Simultaneous inversion of velocity and pre-stack reflectivity with gathers output

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This paper was prepared for presentation during the 18th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 16-19 October 2023.

Abstract

We introduce a novel method for the simultaneous inversion of velocity and angle-dependent reflectivity. A key aspect of our approach is the extraction of angle information from the solution of the vector-reflectivity-based wave equation. The output of pre-stack angle gathers is crucial for improving our understanding of subsurface and reservoir properties. The resulting velocity model, reflectivity image and pre-stack angle gathers, along with the derived relative density and impedance, provide valuable insights for reliable amplitude-versus-angle (AVA) analysis and quantitative interpretation (QI).

Introduction

Seismic attributes are fundamental tools for hydrocarbon exploration and play a vital role in identifying potential prospects. Seismic inversion has traditionally been the go-to method to obtain earth models, specifically velocity and reflectivity, which are then used to calculate various attributes to aid in interpretation.

We developed a new simultaneous inversion workflow that utilizes a vector reflectivity parameterization of the wave equation (Whitmore et al., 2021) and an efficient scale separation of the FWI gradient using inverse scattering theory (Whitmore and Crawley, 2012; Ramos-Martinez et al., 2016). This approach enables both velocity and earth reflectivity to be estimated iteratively within a single simultaneous inversion framework (Yang et al., 2022). Moreover, the resulting inverted velocity and reflectivity models can be utilized to derive relative impedance and density for prospectivity assessment.

To gain a deeper understanding of subsurface geology, seismic amplitude variation with angle (AVA) analysis can provide valuable information about fluid content, porosity, and lithology of rock formations. However, pre-stack reflectivity computation, which is crucial for AVA analysis, is not straightforward using conventional Full Waveform Inversion (FWI) solutions.

Our work extends Yang et al.'s (2022) simultaneous inversion workflow, which updates velocity and stacked 3D reflectivity, by incorporating an additional output of angle-azimuth dependent pre-stack reflectivity. Our method utilizes the geometric information extracted from the dot product between the vector reflectivity and the gradient of the pressure wavefield in the corresponding wave equation. This enables the calculation of the angle between the incident wavefield and the vector reflectivity, which is used to construct pre-stack angle gathers. Our simultaneous inversion process continuously updates the velocity model and angle gathers to improve resolution, while also compensating for incomplete acquisitions and varying illumination.

Method

We start from the acoustic wave equation parameterized in terms of velocity and vector reflectivity (Whitmore et al., 2021),

$$\frac{1}{V(\boldsymbol{x})^2}\frac{\partial^2 P(\boldsymbol{x},t)}{\partial t^2} - \nabla^2 P(\boldsymbol{x},t) - \frac{\nabla V(\boldsymbol{x})}{V(\boldsymbol{x})}\cdot \nabla P(\boldsymbol{x},t) + 2\boldsymbol{R}(\boldsymbol{x})\cdot \nabla P(\boldsymbol{x},t) = S(\boldsymbol{x},t)$$

Where P is the pressure wavefield, V is the velocity,

$$\boldsymbol{R}(\boldsymbol{x}) = \frac{1}{2}\frac{\nabla Z(\boldsymbol{x})}{Z(\boldsymbol{x})}$$

is the vector reflectivity in which Z is the acoustic impedance and S is the source term. With this representation, velocity and reflectivity are directly set as model parameters, eliminating the need to construct a density model. This parameterization, combined with sensitivity kernels for velocity and impedance obtained through inverse scattering theory (Whitmore and Crawley, 2012; Ramos-Martinez et al., 2016), forms the foundation for the simultaneous inversion of velocity and stacked reflectivity (Yang et al., 2022).

To construct angle gathers, it is necessary to compute the incident and reflection angles (or reflector dip direction) at each image point. The vector reflectivity wave equation (equation 1) offers a fundamental feature that allows for the calculation of these angles. Specifically, the gradient of the forward propagation wavefield provides the direction of the incident wavefield, while the vector reflectivity provides information about the reflector. As a result, we can naturally extract the reflection angle required for constructing pre-stack angle gathers as follows:

$$\theta = \arccos\left(\frac{\boldsymbol{R}\cdot\nabla P}{\|\boldsymbol{R}\|\cdot\|\nabla P\|}\right)$$

Figure 1 provides an illustration of the geometric definition of these elements and their relationship with the reflection angle and azimuth maps. Once this information is obtained, the generation of angle gathers from a shot image follows a process similar to that used in reverse time migration.

