From exploration to development: scalable FWI model building with sparse OBN and towed-streamer reimaging

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Summary

Full-waveform inversion (FWI) is widely used to deliver data-driven velocity models that improve imaging in complex settings, with its success closely tied to the acquisition configuration. Long offsets, broad azimuthal sampling, and usable low frequencies materially improve the stability and depth penetration of FWI updates, particularly in salt-affected provinces where velocity uncertainty dominates interpretation risk. Ocean-bottom node (OBN) acquisition has therefore become a benchmark input for high-fidelity FWI, but dense node programs can be difficult to justify when uncertainty is highest, during early exploration and prospect maturation.

At the same time, many basins are already covered by extensive legacy towed-streamer libraries, which retain valuable high-resolution reflectivity but are often limited by the velocity models used for migration.

This paper presents a scalable, lifecycle-oriented strategy that connects these realities: deploy sparse OBN early to obtain FWI-ready wavefield sampling and build a robust Earth model, then reimage existing streamer data to deliver immediate imaging uplift across broad areas. As prospects transition to appraisal and development, the initial sparse OBN footprint can be selectively densified to support higher-frequency objectives and 4D readiness, extending the same model-building framework from exploration through development.

Introduction

FWI performance is fundamentally shaped by acquisition design. Survey geometry controls wavefield sampling, which in turn governs inversion stability, depth sensitivity, and the resolution of recovered model components. In practice, long offsets and broad azimuths provide critical leverage for resolving deeper velocity structure and complex lateral variations, while low-frequency energy expands the inversion's basin of attraction and reduces cycle-skipping risk when initial models are imperfect. These factors become especially important beneath salt, where strong velocity contrasts and complex geometries distort illumination and challenge conventional model building.

OBN acquisition naturally provides wide-azimuth and long-offset coverage, often coupled with low-frequency source strategies that are advantageous for FWI-based model building (e.g. Baptiste *et al*., 2024; Davies *et al*., 2024). Recent field studies show strong results from acoustic and elastic FWI when supported by appropriate OBN sampling in complex settings such as the Gulf of America and offshore Brazil (e.g., Brando *et al*., 2023; Macesanu *et al*., 2024; Vigh *et al*., 2022). However, economics and project maturity frequently constrain what can be acquired early: dense OBN deployments may not be feasible in frontier or early appraisal phases, even when subsalt uncertainty is a primary business risk.

In contrast, legacy streamer data are abundant and often reprocessed multiple times as technologies evolve (bandwidth extension, deghosting, noise attenuation, multiple handling, and imaging improvements). Yet even with advanced processing, streamer imaging remains constrained by the velocity model used for migration, particularly at depth and around complex salt geometries where streamer-only acquisition lacks the offsets/azimuths and low frequencies that strongly stabilize FWI.

This paper reframes hybrid acquisition not as a one-off technical choice, but as a progressive operational strategy:

1. **Exploration / early appraisal**: deploy sparse OBN over selected areas to rapidly establish an FWI-derived model that is geologically consistent and fit-for-purpose.
2. **Reimage** the broader streamer library using this improved model to unlock immediate uplift across large footprints.
3. **Development**: densify OBN selectively over key fields to support higher-frequency FWI, broadband OBN imaging, and a 4D baseline.

The result is a coherent model-building roadmap that scales with asset maturity while maximizing value from both new acquisition and existing data libraries.

Theory and Method

FWI seeks to minimize the mismatch between recorded and modeled wavefields, so the inversion is most effective when the wavefield is sufficiently sampled to constrain both low- and high-wavenumber components of the Earth model. Long offsets and wide azimuths enhance deep illumination and reduce directional bias, improving sensitivity to low-wavenumber velocity structure that governs kinematics and migration positioning. Low-frequency content plays a complementary role by reducing nonlinearity, improving convergence robustness, and enabling meaningful updates from less mature starting models.

Why sparse OBN works early. Sparse OBN designs are positioned as a pragmatic early-phase compromise: coarse node spacing reduces acquisition cost and operational footprint while preserving the key ingredients that matter most for model building – long offsets, broad azimuths, and low-frequency energy. Field experience in complex salt provinces shows that sparse OBN can still deliver geologically consistent model updates when the recorded offsets and low frequencies are sufficient to constrain the low-wavenumber structure, often achieving substantial uplift at relatively modest bandwidths (e.g. Huang *et al*., 2020).

Why streamer reimaging delivers immediate uplift. Streamer data often provide dense spatial sampling and high-resolution reflectivity information that is ideal for detailed imaging, interpretation, and attribute work, once the velocity model is reliable. However, conventional streamer acquisition is typically constrained by limited offsets and narrower azimuth distributions, reducing FWI's ability to converge at depth and around complex structures when streamer data are used alone. The hybrid strategy therefore assigns clear roles: use sparse OBN to build the model (FWI), then apply the improved model to reimage the legacy streamer library for high-resolution interpretation products.

Proposed progressive workflow:

Stage 1 – Targeted sparse OBN acquisition: Acquire sparse OBN over key prospect areas that overlap existing streamer coverage, prioritizing long offsets and usable low frequencies for stable FWI.

