

Unlocking rock properties using elastic multi-parameter FWI

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Summary

Conventional imaging methods like reverse-time migration (RTM) impose assumptions, such as the Born approximation, that introduce strict data pre-processing requirements reducing its effectiveness in regions with complex geology. Multi-parameter full-waveform inversion (MP-FWI) offers an alternative approach enabling the simultaneous estimation of many subsurface properties (e.g., V_p and reflectivity) directly from raw seismic data. MP-FWI is a least-squares solution that utilizes the full wavefield, treating multiples as valuable signals to improve resolution and illumination compensation. In recent years, MP-FWI approaches have assumed acoustic wave propagation to generate robust angle-dependent reflectivity for elastic AVA analysis, which enables P-impedance and V_s/V_p ratio estimation via an additional inversion step. Elastic MP-FWI offers the potential to skip this additional inversion step and determine these AVA properties directly from the acquired data. In this paper, two case studies are presented, from the Australian North West Shelf and the Gulf of America, that demonstrate the fidelity of elastic MP-FWI to deriving AVA attributes. The accuracy of these inverted models is evaluated against the conventional workflow and well data.

Introduction

The increasing geological complexity in which hydrocarbons are identified has driven the development of imaging technologies to produce high-resolution amplitude-versus-angle (AVA) models to reduce exploration and production risk. Conventional workflows to derive such models have relied on imaging methods such as reverse-time migration (RTM) or Kirchhoff depth migration (KDM), both of which impose assumptions like the single-scattering Born approximation. These methods can produce pre-stack image gathers or angle stacks that are used in a secondary inversion step to determine elastic attributes like P-impedance and V_s/V_p ratio (Aki and Richards, 2002). While the least-squares imaging extensions of such techniques (Nemeth et al., 1999; Guitton, 2017) enhance the amplitude fidelity and improve subsurface illumination compensation, their assumptions still ultimately limit their resolution and amplitude fidelity in regions with high impedance contrasts or complex geology.

Furthermore, conventional workflows to derive such AVA models often involve many subjective, time-intensive data pre-processing steps to remove components of the recorded wavefield that do not agree with the assumptions imposed by the conventional imaging algorithms, such as multiples.

Full-waveform inversion (FWI) (Tarantola, 1984) has historically been used to invert for V_p using only diving waves but has since evolved to a multi-parameter (MP-FWI) approach (McLeman et al., 2023) that incorporates reflections and simultaneously determines additional subsurface properties (such as anisotropy and Q) directly from raw seismic data. Unlike the conventional approach, MP-FWI treats multiples as valuable information that can improve illumination and resolution. Although industrial scale MP-FWI applications have traditionally relied on the acoustic-wave assumption, it can generate robust angle-dependent reflectivity for AVA analysis to determine elastic properties such as P-impedance and V_s/V_p ratio via a secondary, conventional AVA inversion step (McLeman et al., 2023; Warner et al., 2022).

With advances in high-performance computing, high-frequency 3D elastic MP-FWI (Gomes et al., 2024; Wang et al., 2021) has become feasible, enabling the estimation of quantities like P-impedance and V_s/V_p ratio from raw (or minimally processed) field data without requiring the secondary AVA inversion step which avoids the need to generate reflectivity with angle. Elastic MP-FWI offers the opportunity to simultaneously resolve not only the subsurface structural features but also accurate AVA-amplitude information while avoiding the need for extensive data pre-processing workflows.

In this paper, we present two case studies that evaluate the fidelity of high-frequency elastic MP-FWI-derived AVA attributes. The first extends the work of McLeman et al. (2023) using a towed-streamer seismic dataset from the Australian North West Shelf. The second case study considers an OBN dataset from the Gulf of America. The results are compared with well-log data and evaluated against the conventional workflow approach.

Case study 1: Australian North West Shelf

The survey in this case study was acquired in 2006 on the Australian North West Shelf, approximately 115 km northwest of Barrow Island. This region contains rapidly changing shallow velocity variations due to localized channel features and carbonates. The acquisition setup consists of a dual-source marine towed-streamer with 8 cables and a maximum offset of 6 km.

The initial V_p model was a smoothed existing legacy model that was refined with diving wave only FWI in frequency steps up to a maximum frequency of 19 Hz. The relatively short maximum offset available, however, restricted the update depth using the diving waves to approximately 2 km.

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Well data located within the survey area and regional knowledge were used to build the initial low-frequency Vs/Vp, density, and anisotropy models.

