

Advancing subsurface imaging through FWI-enabled hybrid acquisition workflows

Introduction

The performance of full-waveform inversion (FWI) is fundamentally shaped by acquisition design. The configuration of survey geometry, azimuth and offset distribution, and frequency content all influence wavefield sampling and impact the stability and resolution of inversion results. Ocean-bottom node (OBN) acquisition has become the benchmark for high-quality FWI input, delivering full-azimuth, long-offset, and low-frequency-rich data that can drive model updates deep into complex geological settings. However, economic limitations can make OBN acquisition unfeasible, especially during the early phases of prospect development. At the same time, many basins remain densely covered by legacy towed-streamer data, which—despite some notable limitations—represents a valuable imaging resource. This paper explores how combining sparse OBN acquisition with legacy streamer datasets enables a flexible, cost-effective approach to FWI-based imaging, balancing short-term efficiency with long-term scalability across for exploration and reservoir development.

Theory

FWI is most effective when the wavefield is well-sampled, with long offset, full azimuth, and low-frequency content providing critical leverage in resolving both low- and high-wavenumber components of the subsurface. Modern OBN acquisition, when paired with low frequency sources, go a long way to meet these requirements (e.g. Baptiste *et al.*, 2024, Davies *et al.*, 2024). In contrast, towed-streamer surveys are typically constrained by limited offset and have significantly narrower azimuth sampling. Some “exotic” exceptions involving multi-vessels configurations have attempted to improve this – MAZ, WAZ, FAZ – however, in most cases, sampling limitations remain. When combined with immature initial earth models, these limitations of streamer acquisition reduce FWI’s sensitivity at depth and around complex structures, decreasing significantly the ability of the inversion to converge quickly. This results in stable results only being achieved in the shallower part of the subsurface, and in simpler geological settings.

The more recent evolution of FWI have been focused on a reformulation of the physics underlying the inversion, moving from acoustic to elastic assumptions in the wavefield propagation. Numerous field studies highlight the advantages of elastic FWI applied to full-azimuth OBN data in complex geological settings like the Gulf of Mexico and offshore Brazil (e.g. Brando *et al.*, 2023, Macesanu *et al.*, 2024, Vigh *et al.*, 2022). However, despite these significant advances, the ability of FWI to succeed remains dependent on the data used in the inversion, and therefore the acquisition geometry, with OBN surveys clearly important in many settings.

Sparse OBN for Velocity Model Building

Sparse OBN surveys provide a practical alternative to more costly, dense layouts, while still meeting the sampling requirements of FWI. Several studies have demonstrated the value of FWI applied to sparse OBN datasets in complex geological settings. Huang *et al.* (2020) demonstrated successful FWI using sparse OBN data in the Gulf of Mexico, achieving geologically consistent updates across a large survey area, where legacy methods have struggled. Recovering clearer pictures of the deep, sub-salt targets is achieved using very low-frequency information from the OBN data, with marked improvements achieved using data up to 15 Hz sufficient for generating a valuable structural picture of the subsurface.

Integrating Legacy Streamer Data for Imaging

While streamer surveys may not always be ideal for FWI, they retain value for high-resolution imaging. The industry maintains extensive archives of legacy streamer data, accumulated over several decades of seismic survey activity around the world. As processing technologies have evolved, these legacy datasets often undergo cycles of reprocessing – extending their bandwidth, suppressing noise,

addressing complex multiples, reimaging – each time unlocking more of the subsurface information imbedded in the data. Despite these technology-driven rejuvenation efforts, our ability to fully harness their potential is inherently limited by the accuracy of the velocity model used to create images.

Thus, a hybrid workflow has emerged: sparse OBN data feeding the FWI process to build a robust, data-driven, geologically consistent earth model; previously processed legacy streamer data is then reimaged using this superior model. The structural picture provided by the FWI derived products is complemented by improved phase and amplitude compliant imaging. The result is an improved understanding of the subsurface due to better image quality and greater continuity of structural and stratigraphic features, underlined by valuable quantitative information—all achieved in a progressive and cost-effective manner.

