical alternative to the necessity of building a density model, for the simulation of the reflectivity contained in the recorded data. In deep-water scenarios with standard streamer survey data only available, this approach plays even a more significant role because of the limited refraction energy recorded for reconstructing the background velocity. The accuracy of the elastodynamic modeling formulation is validated in Macesanu *et al*. (2025). From a synthetic analysis in a complex geological setting, Macesanu *et al*. (2025) show that the elastodynamic modeling using reflectivity, provides a seismic response equivalent to that obtained by solving the conventional elastodynamic equations considering density.

Another important problem to address in the multiparameter inversion is the reduction of the crosstalk between parameters. In the acoustic case, Whitmore and Crawley (2012) and Ramos-Martinez *et al*. (2016) introduced effective approaches to split reflectivity and background velocity, respectively. Following a similar approach based on inverse scattering theory, Huang *et al*. (2025) derived sensitivity kernels for P-wave velocity and reflectivity for the elastic case. This is the key in the application of multiparameter FWI in geological settings where the velocity does not correlate with the density/impedance, as demonstrated in one of the field data examples. The S-wave velocity model is approximated using a relation of Vp and Vs.

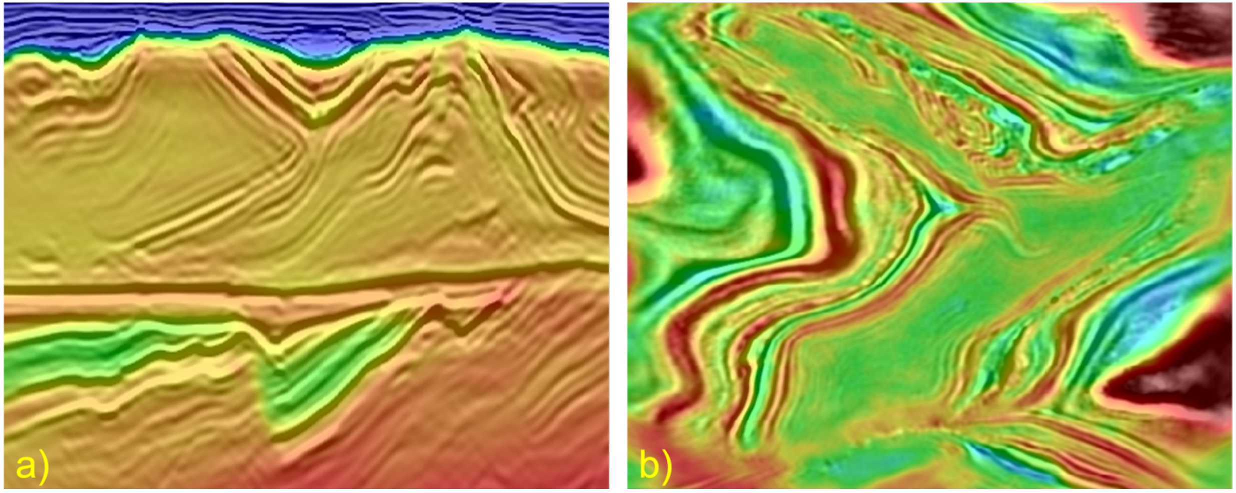

Figure 1. OBN field data example from offshore, Brazil: Inverted velocity field overlaying the reflectivity model for a) crossline and b) depth slice section using the proposed elastic multiparameter inversion. Inverted high resolution velocity model is nicely confirmable to the inverted reflectivity.

Field Data Examples

We show the application of elastic multiparameter FWI to two field datasets corresponding to different deep-water scenarios in offshore Brazil. The first dataset was acquired with OBN technology in the Santos Basin. Data preconditioning consisted in standard acquisition denoising and debubble. Figure 1 shows the inverted P-wave velocity field overlaying the inverted P-wave reflectivity model for one vertical and one depth slice section. The elastic inversion enhances the definition of the salt boundaries and the faults, both shallow and deep, in both the velocity and reflectivity models, with respect to those obtained with the acoustic approximations, as discussed in detail in Huang et al. (2025).

