High-resolution shear-wave velocity model building with elastic full-waveform inversion of multi-component ocean-bottom data

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Summary

Elastic full-waveform inversion (FWI) is becoming more frequently used in compressional velocity (Vp) model building. However, the inversion of shear-waves in elastic FWI is more challenging. Here, we propose a methodology to update a high-resolution shear-wave velocity (Vs) model with elastic FWI, driven largely by the converted waves recorded in multi-component ocean-bottom seismic data. We demonstrate this with a field example from the Central North Sea. Using an accurate Vp model from a 25 Hz elastic FWI update, which utilised both raw compressional hydrophone and vertical geophone components, we subsequently run a 25 Hz elastic FWI update of the Vs model using the raw horizontal geophone components. The Vs update is geologically consistent, showing a good match with the underlying seismic data and the well data. We also show that the inversion result is robust with respect to the starting model. In addition, the extracted Vp/Vs ratio from the elastic FWI highlights geological features such as gas pockets and injectites. A comparison is made to a full-bandwidth amplitude-versus-angle inversion of fully processed and imaged PP-data, highlighting benefits in some areas with the new method, as well as comparable features and anomalies elsewhere.

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Introduction

The industry's adoption of elastic full-waveform inversion (FWI) has accelerated in recent years, with many successful field data examples inverting the compressional-wave (Vp) velocity model. This has been helped by an increased understanding of when elastic FWI is expected to outperform acoustic FWI (Plessix and Krupovnickas, 2021), allowing the FWI user to target geological regimes that will see the most benefit. The accuracy of shear-wave velocities (Vs) is generally considered a second-order effect on elastic Vp inversions (Wang et al., 2021; Masmoudi et al., 2022; Wu et al., 2022). This contrasts with imaging, or inverting, converted-wave (PS) data, where the Vs model has first-order behaviour.

PS data generally has a lower signal-to-noise ratio than PP data and requires accurate Vp and Vs models. Hence, one question that is often asked is, "What use is PS / shear-wave data?" We comment here that PP and PS imaged data comparisons can provide information on local pressure and fluid properties. This is due to changes in those properties changing Vp and Vs in different ways, hence giving different behaviours of the P- and S-wave reflectivities. Furthermore, the Vs model itself, and the subsequent Vp/Vs ratio, can aid geological interpretation and help identify potential exploration targets. This can be by, for example, helping to characterize elastic reservoir properties, illuminate beneath gas zones, show fluid contacts, and highlight other interesting features such as clean sands, injectites, anomalous BCU / sub-BCU responses, etc.

In this paper, we continue the work of Masmoudi et al. (2024), who inverted a Vs model with elastic FWI using raw horizontal component data recorded in multi-component ocean-bottom seismic (OBS). This previous work only updated the background Vs model with the aim of improving conventional PS image. Here, we extend this methodology to invert for frequencies beyond those expected to influence the main Vs kinematics. Our application to a North Sea OBS data set shows a high-resolution Vs that agrees with shear well profiles in the area, as well as Vp/Vs anomalies that highlight geological features such as gas pockets and injectites. We also show comparable results from our method (driven by raw data) to amplitude-versus-angle (AVA) inversions of fully processed and imaged PP-data.

High-resolution elastic Vs updates

An elastic FWI process has the potential to use all parts of the recorded wavefield, for example, reflections, guided-waves, Scholte-waves, diving-waves, and multiples, to drive Vs updates. Our previous methodology (Masmoudi et al., 2024) firstly restricted the multi-component data to the horizontally recorded components, as it is well-known that they contain the most shear-wave energy. Secondly, while raw data was input, the previous methodology concentrated on background Vs model updates with an inversion strategy designed to emphasise the tomographic part of the Vs gradient coming from the PS-reflections. We now remove this constraint and investigate what workflow modifications will allow us to also invert for the high-wavenumber part of the Vs model.

The first step was to obtain an accurate Vp model using elastic FWI, in this case to 25 Hz. The starting Vs model for this Vp update comes from petrophysical relationships, with modifications for local geology using regional well information. Typically, we maintain the Vp/Vs ratio during this first step. The second step here was to update the Vs model using PP-PS event registration and an acoustic-based PS reflection-FWI (PS-RFWI) for background Vs updates (Masmoudi et al., 2021). We adopted this step because these results were available from a production model building of this data. The third step was to run an elastic Vs FWI update driven by the raw horizontal geophone data (minimal processing only) without any Vs FWI gradient terms being enhanced over any others. The inversion was run in a multi-scale manner from 5 to 25 Hz, thus allowing update of both low- and high-wavenumber components of the Vs model, as needed. An advantage of this method is that these low- and high-wavenumber updates are part of a consistent inversion framework, so there is no explicit (or implicit) scale separation. Hence, raw data is used within a fully elastic scheme with no single scattering assumptions, allowing an integrated full-wavenumber model to explain the horizontal geophone data.

