

On the future of reflectivity for understanding elastic attributes with FWI

Introduction

For decades, the quantitative interpretation (QI) of reservoir elastic properties from seismic data has followed a four-stage workflow of preprocessing, model building, imaging, and amplitude-versus-angle (AVA) inversion. Each stage embeds many assumptions that affect the quality of the final result, yet the workflow's overall philosophy, and the cumulative effect of its approximations on amplitude fidelity, has changed very little in this time.

Multi-parameter full-waveform inversion (MP-FWI) provides an opportunity to simplify this workflow. Acoustic MP-FWI inverts the raw (or minimally processed) field data directly to obtain subsurface parameters such as P-wave velocity (V_p), anisotropy, Q-attenuation, and angle-dependent reflectivity simultaneously, treating the multiples and ghosts as valuable signal rather than noise and avoiding much of the subjective preprocessing and model building demanded by the conventional workflow (Burgess et al., 2021; Chemingui et al., 2023; Cooper et al., 2025; McLeman et al., 2021, 2023; Torres & McLeman, 2026; Warner et al., 2022). The reflectivity it produces directly, however, still requires a subsequent traditional AVA-inversion step to yield elastic properties such as P-impedance and V_p/V_s ratio, and the acoustic approximation itself can also break down with high impedance contrasts, e.g., salt and carbonates. Replacing the acoustic assumption with a (visco)elastic propagator removes this additional inversion step entirely, enabling elastic MP-FWI to obtain estimates of the P-impedance, the V_s/V_p ratio and V_p directly from the data, with no reflectivity or traditional AVA inversion generated or needed (Wang et al., 2021; Gomes et al., 2025; McLeman et al., 2026). This, therefore, poses a pressing question, with practical consequences for how QI is performed: what is the future role of reflectivity in imaging and QI?

This paper addresses that question from three directions. Firstly, we review how angle-dependent reflectivity can be generated from an augmented acoustic wave equation in MP-FWI (Burgess et al., 2021; McLeman et al., 2021; Torres & McLeman, 2026) and show an application to real data. Secondly, we show that viscoelastic MP-FWI can obtain the reservoir elastic properties directly (McLeman et al., 2026). Finally, we address the main drawback of dispensing with reflectivity, the loss of an inexpensive way to test alternative rock-physics and low-wavenumber priors, and show this is best treated not by reintroducing reflectivity but as the null-space problem it really is. We show how this can be solved efficiently through a targeted null-space shuttling approach (Keating & Innanen, 2021), including rock-physics and low-wavenumber prior constraints (Matharu & McLeman, 2026).

Elastic attributes: acoustic MP-FWI angle-dependent reflectivity approach

Following Burgess et al. (2021) and McLeman et al. (2021), the acoustic wave equation can be generalised and augmented so that directionally weighted scattering is parameterised explicitly and made invertible at the wave-equation level. In isotropic form this is

$$\frac{1}{V_p^2} \frac{\partial^2 u}{\partial t^2} - \nabla^2 u + \sum_{j=1}^N \nabla r_j \cdot (d_j \nabla u) = s \delta(x - x_0). \quad (1)$$

Where V_p is the P-wave velocity, s is the scaled source term, u is the pressure wavefield, δ is a function that restricts the spatial extent of the source injection, r_j and d_j denote scattering parameters and directivity terms, and N is the number of directional scattering and secondary source terms. Angle-dependent reflectivity can be generated by using scattering proxy components $r_j = \ln(\rho_j)$, and setting directivities to be angle-dependent directivity weights $d_j = w_j(\theta)$. Thus, equation (1) can be written equivalently as

$$\frac{1}{V_p^2} \frac{\partial^2 u}{\partial t^2} - \nabla^2 u + \sum_{j=1}^N w_j(\theta) \nabla \ln(\rho_j) \cdot \nabla u = s \delta(x - x_0). \quad (2)$$

The weights ($w_j(\theta)$) are computed at every point in space and time during propagation from the vector dot product via a Poynting vector-like approach and the reflector normal (many vectors per point can be used to account for multipathing). Inverting for these angle-dependent log density terms recovers the desired AVA trends needed for AVA inversion. This approach is extended to account for anisotropic symmetries.

