MP-FWI imaging in the Gulf of Paria, Trinidad and Tobago

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Summary

Reprocessing legacy seismic data traditionally aims to improve resolution and reduce depth uncertainties, but shallow-water marine datasets pose unique challenges. In OBN and OBC surveys, receiver sampling can greatly impact near-surface illumination and imaging. These environments can feature complex structures that demand detailed models, which conventional methods like reflection tomography struggle to capture. Additionally, short-period multiples and ghosts obscure primary reflections, necessitating their removal before reverse-time migration (RTM) or Kirchhoff imaging. The iterative testing process to achieve this can be subjective, time-consuming, and limited by the subset of the wavefield used for imaging.

This paper presents 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. MP-FWI imaging can simultaneously determine both velocity and reflectivity using the full wavefield, which includes multiples and ghosts. This method enhances velocity and reflectivity resolution without the need for the complex conventional workflow.

Background

The Gulf of Paria is situated at the dynamic boundary between the Caribbean and South American plates. 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). Sands deposited by a proto-Orinoco River overly deep-marine shale source rocks. Large diapiric anticlines which trend E-NE developed in synchrony with deposition and are preferred hydrocarbon traps. The Los Bajos fault, which cuts across the basin, experienced its greatest movement after folding and acts as a feeder between the organically rich shales and sandstone reservoirs (Woodside, 1981).

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 characterization require advanced seismic imaging 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).

Method

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 consisted 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 workflows were needed for each survey to optimize 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. All pressure components, including the single component 1992 dataset, went through a uniquely parameterized and complex denoise flow. These noise attenuation steps played a crucial role in the reprocessing workflow. By 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 RTM and Kirchhoff methods cannot accurately image multiple energy, necessitating an 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 mitigate subsurface sampling issues of the primary signal caused by the acquisition geometry, interpolation and regularization algorithms were applied 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, though 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 offers an alternative approach which can extract

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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 wavefield features 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 bypasses the conventional workflow and has been demonstrated for streamer and OBN acquisitions in various geological environments (Hirst et al. 2024 and Rayment et al. 2023).

Results

Although the outcome of the 2021 reprocessing and imaging effort was robust (Figure 1), it was still limited by the inherent constraints, assumptions and approximations in its construction. With water bottom depths ranging from 5 to 30 meters and sparse line spacing, the conventional RTM image exhibited poor shallow imaging. Interference of residual multiple and noise, combined with a lack of near offsets, impeded the effective building of a velocity model. Furthermore, managing high noise levels in areas of low reflectivity proved challenging without adversely affecting the signal, especially around steeply dipping structures and faults. These issues highlight the difficulties in achieving accurate imaging in such complex geologic settings, underscoring the need for more advanced techniques to overcome these limitations.

MP-FWI imaging was performed using only the pressure component of the 2014 survey. A milder, simpler denoise was applied compared to the conventional workflow. Neither the complex denoise of the vertical component was required nor the extensive Vz-denoise flow. A single source signature was modeled based on the 2014 source configuration. Due to the uncertainties in the positioning and signature of the 1992 survey, it was excluded from the input to MP-FWI. Diving wave FWI was revisited to a maximum frequency of 16 Hz, generating an initial model for MP-FWI imaging. The MP-FWI imaging was then conducted in frequency steps up to a maximum of 37 Hz. The resulting reflectivity (Figure 2) demonstrates a marked improvement in amplitude balance due to the illumination compensation provided by the least-squares imaging aspect of MP-FWI. The MP-FWI image is notably clearer with the steep dips and faulting structures near the white arrows being much more distinct and apparent. Near the yellow arrows there are improvements beneath fold coverage gaps, and regions previously obscured by noise are imaged clearly. Both vertical and lateral resolution have increased thanks to

the least-squares imaging. MP-FWI imaging has utilized 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 outperformed the results of the reprocessing effort. The updated velocity model significantly improves imaging accuracy at all depths. Higher lateral resolution is achieved in the shallow sediments, and structural conformability is improved at depth (Figure 3). When comparing the reprocessing and final MP-FWI imaging velocities with numerous wells within the area, we observe a more precise model with improved vertical resolution, as demonstrated by the well checkshot profile (Figure 4a). The common offset vector regularized gathers from the 2021 reprocessing were migrated with Kirchhoff pre-stack depth migration (PreSDM) to further access accuracy. When migrating with the model from reprocessing (Figure 4d), strong variations of curvature with azimuth were observed. When migrating with the MP-FWI velocity all offsets and azimuths are better imaged at their common depth points, resulting in flatter gathers and indicating the variation was largely due to a lack of velocity resolution (Figure 4e).

