Simultaneous inversion of velocity and reflectivity for enhanced seismic imaging

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Summary

The accuracy of velocity model and the amplitude reliability of an image are extremely important for a successful exploration project. By using a simultaneous inversion workflow based on a vector reflectivity modeling procedure, both velocity and earth reflectivity can be estimated iteratively in a single framework. The approach is equivalent to performing Full Waveform Inversion (FWI) and Least-Squares Reverse Time Migration (LS-RTM), which provides high fidelity velocity and reflectivity models for quantitative interpretation (QI). A key aspect of simultaneous inversion is the separation of the low- and high-wavenumber components of the gradient based on inverse scattering theory, enabling the sensitivity kernels to update the corresponding velocity and reflectivity with minimum crosstalk. The output of the inversion is a well resolved velocity model together with an accurate estimate of the earth reflectivity with compensation for incomplete acquisition, poor illumination, and multiple crosstalk. We demonstrate how simultaneous inversion can deliver better velocity and reflectivity model for interpretation using 3D seismic data from the Orphan Basin, offshore Newfoundland and Labrador, Canada. Also, we show how additional properties such as relative density can be estimated directly from the inverted models.

Introduction

Accurate velocity and reflectivity models are essential for high fidelity seismic interpretation. Full Waveform Inversion (FWI) followed by Least-Squares Reverse Time Migration (LS-RTM) is currently the high-end technique to invert for high resolution velocity and reflectivity models. However, in this sequential workflow, velocity and reflectivity are inverted separately and the leakage between the two parameters are unavoidable. Recently, using a simultaneous inversion scheme introduced by Yang et al. (2021), FWI and LS-RTM can be implemented in a single framework. Velocity and reflectivity are updated simultaneously using their corresponding kernels based on inverse scattering theory, which minimizes crosstalk between the two parameters resulting in more accurate velocity and reflectivity models for interpretation.

In this study, we demonstrate how simultaneous inversion provides high-resolution velocity and reflectivity models from simple tomography model using a challenging frontier area data from the Orphan Basin, offshore Newfoundland and Labrador, Canada. With more accurate inverted models, more insights on prospectivity can be acquired which is beyond the capabilities of conventional processing.

Simultaneous Inversion

FWI and data domain LS-RTM share a similar framework, both aiming to minimize the misfit between modelled and recorded data. Accordingly, it's possible to solve both problems in a compact framework. With acoustic wave equation parameterized in terms of velocity and vector reflectivity (Whitmore et al., 2020) and a robust inverse scattering image condition to separate velocity and reflectivity models (Ramos-Martinez et al., 2016; Whitmore and Crawley, 2012), FWI and LS-RTM can be implemented in a joint scheme. The inversion scheme updates both velocity and reflectivity simultaneously at each iteration as summarized in the inversion workflow shown in Figure 1. A starting velocity model is required for the inversion while an initial reflectivity is computed during the first iteration as an RTM image. The modelling procedure in simultaneous inversion can generate the full acoustic wavefield, including refracted and reflected energy as well as free-surface and internal multiples. Thus, it has the potential to reduce turnround time of a project as minimal pre-processing data could be used as the input and the modeling engine will produce the corresponding events.

Geological Setting and Data Description

The study area for illustrating the benefits of the inversion method is in the Orphan Basin, offshore Newfoundland and Labrador, Canada (Figure 2). Tectonic history indicates that the basin has experienced 2 phases of rifting throughout the Jurassic and Cretaceous periods associated with the opening of the North Atlantic Ocean followed by fairly quiescent deposition within a passive margin setting throughout the Late Cretaceous and Cenozoic where basin architecture is dominated by thermal subsidence. As a result of the depositional and tectonic history, several key play types have been identified within the region ranging from predominantly structurally bound shore face plays in the Mid-Late Jurassic through to turbidites and fan complexes throughout the Cenozoic. The study area Blomidon 3D, located on the present-day shelf to deep water transition shows prospectivity throughout the sedimentary column. Throughout the study area, the Cenozoic section is anomalously thick and characterized by thick marine shale units as well as a large-scale Oligocene aged fan complex, named the Jeffries prospect. These large-scale fans rim the South and West margins of the Orphan Basin and have

