Acquisition and early imaging of a long-offset, low-frequency sparse node survey in the Gulf of Mexico

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Summary

Inspired by the successes of sparse ocean bottom nodes (OBN) programs in recent years, especially the industry's first long-offset, low-frequency (LOLF) sparse OBN survey using the Tuned Pulse Source (TPS) as the seismic source (Merritt et al., 2024), Viridien acquired Laconia OBN, its vast multi-client survey of nearly 800 OCS blocks of source coverage to provide significant uplifts to the full-waveform inversion (FWI) velocity update and imaging of underlying staggered-source full-azimuth data. Despite several weather events impacting this 9-month long 5-vessel operation, the project was executed successfully. Starlink was used to transfer hydrophone data down-sampled at 16 ms upon node retrieval offshore, enabling early validation of the data quality through FWI tests and providing interpreters a 3-month lead time to analyze geological features on full-area 5 Hz OBN acoustic FWI (AFWI) before the Laconia Phase I Fast Track volume release.

Introduction

To unlock the potential of the deepwater Wilcox Paleogene play in the Garden Banks and northern Keathley Canyon protraction areas in the Gulf of Mexico (GOM), also referred to as the Gulf of America in recent U.S. executive orders, the major challenge is to meet subsalt imaging requirements for prospect identification and evaluation in this highly attractive yet structurally complicated region.

To address this challenge, over the past two decades, numerous attempts have nearly exhausted every available towed-streamer acquisition configuration, ranging from narrow-azimuth (NAZ) to wide-azimuth (WAZ) to full-azimuth (FAZ) surveys. Despite all efforts and investments, the resulting images were still suboptimal for resolving the deep exploration targets.

Between 2011-2016, bp conducted a full-scale synthetic 3D modeling and inversion study on the Garden Banks' complex salt geometry (Dellinger et al., 2017). The study suggested that to unlock FWI's maximum potential for resolving deep velocity errors, the input data should meet two criteria: 1) good signal-to-noise ratio (S/N) reaching 2 Hz, ideally 1 Hz, and 2) long offsets > 30 km. While these requirements might have been unachievable at the time, partly due to the high acquisition cost, they served as a guideline for subsequent research efforts to develop fully data-driven, automatic velocity model building solutions.

Sparse OBN paired with conventional air guns offers a cost-effective way to acquire the needed LOLF data and has brought step-change improvements to subsalt velocity model building and imaging when combined with FWI (Roende et al., 2020; Lin et al., 2021; Vigh et al., 2021; Jonke et al., 2024). However, given that both the dominant micro-seismic noise amplitude (Delinger, 2016) and damping effect from the source ghost increase rapidly when approaching 0 Hz, a source with stronger output at ultra-low frequencies offers a better chance for FWI subsalt performance.

The development of the TPS (Ronen and Chelminski, 2017; Chelminski et al., 2021; Tellier et al., 2021) aimed to do just that and provided an opportunity to further enhance sparse OBN data. In 2023, Shell conducted the Momentum project, the first commercial OBN survey using TPS as the active seismic source. Merritt et al. (2024) demonstrated that, with a good low-frequency S/N down to 1 Hz from TPS and 50+ km offsets, FWI can resolve large velocity errors in the deeper section all the way to basement level, revealing geological features that streamer-based FWI was unable to resolve.

With the success of the Momentum OBN project as a reference, Viridien seized the opportunity to incorporate TPS and long-offset sparse OBN into its neighboring 18,000 sqkm acquisition, the Laconia multi-client survey. Figure 1 shows the node coverage of Laconia Phases I and II and their relative position to the legacy streamer coverage. The area covered in yellow outlines the Wilcox Paleogene play.

Survey design

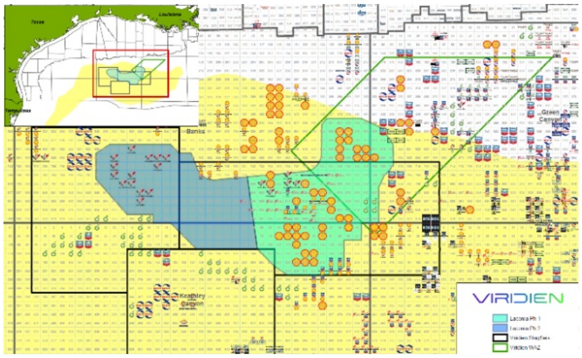

Figure 1: The green and blue shaded areas indicate the Laconia node coverage (~336 OCS blocks in total) for Phase I and Phase II, respectively.

