Enhanced Imaging in the Llanos Basin Through a Novel Acquisition Design and Multi-Parameter Full-Waveform Inversion

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Summary

Legacy 3D surface seismic data in the study area are constrained by limited spatial coverage, narrow bandwidth, and inadequate subsurface illumination. These constraints reduce imaging resolution and increase uncertainty in structural interpretation and reservoir characterization, particularly with respect to fault geometry, compartmentalization, and reservoir distribution.

This paper presents results from a newly acquired 3D seismic survey that employs a fit-for-purpose acquisition design integrated with state-of-the-art processing, depth imaging, and multi-parameter full-waveform inversion (MP-FWI). The acquisition geometry was specifically engineered to enhance subsurface illumination across the target area while maintaining operational efficiency. When combined with broadband processing and advanced velocity model building, the workflow delivers more accurate velocity models, improved depth positioning, enhanced fault delineation, and increased seismic resolution. The resulting seismic image significantly improves confidence in structural interpretation and reservoir characterization, thereby supporting more informed development decisions.

Method

This study is based on a purpose-designed seismic acquisition developed to address the shortcomings of the legacy 3D dataset and to enhance subsurface illumination as well as spatial resolution. The legacy survey employed a conventional orthogonal source–receiver line geometry with relatively sparse line and point spacing, resulting in limited azimuthal coverage and inadequate spatial sampling. Consequently, the legacy data suffered from suboptimal subsurface illumination, diminished resolution in structurally complex areas, and persistent challenges in accurately imaging fault systems.

To address these shortcomings, a new acquisition program was designed with the explicit objective of increasing sampling density and improving illumination over the target area. The integration of the new acquisition with the legacy dataset effectively expands the acquisition footprint, delivering improved wavefield sampling, broader azimuthal coverage, and enhanced offset distribution. Together, these factors enable more complete subsurface illumination and form the foundation for a higher-fidelity seismic image. Figure 1 illustrates the spatial extents of the two surveys, with the new acquisition outlined in red and the legacy coverage shown in grey.

The new survey utilizes colocated sources and receivers deployed in a dense, purpose-built geometry, in contrast to the traditional orthogonal line-based layout of the legacy acquisition. This configuration provides superior near-offset coverage, which is critical for high-resolution imaging. When combined with modern processing and imaging workflows, the acquisition

design becomes a primary driver of improved image quality. Enhanced sampling and illumination support more effective noise attenuation, more stable FWI convergence, and more accurate depth imaging. As a result, the merged dataset delivers markedly improved structural clarity, sharper fault definition, and increased resolution relative to the legacy data alone.



Survey	Year	Source Line (SL)	Receiver Line (RL)	Source Point (SP)	Receiver Point (RP)	Active Patch
New	2025	200 m	200 m	10 m	10 m	All Live
Legacy	2009	600 m	300 m	300 m	120 m	10RL x 300RP

Figure 1: The new acquisition (red) and legacy acquisition (grey) are shown for comparison. The new acquisition is characterized by substantially denser source and receiver line and point spacing, providing improved spatial sampling relative to the legacy survey.

Workflow

The seismic processing workflow was designed to maximize the value of both the newly acquired and legacy datasets through a fully integrated and consistent approach. Pre-processing involved multiple iterations of targeted noise attenuation, including suppression of coherent and incoherent noise, followed by surface-consistent corrections to stabilize the seismic response across the two surveys. Survey matching proved to be a critical component of the workflow, as a single, consistent wavelet was used for the full-waveform inversion stage. To achieve this, a sophisticated time-lapse style matching algorithm was employed. A least-squared-error optimization technique was used to derive a shaping filter that effectively transformed the legacy dynamite data to match the phase and amplitude characteristics of the newly acquired vibroseis data. This process ensured a seamless integration of the two surveys and minimized acquisition-related discrepancies that could otherwise degrade the FWI and imaging results.

Velocity model building (VMB) began with the construction of an initial model derived from a combination of first-break refraction tomography and heavily smoothed well sonic logs. This starting model provided a robust long-wavelength framework; however, it lacked the resolution required to adequately capture shorter-wavelength velocity variations critical for accurate imaging. MP-FWI played a key role in bridging this gap, enabling a substantial enhancement of the velocity model by incorporating the full wavefield information. MP-FWI has been demonstrated to be particularly effective in resolving high-frequency velocity details in the Llanos Basin, leading to improved subsurface characterization and imaging fidelity (Varner et al., 2025; Phillips et al., 2025).