Conclusions

This case study from the Gulf of Paria showcases the capability of MP-FWI imaging to extract new insights from legacy data without the conventional, complex processing workflows. The MP-FWI imaging reflectivity, which incorporates ghosts and all orders of multiple energy present in the data, enables a much simpler workflow. Comparing the reflectivity generated by MP-FWI imaging with that of a conventional RTM reveals significant improvements in resolution, amplitude balancing, and structural continuity, especially in the near surface. With MP-FWI imaging, legacy datasets have the potential to offer new insights into the subsurface without the need for time-consuming reprocessing or the expense of acquiring new seismic data. Further enhancements may be achieved through the use of elastic MP-FWI imaging, which would treat features like mud-roll as valuable signals, offering additional insights into the subsurface.
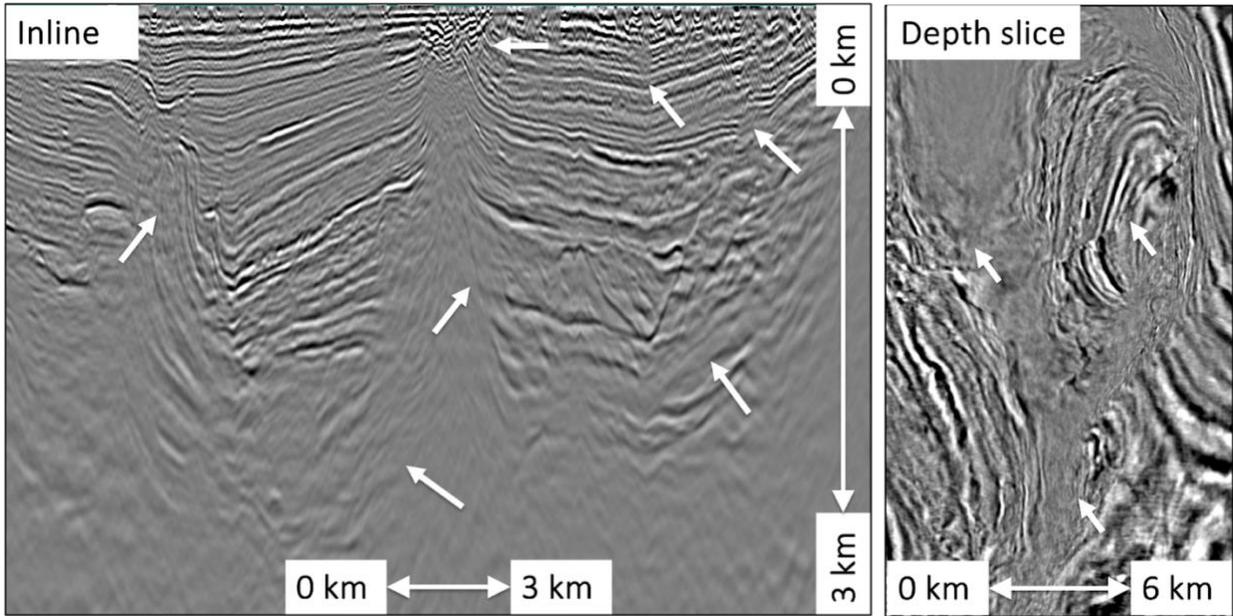
Acknowledgments