An application to a 3D towed-streamer dataset from the Australian North West Shelf is shown in Figure 1. The workflow ran to 30 Hz inverting for angle-dependent density, starting from density and velocity models obtained from a prior MP-FWI run with a frequency continuation from 7 to 12 Hz, and produced angle gathers over 0-45° by using $N=9$ secondary-source terms. In the gas-bearing interval the gathers show coherent reflection events with stable amplitudes across the inverted angle range, with some residual moveout on some events visible (red arrows) indicating the velocity and anisotropy models could be further updated. The raw field data, including ghosts and multiples, were used at every inverted frequency step.

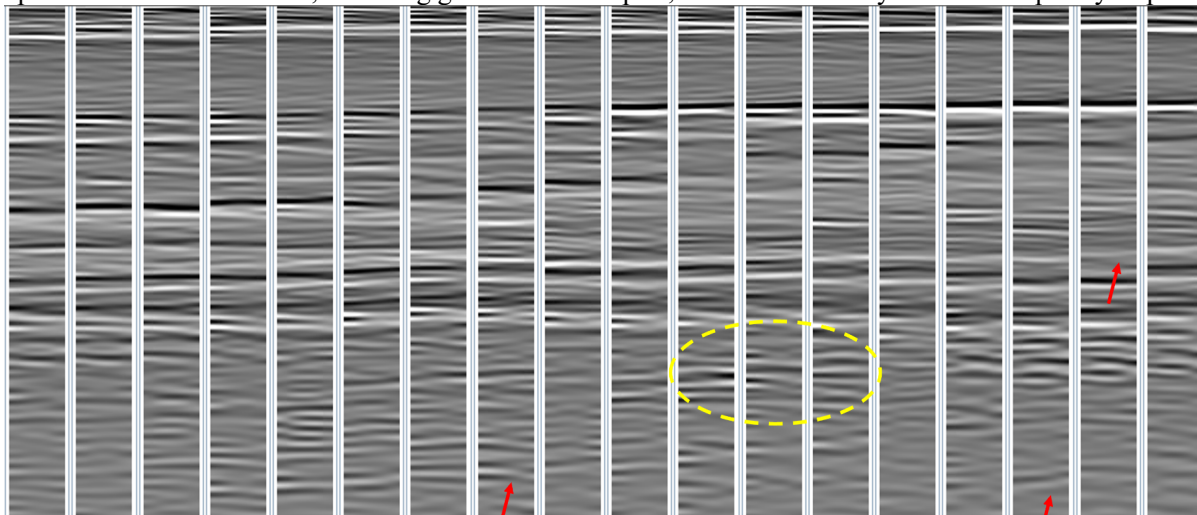


Figure 1 FWI angle gathers along an inline (spaced every 500 m) showing AVA phenomena, the yellow ellipse marks the gas-bearing interval.

Figure 2 shows the intercept, gradient, and their cross-product derived from these FWI angle gathers. They agree well with the expected geology, and the cross-product highlights a localised anomaly at the known gas-bearing interval (orange arrow). The P-impedance, V_p/V_s ratio and other useful reservoir elastic quantities can be obtained from the FWI angle gathers.

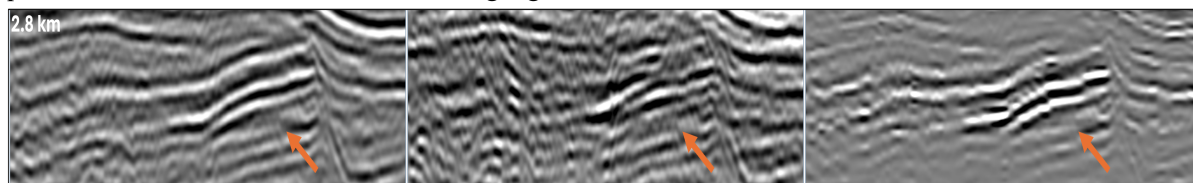


Figure 2 (left) AVA intercept, (middle) AVA gradient, and (right) intercept-gradient cross-product derived from the FWI angle gathers approach.