Case Study – Gulf of Mexico

The central US Gulf of Mexico (GoM) continues to be a highly prospective area for hydrocarbon exploration. However, subsalt exploration in this area is challenging due to the complex salt geometries that obscure underlying reservoirs.

A program of sparse OBN surveys were acquired in the Mississippi Canyon over areas already covered by legacy wide-azimuth (WAZ) towed-streamer data (Figure 1). The objective was to improve our understanding of the complex subsurface, by providing a new dataset better suited to advanced model building. The nominal node spacing for the new acquisition varied between 1000m and 1200m, recording offsets beyond 40km with the objective of recording diving waves reaching the basement. Low-frequency sources were employed to enhance signal below 2Hz, which is crucial for accurate subsalt velocity updates.

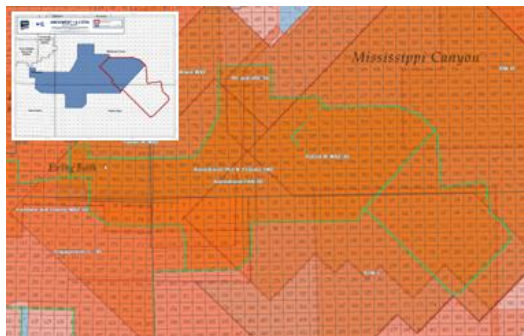


Figure 1: OBN survey locations (insert) and map indicating the various legacy towed-streamer surveys covering the same area (main image).

Results from acoustic and elastic FWI have been presented previously (Xing *et al.*, 2025), focusing on the effectiveness of the log offset OBN dataset and the significant improvements it brings to the velocity model building and QC derivatives. Less attention has been given to the significant uplift brought by the velocity model to the imaging of the legacy dataset.

Figure 2 illustrates the uplift provided by this hybrid acquisition and imaging strategy. FWI applied to the sparse OBN data has reshaped the salt structure and resolved complex velocity variations around them, including identifying additional deep high velocity features (Figure 2c). The impact on the migrated WAZ streamer data is clear (Figure 2d), with sharper terminations of the sediment at the salt interface, clearer imaging of deep sedimentary mini-basins, and the folded structure below the main salt body. The deep Louann salt formation underlying the complex shallower section is notably more continuous and flatter, bringing confidence to the sparse OBN derived velocity model.

The FWI derived reflectivity (FDR, shown in Figure 2e) provides a clear and bold structural QC image, complementing the higher resolution migrated image from the streamer data (Figure 2d). The equivalent migrated image from OBN data (Figure 2f) reinforces the richer low frequencies and better illumination achieved with this type of acquisition; however, it also highlights some of the limitations in spatial bandwidth.

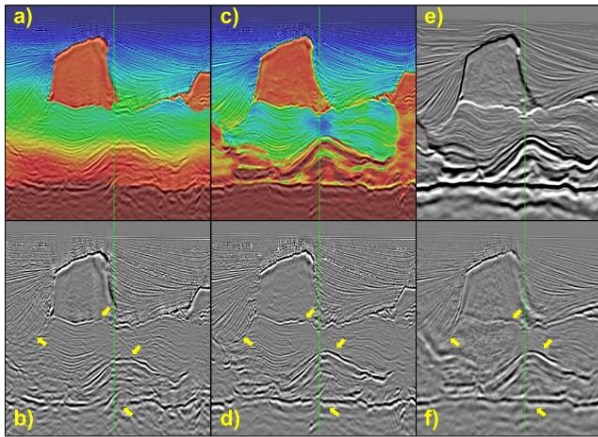


Figure 2: Panels a) & b) show a streamer QC reverse time migration image (RTM) using the legacy model with and without model overlay; panels c) & d) show a streamer QC RTM image using sparse OBN model with and without model overlay; panel e) shows the FDR of the sparse OBN velocity model; panel f) shows the sparse OBN QC RTM image.

