Revealing the subsalt in Garden Banks with a sparsely-shot TPS OBN and FWI

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Summary

The Garden Banks protraction area features some of the most complex geological features in the Gulf of Mexico (GOM), presenting tremendous challenges for subsalt imaging and exploration. Existing streamer seismic, characterized by offsets up to 15 km and poor low-frequency (LF) signal-to-noise ratio (S/N), has not proven effective on its own for subsalt velocity model building with full-waveform inversion (FWI) and imaging. To unlock subsalt exploration in this challenging area, Shell acquired a long-offset (~60 km) sparse ocean bottom node (OBN) survey paired with a game-changing marine source to prioritize LF S/N, the Tuned Pulse Source (TPS^{TM}). While the first full-scale use of this innovative new source, the entire survey was completed successfully with rich LF content visible down to ~1 Hz, enabling FWI to correct large velocity model errors and create a LF image of the subsurface in record-time, all the way into basement. Despite having very sparse shots, the OBN images/velocities spectacularly reveal complicated subsalt structure, including salt feeders, shale bodies, and basement faulting. This resounding success not only demonstrates the feasibility of FWI with TPS OBN data; it also marks a significant, repeatable advancement in marine seismic sources for subsalt exploration.

Introduction

The Garden Banks protraction area in the GOM is notorious for poor subsalt imaging, presenting substantial obstacles to exploration. Thick original salt, multiple episodes of salt advancement, and rapid late sedimentation yield a host of complex (velocity) features to resolve, such as an irregular yet massive allochthonous canopy, steep feeders/welds, deformed shale bodies, sediment inclusions, and encased secondary basins. This setting produces exceptional focusing and illumination challenges, resulting in large subsurface uncertainties that make maturing and executing wells very difficult.

Tremendous efforts to resolve the large-scale velocity errors with streamer data have largely been unsuccessful, even with the increased offsets (~15 km) in full-azimuth streamer data. While some velocity improvement with streamer data can be achieved shallow and in select locations, subsalt images generally remain quite poor due to limited reflection aperture for tomography, as well as limited diving wave depth penetration and poor LF S/N for FWI. Certainly, scenario tests tend to be very unsatisfying here because of the complexity of the errors (Dellinger et al., 2017).

Better low frequencies and ultra-long offsets are well-known to be the key ingredients for FWI to fully resolve the velocity issues in this complex region (Dellinger et al., 2017). Over the past decade, on the receiver side, a pivotal shift from streamer acquisition to OBN surveys has significantly improved LF S/N, reaching approximately 1.6 Hz using conventional airgun sources. This transition to OBN has also facilitated the acquisition of longer offsets up to ~60 km, enabling successful deep FWI applications as demonstrated by recent studies (Shen et al., 2017; Zhang et al., 2018; Mifflin et al., 2021). On the source side, to achieve the desired LF S/N to mitigate cycle-skipping in immature starting models, one can utilize a powerful LF source, or equivalently, stack up more conventional airgun shots (Brenders et al., 2022). A recent breakthrough for the former was the introduction of the TPS, which exhibits unprecedented capability in generating LF signals below 3 Hz by releasing much larger air volume (>26 kcui) albeit at lower pressure (~1000 psi) than conventional airgun arrays, and yet simultaneously generates weaker high frequencies (HFs) to protect marine mammals (Ronen and Chelminski, 2017; Chelminski et al., 2021; Tellier et al., 2021). Also, imaging with TPS LFs might also provide structural information unavailable in HFs (Shang et al., 2023).

In 2023, after years of meticulous planning, Shell conducted the industry's *first commercial OBN survey with TPS*. In this paper, we demonstrate that despite a sparse-shot design, the TPS OBN data combined with FWI has delivered unprecedented subsalt velocity and LF image improvements (already in the fast-track) in this extremely challenging area.