Elastic attributes: direct estimation from viscoelastic MP-FWI approach

The same dataset was inverted with viscoelastic MP-FWI through a sequence of frequency bands to 60 Hz, following a workflow similar to McLeman et al. (2026). V_p and P-impedance were updated simultaneously from reflections to 19 Hz, without partitioning the data into near and far angles, to constrain both while limiting density leakage into V_p . The large changes in V_p prompted an anisotropy update at 19 Hz. At this stage, the P-impedance was also further refined in a single-parameter FWI using the near angles. A simultaneous P-impedance, V_s/V_p , and V_p inversion then followed up to 35 Hz, and finally V_p , V_s , and density were simultaneously inverted up to 60 Hz, decoupling V_p and density only once the other parameters were well developed. This staging suppresses crosstalk by exploiting the different scattering patterns and wavenumber sensitivities of the parameterisation, and by minimising the complexity of the problem by inverting parameters with different pieces of the data; a complexity which was further reduced by an L-BFGS optimiser with an improved adaptive-gradient estimate of the inverse Hessian (McLeman et al., 2021). The raw field data, including ghosts and multiples, were used at every frequency step.

Figure 3 shows the updated models with high spatial resolution and fine, thin layers well delineated, and the hydrocarbon reservoir is easily identified (black ellipse). The V_p should decrease due to the gas saturation

of the rock, which will have minimal impact on V_s , so the V_s/V_p ratio should increase, and indeed that is what is observed. The gas saturation will cause a decrease in the density as well as V_p , and so the P -impedance should drop and this is also observed. The well data were not used to constrain the inversion.

Viscoelastic MP-FWI recovers elastic properties directly, with no reflectivity or traditional AVA inversion needed. Recovering absolute elastic properties, however, required a QI specialist to build the low-wavenumber priors and rock-physics constraints from the outset, because seismic data are insensitive to background density perturbations, and hydrophone-only data are largely insensitive to background V_s , so FWI alone cannot recover these missing wavenumbers. This creates a dilemma since the correct priors are not always obvious upfront, and testing each one means re-running viscoelastic MP-FWI, which has a larger computational cost than traditional AVA inversion using angle-dependent reflectivity. An alternative approach would be to generate elastic MP-FWI reflectivity angle-gathers instead of going straight to the elastic parameters, but this would then require us to reintroduce traditional AVA inversion approximations into the workflow. Additionally, any changes to the models made by a QI specialist during the traditional AVA inversion stage are not guaranteed to maintain the MP-FWI misfit. This missing wavenumber problem is the same null-space problem a QI specialist faces with reflectivity alone since it carries only part of the information needed, which is why their priors are essential to obtain absolute properties.