Stage 2 – FWI model building + QC derivatives: Run acoustic and/or elastic FWI to update velocity structure, supported by QC products such as FWI-derived reflectivity and migrated QC volumes that help validate structural plausibility and illumination.

Stage 3 – Streamer reimaging: Reimage legacy streamer datasets using the OBN-derived model to improve focusing, continuity, and confidence in complex areas.

Stage 4 – Development scaling: As assets mature, selectively densify portions of the OBN layout over producing fields to enable higher-frequency objectives, broadband imaging, and a baseline for future 4D monitoring, without discarding the early sparse OBN investment.

This progression connects early, cost-efficient risk reduction (better models sooner) with longer-term development deliverables (higher-resolution imaging and monitoring), aligning technical design with the asset lifecycle implied by the chosen title.

Case Study 1 – Gulf of America

The central U.S. Gulf of America remains highly prospective, but subsalt exploration is challenging due to complex salt geometries that degrade illumination and increase velocity uncertainty. In this case study, a program of sparse OBN surveys was acquired in the Mississippi Canyon over an area already covered by legacy wide-azimuth (WAZ) towed-streamer data (Figure 1). The purpose was to introduce an acquisition component that better supports advanced model building while leveraging the existing streamer library for high-resolution imaging.

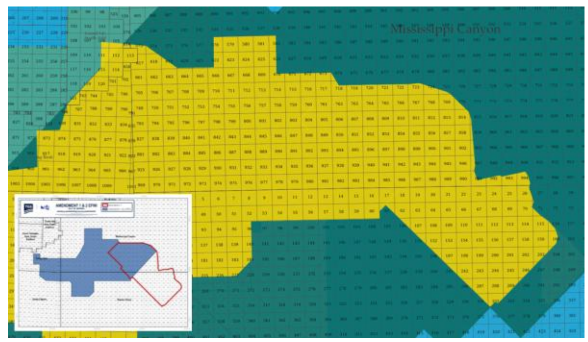

Figure 1*: Map indicating the various legacy towed-streamer surveys covering the same area (main image).*

The OBN acquisition used node spacing of approximately 1000–1200 m and recorded offsets beyond 40 km with the objective of capturing diving waves reaching the basement. Low-frequency sources were employed to enhance signal below ~2 Hz, supporting stable subsalt velocity updates. FWI applied to the sparse OBN data reshaped the salt structure and resolved complex velocity variations around it, including additional deep high-velocity features. A more complete description of the velocity model building is described by Xing *et al*. (2025), which include a demonstration of the importance of elastic FWI in this complex setting.

Reimaging the legacy WAZ streamer data using the OBN-derived model produced a clear uplift: sharper sediment terminations at the salt interface, improved imaging of deep sedimentary mini-basins, and clearer folded structure beneath the main salt body (Figure 2). The deeper Louann salt event became more continuous and flatter, increasing confidence in the velocity model derived from sparse OBN. FWI-derived reflectivity provided a bold structural QC complement to the higher-resolution streamer migration, while OBN migrated QC imaging highlighted the richer low frequencies and improved illumination, alongside expected spatial bandwidth limitations from sparse receiver sampling.

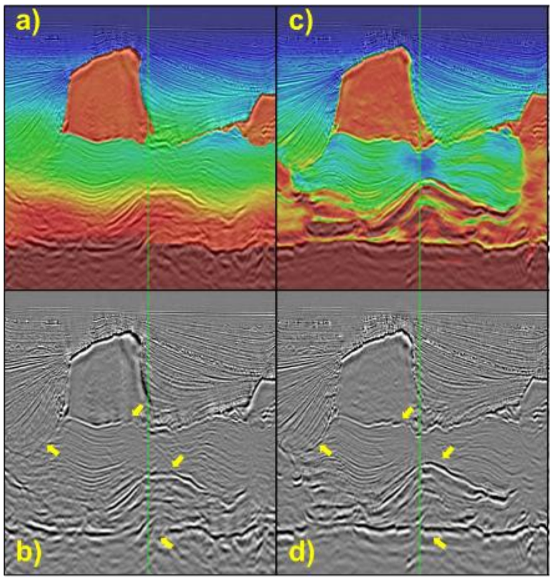

Figure 2*: Panels a) & b) show a streamer QC reverse time migration image (RTM) using the legacy model with and without model overlay; panels c) & d) show a streamer QC RTM image using sparse OBN model with and without model overlay.*

Case Study 2 – Santos Basin

Offshore Brazil, the Santos Basin has been extensively surveyed for decades, primarily with narrow-azimuth (NAZ) towed-streamer acquisition, resulting in an extensive legacy library that supports exploration and appraisal across broad areas (Figure 3).