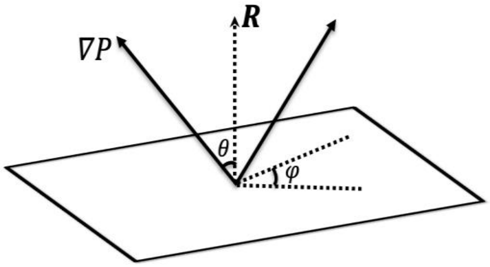

Figure 1 *Geometric relation between reflection angle, vector reflectivity and the gradient of the pressure field.*

The wave equation parameterized in terms of vector reflectivity and velocity (equation 1) and its adjoint are utilized for both forward and backward propagation, respectively. During the modeling process, the reflectivity extracted from current angle gathers based on the corresponding angle map is incorporated. At each iteration, the angle gathers are updated using the mapped shot images. Additionally, the solution can also output angle-azimuth gathers by incorporating azimuth maps, which allows for further characterization of subsurface structures with azimuth.

Examples

We demonstrate the effectiveness of our workflow using field data acquired in the Salar Basin in southeast Newfound and Labrador, Canada. The field survey was acquired in 2020 using multisensor streamer technology. It consisted of 16 cables with 100-m streamer separation and an 8.1 km streamer length. Many fan systems have been identified along the margin using existing seismic data. They are interpreted as Oligocene in age, and the main prospectivity is believed to lie in these fans originating from the shelf and shelf edge deltas. Class II anomalies are observed in the reservoir interval, along with class IV responses in the deeper section analogous to a modeled source rock in the region. The average water column depth is more than 3 km in this area. The objective of this study was to build a more-detailed higher-resolution velocity model and to better define the target fan system. We aim to refine the velocity over the lead as well as provide reliable pre-stack angle-dependent reflectivity for further interpretation analysis. Achieving these objectives would aid in de-risking exploration in this basin.

Results

The maximum frequency used for the inversion is 40 Hz and the initial velocity model (Figure 2a and 2c) is a smooth version of a tomographic velocity model. After simultaneous inversion the background model is further repaired and the resolution is greatly enhanced (Figures 2b and 2d). Figure 2f shows the final reflectivity, which is equivalent to performing a non-linear least-squares RTM. The angle gathers are shown in Figure 2e, they are directly generated and updated at each iteration using the updated velocity and reflectivity fields, without requiring additional migrations. The updated velocity model results in improved coherency of the reflectors below the Cretaceous, which is supported by the quality of the pre-stack image gathers. The inverted angle gathers exhibit good flatness and balanced illumination.

The inversion of velocity and reflectivity models also enabled the derivation of additional properties, such as relative impedance and density (Yang et al., 2022). Depth slices at the target reservoir level (Figure 3) for a 25 Hz inversion demonstrated detailed and structurally conforming velocity updates (Figure 3c). The relative density derived from velocity and reflectivity (Figure 3d) exhibited a strong correlation with other earth properties. Notably, the prospect zone displayed a velocity and density decrease.

Conclusions

We presented a novel extension to our simultaneous velocity and reflectivity inversion, aimed at producing angle gathers as output. The advancement greatly improves our understanding of subsurface properties and enables more comprehensive reservoir analysis. Our approach leverages the solution of the wave equation, which is parameterized in terms of velocity and vector reflectivity, to extract valuable angle information. Through an iterative inversion workflow, we simultaneously update both the velocity model and the angle-dependent reflectivity.

We validated our workflow on a field dataset from offshore Newfoundland and Labrador, Canada. Our results demonstrate the effectiveness of our approach in updating the background velocity model and generating accurate estimates of angle-dependent reflectivity. The final models comprise inverted velocity and reflectivity models, as well as derived relative impedance and density maps. Additionally, the new inversion process produces pre-stack angle gathers, which serve as reliable inputs for subsequent QI and AVA (Amplitude analysis.