The second dataset we use for the application of this novel approach was acquired with dual-sensor streamer technology in the Sergipe-Alagoas basin. This is also a deep-water scenario with water bottom depths ranging between 1564 to 3140 m. Data was acquired with a narrow azimuth 12-cable configuration separated by 75 m, with a maximum inline offset of 8100 m. As in the OBN data example, we applied minimal preprocessing comprising acquisition denoising and source debubble.

The maximum full power frequency in the inversion is 25 Hz. In Figure 2a and 2b, we show the initial tomographic velocity model and elastically inverted Vp velocity model overlaid on the RTM image and the inverted reflectivity images. We compare the reflectivity images in Figure 2d with those computed from RTM imaging (Figure 2c). It is important to note that in the construction of the RTM images, we use a conventional pre-processing workflow including deghosting, designature and demultiple. As observed, there is a significant uplift in the resolution of the inverted images with respect to the those constructed with conventional RTM. Reflectors below the high-impedance events associated with the presence of volcanic plugs in the basin, show enhanced continuity and resolution for the inverted reflectivity. Figure 3a and 3b compare the depth slice of the conventional RTM image from the initial model and the inverted reflectivity model after the multiparameter elastic FWI, which clearly shows high resolution reflectivity delineates the faults structures and sharpens the boundary of body with high impedance contrast.

Conclusions

We applied a novel multiparameter elastic FWI for estimating P-wave velocity and P-wave reflectivity in elastic media from OBN and streamer NAZ data in deep water scenarios. The workflow comprises the scale separation of FWI gradients to mitigate the crosstalk between velocity and reflectivity, and a reflectivity-based elastodynamic wave equation to tackle the challenge of constructing a density model. We demonstrated the performance of the implementation to improve the velocity model tied to an increase in resolution of the reflectivity image, from data with minimal pre-processing. The approach has the potential to provide valuable information to assist quantitative interpretation.

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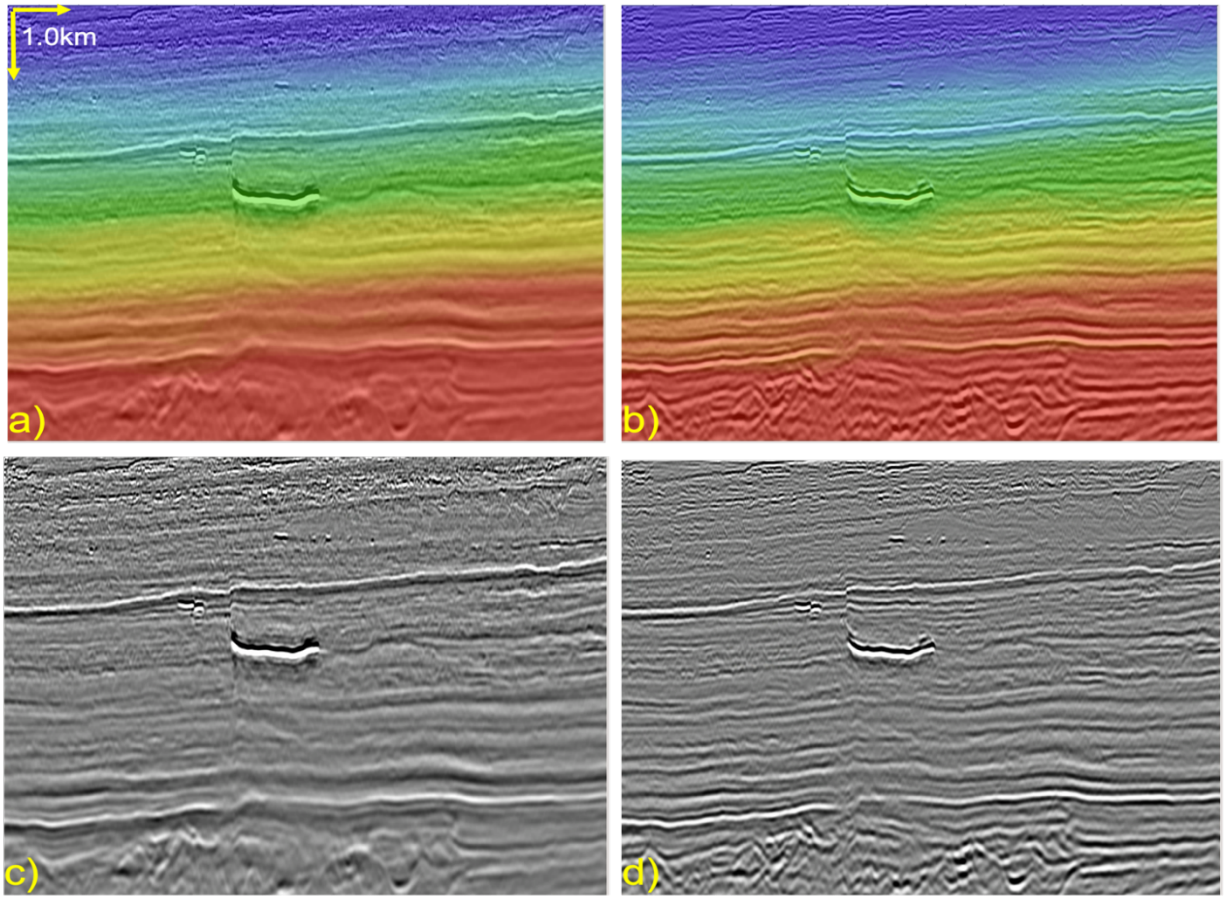