Survey Acquisition

Although originally an OBN designed to deliver both normal bandwidth "high-frequency" imaging and long-offset LFs both for FWI velocity model building and LF imaging, new permitting regulations in the GOM emerged during planning that restricted the number of active shooting days with a given source configuration/area. This prevented airgun shot grids dense enough for HF imaging and for stacking up sufficient LF S/N for FWI/imaging. However, since a single TPS shot produces an order of magnitude more LF power than an airgun shot, if we could use TPS for the whole survey, then regulatory limits could be met while achieving equivalent (or better) LF S/N for FWI/imaging. In terms of TPS performance, two successful sea trials (Chelminski et al., 2021; Shang et al., 2023) had already increased our confidence that it could endure a commercial survey, and Sercel was using those learnings to develop larger, more robust TPSs in earnest preparation for a robust full-scale survey. Despite remaining performance uncertainties, Shell made the bold decision to acquire an entirely-TPS-driven survey, risking that the LF images and velocities might not achieve our exploration objectives. As mitigation, we planned to also co-process with streamer data for HF imaging and FWI.

The "Momentum" TPS OBN survey (Figure 1) was conducted by TGS during May-September 2023, encompassing a node patch spanning 3343 sq km with a shot area >9000 sq km, including a 20 km shot halo. Nodes (~3500) were deployed on a grid of 800 m x 1200 m (Figure 1b). Two vessels simultaneously shot in a north-south orientation, each equipped with two 28 kcui Sercel TPSs (Figure 1c) towed at 8 m water depth and separated by 20 m, firing at the same time to enhance LF signal. Shots were fired on time roughly every 25 s (with dithering) to protect S/N of early arrivals from previous shot self-blended noise interfering at ultra-long offsets. As a result, the shot point interval is ~60 m with a sail line spacing of 400 m (Fig. 1b).

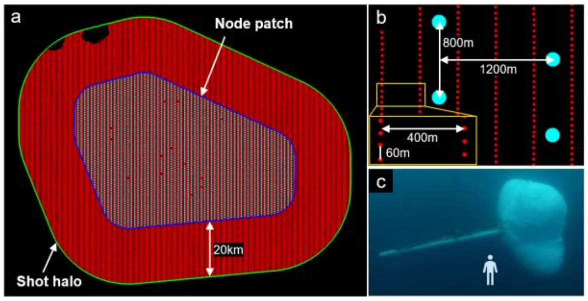

Figure 1. (a) Momentum TPS OBN acquisition shot and node map, with a node patch ~3340 sq km and shot halo of 20 km. (b) Node (cyan dots) spacing of 800 m x 1200 m and shot (red dots) spacing of 60 m x 400 m. (c) Photo showing the TPS firing in the water, releasing large bubble for low-frequency signal generation.

Operationally, while there were some challenges to be expected on the first commercial use of such novel technology, overall the project was a success with the planned ~371k shot points acquired with two fully-functional TPSs shooting simultaneously from each vessel. As a contingency, two conventional airgun arrays were onboard each vessel, but were never deployed. As this was the first use of four larger-volume TPSs on two different vessels with unique umbilical lengths, source controllers, compressor setups, etc., several tests were conducted before production began to tune parameters. Importantly, Sercel technicians were onboard to work out the kinks and assist the crew with TPS operation and maintenance/repair. Practically, the crew reported that the two large TPSs seemed easier and safer to move around than standard arrays with many elements, and there were few issues with deployment and retrieval.

The acquired TPS data demonstrates remarkably rich LFs (Figure 2). Frequency panel and phase ring QC of the survey reveals noticeable signal down to ~1 Hz (Figures 2c and 2g). Besides exceptional LF S/N, Momentum also achieved ultra-long offsets, with dominant fold coverage up to ~60 km in the inline direction and ~40 km in the crossline direction, as indicated in the rose diagrams in Figure 3. This extensive coverage ensures sufficient illumination for the subsalt area, as well as reaching down to the basement at a depth of at least 14 km, as illustrated by the diving wave illumination analysis (Figure 3b). In contrast, a full-azimuth streamer dataset with offsets up to ~15 km translates to about 5 km diving wave penetration—significantly shallower than the depths of the subsalt targets in this area (Figure 3a).

