Unlocking new reservoir insights with FWI

Sylvain Masclet[1]*, Yasmine Aziez[1], Nicolas Salaun[1], Anais Montagud[1], Sulaim Al Maani[1] and Vimol Souvannavong[1] present two case studies demonstrating the benefits brought by high-resolution FWI results for seismic reservoir characterisation.

Abstract

Full Waveform Inversion (FWI) has become a standard method for generating high-resolution subsurface velocity models. Advances in FWI now allow the use of the full recorded wavefield, including diving waves, primary reflections, and multiples, leading to improved velocity updates even below the maximum penetration depth of diving waves. These detailed velocity models enhance seismic imaging and provide valuable input for Quantitative Interpretation (QI), which is essential for reservoir characterisation.

We present here two case studies that illustrate the benefits of FWI for QI purposes. The first study, offshore Norway, applies elastic FWI to handle strong velocity contrasts beneath thick chalk layers, demonstrating how high-resolution velocity and seismic images improve fault detection and stratigraphic amplitude-versus-angle (AVA) inversion. The second case study, onshore Oman, showcases recent advances in land FWI and FWI Imaging, leading to sharper fault imaging and better stratigraphic AVA inversion when combining high-frequency velocity models with improved seismic images.

These two case studies highlight the importance of retrieving velocity models within the same frequency bandwidth as the seismic images to accurately capture thin geological features. They also demonstrate the added value of using FWI-derived velocity models to enhance subsequent stratigraphic AVA inversion.

Introduction

Full Waveform Inversion (FWI) is now a widely adopted technology for estimating the seismic wave propagation velocity in the subsurface. Through the inversion of recorded seismic data, FWI builds high-resolution velocity models directly in the data domain, in contrast to stratigraphic elastic inversion which relies on the 1D convolutional modelling assumption between reflectivity and the seismic trace (Coulon et al., 2006). Over the past few decades, significant advancements have been made to

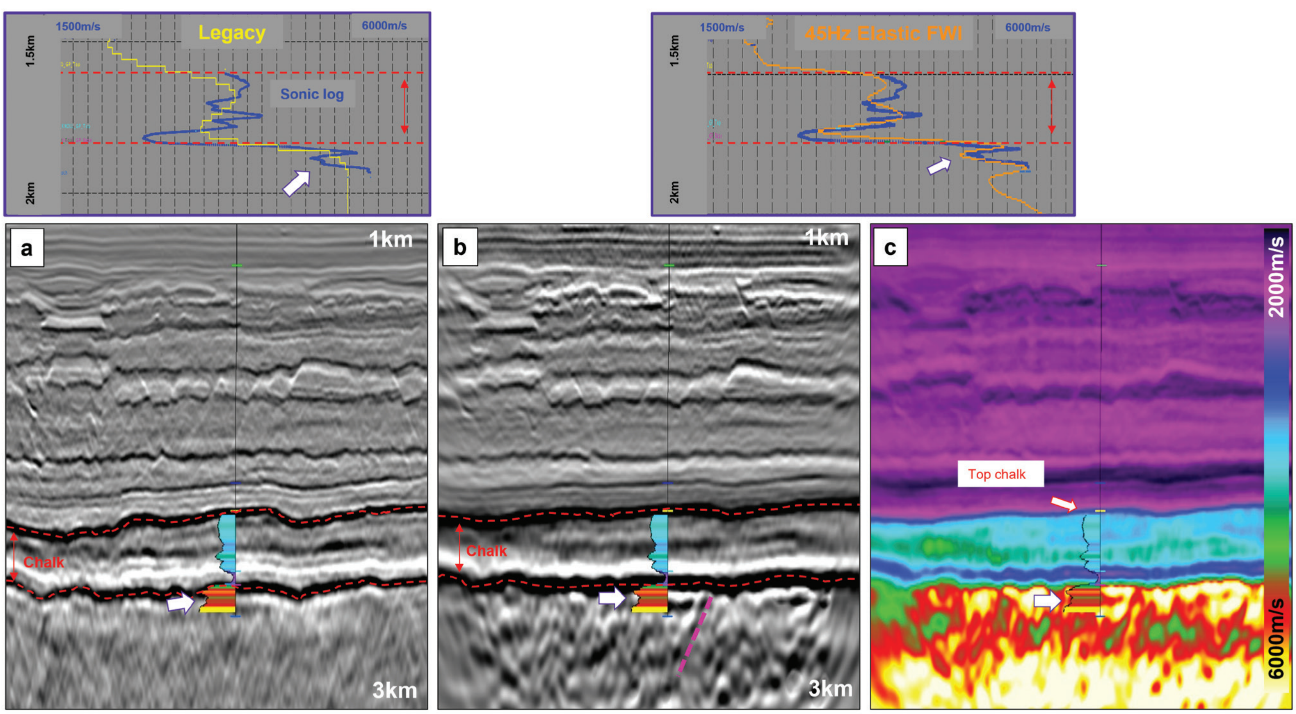

Figure 1 High-resolution elastic FWI – Comparison of the legacy K-PSDM stack (a) with the 45 Hz elastic FWI Image (b) derived from the 45 Hz elastic FWI velocity model (c). Red dash lines indicate the position of the chalk interval. Velocity profiles overlaid with sonic log are displayed above these images.