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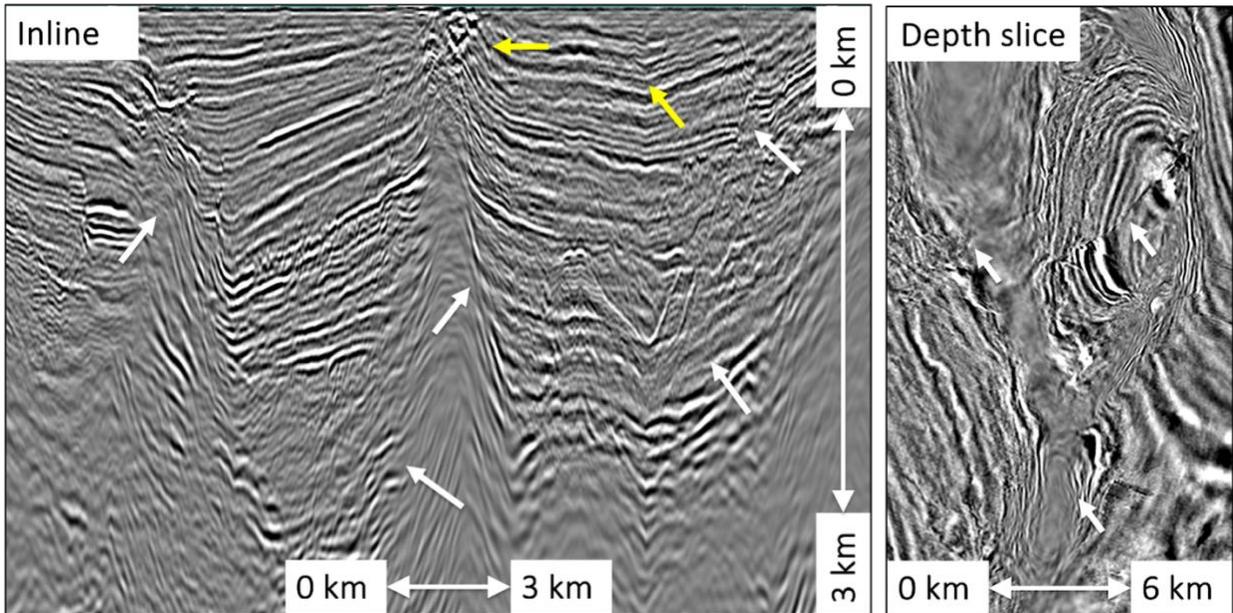

Figure 2: MP-FWI imaging reflectivity produced from minimally processed data using the full wavefield demonstrates improvements in imaging of the shallow section, steeply dipping events, fault shadows and illumination.

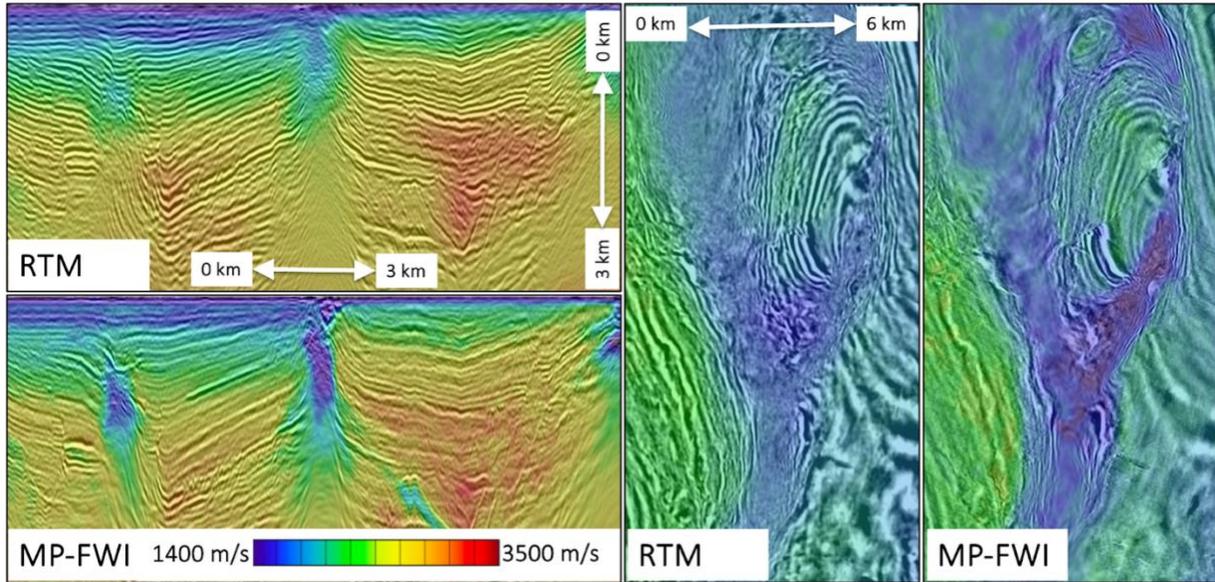# MP-FWI imaging in the Gulf of Paria, Trinidad and Tobago