Acknowledgments

The authors would like to thank PGS for granting permission to publish this paper and providing the data used in this study through PGS multiclient. We also thank the Oil and Gas Corporation of Newfoundland and Labrador (OilCo) for their valuable support.

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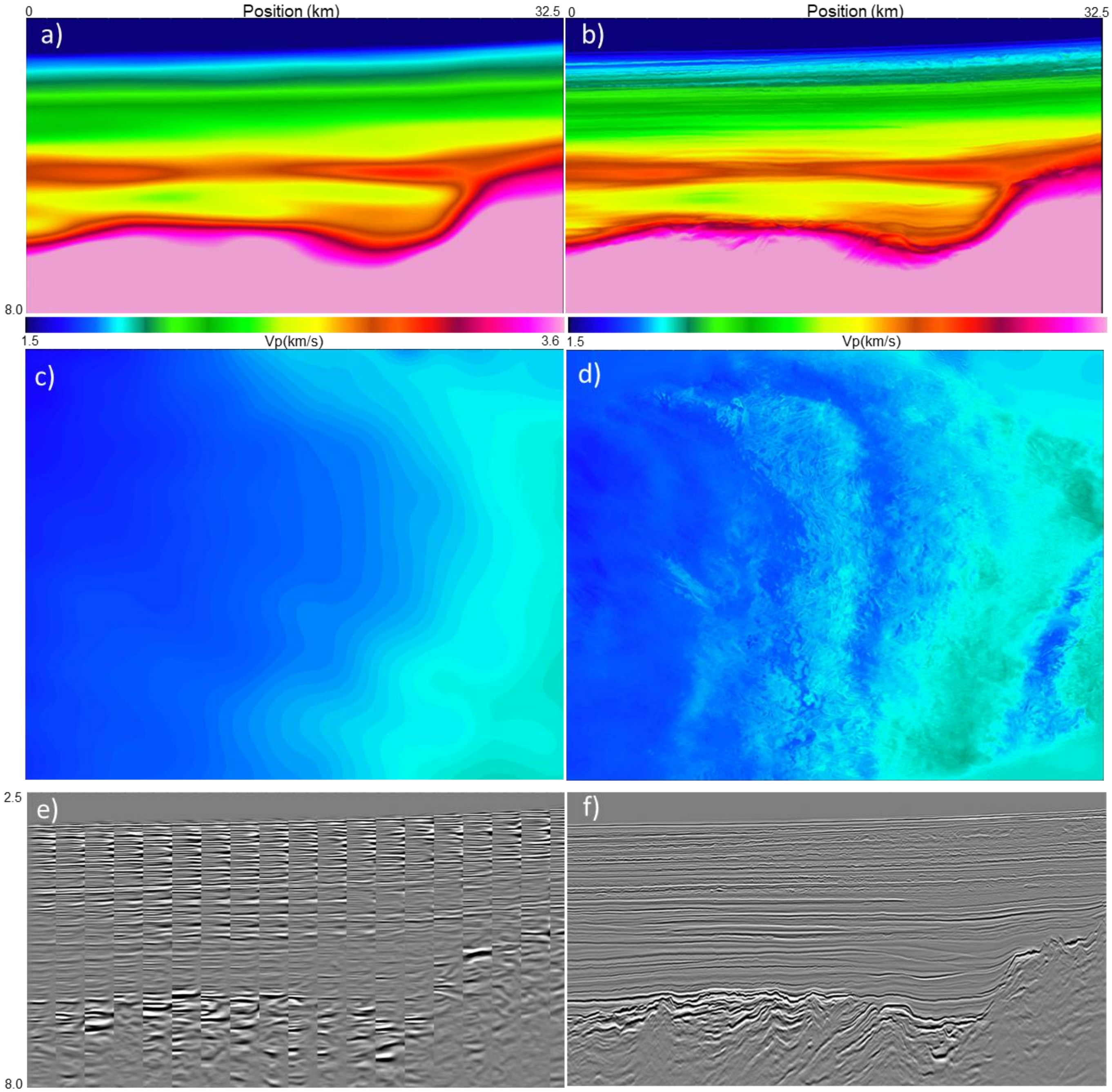

Figure 2: (a) Starting velocity inline section (b) inverted velocity inline section; (c) depth slice from the initial model at 3.4 km (d) depth slice from the inverted velocity model at 3.4 km. (e) Inverted angle gathers and (f) stacked reflectivity.