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reduce the risk of cycle skipping and to fully leverage the whole recorded wavefield (Zhang et al., 2018).

Industrial FWI approaches now incorporate the entire recorded dataset, including diving waves, primary reflections, and multiples (Zhang et al., 2020). As a result, FWI not only contributes to a more accurate velocity field but also improves seismic imaging by addressing both long and short wavelength velocity errors.

Quantitative interpretation (QI), usually carried out after seismic imaging to estimate reservoir properties such as P-impednce, S-impedance, Poisson's ratio, and P-wave velocity (Vp)/Shear velocity (Vs) ratio, plays a critical role in both exploration and development by providing estimates of rock attributes (lithofluid properties, porosity, etc.) and, consequently, the reservoir volume.

While detailed velocity models improve the migrated image and reveal valuable geological information about the subsurface (Lu et al., 2016; Shen et al., 2018; Salaun et al., 2021), using accurate subsurface velocity models derived from FWI makes it possible to generate more reliable amplitude-versus-angle (AVA) attributes. This, in turn, enables clearer discrimination of fluid indicators in intercept-gradient cross-plots (Russell et al., 2003). Moreover, these FWI-derived velocity models enhance the accuracy of stratigraphic AVA inversion results when used as the initial model, because they provide robust low-frequency (geological-trend) information that is essential for QI. A second advantage of the FWI-derived velocity models is that they help bridge to the gaps in information between wells, especially in areas where the geology is highly variable and complex, improving both lateral and vertical resolution.

In this paper, we present two case studies demonstrating the benefits brought by high-resolution FWI results for seismic reservoir characterisation.

Offshore shallow water

The first case study is located in the southern Norwegian Sea, around the Utsira High platform. In this area, the known reservoir lies just beneath a thick and highly reflective chalk package, making imaging particularly challenging. This dataset was acquired using towed streamers with a maximum offset of 6 km. The chalk package presents a strong Vp contrast that limits diving wave penetration and generates converted waves. Additionally, sand injectites located above the chalk layer in the overburden create fast velocity contrasts. These sands, whether water- or hydrocarbon-filled, produce strong anti-correlations between Vp, Vs, and density, as explained by Aziez et al. (2024). Elastic FWI (E-FWI) was applied in this study to leverage a modelling engine capable of fully capturing the complex wave phenomena characteristic of this geological setting. During E-FWI, the Vp model is inverted while the Vp/Vs ratio and density are refined iteratively using stratigraphic AVA inversion to properly decouple Vp, Vs, and density parameters for the sand injectites (Masclet et al., 2025).

The workflow begins with an E-FWI update of Vp only; starting from an initial Vp/Vs derived from well data, yielding a reliable low-frequency Vs velocity model. The density model is at this stage passively updated using a single Gardner's law. After migration, stratigraphic elastic inversion is performed to obtain an updated density and Vp/Vs. This updated Vp/Vs and density