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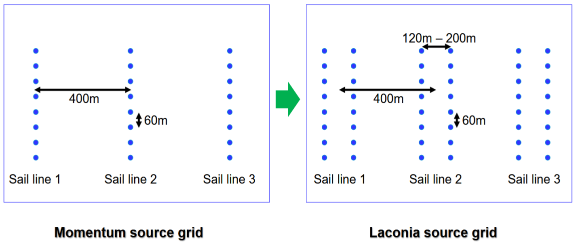
The node spacing in Laconia is 800 m NS along the inline (IL) direction in a staggered pattern, and 1200 m EW along the crossline (XL) direction, the same as in Momentum. The source grid in Laconia also follows Momentum, using 400 m sail line spacing and 60 m inline shot spacing, as illustrated in Figure 2.

A key difference, however, is the shot configuration. In Momentum, two TPS sources towed by the same boat shooting simultaneously with a 20 m XL separation were effectively a single source (small array), meaning that the shot line spacing is the same as the sail line spacing. In Laconia, those two TPS units were configured with 120-150 m XL separation, and were later extended to 200 m. Additionally, those two TPS units were fired separately with independent 1.5 seconds of dithering. As a result, the average shot line spacing in Laconia becomes half of the sail line spacing, but the total downward energy emitted per unit area from TPS remained the same for both the Momentum and Laconia projects.



Momentum source grid

Laconia source grid

Figure 2: The source grid comparision for Momentum and Laconia.

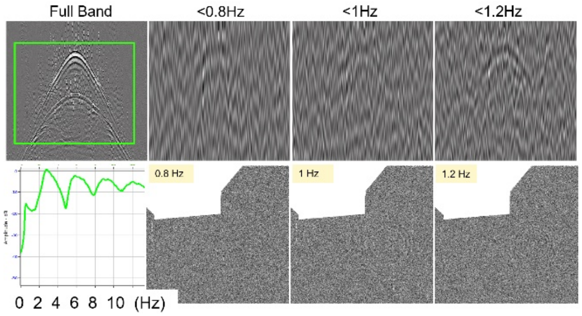


Figure 3: Single node frequency panel, amplitude spectrum, and phase ring.

Operational highlights: quality and efficiency

The total node coverage of the Laconia survey is 336 OCS blocks, or about 8000 sqkm; this equates to more than 8000 node locations. With a 20 km shot halo, the total shot coverage extends to nearly 800 OCS blocks, or over 18,000 sqkm, with a total source effort spanning ~46,000 linear km. Laconia's 9-month long operation, involving two source vessels, two node handlers, and one support vessel, with over 200 people offshore, was successfully completed on-time and without HSE incidents, despite the continuous operational challenges from strong weather events. Technical downtime related to TPS was kept below 4%, comparable to surveys using conventional air gun arrays.

A satellite transmission channel (Starlink) was implemented to stream the hydrophone data down-sampled to 16 ms, enabling quasi-real-time onshore data QC and processing. This implementation was critical for conducting early FWI tests using 2000 nodes, ready by early January 2025, for data quality validation while the acquisition was still ongoing. Additionally, it delivered the Phase I full-area 5 Hz AFWI results by late February, within 40 days after the last Phase I node was retrieved, providing interpreters with significant lead time to analyze geological features before the Fast Track volume release.

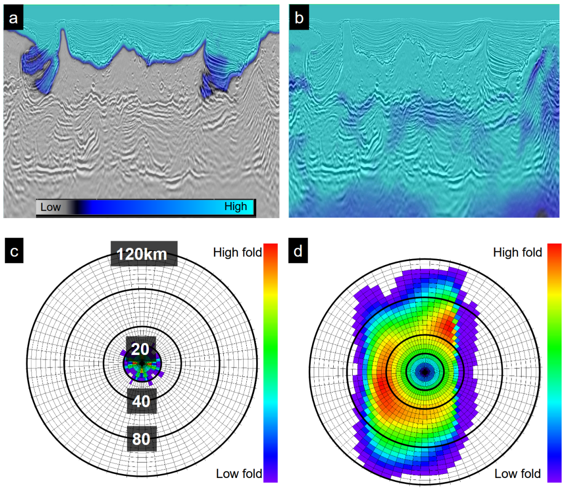


Figure 4: (a) FAZ streamer and (b) Laconia OBN diving wave illumination pattern; (c) FAZ streamer and (d) Laconia OBN rose diagram.

Early-out result

The first aspect examined in the 16 ms node data from the Laconia survey was its low-frequency content. Figure 3 displays the frequency panels for 0.8 Hz, 1.0 Hz, and 1.2 Hz, along with the corresponding phase ring QCs. Coherent signals were detected as low as 1.0 Hz, consistent with observations from the Momentum project.