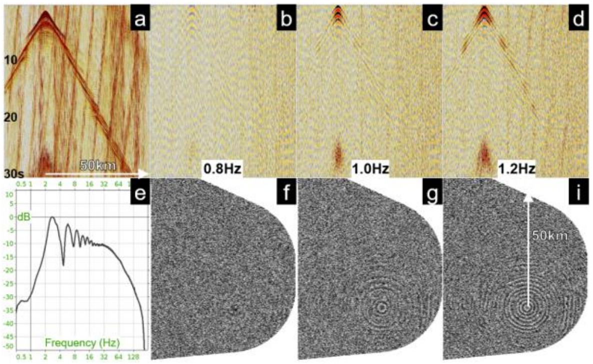

Figure 2. Frequency panel QC for TPS OBN data (a) full frequency, (b) 0.8 Hz, (c) 1.0 Hz, and (d) 1.2 Hz. (e) displays the frequency spectrum of the TPS OBN data. (f)-(g) show the phase rings of frequency at 0.8 Hz, 1.0 Hz, and 1.2 Hz, respectively. Coherent energy becomes apparent at 1 Hz.

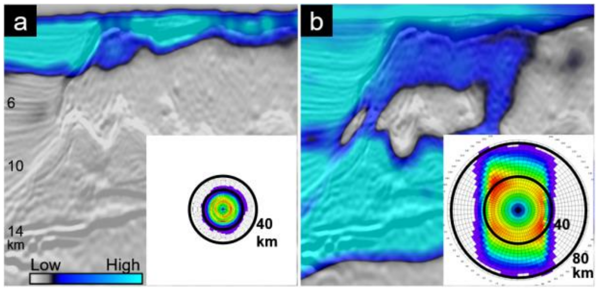

Figure 3. Diving wave illumination (DWI) and rose diagram comparisons between (a) full-azimuth streamer data and (b) TPS OBN data. Compared with the streamer rose diagram with offset coverage up to ~15 km, the OBN data displays longer offsets of ~60 km in the inline direction and ~40 km in the crossline direction, providing deeper diving wave penetration down to the basement level.

Velocity model building

The velocity model building process shown here is comprised of two phases: Phase 1 utilized a full-azimuth streamer dataset as input for FWI before the Momentum OBN data became available, while Phase 2 employed OBN input for FWI, starting from the velocity model derived from the streamer data in Phase 1. The FWI algorithm used was