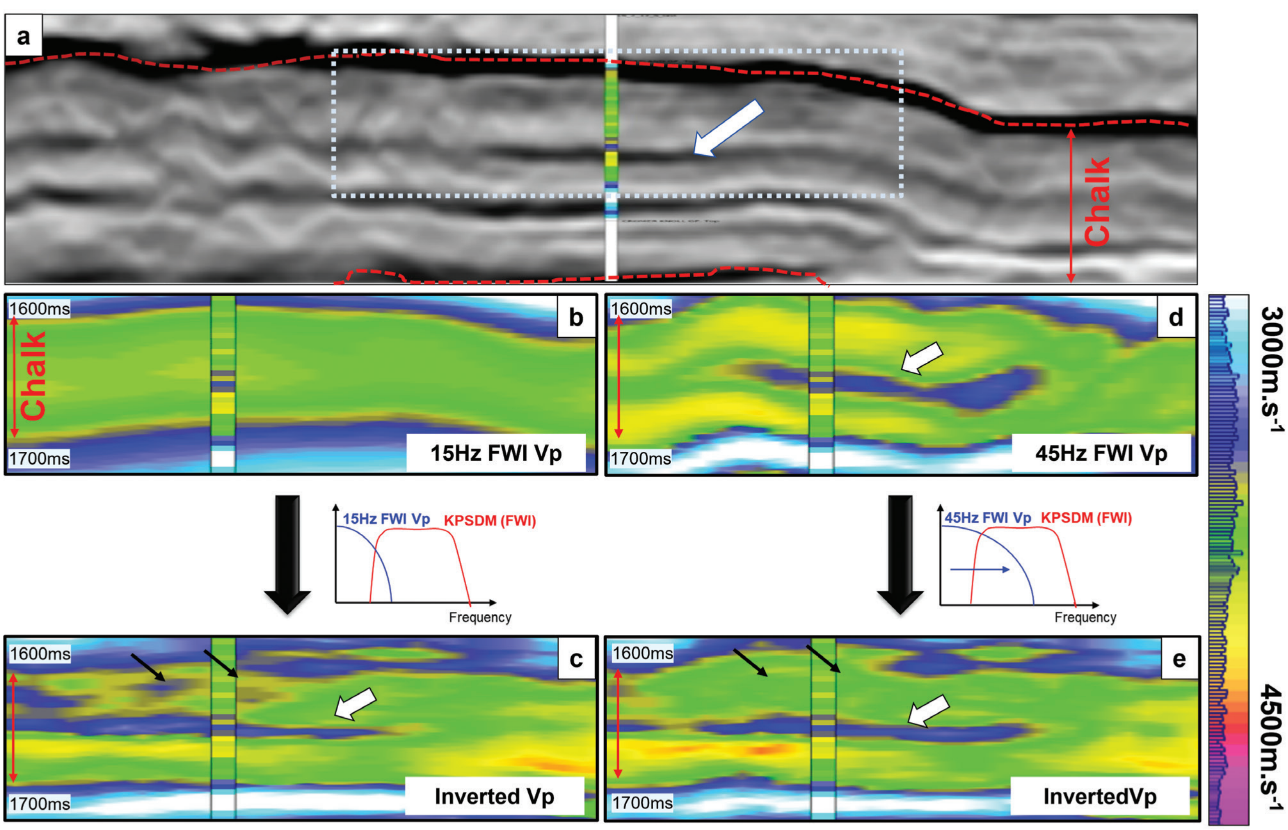

Figure 2 Benefits of high-resolution FWI for QI. a) full stack migrated section zoomed in the chalk layer. 15Hz E-FWI b) and 45Hz E-FWI d) velocity models used as initial model for stratigraphic inversion. c) and e) resulting inverted Vp from stratigraphic inversion. The white arrows highlight the reservoir level, while the black arrows indicate the areas where the stratigraphic inversion performs better when a more accurate initial model is used.

