Multi-component and multi-dataset MP-FWI

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Summary

Shallow water free-surface multiples have historically posed a significant challenge for processing and imaging seismic data. In recent years, multi-parameter full-waveform inversion (MP-FWI) imaging has achieved higher-resolution subsurface reflectivity images by using the entire recorded wavefield, including multiples, now seen as useful additional subsurface information. In the case of Ocean Bottom Seismic (OBS), MP-FWI imaging naturally uses both upgoing and downgoing wavefields simultaneously, most commonly by inverting the hydrophone component only. Including the vertical geophone component can guide the inversion towards a more robust solution by leveraging the complementarity of the pressure and vertical velocity. A direct comparison of MP-FWI imaging using the hydrophone component only and using hydrophone and vertical geophone simultaneously shows the benefits of including several measurements, with faster convergence and better handling of the strong multiple content. Careful use of the NFH data was also beneficial in decoupling source amplitude from water-bottom reflectivity and in ensuring accurate modelling of both primaries and multiples. In addition, integrating NFH data in the MP-FWI, in a joint inversion with the OBS data, provides an elegant solution to capture spatial variability of the seabed reflectivity early in the inversion, ensuring an efficient and robust use of strong water bottom multiples.

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Motivation

Shallow water free-surface multiples have historically posed a significant challenge for processing and imaging marine seismic data. To satisfy the assumptions made by legacy migration algorithms, whether ray-based or wave-equation-based, multiples are treated as noise and a great deal of processing effort is spent attempting to remove this unwanted energy, while preserving primary reflections and their crucial amplitude information. Workflows mostly rely on generating models of the multiples followed by adaptive subtractions in various domains, targeting sequentially short-period, long-period multiples, source-side, receiver-side (and eventually interbed multiples). While simpler geology challenges our subtraction methods, complex geological structures challenge both modelling and subtraction steps.

In the case of Ocean-bottom seismic (OBS), the wavefield is recorded through several independent co-located physical measurements: the hydrophone captures the pressure wavefield, while the geophone (or accelerometer) captures particle velocity (or acceleration). Considering the wavefield as the combination of upgoing and downgoing wavefields, the pressure measurement (P), being omnidirectional, records the sum of upgoing and downgoing. The vertical velocity measurement (Z), however, is directional and therefore records the difference between downgoing and upgoing wavefields. The receiver ghost is recorded with opposite polarity on the P and Z components, resulting in interleaved notches in the respective amplitude spectra. Conventional processing and imaging workflows leverage the complementarity of pressure and vertical velocity to separate the upgoing and downgoing wavefields, attenuate multiples and ghosts and create subsurface images from either the upgoing or downgoing processed data. In recent years, up-down and down-down deconvolution methods (Amundsen, 2001; Hampson and Szumski, 2020) have proven very successful in attenuating source ghost, signature and free-surface multiples. Mirror migration of the processed downgoing data has been widely adopted to address the lack of shallow subsurface illumination in the upgoing images, representing a significant step in recognising the benefits of using free-surface multiples to improve subsurface imaging.

In recent years, multi-parameter full-waveform inversion (MP-FWI) imaging has achieved higher-resolution reflectivity images of the subsurface (McLeman et al., 2023; Rayment et al., 2023; Phillips et al., 2024) through the use of the entire recorded wavefield, including not only primary reflections but also ghosts and multiples (both free-surface and interbed). This approach replaces the conventional processing and imaging workflows: thanks to more accurate physics, multiples are no longer seen as noise but rather as useful additional subsurface information. Therefore, MP-FWI imaging naturally uses both upgoing and downgoing wavefields simultaneously, most commonly by inverting the P component only.

In the presence of strong shallow-water reverberations, the challenge for MP-FWI is to be able to use these multiples efficiently by simultaneously resolving the water-bottom reflectivity, the dominant free surface multiples and the much weaker underlying primaries. The inclusion of additional measurements of the wavefield - such as the Z component, or near-field hydrophone (NFH) data - in addition to the P component within MP-FWI, should provide additional data constraints that can be used to guide the inversion more efficiently towards a more robust solution. This paper presents a direct comparison of MP-FWI imaging using the P component only and using both P and Z components simultaneously in a joint inversion and explores the benefits of using NFH data.

Case study

Ocean-bottom seismic (OBS) was recently acquired over a producing field in the North Sea. The reservoir is located below the Base Cretaceous Unconformity in a fault block adjacent to a salt diapir, with secondary faulting also present. Initially acquired to monitor the 4D response, the OBS survey is used as input to MP-FWI imaging with the objective to improve the reliability and interpretability of the subsurface images and properties. The water bottom is relatively flat at a depth of around 90 m, with a varying impedance contrast across the survey, including shallow channels. The resulting strong multiple contamination presents a significant challenge for conventional processing. However, these multiples are included as an important part of MP-FWI, providing valuable extra information to the inversion.