Building on this foundation, the shallow velocity field was significantly refined using refraction FWI to better resolve near-surface heterogeneity, which is essential for mitigating statics-related uncertainties and improving downstream imaging. The refraction FWI was implemented using a multi-scale strategy, starting at 7 Hz and progressing through three frequency stages—7 Hz, 9 Hz, and 12 Hz—ensuring stable convergence from long to intermediate wavelengths while progressively increasing model resolution.

For the deeper section, two iterations of reflection tomography were required to update the long-wavelength background velocity field. Following tomography, viscoacoustic MP-FWI was applied to further refine the velocity model and capture higher-resolution structural detail beyond the limits of conventional ray-based methods. The inversion employed a cascaded frequency strategy, with the maximum frequency progressively increased from 17 Hz to 40 Hz in four stages (17 Hz, 25 Hz, 30 Hz, and 40 Hz). This hierarchical approach first resolved the broad, regional velocity trends at low frequencies and then incrementally incorporated higher-frequency information to sharpen velocity contrasts.

In the MP-FWI workflow, velocity and reflectivity were inverted simultaneously. The resulting velocity model served as input for a conventional Kirchhoff migration, whereas the reflectivity was retained as an independent imaging output. One of the principal strengths of MP-FWI lies in its capacity to account for both primary and multiple reflections within a unified least-squares inversion framework. In contrast to traditional approaches that rely on pre-imaging multiple attenuation, MP-FWI leverages multiple energy as part of the inversion process, effectively increasing wavefield sampling and enhancing illumination of the subsurface. This leads to improved image quality and robustness, particularly in structurally complex geological environments (Phillips et al., 2024).

Upon completion of velocity model building, the final imaging phase was carried out using Kirchhoff prestack depth migration. The migrated volume was then processed through a comprehensive post-migration workflow, including amplitude balancing and structural filtering, to enhance continuity, resolution, and interpretability of geological features. The integrated workflow—anchored by the novel acquisition design and advanced MP-FWI—resulted in a high-quality depth image with significantly improved structural definition and resolution compared to the legacy dataset.

Results

The final Kirchhoff prestack depth-migrated seismic volume exhibits a marked improvement in image quality relative to the legacy 3D dataset (Figure 2). Structural features are imaged with enhanced clarity, continuity, and resolution, while fault planes are more sharply defined and readily interpretable.

The FWI-updated velocity model (Figure 3) provides more accurate depth positioning and a meaningful reduction in structural uncertainty. Improved low-frequency content enables stable long-wavelength velocity updates, while the broadband nature of the data enhances vertical resolution. The synthetic gathers shown in Figure 3 demonstrate significantly improved event alignment and amplitude behavior in the final model compared to the initial model, confirming the kinematic as well as dynamic validity of the FWI solution. In addition, the optimized acquisition geometry improves spatial sampling density and offset–azimuth diversity, increasing effective wavefield coverage and subsurface illumination uniformity,

which in turn enhances imaging resolution and yields a more balanced and geologically consistent seismic image.