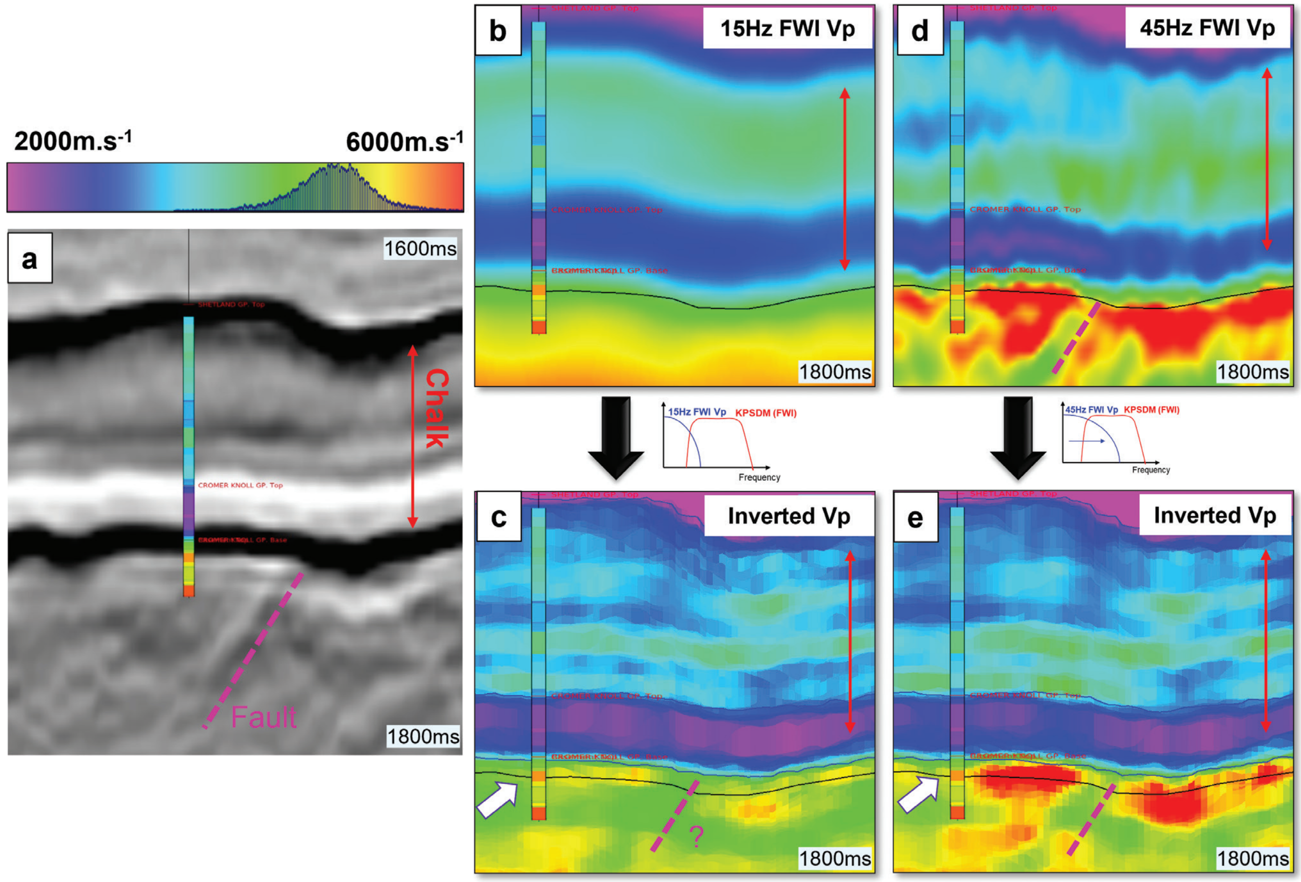

Figure 3 Benefits of high-resolution FWI for QI at the main reservoir. a) full stack migrated section zoomed in the chalk layer. b) and d) 15Hz E-FWI and 45Hz E-FWI used as the initial model for acoustic stratigraphic inversion. c) and e) resulting inverted Vp from acoustic stratigraphic inversion.

exhibit lateral and vertical resolutions. They are then used as the initial model for a subsequent E-FWI run, again updating Vp only with passive updates of Vs and density. Elastic FWI was applied up to 45 Hz (Figure 1) because analysis of well sonic logs identified that a minimum frequency of 45 Hz was necessary to capture the velocity variations at the reservoir level. Figure 1 compares the legacy Kirchhoff Pre-Stack Depth Migration (KPSDM) image with the FWI Image (Zhang et al., 2020), derived from the 45 Hz FWI result. The FWI Image exhibits a higher signal-to-noise ratio (S/N) and supports more accurate structural interpretation by better highlighting the reservoir location, notably delineating the faulting that limits the reservoir laterally.

Given the high-quality seismic image, the next step is to evaluate the benefits for QI. Here, we analyse the impact of the velocity resolution by considering the same seismic data migrated with the 15 Hz E-FWI velocity model (Figure 2) but using two different initial velocity models for the acoustic stratigraphic inversion: scenario 1 uses the 15 Hz FWI velocity (Figure 2b), while scenario 2 uses the 45 Hz FWI velocity (Figure 2d). As anticipated by the well log analysis exercise, the 15 Hz FWI velocity (Figure 2b) lacks sufficient details to recover the prospect embedded within the thick chalk layer.

When performing stratigraphic inversion to estimate Vp, both scenarios retrieve the velocity inversion with the information contained in the seismic image itself (see white arrow in Figures 2c and 2e). With the 15 Hz model, we observe a low-velocity halo that does not align with the well velocity profile (black arrows in Figure 2c). In contrast, the 45 Hz-based result shows a much more confined and well-delineated anomaly, matching the well data more accurately. This example illustrates that the migrated seismic data alone cannot fully recover all necessary information, due to imperfections in primary-only migration, which makes an accurate velocity model essential.

In the second test, we compared similar scenarios, this time focusing on the main reservoir area (Figure 3), where the seismic response is more challenging and AVO response more limited, suffering from refraction energy contamination of the mid/far offset ranges. In this case, the Vp inverted from scenario 1 using the 15Hz FWI model as the initial model failed to properly recover the velocity contrast at the chalk and basement interface (white arrow in Figure 3c) and more importantly to capture the critical fault information below the chalk layer, which is needed to understand the lateral extent of the reservoir. In contrast, we can see in Figure 3e how the added detail from the 45 Hz elastic FWI-derived Vp model brings significant improvement at the chalk/basement interface. It helps to support and better constrain the inversion in areas where the quality of the migrated seismic data is limited.

