# New insights from legacy data: MP-FWI imaging in the Gulf of Paria

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## Summary

Traditional reprocessing of legacy seismic data aims to enhance resolution and reduce depth uncertainties, but this is particularly challenging in shallow-water marine environments. These environments often feature complex structures that demand detailed models, which are difficult to capture with traditional methods. This paper introduces an alternative approach using multi-parameter full-waveform inversion (MP-FWI) imaging, applied to legacy field data from a shallow water OBC survey in the Gulf of Paria, Trinidad & Tobago. This new method of seismic processing and imaging bypasses the conventional workflow, offering a more efficient and effective solution. By leveraging the full wavefield, MP-FWI imaging not only simplifies the workflow but also improves the accuracy and detail of the seismic images, making it a valuable tool for working in challenging environments like the Gulf of Paria.

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## Introduction

The traditional reprocessing of legacy seismic data often aims to enhance resolution and reduce depth uncertainties, but achieving such improvements presents unique challenges for shallow-water marine datasets. For OBN and OBC surveys, receiver sampling can significantly impact illumination and imaging of the near surface. These environments can feature complex structures that demand detailed models; however, conventional methods like reflection tomography often fail to capture such intricacies. Additionally, short-period multiples and ghosts obscure primary reflections, necessitating their removal before RTM or Kirchhoff imaging. The iterative testing process to achieve this can be subjective, time-consuming, and the final imaged result is limited by the subset of the wavefield used for imaging.

This paper demonstrates the application of an alternative approach utilising multi-parameter full-waveform inversion (MP-FWI) imaging (McLeman et al., 2023), using legacy field data from a shallow-water OBC survey in the Gulf of Paria, Trinidad & Tobago that had exhausted the potential of traditional reprocessing. MP-FWI imaging is a technique that can simultaneously determine both velocity and reflectivity using the full wavefield, which includes multiples and ghosts. This approach enhances velocity and reflectivity resolution without the need for the complex traditional workflow.

## Background

The Gulf of Paria is situated at the dynamic boundary between the Caribbean and South American plate zones. This region is tectonically active, prominently featuring the El Pilar Fault, which traverses the area. The El Pilar Fault is a major strike-slip fault responsible for significant seismic activity, shaping the geological landscape of the Gulf of Paria (Sierra et al., 2009). This seismic activity has led to the formation of complex geological structures; the Gulf is characterised by its extensive sedimentary basin, which contains thick sequences of Paleogene sediments, including shales and deep-water sandstones, deposited over a fold-thrust belt.

The complex geology of the Gulf of Paria presents significant challenges for seismic processing and imaging. The thick sedimentary layers and faulted structures can create traps and reservoirs for hydrocarbons, but their detection and characterisation require advanced seismic techniques and detailed geological models. The interplay between tectonic forces and sedimentation processes has resulted in a rich but challenging environment for geologists and geophysicists working in the region. Understanding and navigating these challenges is essential for successful exploration and development (Howe et al., 2024).

Reprocessing efforts using conventional methods were undertaken in 2021 to enhance the seismic data quality of an area covered by three OBC datasets acquired in 1992, 2005, and 2014. This workflow comprised of many steps, each requiring meticulous consideration of numerous parameters. Legacy results suffered from poor signal-to-noise content and limited imaging of shallow and steep dipping structures. Tailored methodologies were needed for each survey to optimise the recovery of primary signal. Addressing the significant mud roll noise on the vertical velocity component for both the 2005 and 2014 datasets was key, particularly in areas of poor illumination. FKK filtering was applied to 3D cross-spread sorted data for the 2014 survey to target mud roll noise with a coherent linear 3D character. For the narrow azimuth 2005 OBC, the repeatability of the signal between the components was leveraged to limit primary leakage during Vz-denoise. All pressure components, including the single component 1992 dataset, went through a uniquely parameterised and complex denoise flow. These noise attenuation steps contributed to a significant portion of the reprocessing workflow. Through deghosting, the bandwidth limitations caused by free surface ghost reflections were addressed, broadening the spectrum. Demultiple was necessary due to the limitations of conventional migration algorithms. Traditional reverse-time migration (RTM) and Kirchhoff methods cannot accurately image multiple energy, necessitating input that contains only primary reflections. By attenuating multiples in the input data, they are prevented from being mapped incorrectly into the image domain. To reduce subsurface sampling issues of the primary signal caused by the acquisition geometry, interpolation and regularisation algorithms were employed before migration.

