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Full waveform inversion derived subsurface angle gathers

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Summary

Classical AVO/AVA analysis/inversion based on the elastic Zoeppritz equation is used to derive rock/fluid properties from pre-stack migration image gathers. To improve the quality of the common image gathers, we propose to use full-waveform inversion (FWI) derived subsurface angle gathers as a substitution for the pre-stack migration image gathers for extracting AVA/AVO parameters. By taking advantage of the inversion-based process of the full wavefield forward modeling in FWI, the FWI subsurface angle gather can provide higher amplitude fidelity for AVO analysis than conventional migration methods.

Introduction

Full-waveform inversion (FWI) has become an essential tool for velocity model building using seismic data. Recently, FWI derived reflectivity has been extracted by calculating a dierctional derivative of the FWI inverted model. It carries additional structural information compared to the conventional imaging products. The classical imaging techniques use primary events, whereas FWI intends to use the raw full-wavefield data without significant data pre-processing, as the different wave modes can be simulated with a proper forward modeling engine for any acquisition geometry. The reflectivity extracted from the FWI updated velocity model has become an important addition to the FWI deliverables and has proven to be valuable for better structural interpretation than conventional imaging methods (Bai et. al., 2022). However, to extract AVA/AVO information from FWI, we need to produce pre-stack reflectivity gathers rather than the post-stack only reflectivity within the iterative framework of FWI. Here we demonstrate a method for achieving this goal and further improving the extracted attributes from the FWI outputs. First, we use a conventional FWI workflow to minimize the kinematic differences between the observed and modeled data using all the available offsets. Then with a reasonably kinematically accurate velocity model, we further improve the amplitude fidelity by going to higher frequencies in FWI and output the pre-stack subsurface angle gather of pseudo reflectivity.

Method

In this work, we employed the enhanced template-matching (ETM) objective function that minimizes both dynamic and kinematic errors by matching the predicted data to the observed data in a time and space window (Cheng, et al., 2023). The ETM objective function has proven to be less sensitive to cycle-skipping while retaining the ability to resolve large velocity errors, such as reshaping complex salt geometries.

Using a conventional multiscale FWI flow, we can invert for a reasonably kinematically accurate velocity model with the travel time information used from the full-offset data. We can then derive the pre-stack FWI gathers based on this model. The prestack FWI surface offset gathers (Mao et. al., 2024) can be obtained by splitting the data to offset bins. To get prestack FWI gathers more efficiently, we form the subsurface angle dependent gradient during FWI. Then we update impedances for each angle with the dynamic information of the data, such that we have angle-dependent impedances. The angle dependent reflectivity can be calculated by the directional derivative of angle dependent impedances. Using the pre-stack FWI pseudo-reflectivity gathers, we can then perform AVA/AVO analysis.

Results

The field-data example is from the Gulf of Mexico which contains massive complex shallow and deep structurally connected salt bodies. The sparse OBN acquisition was designed for FWI application to update the complex salt geometry. The nominal node separation is 1.2 km and the source spacing is 50 m by 100 m. A minimum 40-km offset for each node location was acquired to capture diving waves down to the original Louann salt level. Using the low-frequency ultra long-offset data, we are able to invert a velocity with much more accurate salt geometry than the legacy model. We observed large subsalt structural changes with a clearly defined deep salt feeder and salt-ascension zones surrounding encapsulated mini basins in between. Based on this kinematically accurate FWI model, we applied our flow to generate FWI pre-stack pseudo reflectivity gathers for each subsurface angles (figure 1b). We also compared with RTM subsurface angle gathers (figure 1a). From the comparison, we can see the FWI angle gathers have more reliable amplitude behaviour which is verified by well information.

Conclusions

We proposed a method to produce pre-stack pseudo-reflectivity gathers in subsurface angle domain that can be used for AVA/AVO analysis directly from FWI. The robust amplitude fidelity in the FWI-derived pre-stack gathers helps in a better understanding of the rock-physics properties at the reservoir level than the conventional migration-derived pre-stack gathers.

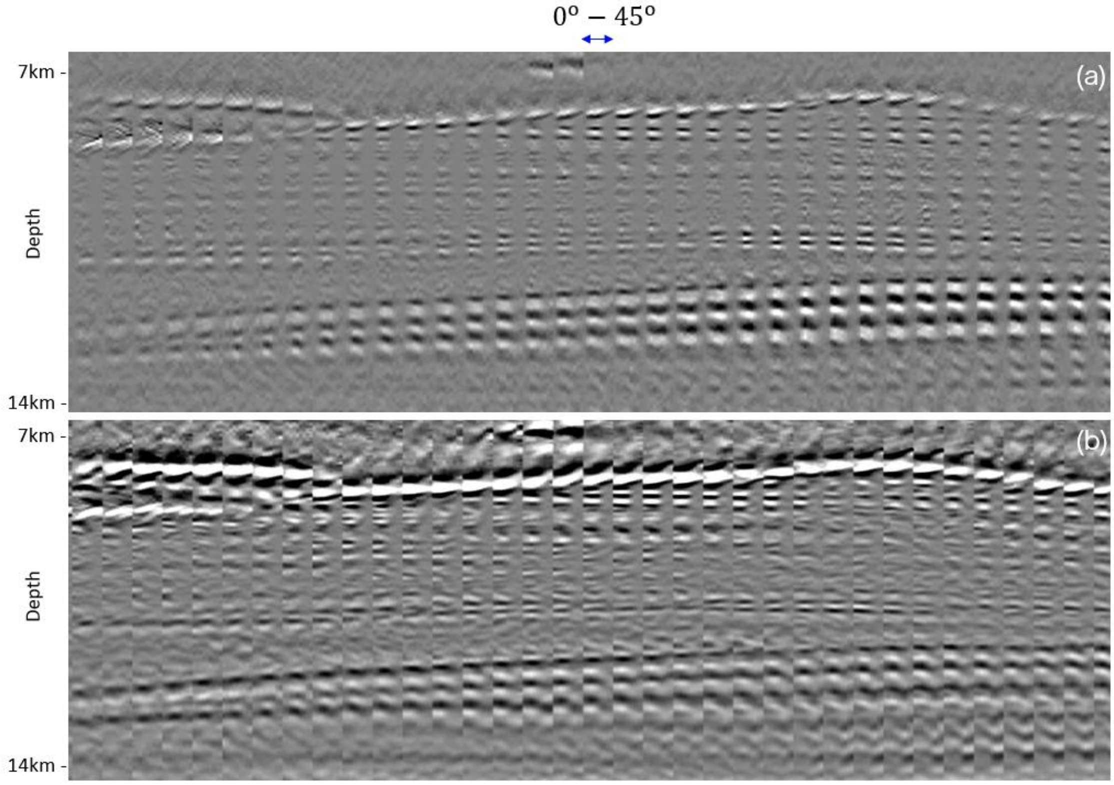

Figure1 (a) RTM subsurface angle gather; (b) FWI subsurface angle gather

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