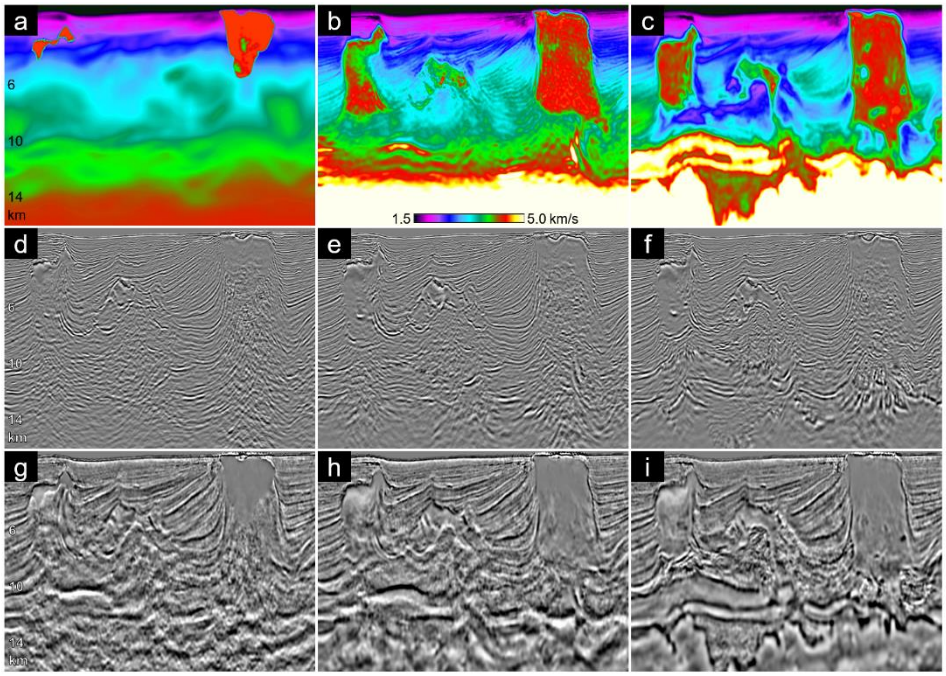

Figure 4. Velocity models of (a) legacy, (b) Phase 1 from streamer FWI at 6 Hz, and (c) Phase 2 from OBN FWI at 5 Hz. Compared to the legacy model, the Phase 1 model exhibits some improvements, while the Phase 2 model shows a substantial update with resolved complex velocity features. Panels (d)-(f) display their corresponding 15 Hz streamer RTM stacks, which demonstrate only a moderate degree of uplift despite the significant model change. Panels (g)-(i) show the corresponding 5 Hz OBN RTM stacks. With the OBN FWI velocity model, the OBN RTM image shows a much more dramatic improvement in image quality, better reflecting the velocity model uplift.

designed to minimize the adverse effects of large amplitude mismatch between synthetic and real data and make it work stably in the salt environment (Zhang et al., 2018; Wang et al., 2019). However, due to the limitations of the streamer data, e.g. shorter offsets and low LF S/N (usable from ~3 Hz), the Phase 1 FWI could not fully resolve the velocity errors in this complex area; only incremental focusing improvements subsalt can be observed. To further improve velocities in Phase 1, extensive scenario tests were performed, interleaved with local FWI updates, to iteratively update the velocity model area by area. This labor-intensive model building process spanned over *22 weeks*, leading to some improvements mostly in areas where the legacy model had obviously misinterpreted salt (Figures 4a and 4b). However, the uplift was still inadequate to support structural interpretation for subsalt exploration.

With the improved velocity model from FWI with streamer data and scenario tests, we initiated OBN FWI in Phase 2 after the Momentum data had become available. The (acoustic) FWI inversion started from 1 Hz, the lowest usable frequency with visibly good S/N, and ran up to 5 Hz. The inverted velocity model exhibited significant modifications to the input models (Figure 4c). Remarkably, large allochthonous salt bodies have undergone significant reshaping, revealing intricate salt-related structures such as open feeders, thin welds feeding the canopy, and sediment intrusions where Phase 1 had salt. Additionally, extensively deformed shale bodies have been unveiled, interacting with salt, and resulting in pronounced lateral velocity variations. The high-dip welds between primary and secondary basins are better delineated, providing clearer insights into basin architecture. Top basement and the thick high-velocity layers above exhibit significant structure. These intricate velocity features far surpass the complexity observed in the velocity model constructed with the full-azimuth streamer data, even exceeding our initial expectations. Note that the first major FWI result (almost identical to the final Phase 2 model) was achieved *6 weeks* after final node pick-up with no deblending or manual intervention, speaking to the quality of the TPS OBN data.

Improving the subsalt image with TPS OBN data

Despite the greatly improved velocity model, the corresponding full-azimuth streamer RTM shows limited uplift (Figures 4d-4f). Comparing to the legacy, the Phase 1 RTM (Figure 4e) shows only minor improvements in focusing. Even with a significantly more mature model in Phase 2 (Figure 4f) where some subsalt features exhibit further-improved focusing, migration swing noise and residual multiples are commonly observed in places associated with low-velocity zones, making this full-azimuth streamer HF image alone insufficient to meet the needs of structural interpretation for subsalt exploration.