The multi-faceted benefits of NFH data

Accurate modelling of these multiples requires accurate source modelling and an accurate model of the water-column and seabed contrasts. Shot-by-shot source signatures were derived by inverting NFH data. The absolute amplitude of the source response is typically obtained using FWI, focusing on the direct arrivals. This presents a challenge for OBS data, where these direct arrivals coincide with the water bottom reflection. Decoupling the source amplitude from water bottom reflectivity is crucial to accurately model both primaries and multiples, as these are affected differently by the two factors. To this effect, passive NFH data were used as input to MP-FWI to derive a model of the water-bottom reflectivity. This then allows appropriate scaling of the source response for the OBS data.

The benefit of the NFH passive data extends further: providing additional illumination of the near-surface, it can complement the OBS P data, allowing MP-FWI to converge much faster towards a robust solution for the complex shallow subsurface, explaining both strong multiples and weaker primaries. This is illustrated in Figure 1 with a comparison of the reflectivity obtained from MP-FWI imaging using the OBS P component only and using both OBS P component and NFH passive data in a joint inversion. After the same number of iterations, the joint inversion shows a better handling of the strong multiple content and improved shallow-channel imaging (Figure 1a and b). Capturing the spatial variability of the water bottom reflectivity (see Figure 1c) is crucial for efficient imaging of both primaries and multiples throughout the subsurface.

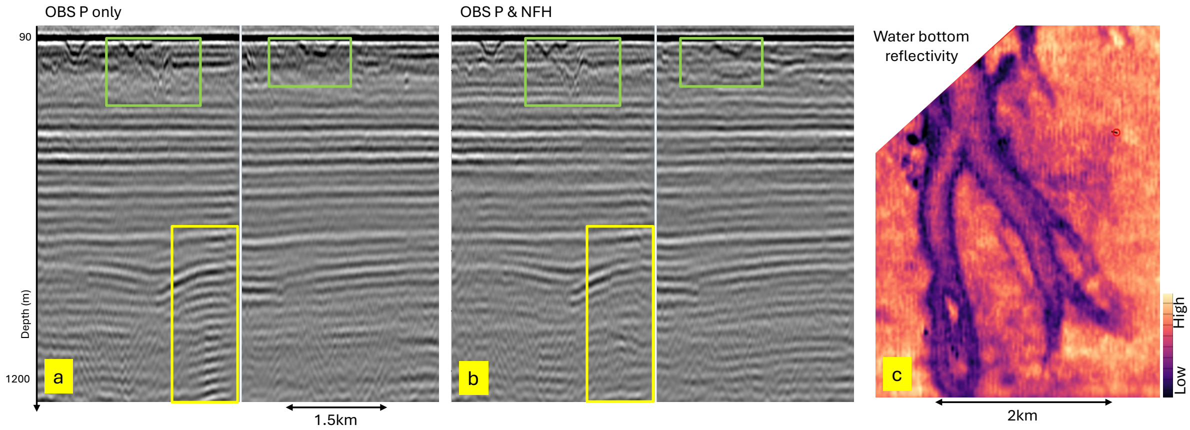

Figure 1 *(a) Inline (left) and crossline (right) through MP-FWI imaging reflectivity from OBS P component inversion (left) and (b) joint OBS P and NFH inversion (right), highlighting better handling of strong multiple content (yellow box) and improved imaging of complex shallow channels (green). (c) Map of water bottom reflectivity from the joint OBS P and NFH MP-FWI.*

Using the complementarity of the OBS Z component

The reflectivity, both shallow and deep, is then further updated through MP-FWI imaging of the OBS data until both primaries and multiples can be explained. Initially, only the hydrophone component is modelled. To reduce the computational cost, the reciprocity principle is invoked, and we model a pressure source at the node location, recording the pressure wavefield at the source location. This is compared to the observed pressure wavefield. Back-propagation of the residual, while separating the dynamic and kinematic components, provides both a velocity update and an acoustic impedance update. The iterative process continues until the modelled P data closely matches the observed P data. This approach can be extended as MP-FWI can use multiple physical sensor types as data constraints. The particle velocity component can also be modelled as a reciprocal experiment, with the modelled Z data then being compared to the observed Z data, after careful control and correction of the geophone orientation and instrument response to ensure balance of the respective terms that contribute to the objective function. This can be included in a joint inversion with MP-FWI, iterating until both the modelled P- and Z-data match the observed P-and Z-data.