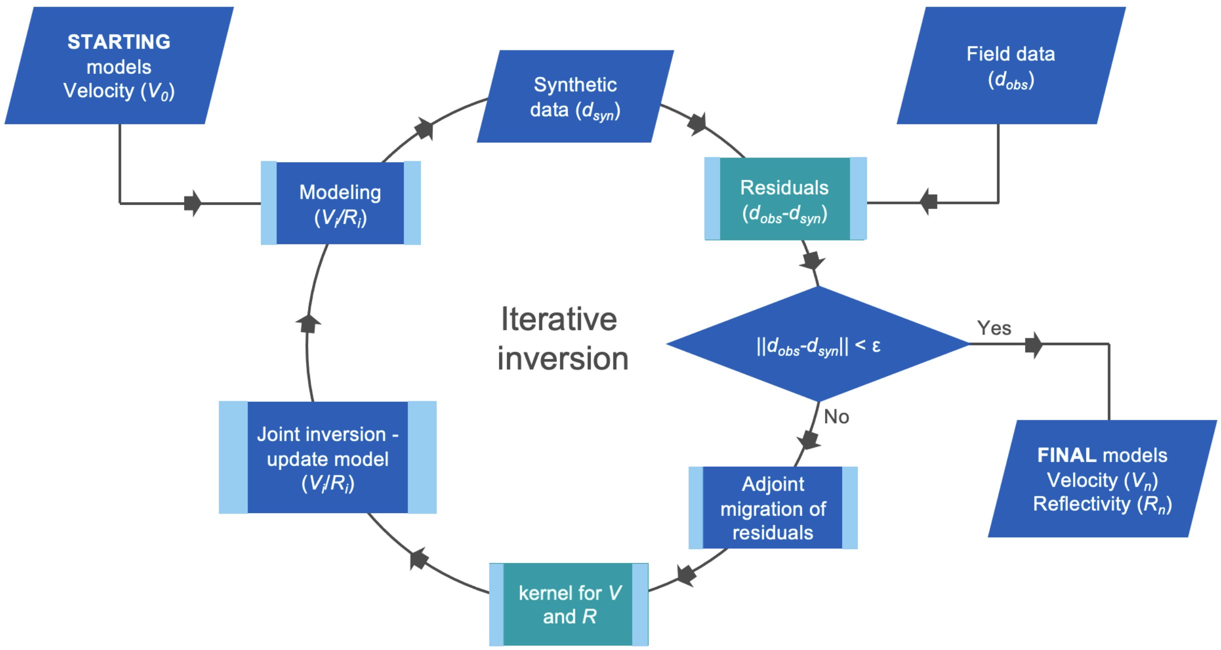

Figure 1: Simultaneous full waveform inversion workflow for velocity and reflectivity.

sparked recent exploration interest in the region due to their size and insights from advanced geophysical interpretation.

The contributing 3D survey for this study was acquired in 2020 using multi-sensor technology. This narrow azimuth (NAZ) data was acquired using 16 cables, 100 m streamer separation and 8 km streamer length. An inaccurate initial velocity model was used as a starting point for the inversion. The objective of this study was to build a reliable velocity model and to improve imaging of the Tertiary (~1 km – ~6 km) and Jurassic sections (> ~6 km) (see Figure 3). A shallow water column (~300 m) with a strong water bottom reflectivity produces strong short period multiples in the area of interest.

Of particular interest for this study are large scale fan systems identified directly below the present-day shelf and shelf break in shallow water. This juxtaposition of prospectivity and imaging challenges related to multiple suppression create a situation in which Class II/IIp anomalies are not confidently interpretable. The large-scale fan systems line the shelf margin off the NE Coast of Newfoundland, several of which have sparked exploration interest in this new play fairway for the region. The uplift from simultaneous inversion progresses the understanding of these leads and prospects.

Results

The initial velocity model for the inversion was a time velocity model converted to depth. Background velocity is not well resolved in the shelf due to multiple contamination in the model building phase. Figure 3a shows the reflectivity from the first iteration of the inversion, which is equivalent

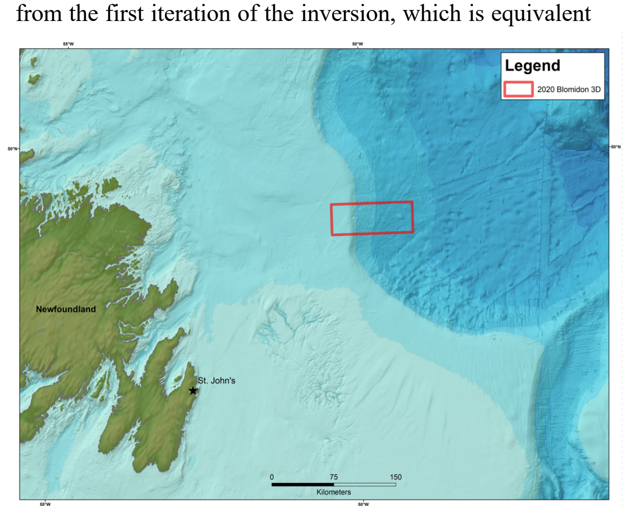

Figure 2: Location of of the Blomidon 3D survey in the area of study. Data acquired with multi-sensor technology corresponnding to this survey are used in this work.