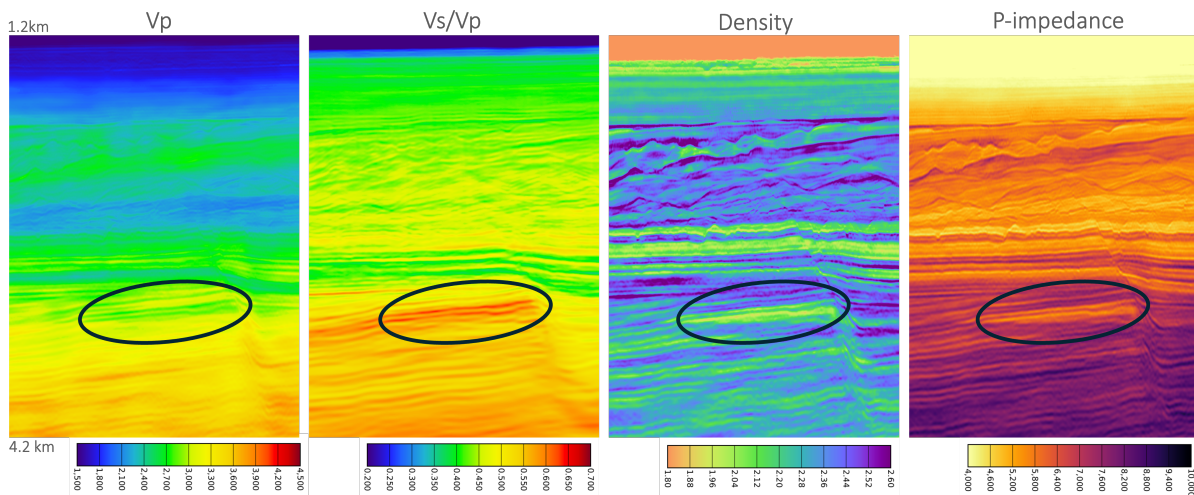


Figure 3 V_p , V_s/V_p , density, and P -impedance results after 60 Hz viscoelastic MP-FWI workflow.

Elastic attributes: targeted null-space shuttling approach

Because many models can fit the seismic data equally well, viscoelastic MP-FWI is first used to recover the best models the data can constrain. For the wavenumbers and regions it cannot, the targeted null-space shuttling (Keating & Innanen, 2021) approach can be extended to incorporate low-wavenumber priors and rock-physics constraints (Matharu & McLeman, 2026). This approach is applied to the elastic MP-FWI outputs. This enables a QI specialist to rapidly trial many priors and recover absolute properties under a quadratic approximation of the elastic FWI objective function, without re-running elastic MP-FWI, and without increasing its data misfit. Figure 4 shows an application of this approach to synthetic data.

Conclusions

Reflectivity is no longer a necessary intermediary for recovering reservoir elastic properties. Acoustic MP-FWI removes much of the conventional workflow's preprocessing and model building, and hence its subjectivity, while still producing angle-dependent reflectivity for AVA inversion from the full wavefield via an augmented acoustic wave equation. Viscoelastic MP-FWI removes the intermediary altogether, recovering P -impedance, V_s/V_p ratio, density and V_p directly from raw or minimally processed data. Dispensing with reflectivity does remove an inexpensive way for a QI specialist to test alternative rock-physics and low-wavenumber priors, but treating this as the null-space problem it really is lets techniques such as targeted null-space shuttling impose evolving priors without re-running computationally intensive viscoelastic MP-FWI. QI expertise is thereby embedded from the very start of a project, in building and refining the low-wavenumber models and constraints through an understanding of the null-space.