After verifying that the node data contains the desired low-frequency signal, the next step validated that the acquisition geometry — featuring a minimum 30 km XL offset, with significantly longer IL offsets — allowed diving waves to penetrate the targeted subsalt geological formation.

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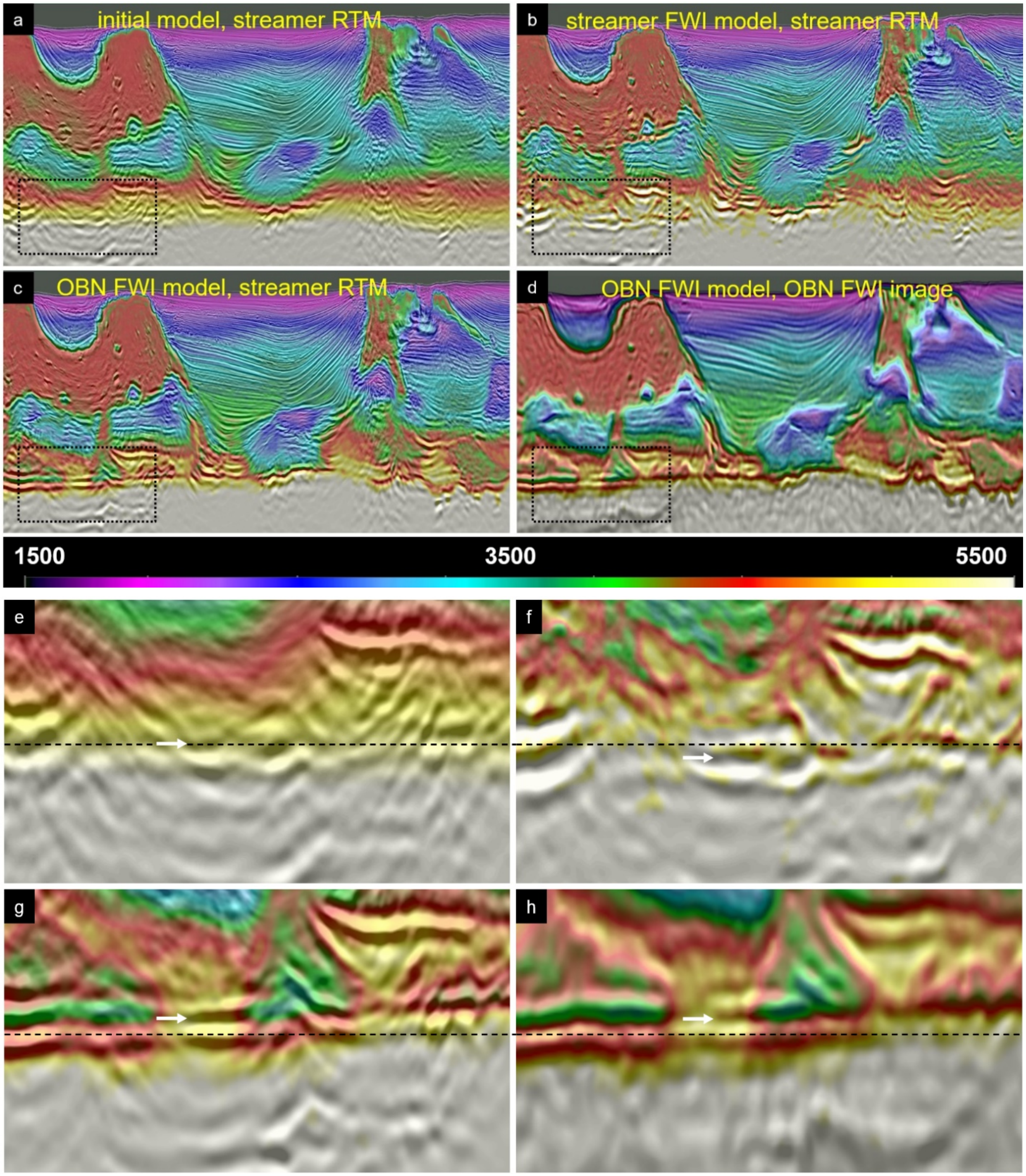

Figure 5. Streamer and Laconia sparse OBN FWI test: (a) initial model overlaid on streamer data 15 Hz RTM image, (b) 6 Hz streamer FWI updated model overlaid on streamer data 15 Hz RTM image, (c) 5 Hz OBN FWI updated model overlaid on streamer data 15 Hz RTM image, (d) 5 Hz OBN FWI updated model overlaid on 5 Hz FWI Image. Figures (e-h) are zoom-in windows from Figures (a-d), respectively, with the black dashed lines marking the same depth.