Single (P-only) and multi-component (P and Z) MP-FWI have been run up to a maximum frequency of 27 Hz. Figure 2a shows an excellent match between the well velocity and MP-FWI velocity (virtually identical for the P-only and P and Z inversion), as well as between the MP-FWI reflectivity and a synthetic trace derived from the available well information (Figure 2b). However, the single-component reflectivity shows signs of unresolved multiple energy, more visible in the relatively quiet interval between 800 m and 1400 m (highlighted in red). The multi-component result does not suffer from the same compromise with an improved well match and better event continuity. This observation is confirmed by the autocorrelations presented in Figure 2c. A spectral analysis at different stages of the inversion (Figure 2d) provides further insight. Destructive interference from water layer reverberations creates visible notches in the spectrum. As the inversion converges and multiples are better explained, these notches are resolved. When destructive interference occurs in the pressure data, constructive interference occurs in the vertical velocity component, thus providing the missing information to the multi-component inversion. The multi-component MP-FWI converges faster, requiring half as many iterations as the single-component inversion to reach a similar point. By continuing the inversion to the same number of iterations as used in the single-component inversion, the multi-component inversion is able to resolve the notch entirely (Figure 2e).

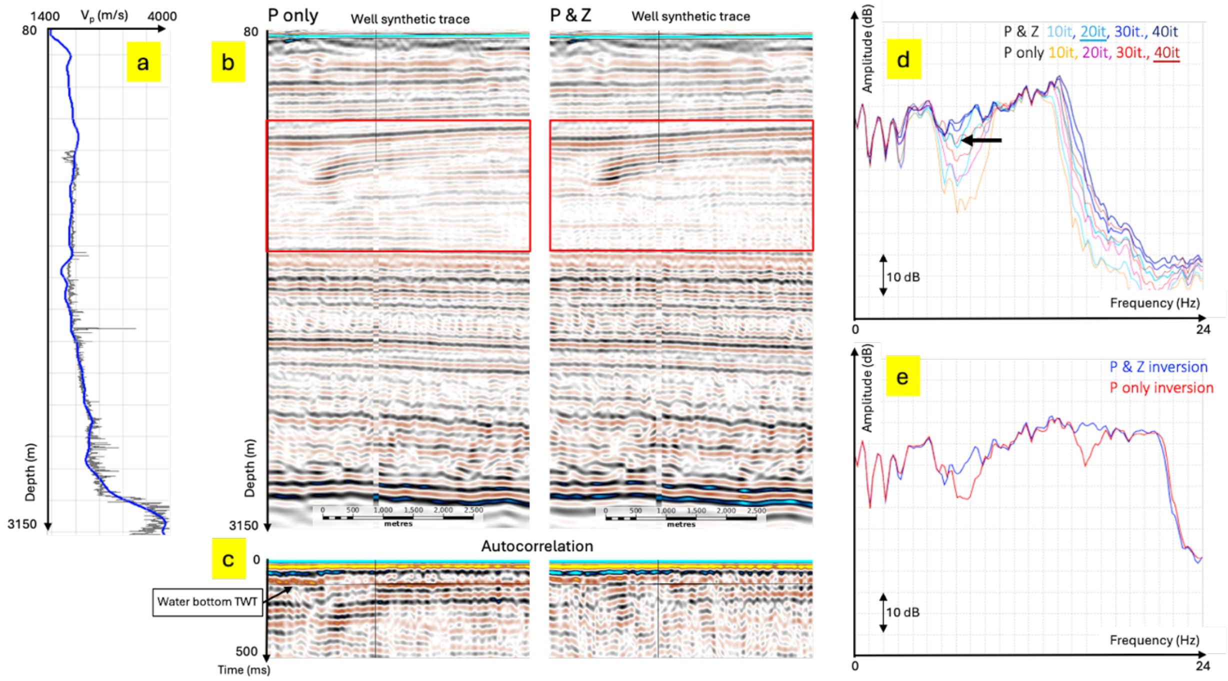

Figure 2 *(a) Well velocity in grey and MP-FWI velocity in blue (b) Inline through MP-FWI imaging reflectivity with well synthetic trace from single component inversion (left) and multi-component inversion (right) (c) Corresponding time domain autocorrelation sections computed over the highlighted red section (d) Amplitude spectra of MP-FWI imaging reflectivity (up to a maximum frequency of 18.5 Hz) at different stages of the inversion (e) Amplitude spectra of MP-FWI imaging reflectivity (up to a maximum frequency of 27 Hz) from single component inversion (red) and multi-component inversion (blue).*

Conclusions

In this paper, we have demonstrated the benefits of using both the P and Z components simultaneously in MP-FWI imaging of OBS data. The multi-component MP-FWI imaging shows significantly faster convergence and better handling of the strong multiple content, therefore achieving a superior result.

Careful use of the NFH data was also beneficial in the workflow by decoupling source amplitude from water-bottom reflectivity and ensuring accurate modelling of both primaries and multiples. In addition, including passive NFH data in the MP-FWI, as part of a joint inversion with the OBS data, provides an elegant solution to capture the shallow complexity and spatial variability of the water-bottom reflectivity early in the inversion process, therefore ensuring an efficient and robust use of the strong water-bottom multiples. MP-FWI imaging unlocks superior imaging through the use of the entire wavefield. Honouring several independent observations, in this case pressure and vertical particle velocity from the OBS data, as well as pressure from the near-field hydrophones, brings valuable additional information, which accelerates the convergence and better constrains the solution.

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