Central North Sea field data example

We applied this workflow to a multi-component OBS data set from the Central North Sea, offshore Norway. The water bottom depth was ~110 m, with a node spacing of 50 m by 300 m in x and y, respectively, and a 50 m by 25 m shot carpet at a depth of 5 m. The key geological features in the area are a local basement high overlain by a chalk layer of variable thickness with various injectite bodies and shallower gas pockets. Figure 1 shows the results of the 25 Hz elastic Vs update, with the black arrows on Figures 1b and 1c highlighting details added to the model in the Grid Sands formation (~1500 m depth). Shallower layering has also been added to the Vs model, which along with the Grid Sands perturbation, can be seen to be geologically consistent with the details observed in the PS reverse time migration (RTM) in Figure 1e. Comparing PS-RTM (Figure 1e, green arrows) with PP-RTM (Figure 1f, orange arrows) highlights the character difference between the two data types at the Grid Sands.

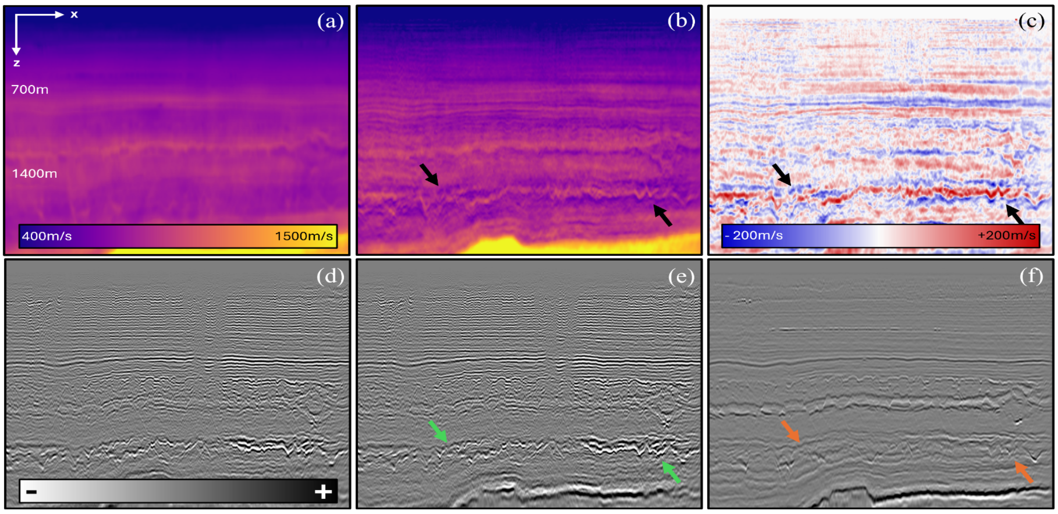

Figure 1 *Section displays of Vs models: (a) starting, (b) 25 Hz elastic FWI update, and (c) 25 Hz Vs perturbation. Section displays of 40 Hz RTM images: (d) PS with starting Vs model, (e) PS with 25 Hz elastic Vs FWI model, and (f) PP with 25 Hz elastic Vp FWI model.*

One of the key motivations for this work was the ability to invert a high-resolution Vs model directly from raw data. Our previous work (Masmoudi et al., 2024) induced some high-wavenumber components in the Vs model by using a high-resolution Vp model with a given Vp/Vs ratio. We now test the impact of this on our inversion when we start from a good initial Vs model without any detail. Figure 2 shows the updates starting from a Vs model with some high-resolution details present and a model with this detail removed. Comparing Figures 2c and 2d, we observe that a comparable level of detail has been resolved from the FWI inversion with key features, such as the Grid Sands, having comparable velocity profile and physical appearance. The well profile in Figure 2e shows the resulting velocities from FWI have converged on a result with comparable match to the Vs well sonic in blue.