This case study demonstrates the significant benefits of employing an initial velocity model for stratigraphic inversion that reaches the expected frequency of minimum resolution in the reservoir. While seismic imaging provides important information, it cannot compensate for low-wavenumber velocity models, especially in complex geological settings where imaging issues may degrade the seismic AVO response.

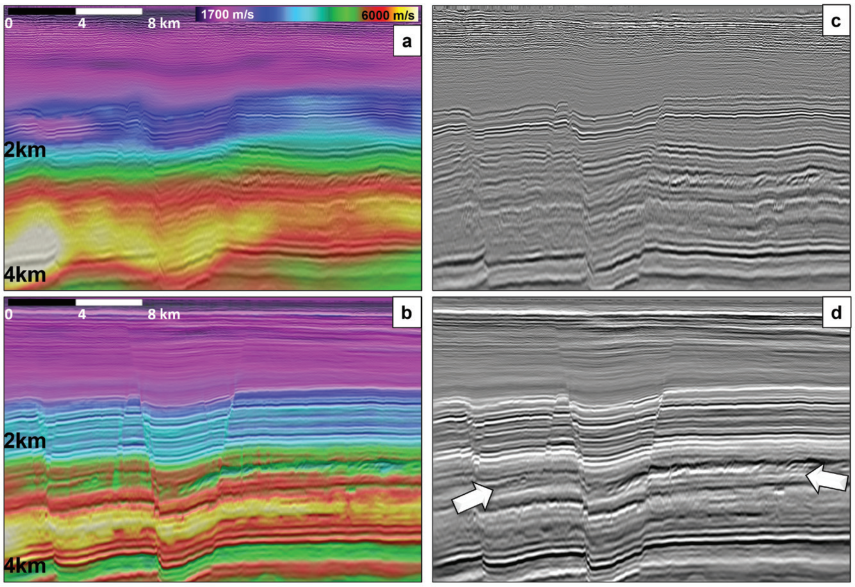

Figure 4 Power of FWI and benefits of FWI Imaging. a) Legacy velocity from tomography and c) the KSPDM migrated with the tomography velocity. b) 40Hz FWI and its associated FWI Image d). White arrows indicate the thin channel details that are more visible on the FWI Image.

Onshore

The second case study is located onshore in the Sultanate of Oman. Obtaining high-resolution velocity models in onshore environments has long been a challenge due to the complexity of seismic data affected by near-surface complexity and elastic phenomena (Guo and Aziz, 2024). However, in recent years there has been increasing success in producing onshore high-resolution FWI velocity models and FWI Images (Guo et al., 2025; Culianez, 2025; Reinier et al., 2025). This progress is primarily due to advances in near-surface velocity estimation (Bardainne et al., 2018; Masclet et al., 2019), the use of interferometry to recover ultra-low frequencies (Masclet et al., 2021; Le Meur et al., 2021), and improvements in FWI algorithms.

Figure 4 illustrates how high-resolution FWI velocity models and FWI Images can significantly enhance the interpretation of geological structures compared to conventional KPSDM. Indeed, the FWI Image provides better illumination in shallow intervals thanks to full-wavefield illumination, and better low frequency thanks to the long-wavelength components updated by FWI, helping with fault definition. The FWI Image also exhibits much more balanced amplitude thanks to iterative least-squares fitting and consideration of transmission effects and multiples, all contributing to more accurate geological interpretation.

Similarly to the first case study, our goal here is to demonstrate the benefits of high-quality velocity models for QI. We compare three scenarios described in Figure 5: (SET 1) using a lower-quality velocity model derived from tomography for both migration and as the initial model for acoustic stratigraphic inversion; (SET 2) using a 40 Hz FWI velocity model and its associated seismic migration; and (SET 3) using the same 40 Hz velocity model but replacing the seismic image with the FWI-derived image.