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to performing RTM with the initial model. In this image, note the key areas in Tertiary and rift sections that are not well imaged.

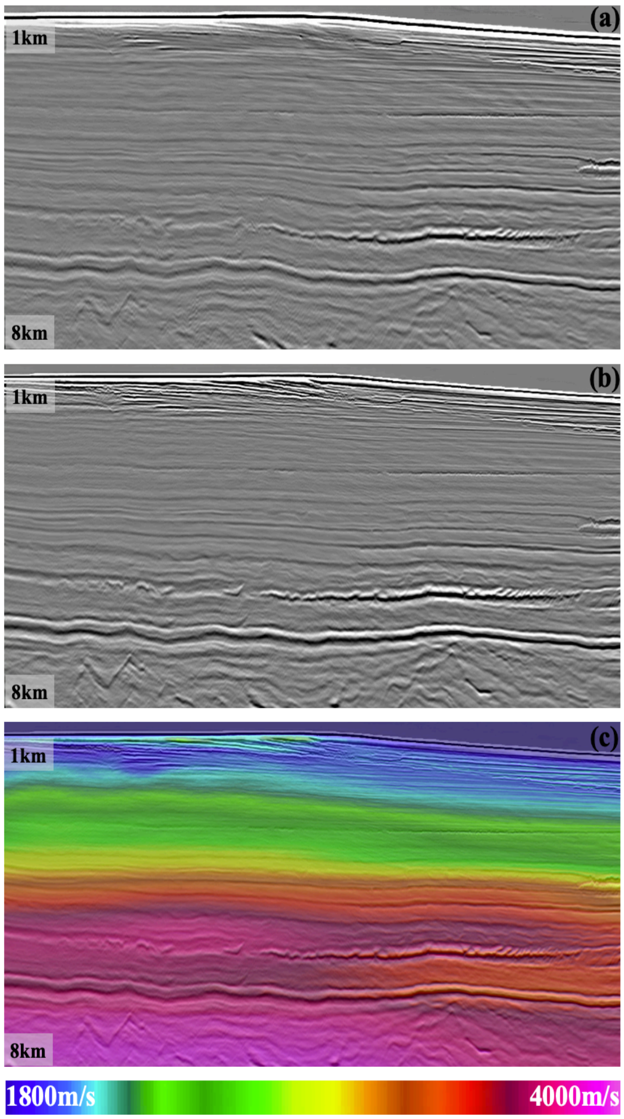

Figure 3: Orphan Basin field data example (a) The initial and (b) the final inverted reflectivity. (c) Inverted velocity model. Significant imaging improvements can be observed after inversion.

The results from the simultaneous inversion are shown in Figures 3b and 3c. The inverted velocity model shows significant improvement with details in the shallow section driven by diving waves and a geologically consistent velocity model in the deeper sections achieved using reflection data. The inverted reflectivity shows uplift in imaging allowing for a better interpretation of the key lead (top arrow) and consequently a better understanding of the petroleum system. Obtaining reflectivity directly from the simultaneous inversion in a data-driven approach and has the potential to significantly reduce turnaround time for imaging and potentially for subsequent exploration activities.

Figure 4a and 4b display a depth slice of the initial model and the inverted velocity model from simultaneous inversion. Enhanced resolution of the inverted velocity model better constrains depth structures throughout the study area, which is of particular importance in the shelf to slope transition. Velocity updates correct for structure misplacements between the initial and inverted reflectivity in the order of 200-300m in some areas. Likewise, velocity updates change dip orientations on specific leads. In addition, the shallow velocity resolution improves the illumination problems observed deeper in the images obtained with the initial model. By combining the high-resolution velocity and the improved reflectivity models from the inversion, we are able to confirm the presence and enhance the mappability of anomalies in this shallow water scenario. These anomalies are critical to understand from a prospectivity, shallow hazard and DHI perspective.

Figure 4c shows an estimate of relative density on a depth slice derived directly from the inverted velocity and reflectivity. The relative density estimate is structurally consistent and can be potentially used for prospectivity analysis. The inversion outputs, in addition to individual lead evaluation, also give a better geologic understanding via enhanced imaging and property constraints throughout the entire seismic section. Overall, the direct outputs of velocity and density produce constrained layer-based properties for quantitative interpretations while the reflectivity outputs are of significant interest as the product works to solve illumination issues created by traditional pre-processing of datasets and more accurately reflect true amplitudes within the datasets.