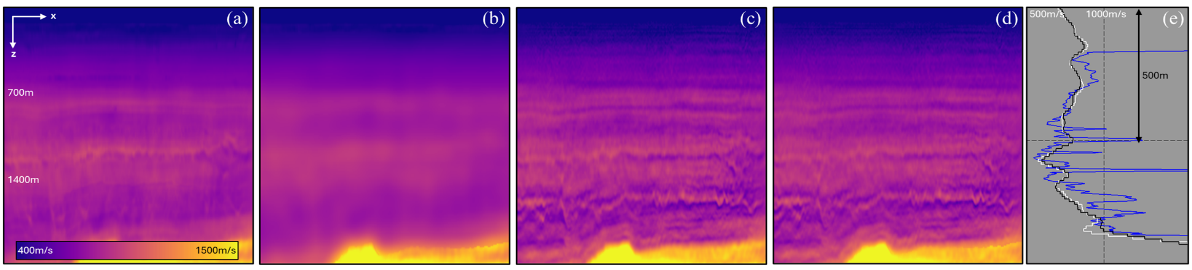

Figure 2 *Section displays of Vs models: (a) starting model including some high-resolution detail, (b) starting model without high-resolution detail, (c) 25 Hz elastic FWI update from model with detail, and (d) 25 Hz elastic FWI update from model without detail. The well comparison (e) shows both inversions add similar detail, with the results shown in (c) and (d) being the white and black curves, respectively.*

Vs updates: to what end?

Due to an accurate initial model, with Vs having been derived from PP-PS event registration and PS-RFWI, we do not observe a large uplift in the PS-RTM image with the 25 Hz elastic FWI Vs update. However, by generating high-frequency Vs updates, we have other possibilities to use the results. In Figure 3, we show the FWI Images formed from the initial and updated Vs models compared to the 40 Hz PS-RTM using the inverted 25 Hz Vs model. We clearly see the starting model (Figure 3a) contains some high-resolution reflectivity, coming from the high-resolution Vp model and associated Vp/Vs ratio. The 25 Hz Vs FWI inversion, driven by the horizontal components, gives the result shown in Figure 3b. As mentioned before, differences in P- and S-wave imaging can indicate potential changes in pressure and fluid properties, for example, at the injective level (yellow arrows). Also, when compared with the 40 Hz PS-RTM migrated using the same Vs model (Figure 3c), the 25 Hz Vs FWI Image (Figure 3b) shows better image continuity underneath the shallow channel (upper white arrow), and signal enhancements above the basement (lower white arrow). In addition, at the depth level of the upper white arrow (~850 m) we see different image responses in the Vs FWI Image and PS-RTM across the section. Part of this will be due to the local geology and the different wavenumber content of these two images (the FWI Image is naturally richer in lower frequencies and, in theory, completely free of the wavelet), but also part of this is due to the FWI Image being derived from a Vs update, whereas the PS-RTM represents changes in the shear-wave impedance.

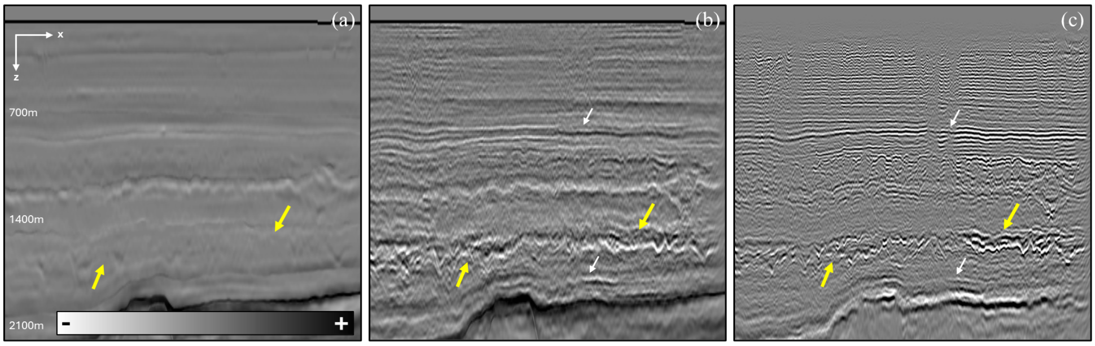

Figure 3 *Section displays of FWI Images: (a) starting Vs model and, (b) 25 Hz elastic FWI Vs model compared to (c) 40 Hz PS-RTM using the 25 Hz elastic FWI Vs model.*

Further, we can use this model for more than just imaging. Specifically, we have inverted both Vp and Vs to 25 Hz and can form a fully inverted Vp/Vs ratio, as shown in Figure 4a. Here, we extract complementary information to the FWI Images in Figure 3, where low Vp/Vs measurements aid the interpretation of many of the interesting geological features, both in the injectites and known reservoir zone, as indicated by the white and black arrows, respectively, in Figure 4a. In addition, we can contrast the Vp/Vs ratio obtained directly from FWI using raw data to a more conventional AVA inversion from processed PP data and well information in Figure 4b. More details can be seen in the PP inversion; however, this is a full bandwidth Kirchhoff pre-stack depth migration (KPSDM) compared to a 25 Hz FWI. Despite this, the known reservoir can be observed in both Vp/Vs ratios with a clearer picture of the injectites observed with the FWI. The overlaid Vp/Vs well logs extractions show a comparable ratio to those from the FWI and conventional AVA routes.