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As shown in Figure 4, the Laconia acquisition geometry provides sufficient diving wave penetration into the subsalt formation, whereas surface streamer acquisition geometry offers limited penetration into the target subsalt formation.

Once the above-mentioned conditions for a successful FWI had been validated, an initial FWI update with nearly 2000 nodes of raw 16 ms hydrophone-only node data was produced. The initial model for this test was created by smoothing the best available streamer FWI model. To ensure a fair comparison, the same initial model was used for separate FWI updates using streamer data (FAZ and WAZ) and Laconia sparse OBN data.

The result of this FWI test is summarized in Figure 5. The early-out FWI tests with a limited number of nodes already showed significant uplifts compared to the streamer FWI results. From initial observations, the shallow salt geometry was not significantly modified by the FWI in either the streamer or node updates. This is largely because the shallow salt geometry had already been extensively inverted by several applications of streamer FWI from legacy work.

In contrast, the deeper and more complex velocity features, such as the highly deformed mobile shale, with its significantly lower velocity and complex geometry, the fast Mesozoic layers, and allochthonous salt, were unveiled only in the OBN FWI. Due to the strong velocity contrasts between deformed shale bodies and surrounding geological formations, those shale bodies play a critical role, similar to salt bodies, in properly illuminating and imaging the subsalt area. In the OBN FWI velocity and FWI Image (Zhang et al., 2020; Huang et al., 2021), we start to realize how critical a clear image of the allochthonous salt and remobilized low-velocity shales is because these highly complicated geobodies are close to the key exploration targets, presenting a combination of risks and opportunities for prospect evaluation and drilling operations. More detailed analysis is expected as exploration geologists continue to examine the insights revealed by the OBN FWI update. It is anticipated that this will lead to a major upgrade in geological understanding and an improved assessment of hydrocarbon prospectivity.

A geophysically significant observation emerges when comparing the details of the streamer update against the node update, as indicated by the zoom-in windows in Figures 5e-5h. The streamer update (Figures 5b and 5f) increased the subsalt sediment velocity, pushed down the deep strong reflector (indicated with a white arrow), and appeared to enhance the event with overall improved focusing and continuity.

In the past, without well data, this was considered a sign of a good velocity update. However, the OBN FWI (Figures 5c and 5g) suggests that the update could be in the opposite direction — slowing down the subsalt sediment velocity (mobile shale) — which results in a model that aligns better with geological expectations. Together with more geologically sound deeper structures in both the RTM image (Figures 5c and 5g) and OBN FWI Image (Figures 5d and 5h), the OBN FWI model is believed to be more accurate, and the erroneous velocity update in the streamer FWI was likely caused by the lack of diving wave illumination at this depth, a lower low-frequency S/N, and thus the inability to update the background velocity properly.

Discussion and conclusions

The early-out result confirms the power of LOLF sparse OBN FWI in providing a high-quality subsalt velocity model and improved subsalt structural images. It is expected that both the velocity model and subsalt images will be further improved in production processing when upgrading from acoustic FWI to elastic FWI and using both sparse OBN data and the underlying streamer data as input to elastic FWI, especially at higher frequencies.

The Laconia project demonstrated the operational reliability of TPS, delivering a stable low-frequency output for a survey of 1.5 million shots. The use of deepwater nodes with a 150-day battery life made the recording of long and ultra-long offsets possible with minimal node failures.

The long-offset, low-frequency survey design is well-suited for subsalt velocity updates. The combination of these two technologies maximizes the potential of FWI, satisfying the long offsets condition to enable diving waves to penetrate deep subsalt geological formations, and the low-frequency signal condition to resolve large-scale velocity model errors.

The quasi-real-time onshore processing enabled by the streaming of 16 ms hydrophone data through Starlink and the close collaboration between groups — acquisition, operations, logistics, technical, and processing — provided interpreters with a 3-month lead time to analyze geological features on the 5 Hz OBN FWI velocity and FWI Image before the Phase I Fast Track volume release.

Acknowledgments

We thank Viridien for permission to publish this work. We also thank the TGS acquisition team and vessel crews for the OBN acquisition and the Sercel team for technical support in TPS operations. Special thanks to Zhiyuan Wei and Alex Hao for source configuration tests, Scott Downie and Michael Whitehead for supporting daily operations, and Carl Watkins and Daniel Carruthers for geological insight.

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