Conclusions

An iterative inversion method to simultaneously estimate velocity and earth reflectivity was successfully applied to a field dataset from offshore Newfoundland and Labrador, Canada. Results show that while the background velocity model is iteratively updated, a more accurate estimate of the earth reflectivity is simultaneously generated. The resulting images contain higher amplitude fidelity and higher signal-to-noise ratio. The inverted models can be used to calculate additional properties such as relative density, which is useful for improving prospectivity analysis.

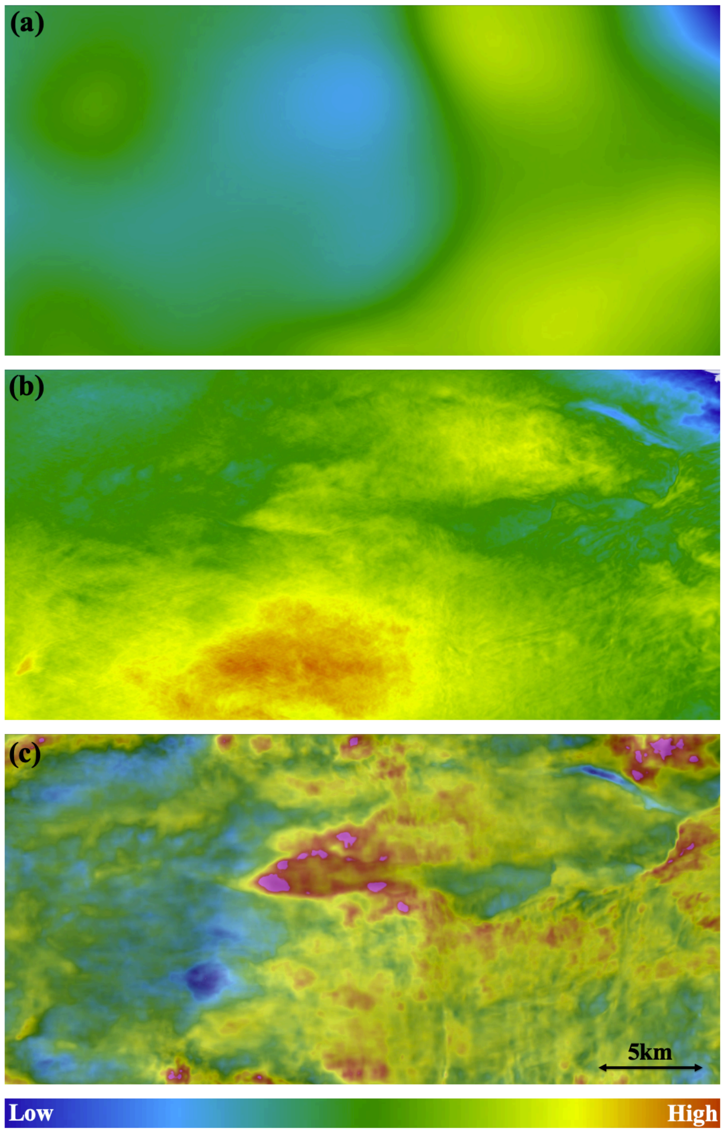

Figure 4: (a) Initial tomography velocity model. (b) Inverted velocity model from simultaneous inversion. (c) Relative density estimated from inverted velocity and reflectivity.

Simultaneous inversion products, i.e., velocity, reflectivity and the derived relative density, in addition to improve individual lead evaluation, also provide better property constraints for QI and shallow anomaly interpretation. To this point, the technology assists in derisking this challenging dataset and produces markedly different but more trustable results compared to conventional processing techniques.

The current implementation of the simultaneous inversion is based on stacked vector reflectivity. A worthwhile future development is to extend the inversion to generate angle gathers, which can provide more properties to help quantitative interpretation of potential hydrocarbon prospects.

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REFERENCES

Ramos-Martinez, J., S. Crawley, K. Zou, A. A. Valenciano, L. Qiu, and N. Chemingui, 2016, A robust gradient for long wavelength FWI updates: 78th Annual International Conference and Exhibition, EAGE, Extended Abstracts.

Whitmore, N. D., J. Ramos-Martinez, Y. Yang, and A. A. Valenciano, 2020, Full wave field modeling with vector- reflectivity: 82nd Annual International Conference and Exhibition, EAGE, Extended Abstracts, 1–5.

Whitmore, N. D., and S. Crawley, 2012, Application of RTM inverse scattering imaging conditions: 82nd Annual International Meeting, SEG, Expanded Abstracts, doi: https://doi.org/10.1190/segam2012-0779.1.

Yang, Y., J. Ramos-Martinez, N. D. Whitmore, G. Huang, and N. Chemingui, 2021, Simultaneous inversion of velocity and reflectivity: First International Meeting for Applied Geoscience & Energy, SEG/AAPG, Expanded Abstracts, doi: https://doi.org/10.1190/segam2021-3594405.1.

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