The reprocessing efforts, which included diving wave FWI up to 12 Hz maximum and ray-based RMO tomography, improved the imaging of the deeper sections beneath the Mid-Miocene, simplified the stack structure, and improved spatial resolution but the extent of the uplift was limited by the data itself. Modern seismic acquisition techniques hold the potential to reduce remaining issues related to non-surface consistent amplitude variations, spatial sampling, velocity uncertainty, fault shadows, and limited source penetration, but can be expensive. Therefore, the MP-FWI imaging approach was deployed and indicated additional improvement was possible with this legacy data. MP-FWI imaging, utilises the full wavefield and offers an alternative approach to extract more information from legacy data than is possible using conventional techniques (McLeman et al., 2023).

MP-FWI imaging requires minimal pre-processing and can leverage previously discarded features of the wavefield such as free surface and interbed multiples as well as ghosts. MP-FWI imaging is designed to discriminate kinematic and dynamic effects allowing for the simultaneous determination of a velocity model and true-amplitude reflectivity. This new approach to seismic processing and imaging is able to bypass the conventional processing and imaging workflow and has been demonstrated for streamer and OBN acquisitions in a wide range of geological environments (Hirst et al., 2024; Rayment et al., 2023).

**Examples**

The 37 Hz (maximum) RTM result of the 2021 reprocessing and imaging (Figure 1) demonstrates the challenges that MP-FWI imaging successfully resolved. The conventional migration suffers from poor shallow imaging due to sparse line spacing and a lack of near offsets, which hindered effective velocity model building. Additionally, high noise levels in areas of low reflectivity proved difficult to manage without negatively impacting the signal, particularly around steeply dipping structures and faults. While the final result was robust (Figure 1), it remained constrained by the limitations, assumptions and approximations inherent in its construction.

As MP-FWI imaging was performed using only the pressure component, the denoise of the vertical component was not required nor the extensive Vz-denoise flow. Additionally, the denoise steps required for the pressure component were much reduced compared to the conventional workflow. Statistical survey matching was applied so that a single modelled wavelet based on the 2014 source configuration could be used. The velocity model from reprocessing was smoothed and diving wave FWI up to 16 Hz (maximum) was applied to generate the initial model for MP-FWI imaging which was run up to 37 Hz (maximum) in frequency steps. The resulting reflectivity (Figure 2) demonstrates significantly improved illumination across the area. The MP-FWI image is significantly clearer; the steep dips and faulting structures, near the white arrows, are more apparent. Near the yellow arrows there are notable improvements in the imaging beneath fold coverage gaps and regions previously obscured by noise are imaged clearly. Both temporal and lateral resolution have increased thanks to the least squares imaging. MP-FWI imaging has utilised the full wavefield providing a more comprehensive view of the subsurface compared to the up-going, primary-only conventional image.

The velocity update achieved here significantly surpassed the results of the reprocessing effort. The velocity variations caused by the Gulf's complex geology have been explained by a laterally high-resolution model of the shallow sediments with stronger structural conformability even at depth (Figure 3). Comparing the reprocessing and final MP-FWI imaging velocities with numerous wells within the area, we observe a more accurate model with improved vertical resolution as demonstrated by the well checkshot profile (Figure 4).