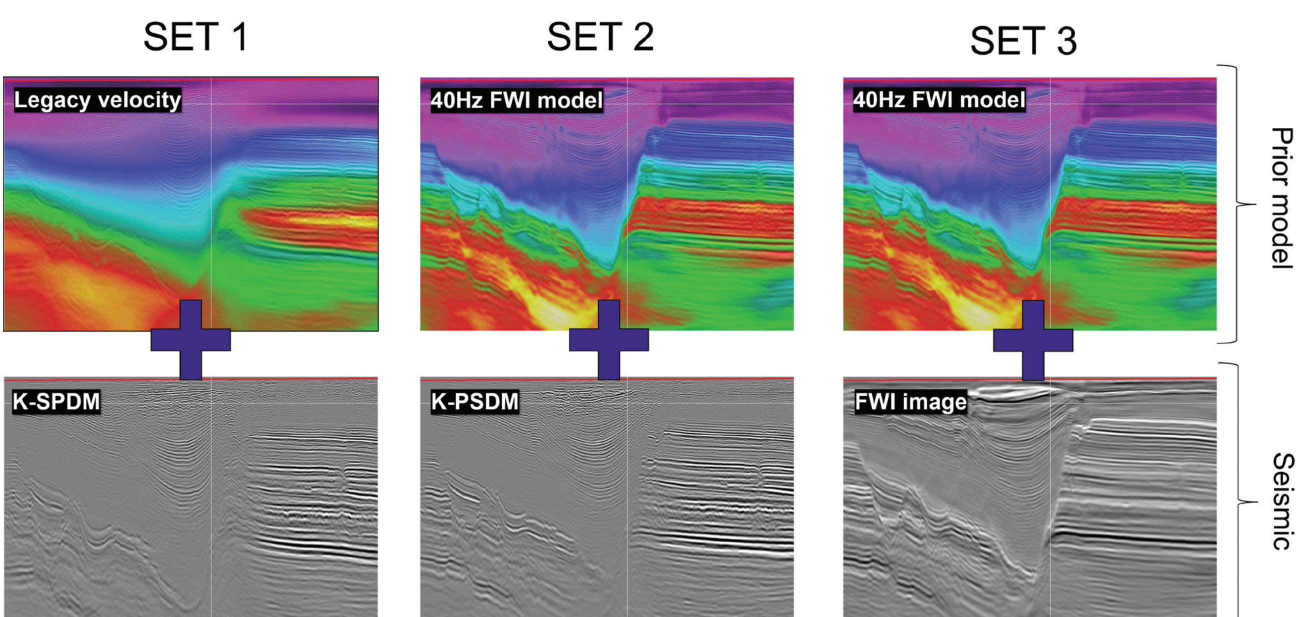

Figure 5 Scenarios compared in the study. a) Legacy velocity from tomography and d) the KSPDM migrated with the tomography velocity. b) 40Hz FWI and e) its associated KPSDM. c) 40Hz FWI and f) the generated FWI Image.