These initial models were input to an elastic MP-FWI update of Vp and P-impedance at 11 Hz, 14 Hz, and 19 Hz (maximum frequency), using reflections. The anisotropy was then updated at 19 Hz, and the P-impedance was further refined using a single parameter FWI where only the near reflection angles were considered. Elastic MP-FWI was then used to simultaneously invert for Vp, Vs/Vp ratio, and P-impedance using all reflection angles with the frequency steps of 19 Hz, 25 Hz, 34 Hz, and finally 46 Hz. The least-squares objective function was used during elastic MP-FWI. The crosstalk between the three inverted parameters was reduced using the chosen inverted model parameterization, reducing the problem complexity by inverting parameters with different parts of the data, and further mitigated using an L-BFGS optimizer with a novel adaptive gradient-like approach to better estimate the inverse Hessian (McLeman et al., 2023). The source wavelet was derived using a modelled signature and further refined via source inversion within FWI; near-field hydrophone data was not available for this acquisition. The input seismic data was the raw hydrophone field data.

A second workflow was run for comparison purposes to generate a conventional processing and imaging result using designature, deghosting, demultiple, and 46 Hz acoustic LS-RTM angle stacks. The input models to LS-RTM were the output models from the 46 Hz elastic MP-FWI. Tidal variations were accounted for in the wave equation modelling for both workflows.

In Figure 1, a comparison is shown through an inline at the well location between the initial models and the models inverted by elastic MP-FWI of P-impedance, Vs/Vp ratio, and Vp. The updated models demonstrate an increase in spatial resolution, with the thin layers becoming well delineated. We can also readily identify the hydrocarbon reservoir location in the updated models, as highlighted by the black circle. At this location, we see a decrease in the Vp due to the gas saturation of the rock (Figure 1f)), where such gas saturation will have minimal impact on the Vs, causing the Vs/Vp ratio to increase (Figure 1d)). Gas saturation will cause a decrease in density as well as Vp, meaning the P-impedance should also decrease, and indeed, this is observed in Figure 1b). To validate these results, we compare these updated models with the well logs.

Well information from within the survey area is shown in Figure 2 (black), where the elastic MP-FWI initial models are shown in red, and the updated models are shown in blue. The orange arrow indicates a location in which the well data predicts a decrease in P-impedance driven primarily by a

decrease in density and by a decrease in Vp, but the Vs/Vp ratio is predicted to increase. This shows that the elastic MP-FWI updated models correctly predict these trends, demonstrating that the crosstalk between these parameters has been successfully mitigated. The well information was only used to build the initial low-frequency models and was not used to guide the elastic MP-FWI.

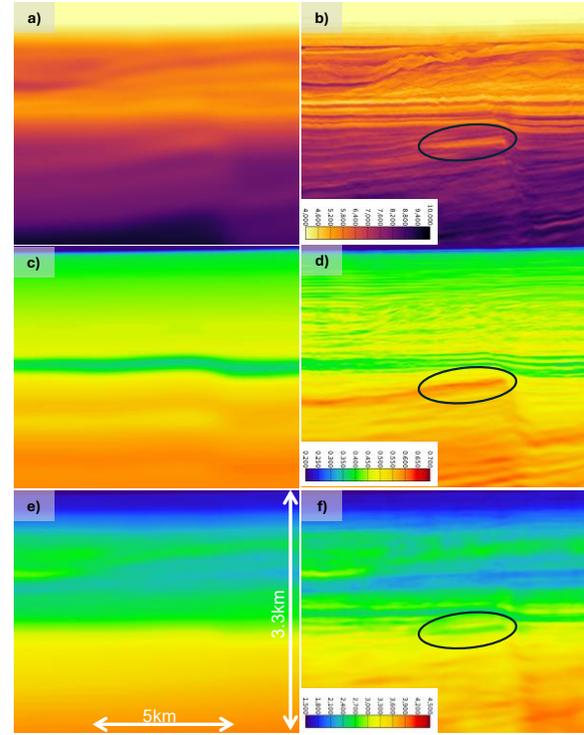


Figure 1: The initial models input to elastic MP-FWI of a) P-impedance, c) Vs/Vp ratio, and e) Vp. The elastic MP-FWI updated equivalents are shown in b), d), and f).

The amplitudes of the LS-RTM angle stacks were inverted to obtain estimates of P-impedance and Vs/Vp ratio. This is shown in Figure 3, where the conventionally derived results are shown in brown, the elastic MP-FWI inverted models are shown in blue, and the well information is shown in black. A better match is observed between the elastic MP-FWI derived models and the well information.

The reflectivity derived from elastic MP-FWI is shown in Figure 4 with a depth slice at 2570 m in comparison to the reflectivity generated by the LS-RTM. It is important to note that the elastic MP-FWI results used the raw unprocessed shots as input, whereas the LS-RTM used highly pre-processed input data. The reflectivity generated by elastic MP-FWI demonstrates an increase in spatial resolution over the acoustic LS-RTM, where the subsurface channel features

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and complex faulting are sharper and more clearly delineated, as highlighted by the yellow arrows.