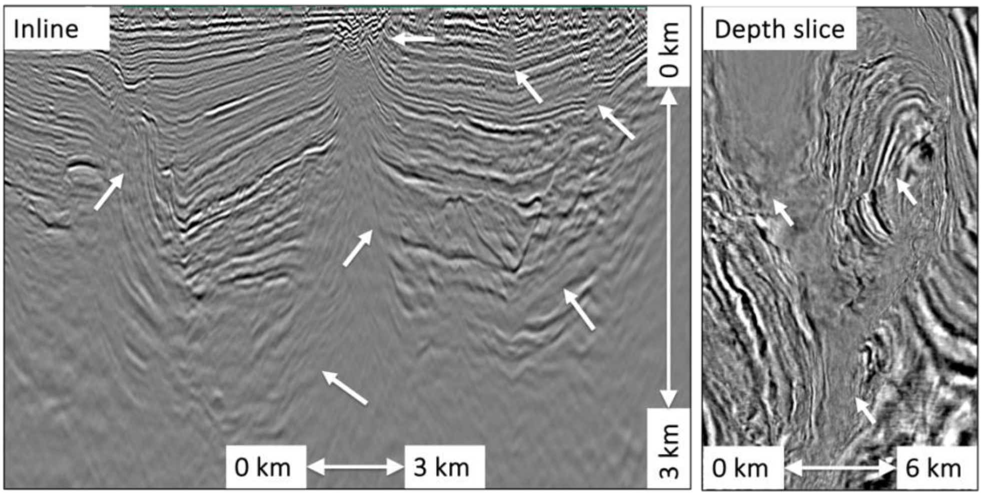


***Figure 1*** *RTM of the prior reprocessing demonstrates challenges of imaging the shallow section, steeply dipping events and fault shadows.*

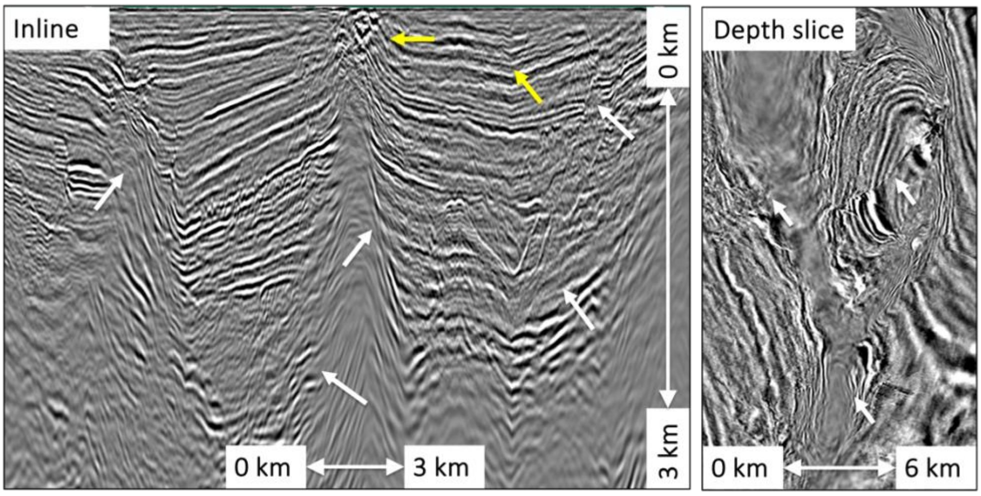


***Figure 2*** *MP-FWI imaging reflectivity produced from minimally processed data using the full wavefield demonstrates improvements in imaging of the shallow section, steeply dipping events, fault shadows and illumination.*