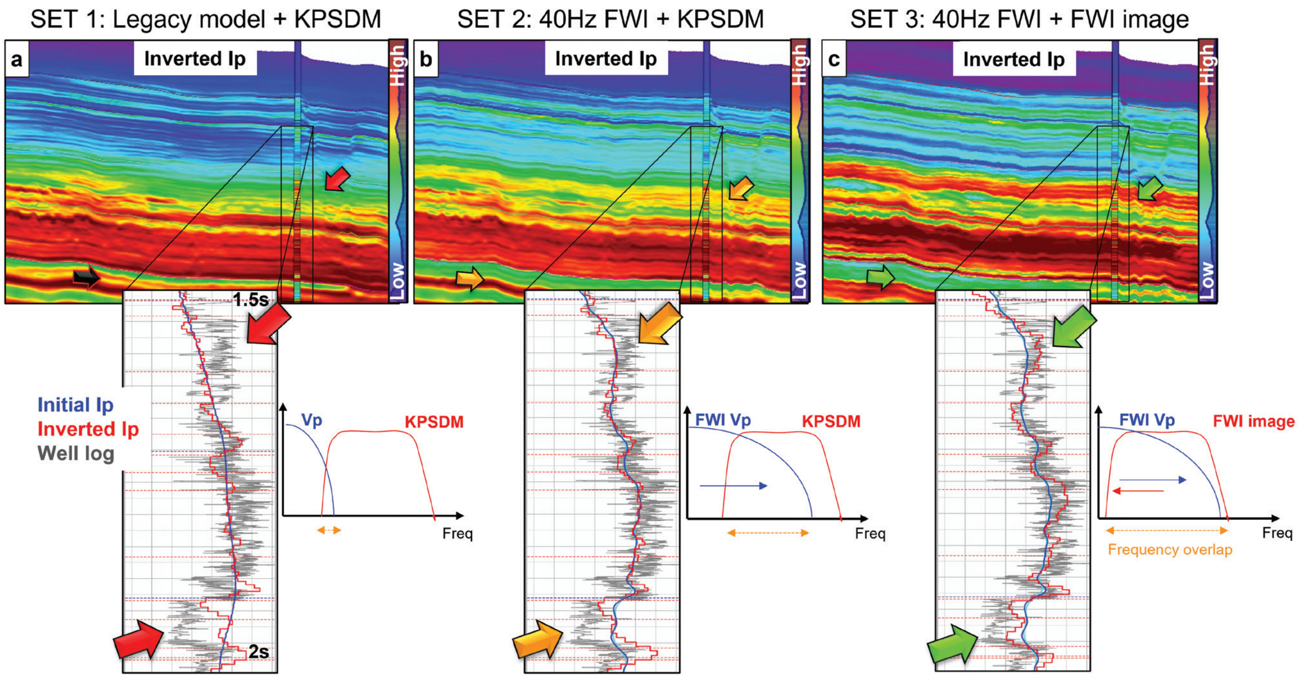

Figure 6 Impedance from stratigraphic acoustic inversion, as a section (top) and extracted at well (bottom), using as input a) tomography velocity and its associated migrated seismic, b) FWI velocity and its associated migrated seismic, c) FWI velocity and its associated FWI Image. For each scenario, a scheme indicates the frequency overlap between initial velocity models and seismic. Arrows indicate the improvement from using better velocity and better reflectivity as input.

The purpose of SET 3 is to evaluate how the extra low-frequency energy present in the FWI Image influences the acoustic stratigraphic inversion results, especially in the presence of strong velocity contrasts. The conversion of a FWI impedance model into an FWI-derived reflectivity can be done through a normal derivative of FWI velocity against local reflectors but its interpretation through stratigraphic inversion may still suffer from its oversimplified 1D time convolution modelling. By deconvolving the FWI Image from its wavelet and then performing acoustic stratigraphic inversion, we obtained an Ip attribute that is indeed limited to 40 Hz high-frequency content but appears better resolved and more consistent with the expected reservoir properties.

Figure 6 shows the inverted attributes for the Ip result for each scenario, with a zoom on the well data for detailed comparison. A statistical wavelet was extracted from each seismic dataset using enough traces to capture the seismic characteristics and a sufficiently large vertical-time window to include the low-frequency information.

In Scenario 1, Figure 6a, the initial Ip model (blue line at the well, where density is derived using Gardner's law) deviates significantly from the measured logs in some intervals, making it difficult for the stratigraphic inversion (red line) to recover the elastic properties accurately from the seismic reflectivity. This is highlighted by the red arrows pointing at two targeted intervals. Scenario 2, shown in Figure 6b, demonstrates the importance of having a good velocity model as input, producing an inversion that better matches the well data. However, at the deeper interval, where a stronger contrast is observed, a mismatch remains between the inversion results and the well log, likely due to the lack of usable very-low-frequency content in the migrated seismic, a common issue in land data. Finally, scenario 3, Figure 6c, shows how incorporating better low-frequency content in the seismic image, here using the FWI Image, can overcome this limitation and improve the capture of those stronger contrasts. This emphasises the importance of combining a high-frequency velocity model with a seismic image containing accurate low-frequency information to achieve improved inversion results. It also shows the benefits of frequency overlap between the a-priori model and the seismic used for stratigraphic inversion.

To emphasise the importance of frequencies below 5 Hz, the low-frequency content (< 5 Hz) was removed from the FWI Image, the wavelet recomputed, and the acoustic stratigraphic inversion rerun. The results, shown in Figure 7, demonstrate that the match between the inversion and the well log in both intervals (indicated by the arrows) is reduced when the FWI Image's low frequencies are omitted.

Finally, by comparing the lowfrequency content (<5 Hz) of the migrated seismic with the 40 Hz FWI model (Figure 8a) and with the FWI Image of the same model (Figure 8b), we see that the FWI Image exhibits superior quality in terms of S/N, event continuity, and amplitude balance. This observation suggests that the high-quality lowfrequency component of the FWI Image can serve as an effective alternative for land data, where reliable low-frequency information is often lacking.

Discussion

While FWI is becoming increasingly powerful and already offers multi-parameter updates of Vp and Q (Xiao, 2018), Vp and Epsilon, or Vp and Vs (Cao et al., 2025), a truly robust multi-parameter FWI for Vp, Vs, and density updates without parameter leakage has yet to be achieved. In the meantime, QI through stratigraphic elastic inversion remains a critical step for extracting essential subsurface properties from the seismic image.

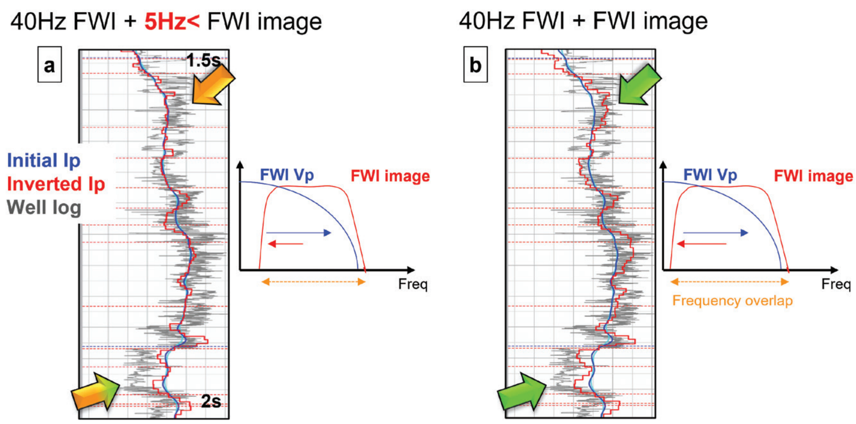

Figure 7 Inverted Ip using FWI velocity and its associated FWI Image. a) results after removing low frequencies below 5Hz, b) with keeping the full frequency content in the image. Arrows indicate the targeted intervals.