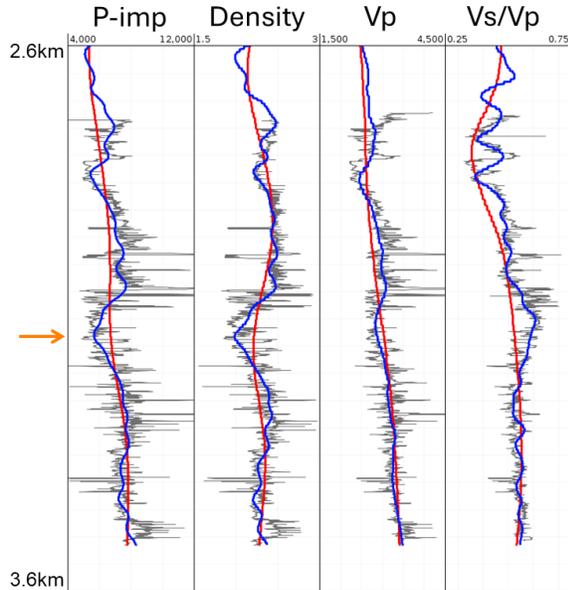


Figure 2: Comparison between the well information (black), the initial models input to elastic MP-FWI (red), and the models inverted by elastic MP-FWI (blue).

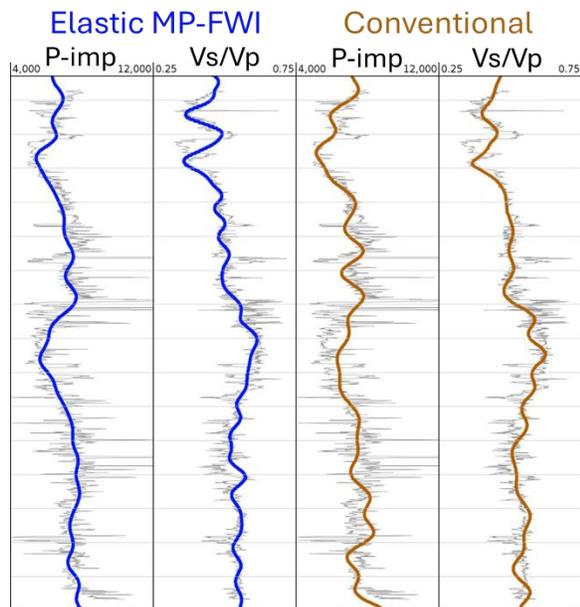


Figure 3: Comparison between the well information (black), the inverted LS-RTM result (brown), and the models inverted by elastic MP-FWI (blue).

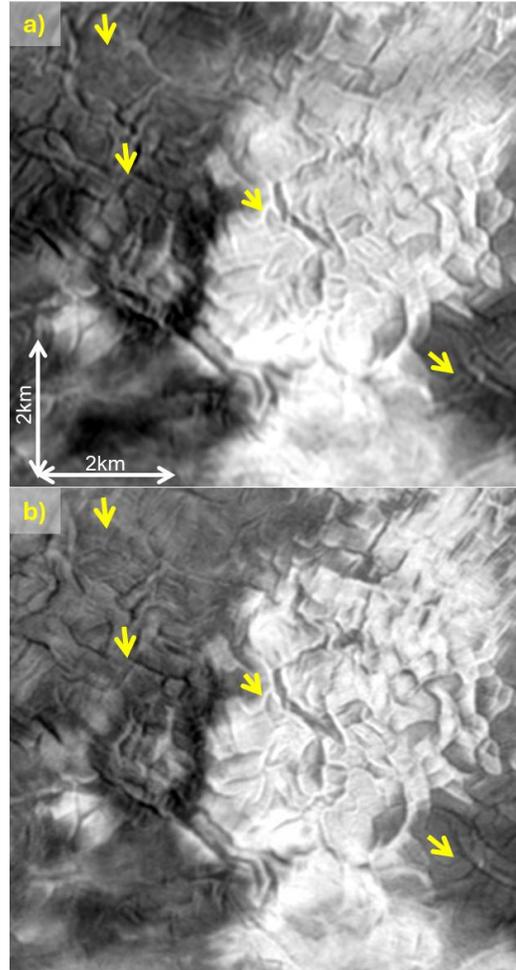


Figure 4: Depth slice images at 2570 m, a) the reflectivity generated by acoustic LS-RTM, and b) the elastic MP-FWI derived reflectivity.

Case study 2: Gulf of America

This case study considers a sparse ocean-bottom node (OBN) dataset acquired in the Gulf of America (GoA), in a region where the water depths are approximately 2 km. The initial anisotropy, Vs/Vp ratio, and density models were derived using regional knowledge and well constraints.