Figure 2: NAZ data from offshore Brazil: a) initial velocity overlaid on the RTM image, b) inverted veloctiy overliad on the inverted reflectivity from the elastic multiparameter inversion; c) RTM image from the initial velocity and (d) inverted reflectivity from the elastic multiparameter inversion.

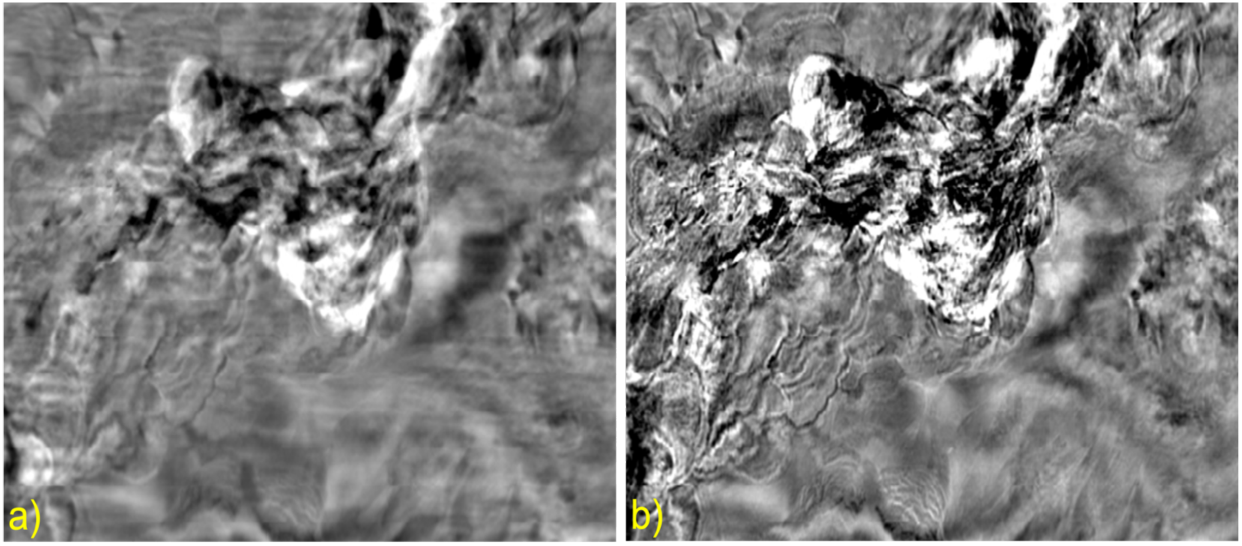

Figure 3: A depth slice of the RTM migration (a) and the inverted reflectivity using the elastic multiparameter inversion (b). High resolution reflectivity enhances the sharper boundary after inversion.