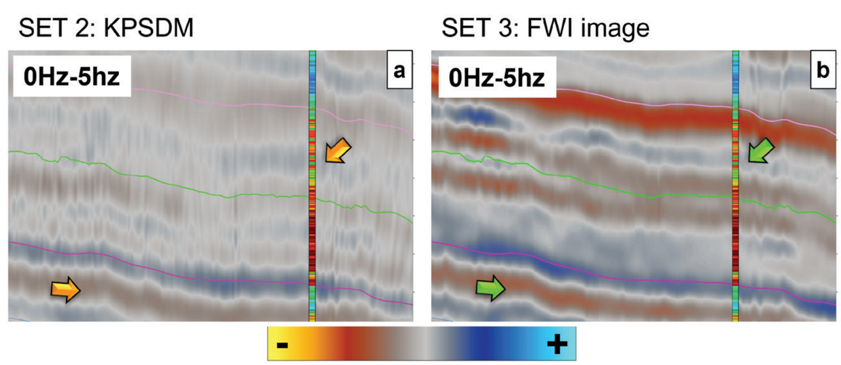

Figure 8 Low-frequency panels for two seismic sets used for the inversion. a) KPSDM seismic migrated with the 40 Hz FWI model. b) FWI Image derived from the 40 Hz FWI model. Embedded in sections, the well with P-Impedance log displayed: red intervals corresponding to high Impedance, blue intervals to low Impedance.

As demonstrated through these two case studies, maximising the frequency bandwidth's overlap between the seismic image and the velocity model appears to be crucial for stratigraphic inversion. Velocity models extrapolated from well data are often insufficient for stratigraphic inversion, because they are limited vertically and laterally by the log coverage, the quality of the logs, and the number of available wells, which markedly increases the uncertainty of the model away from the wells. Therefore, stratigraphic inversion has to rely on the seismic data itself which can be risky when interpreting thin geological features such as channels and stratigraphic traps.

Additionally, here the very low-frequency (<4Hz) components in the seismic image have been filtered out due to their poor quality prior to stratigraphic AVA inversion. Our results indicate that this can lead to suboptimal stratigraphic inversion outcomes. Therefore, improving the quality of low-frequency information in the seismic image is a key factor for successful QI. Moreover, for seismic imaging, in addition to accurate velocity models, preprocessing plays a critical role in removing noise and multiples while preserving AVA information from primary reflections.

While the results presented here provide valuable insights, it is worth noting that the obtained velocity models, particularly for the second case study, could be further improved by using elastic FWI rather than acoustic FWI. Moreover, although the impact of density has been touched upon, it warrants further refinement. Finally, the use of the FWI Image, considered as a reflectivity, for AVA inversion, highlights the potential of its full-bandwidth content and opens the door to further investigation into the impact of FWI Imaging on reservoir characterisation.

FWI remains an active research field with promising developments, such as angle-restricted FWI (Espin et al., 2024) and independent inversion of Vp and Vs (Rest et al., 2025), which continue to advance the integration of FWI with reservoir characterisation.

Conclusions

FWI has now moved from a velocity model-building tool in complex areas to a highly accurate imaging tool. It not only enables improved migrated seismic images, it also offers significant benefits for reservoir characterisation. Through two case studies, we have demonstrated the advantages of using high-resolution velocity models as input for stratigraphic inversion. The velocity details obtained from FWI, taking advantage of a full wavelength update and incorporating not only information from primary reflections but also multiples, ghosts, and diving waves, complement the migrated seismic image information. Furthermore, we have shown the importance of using the low-frequency content recovered by FWI in the stratigraphic inversion process.

Since a robust decoupling of Vp, Vs, and density in FWI is still an ongoing challenge, using QI in combination with FWI remains a crucial step for improving reservoir understanding. Compared to present-day FWI, QI relies on a simplified physical modelling (1D time convolution) but compensates for this through a global optimisation framework that enables a much better decoupling of model parameters and provides greater flexibility for incorporating a priori information. To ensure an effective integration of FWI and QI, it is essential to maintain the highest possible S/N and bandwidth in both seismic images and velocity models.

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