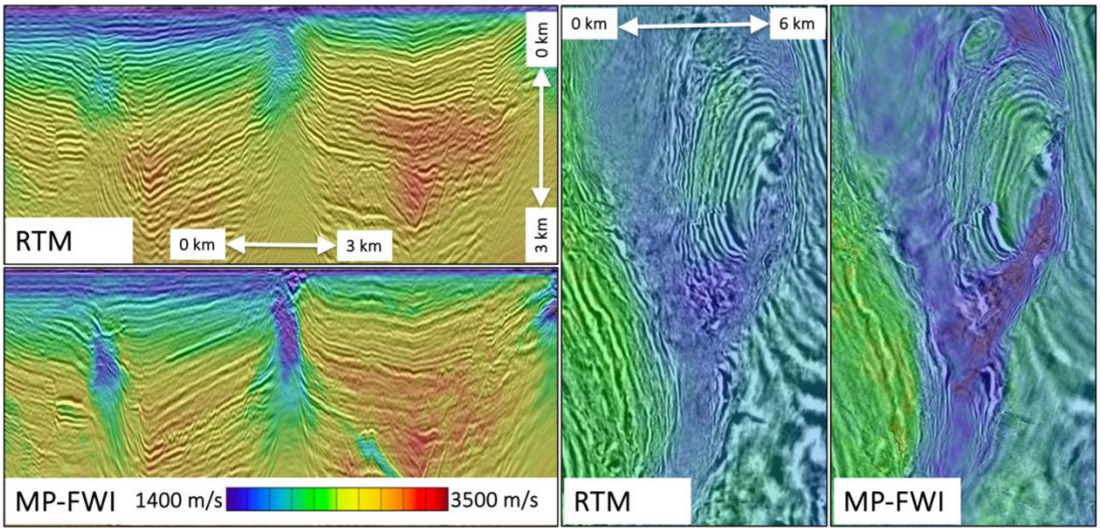


***Figure 3*** *RTM and MP-FWI imaging velocity overlay illustrating the increased resolution and structural conformability of the velocity.*

## Conclusions

This case study from the Gulf of Paria demonstrates the ability of MP-FWI imaging to uncover new insights from legacy data without the conventional complex processing workflow. The MP-FWI imaging reflectivity, formed using ghosts and all orders of multiple energy present in the data, allows for a much simpler workflow. Comparing the reflectivity generated by MP-FWI imaging with that of a conventional RTM highlights improvements in resolution, amplitude balancing, and structural continuity, particularly in the near surface. With MP-FWI imaging, legacy datasets have the potential to offer new insights into the subsurface without complex and time-consuming reprocessing or investing in newly acquired seismic data. Further improvements may be realised through the use of elastic MP-FWI imaging which would treat features like mud-roll as valuable signal, providing additional insights into the subsurface. This region's exploration history includes both oil and gas discoveries, underscoring the importance of improving our understanding of the Gulf to the hydrocarbon industry.


## Acknowledgements

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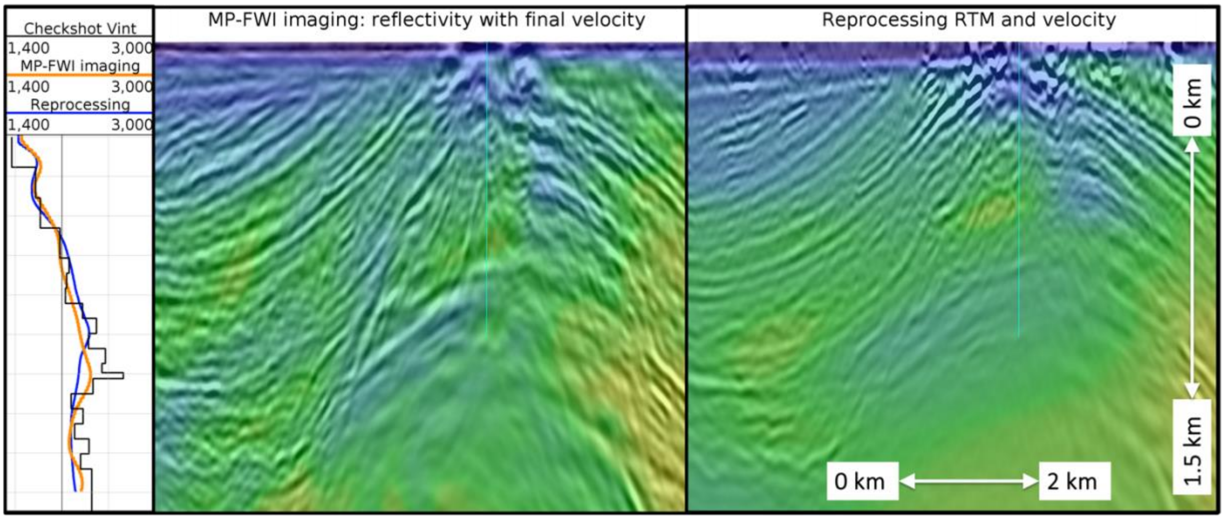


***Figure 4*** *Comparisons of the well checkshot velocity (black), MP-FWI imaging velocity (orange), and final velocity from reprocessing (blue). Overlay of the final 37 Hz MP-FWI reflectivity and imaging velocity. Overlay of the 37 Hz RTM and velocity from the prior reprocessing effort.*

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