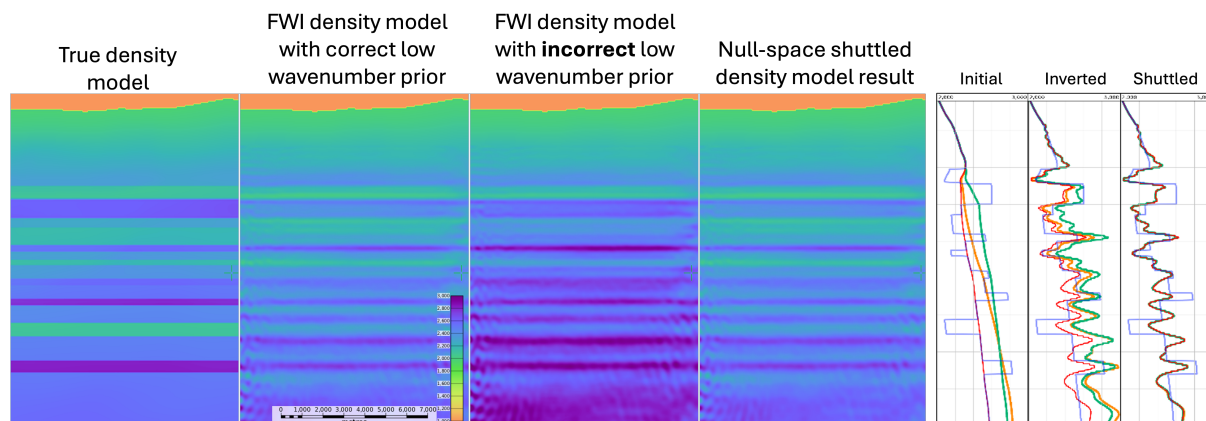


Figure 4 (left) the true density model; FWI starting from a correct low-wavenumber prior; FWI starting from an incorrect prior, the relative but not absolute trend is correct; and the null-space shuttled result, which recovers the true density. The well profiles (right) compare the initial, inverted, and shuttled models where blue is the true model, red starts from a correct initial background density and green and orange start from incorrect initial background density.

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References

- Burgess, T., McLeman, J., Sinha, M., Hampson, G. and Thompson, T. [2021] Seismic wavefield modeling honoring AVO/AVA with applications to full waveform inversion and least-squares imaging.
- Chemingui, N., Yang, Y., Ramos-Martinez, J., Huang, G., Whitmore, D., Crawley, S., Klochikhina, E. and Arasanipalai, S. [2023] Simultaneous inversion of velocity and angle-dependent reflectivity, *Third International Meeting for Applied Geoscience & Energy*, Expanded Abstracts, 625-629.
- Cooper, J., Ratcliffe, A. and Poole, G. [2025] Extracting elastic AVA information from acoustic FWI via an angle-dependent density, *86th EAGE Annual Conference & Exhibition*, Extended Abstracts, 1-5.
- Gomes, A., Rocha, D., Plessix, R.-E., Wong, M., Perkins, C. and Goh, V. [2025] High-resolution impedance estimation using multi-parameter visco-elastic FWI in a Gulf of Mexico setting, *The Leading Edge*, **44**(5), 394-402.
- Keating, S. D. and Innanen, K. A. [2021] Null-space shuttles for targeted uncertainty analysis in full-waveform inversion, *Geophysics*, **86**(1), R63-R76.
- Matharu, G. and McLeman, J. [2026] Imposing rock-physics constraints in full-waveform inversion via targeted null-space shuttling, *Sixth International Meeting for Applied Geoscience & Energy*, Expanded Abstracts.
- McLeman, J., Burgess, T., Sinha, M., Hampson, G. and Thompson, T. [2021] Reflection FWI with an augmented wave equation and quasi-Newton adaptive gradient scheme, *First International Meeting for Applied Geoscience & Energy*, Expanded Abstracts, 667-671.
- McLeman, J., Rayment, T., Burgess, T., Dancer, K., Hampson, G. and Pauli, A. [2023] Superior resolution through multiparameter FWI imaging: A new philosophy in seismic processing and imaging, *The Leading Edge*, **42**(1), 34-43.
- McLeman, J., Badry, J., Rayment, T. and Pauli, A. [2026] Unlocking rock properties using viscoelastic multiparameter FWI, *The Leading Edge*, **45**(5), 370-377.
- Torres, K. and McLeman, J. [2026] Identifying hydrocarbons with FWI-derived angle gathers from an augmented wave equation, *87th EAGE Annual Conference & Exhibition*, Extended Abstracts, 1-5.
- Wang, H., Burtz, O., Routh, P., Wang, D., Violet, J., Lu, R. and Lazaratos, S. [2021] Anisotropic 3D elastic full-wavefield inversion to directly estimate elastic properties and its role in interpretation, *The Leading Edge*, **40**(4), 277-286.
- Warner, M., Armitage, J., Umpleby, A., Shah, N., Debens, H. and Mancini, F. [2022] Full-elastic AVA extraction using acoustic FWI, *Second International Meeting for Applied Geoscience & Energy*, Expanded Abstracts, 907-911.