To address the imaging challenges encountered with RTM using streamer, we turned to long-offset OBN data, which offers improved illumination in complex subsalt target areas and better LF content from TPS. Leveraging the fast-track

OBN data with processing steps such as deblending, debubble, wavefield separation, and deghosting, we conducted 5 Hz RTM with a migration aperture of 30 km for the velocity model of each phase. The resulting OBN RTM (Figures 4g-4i) demonstrates an exceptional improvement in LF imaging of regional structures compared to the streamer RTM. Migration swings previously observed under low-velocity zones are mitigated, and greater continuity is observed at top basement and the top of the overlying fast layer. The degree of image enhancement now aligns more closely with the improvements in velocity models. Despite the lower frequency, the OBN RTM offers improved structures for subsalt interpretations, benefiting from its LFs and longer offsets.

Although the OBN RTM could provide better illumination of deep subsalt events, its low stacking power due to the sparse acquisition on both the node and shot sides could degrade the S/N in complex subsalt areas. Indeed, we observed considerable migration noise in the subsalt area of the 5 Hz OBN RTM images. To further improve the S/N of subsalt images, we employed OBN FWI Imaging, which leverages full-wavefield information through least-squares data fitting (Zhang et al., 2020; Huang et al., 2021). The 5 Hz FWI Image provides improved coherency, compared to the RTMs (Figure 5) so that previously noisy or ambiguous subsalt events are now more interpretable.

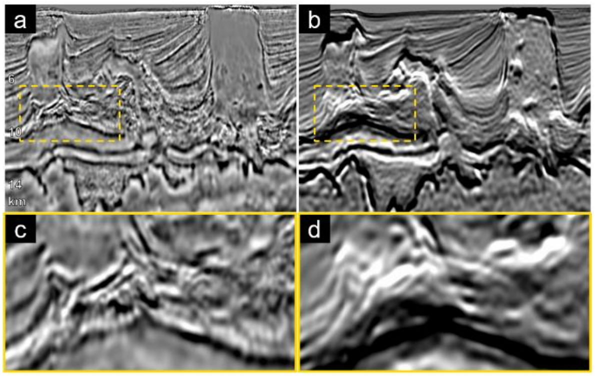

Figure 5. (a) 5 Hz OBN RTM and (b) 5 Hz FWI Image. (c)-(d) zoomed-in areas. FWI Image provides improved imaging quality with more continuous structures and higher S/N.

Discussions and conclusions

Momentum, the industry's first commercial TPS OBN survey, demonstrates TPS is a viable production source to record unprecedented LF S/N transmitting deep through the basement with ultra-long offsets. Considering the GOM regulations limiting shooting days and the availability of TPS, our design approach prioritized LF S/N for model building and imaging, and minimized self-blended noise to ensure the highest probability of success for FWI to work in the complicated Garden Banks setting. Less conservative designs with TPS could probably achieve even better imaging resolution, for similar survey sizes, if one is willing to risk increased blended noise degrading FWI results and is able to tow TPS sources wider.

The fast-track results are outstanding. Frequencies as low as 1 Hz (0.8 Hz in some experiments) have been successfully utilized to correct large velocity errors with FWI, unveiling intricate geological features critical to properly de-risking subsalt exploration. Migrations using long-offset OBN data and FWI velocities have demonstrated clear improvement, providing valuable new structural insights on basin architecture and polarizing geological scenarios that were previously ambiguous. Coupling TPS OBN with FWI, if these results in Garden Banks are any indication, we are witnessing a step-change in subsalt imaging.

Despite significant improvement in the subsalt image with FWI, the current 5 Hz FWI Image still lacks the necessary HF content for detailed interpretation, highlighting the need for a high-resolution image with good S/N (Buist et al., 2023). While long-offset OBN data with dense node and shot sampling would be ideal and may even be required, there may also be more economic alternatives like a hybrid strategy. In fact, the next phase of this project seeks to utilize the full-azimuth streamer data more to push FWI to higher frequencies and improve the HF images referenced. Actually, early experiments already reveal that combining the streamer data with Momentum yields improved high-resolution FWI Images/velocities subsalt, pointing to hidden value in existing streamer datasets processed jointly with newer sparse TPS OBNs like Momentum.

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