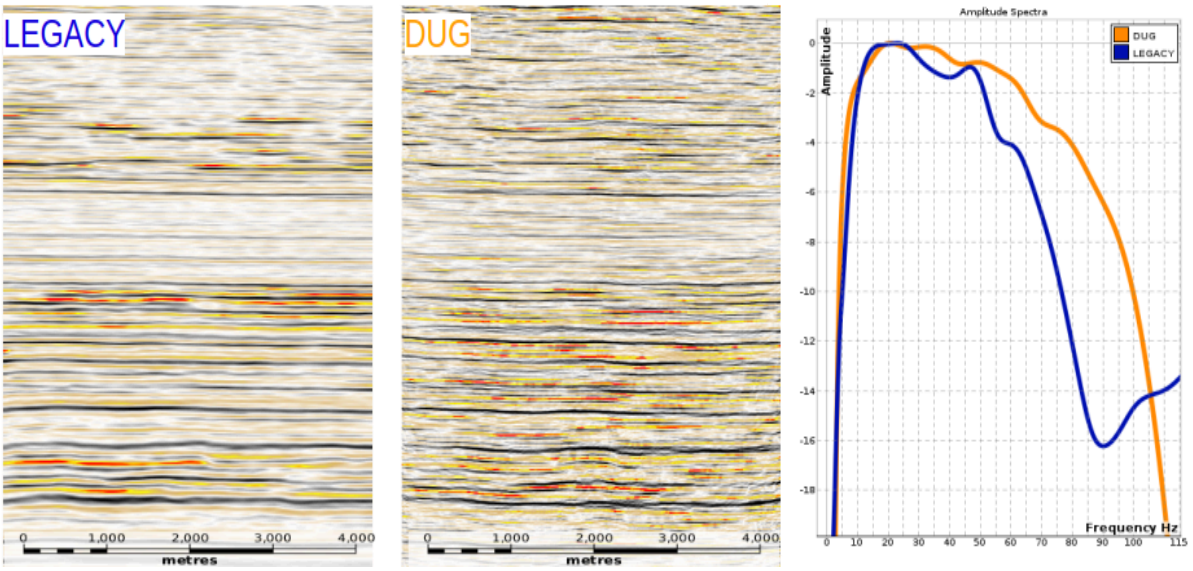


Figure 2: Stack comparison of legacy and the new depth migrated volumes highlighting improvements in structural definition and resolution. The amplitude spectra indicate a large increase in bandwidth on the new product relative to the legacy section.

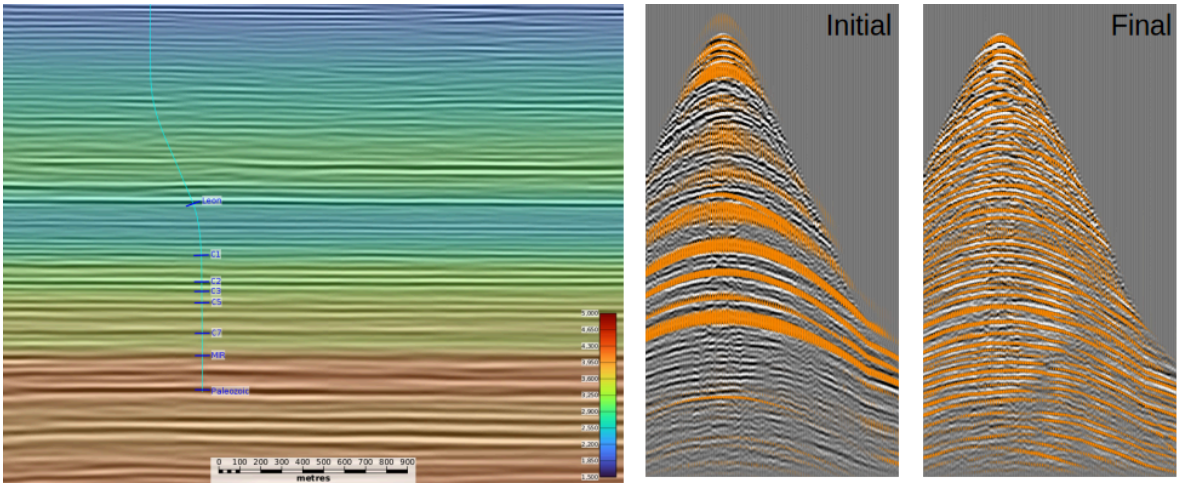


Figure 3: High-resolution 40 Hz velocity model derived through MP-FWI, overlaid on the reflectivity volume. Synthetic gathers from the initial and final models are included, showing significantly improved event alignment and amplitude after MP-FWI.

Several important observations arise from the results. Enhanced fault delineation enables more reliable evaluation of structural compartmentalization, while improved structural depth accuracy supports more confident well planning and field development decisions. The increased resolution allows better mapping of reservoir geometry and stratigraphic terminations. Collectively, these advances demonstrate that the integration of a fit-for-purpose acquisition design with MP-FWI effectively overcomes the inherent limitations of legacy seismic data, delivering a substantial increase in subsurface interpretability.

Conclusions

The integration of a novel vibroseis acquisition design with advanced processing, MP-FWI, and depth imaging has delivered a significant improvement in seismic image quality. Enhanced illumination and improved spatial sampling have resulted in more accurate velocity models and superior structural definition. The combined dataset provides improved depth positioning and increased resolution compared to the legacy seismic alone. This study demonstrates that fit-for-purpose acquisition, when coupled with modern imaging workflows, can substantially reduce subsurface uncertainty and enable more confident exploration and development decisions.

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