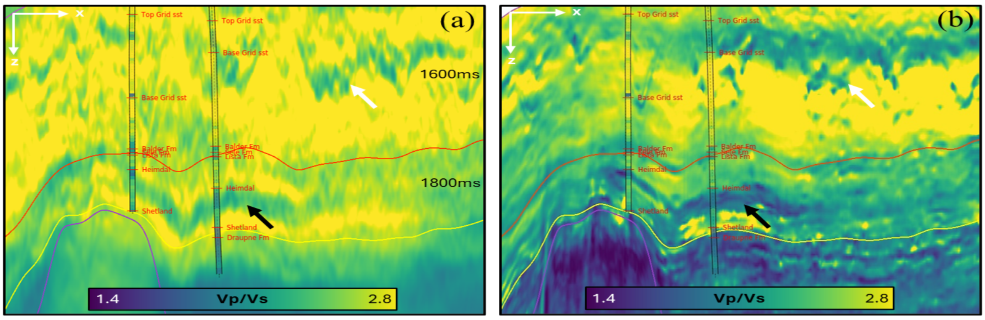

Figure 4 *Vp/Vs ratio derived from: (a) 25 Hz FWI update, and (b) full bandwidth PP inversion. Inset well logs show corresponding Vs and Vp/Vs information from the respective inversions.*

In addition, we can use the extracted Vp/Vs ratio to examine shallow features; for example, gas bodies as shown in Figure 5a. This gas results in a lower Vp compared to the surrounding geology. By utilising a Vp/Vs ratio to create the starting Vs model, the low Vp from the gas induces a low Vs (Figure 5b), which is known to be incorrect as S-waves are insensitive to fluid changes. By running FWI to update the Vs model, this incorrect Vs anomaly has been removed (Figure 5c). The Vp/Vs ratio can then be computed for both the starting and 25 Hz FWI Vs models. Figure 5d shows no anomaly in the Vp/Vs ratio, but after elastic Vs FWI (Figure 5e), the shallow gas pocket can be clearly observed.

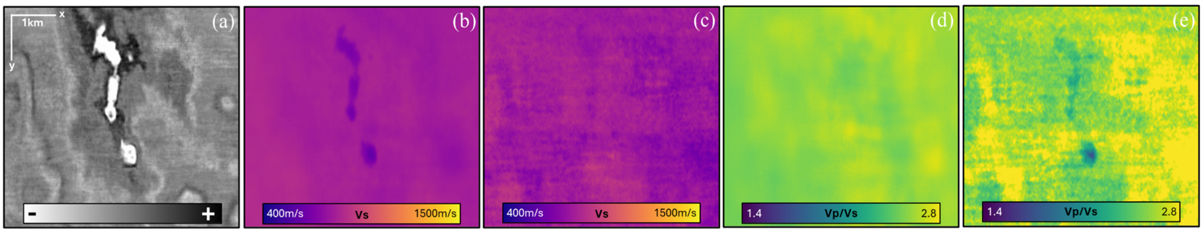

Figure 5 *Depth slices (at 835 m) through a shallow gas pocket for: (a) KPSDM, (b) starting Vs model, and (c) Vs model from 25 Hz elastic FWI update. The corresponding Vp/Vs ratio derived from: (d) starting model, and (e) 25 Hz FWI update.*

Conclusions and discussion

We have described a methodology for a high-resolution elastic Vs FWI update using raw horizontal components of OBS data and have shown field data results to 25 Hz from the Central North Sea. We use this Vs model to motivate the value in converted-wave data by highlighting interesting geological features, such as gas pockets and injectites, and the benefits a good Vs model brings to the associated reservoir characterization. In terms of potential future work, two aspects stand out: 1) the very shallow part of the Vs model (directly under the water bottom) is very challenging to update, and 2) typically the vertical/pressure and horizontal components are used to update the Vp and Vs models, respectively, rather than jointly. Hence, to address these issues: for 1), if they are well recorded, then either a dedicated Scholte-wave, or S-diving wave, FWI might be helpful, and for 2), a joint multi-component update of Vp/Vs ratio using information in the PP AVA response as well.

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