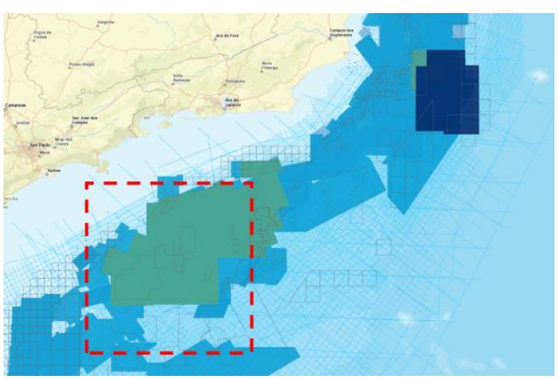

Figure 3: *Map showing the general area of the case study (red) in Santos Basin. The numerous legacy towed-streamer surveys covering the region and shown by the green and blue polygons.*

In recent years, targeted OBN surveys have been acquired over large pre-salt reservoirs entering early development, creating collocated datasets well-suited to testing a scalable "exploration to development" workflow.

The comparison in Figure 4 focuses on the impact of velocity model provenance on streamer imaging: NAZ data migrated with a velocity model derived from streamer data alone versus the same streamer data migrated with a model derived from long-offset OBN data using FWI. The OBN-driven model improves imaging through complex salt by delivering a flatter, more continuous base-salt reflector and improved focusing in the pre-salt interval.

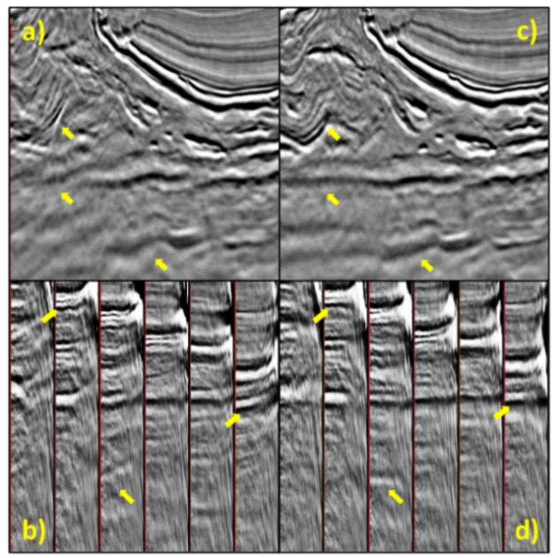

Figure 4: *Panels a) & b) show the NAZ KPSDM QC stack and gathers migrated using the model derived from streamer data; panels c) & d) show the NAZ KPSDM QC stack and gathers migrated using the model derived from OBN data.*

A key diagnostic is gather behavior: image gathers migrated using the OBN-derived model (Figure 4d) are noticeably flatter than those produced with the streamer-derived model (Figure 4b), indicating improved kinematic consistency and reduced residual moveout.

Benefits of the improved imaging are also observed in the amplitude behavior of the data. Figure 5 shows RMS amplitude maps extracted from the KPSDM stack image, over a window centered on the base of salt reflection. The improved NAZ imaging using the OBN derived velocity model provides a better stack response with more laterally consistent amplitude behavior.

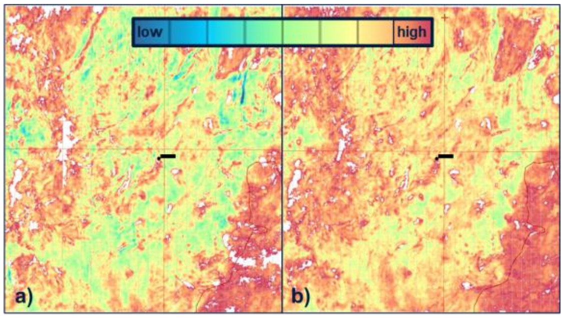

Figure 5: *RMS amplitude measured at the base of salt reflector on the KPSDM stack migrated using the NAZ-derived velocity model, panel a), and with the OBN derived velocity model, panel b).*

The improvements illustrated in this case study directly support the value proposition of the scalable approach: a targeted OBN program, often justified as development needs increase, can materially improve velocity model fidelity, and that model can immediately uplift the interpretation value of the existing streamer data library without requiring a basin-wide dense node deployment.

Conclusions

This paper presents a hybrid workflow explicitly aligned with the asset lifecycle. Sparse OBN acquisition provides an operationally efficient means of capturing the long-offset, wide-azimuth, low-frequency wavefield content that stabilizes FWI and enables robust model building in complex salt settings. Once an OBN-driven model is established, reimaging the legacy streamer library delivers immediate, high-resolution imaging uplift across larger footprints, extracting additional value from existing data investments while enabling earlier, better-informed decisions.

The Gulf of America and Santos Basin examples demonstrate consistent benefits across different acquisition histories (WAZ and NAZ): improved salt geometry definition, enhanced structural continuity, better focusing at depth, and diagnostic improvements such as flatter gathers when migrating streamer data with OBN-derived velocity models. Beyond near-term imaging uplift, the workflow supports a clear scaling path: as prospects mature into development assets, the initial sparse OBN footprint can be selectively densified over key fields to support higher-frequency FWI, broadband imaging with OBN data, and a baseline for future 4D monitoring.

Overall, this progressive strategy maximizes the value of both new acquisition and legacy streamer libraries, providing a coherent roadmap for velocity model building and imaging that evolves from early exploration through development without requiring an upfront commitment to dense node deployment.

Acknowledgments

We would like to thank TGS for permission to publish this paper, and to show data examples from the Multiclient data library.