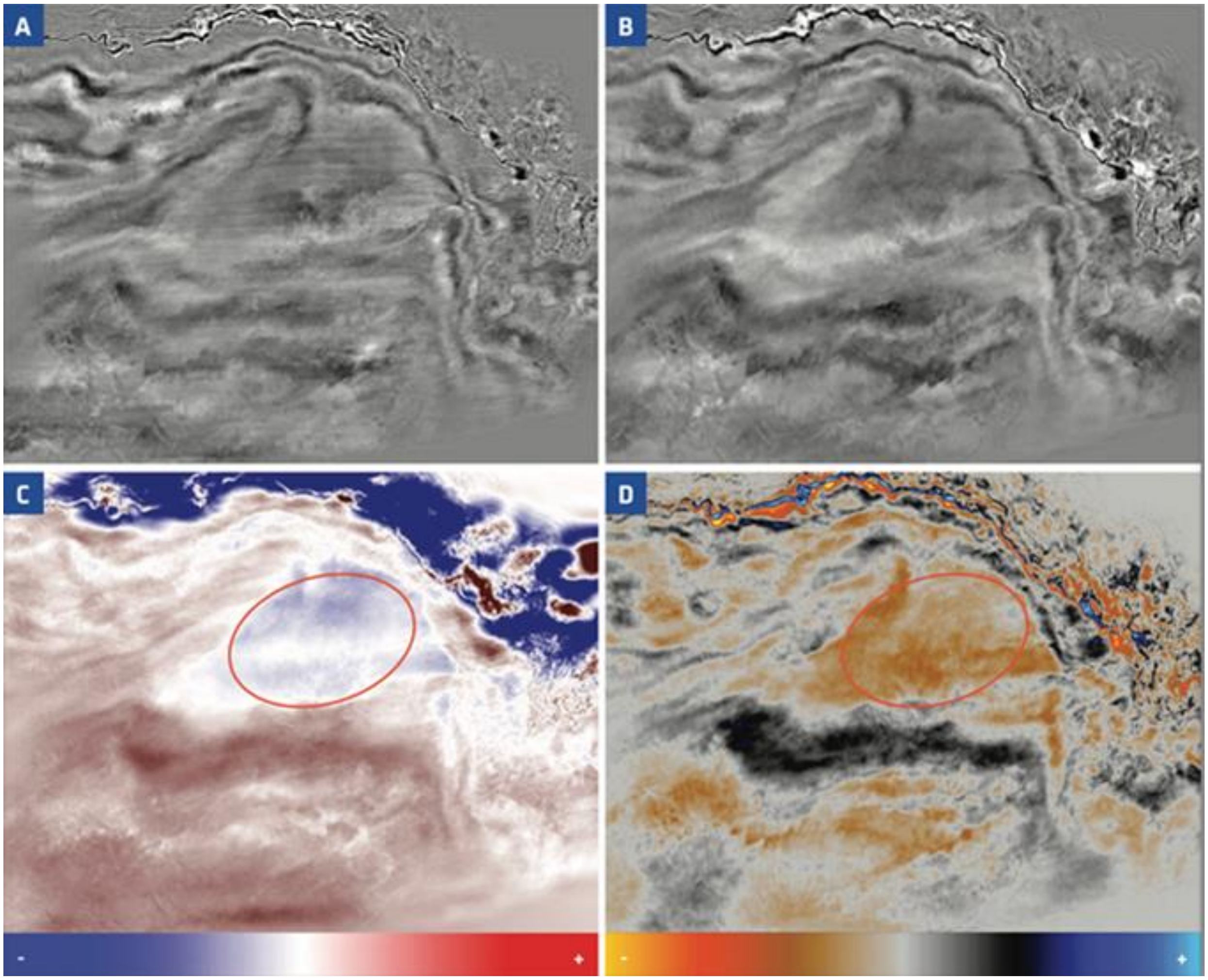

Figure 3: Depth slice extraction at the target fan system level for (a) initial reflectivity, (b) final inverted reflectivity, (c) velocity updates and (d) derived relative density.