Case Study - Santos Basin

The waters offshore Brazil have been extensively surveyed over the last three decades primarily by narrow-azimuth (NAZ) towed-streamer acquisition (Figure 3). In recent years, some of the huge pre-salt hydrocarbon reservoirs have begun to enter the early development phase, which is being facilitated by targeted OBN surveys overlying the legacy streamer surveys. These OBN survey designs have tended to be configured with a denser spacing that the earlier case study, however having complimentary, collocated surveys provides an opportunity to explore the benefits in another setting.

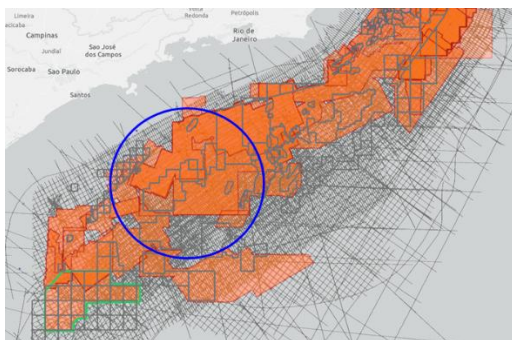


Figure 3: Map showing the case study area location (blue) in Santos Basin, along with the abundance of legacy towed-streamer surveys covering the region (orange with gray outlines).

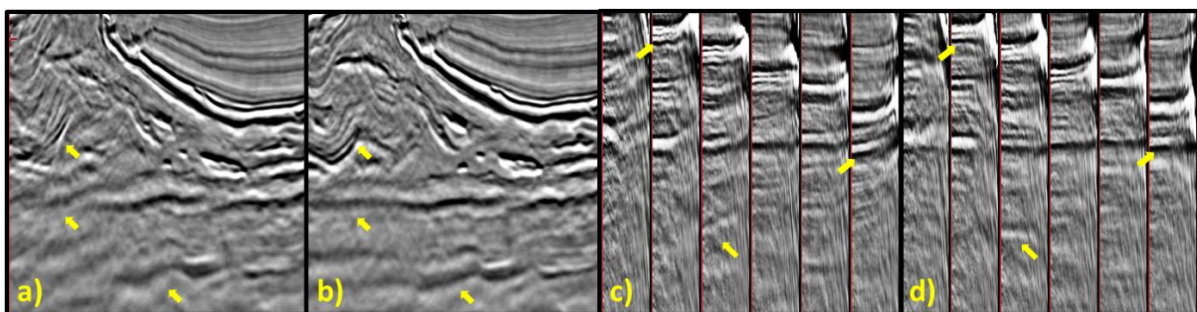


Figure 4: Panels a) & c) show the streamer KPSDM QC stack and gathers migrated using the model derived from streamer data; panels b) & d) show the streamer QC KPSDM stack and gathers migrated using the model derived from OBN data.

Figure 4 compares a NAZ towed streamer dataset migrated with velocity models derived from streamer data (4a and 4c) and long-offset OBN data (4b and 4d). These examples clearly show how the more accurate velocity model derived from the OBN data using FWI provides a superior image through the complex salt with a flatter and more continuous base-salt reflector. This leads to improved focusing of the pre-salt, evident by the flatter image gathers (Figure 4d) compared to those achieved with the streamer data alone (Figure 4c).

Conclusions

The benefits of FWI are maximized when acquisition design matches the demands of wavefield modeling. Full-azimuth, long-offset OBN data enables high-fidelity FWI, particularly in complex subsurface settings. Sparse OBN, when combined with legacy streamer data, provides a pragmatic path toward high-resolution imaging and robust velocity model building—without the need for a dense deployment from the outset. The two case studies have shown that this hybrid strategy allows more value to be extracted from legacy streamer datasets. This is enabled by FWI, extending the utility of existing data while offering a scalable, cost-efficient roadmap for both exploration and reservoir development programs.

As prospects become proven reserves, the initial sparse OBN acquisition provides the foundation for scalable workflows that can grow with reservoir development. The OBN sampling can be expanded incrementally, with a subset of the sparse layout being densified over key fields to support higher-frequency FWI, broadband imaging using the OBN data while establishing a baseline for future 4D monitoring. This progressive approach enables improved early insights, balancing them with long-term imaging capability.

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