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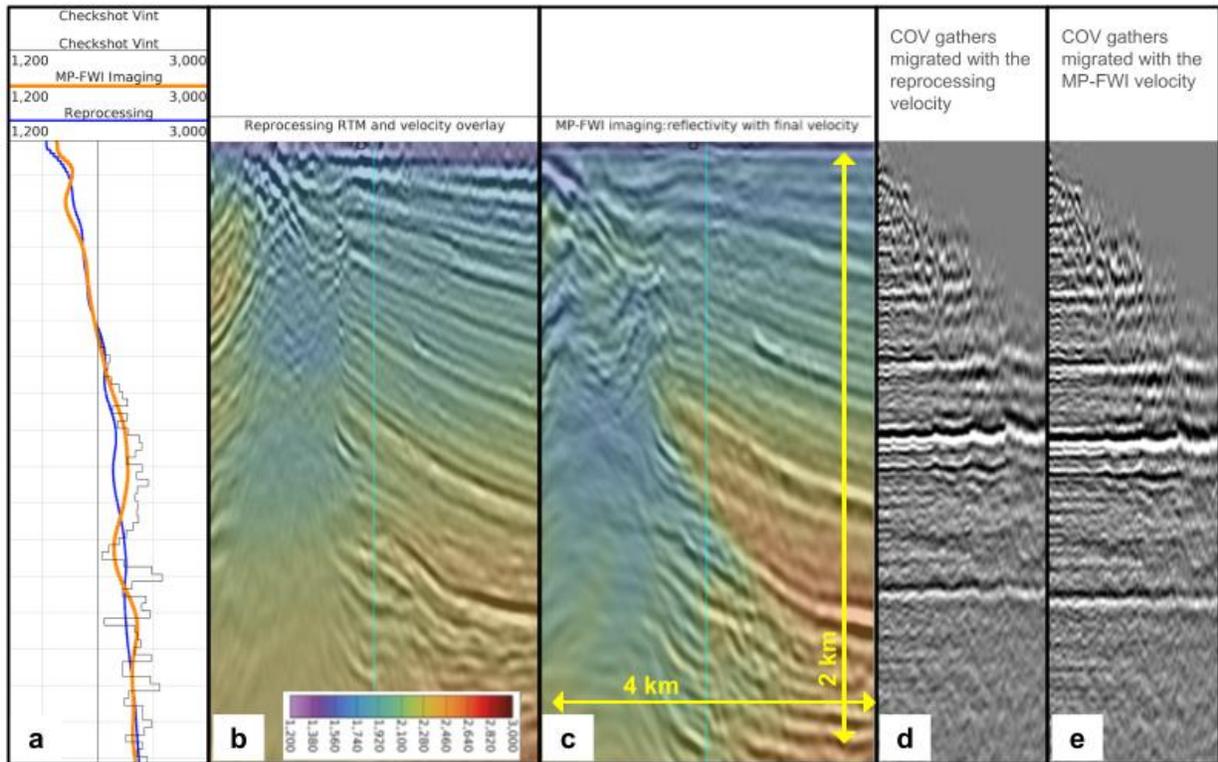

Figure 4: a) Comparisons of the well checkshot velocity (black), MP-FWI imaging velocity (orange), and final velocity from reprocessing (blue). b) Overlay of the 37 Hz RTM and velocity from the prior reprocessing effort with the well marked in cyan. c) Overlay of the final 37 Hz MP-FWI reflectivity and imaging velocity with the well marked in cyan. d) Kirchhoff PreSDM COV gathers migrated with the velocity from reprocessing. e) Kirchhoff PreSDM COV gathers migrated with the velocity from MP-FWI imaging.