Elastic MP-FWI, including reflections, was run in stages up to a frequency of 30 Hz. These stages initially involved inverting simultaneously for P-impedance and Vp (holding the Vs/Vp ratio fixed). The updated P-impedance model was then carried into subsequent elastic MP-FWI runs, where the P-impedance, Vs/Vp ratio, and Vp were simultaneously updated. This approach, like the previous case study, aimed to mitigate crosstalk between the parameters by reducing the

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complexity of the problem by inverting for combinations of the various parameters incrementally. The choice of parameterization of P-impedance, V_s/V_p ratio, and V_p combined with the aforementioned optimization scheme were used again to reduce the issue of parameter crosstalk.

The seismic data input to elastic MP-FWI had minimal pre-processing, including node repositioning based on direct arrival analysis. Only the hydrophone component was considered. In parallel a conventional data pre-processing workflow was run to create input data for a downgoing mirror RTM, using the velocity model output from elastic MP-FWI.

Figure 5 shows a comparison of the elastic MP-FWI inverted parameters at a well location. The initial models are shown in red, the inverted models are in blue, and the well data is in black. We observe a good match between the inverted P-impedance, V_s , density, and V_p with the well data.

Figure 6 shows a comparison of the downgoing mirror RTM using pre-processed data, the acoustic MP-FWI derived reflectivity, and the elastic MP-FWI derived reflectivity. We can immediately see the improvements that the MP-FWI approaches bring over the conventional RTM due to the least-squares nature of the approach and the inclusion on the multiples, resulting in an improvement in resolution and illumination. However, we can see a further improvement in focusing around the high-impedance contrast given by the salt, and as a result the structures beneath it too in the elastic MP-FWI derived reflectivity, shown by the yellow arrows.

Conclusions

In this paper, we have shown two case studies that demonstrate the successful application of elastic MP-FWI to generate accurate models of P-impedance, V_s/V_p ratio, and V_p directly from the raw (or minimally processed) field data. These quantities were derived without the need to generate reflectivity angle stacks or pre-stack image gathers for a secondary AVA inversion step. The elastic MP-FWI-derived quantities are geologically conformable and show a good match to the well information. The reflectivity derived from elastic MP-FWI also demonstrates notable improvements in resolution over conventional methods, further showing that complex pre-processing stages required by the conventional workflows are no longer required. Thus, simplifying and reducing the subjectivity surrounding the generation of vital quantitative interpretation attributes.

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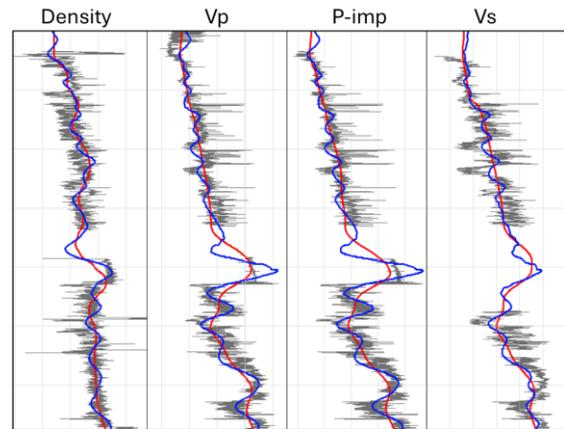


Figure 5: Comparison between the well data (black), initial models (red), and elastic MP-FWI inverted results (blue).

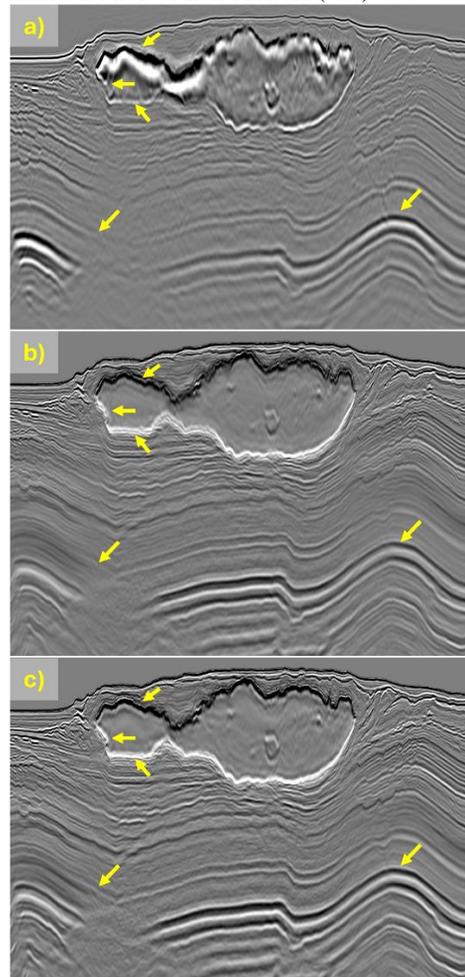


Figure 6: a) RTM from conventional approach, b) acoustic MP-FWI reflectivity, and c) elastic MP-FWI reflectivity.