Improving reservoir imaging using long-offset OBN data: a case study from Conger field, Gulf of Mexico
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Summary

The Conger field is a subsalt Miocene play situated beneath a complex overburden. It was discovered in 1997, with production beginning in 2000. Since then, significant efforts have been dedicated to improving the reservoir imaging for further field development. On the data side, a conventional OBN dataset was acquired in 2013, providing improved illumination from full azimuth and increased offsets compared to the vintage WATS datasets. This led to clear uplift of the image of the Conger reservoir, even with models built using a conventional velocity model building (VMB) workflow driven by ray-based reflection tomography and manual salt interpretation. On the technology side, the value of vintage datasets, particularly the 2013 OBN data, has been better realized through the adaption of continuously evolving full waveform inversion (FWI) techniques, transitioning from reflection FWI (RFWI) to acoustic Time-lag FWI (TLFWI). However, despite advancements in both seismic data and imaging technologies, structural and amplitude uncertainties remain at the field, and one of the main reasons for this is the limited coverage and offsets of the 2013 OBN data. Therefore, a new long-offset OBN data was acquired in 2020 over this area. With the new long-offset OBN data, TLFWI further improved the velocity model, and consequently, the structural image of the field. Furthermore, FWI Imaging helped improve the amplitude fidelity for reservoir interpretation, where least-squares RTM (LSRTM) was found limited.

Introduction

The Conger field is located in the Garden Banks area of the Gulf of Mexico, with main reservoirs consisting of Miocene plays situated around or beneath the Conger salt. The Conger salt body has a triangular shape and is located approximately 6 km below the sea surface. Surrounding the Conger salt, there are notable geological features with velocity complexities. For instance, to the north, there is an over-pressured shale geobody, while to the east of the Conger salt, there are uncertain geobodies of low reflectivity. Given the overburden complexities as well as the proximity of the reservoirs to these velocity complexities, accurately resolving the overburden and subsalt velocity is crucial for achieving a high-quality reservoir image.

Over the years, tremendous efforts have been dedicated to improving the imaging of the Conger and nearby reservoirs. These efforts include, for example, acquiring OBN data in addition to vintage streamer data, as well as conducting a series of re-imaging campaigns aimed at leveraging continuously evolving FWI technologies. Figure 1a shows one of the vintage seismic images using the streamer datasets, along with the conventional VMB workflow based on ray-based reflection tomography and manual salt interpretation. At that time, the reservoir imaging at the Conger field was inadequate due to the limitations from both the streamer seismic data and the conventional VMB workflow.

In 2013, significant advancements were made to the seismic data over this area. A conventional OBN dataset was acquired at the Conger field, with a maximum inline offset of 18 km and a crossline offset of approximately 9 km. This 2013 OBN data, with its full azimuthal coverage and increased offset, introduced additional illumination to better image the reservoirs that were previously absent in the nearby reservoirs. These efforts include, for example, acquiring OBN data in addition to vintage streamer data, as well as conducting a series of re-imaging campaigns aimed at leveraging continuously evolving FWI technologies. Figure 1a shows one of the vintage seismic images using the streamer datasets, along with the conventional VMB workflow based on ray-based reflection tomography and manual salt interpretation. At that time, the reservoir imaging at the Conger field was inadequate due to the limitations from both the streamer seismic data and the conventional VMB workflow.

Figure 1: Velocity models built from different vintage datasets and technology: (a) streamer data using conventional VMB; (b) streamer/2013 Conger OBN using conventional VMB; (c) streamer/2013 Conger OBN using conventional VMB and RFWI; (d) streamer/2013 Conger OBN using TLFWI; (e) to (h) are the corresponding 15 Hz RTM images using the same 2020 OBN data as migration input for models (a) to (d).

Figure 2: 25 Hz RTM using: (a) vintage streamer data, and (b) 2013 Conger OBN data. The same migration velocity was used for this comparison.
convergent streamer data (Figure 2). Besides the benefits to the image, this additional illumination helped the conventional VMB flow delineate the overburden velocity as well as a slow salt-exit beneath the Conger salt. This improved the velocity model and enhanced the Conger reservoir images (Figure 1e vs. 1f).

To better realize the value of existing vintage datasets, particularly the 2013 OBN data, FWI was incorporated into the VMB workflow as soon as the technology became available. The first successful attempt involved applying RFWI using the 2013 OBN data (Lin et al., 2018). By promoting the tomography term, RFWI was able to generate low-wavenumber kinematic updates beyond the diving wave penetration depth, leading to an overall improvement in event continuity and focusing (Figure 1g). However, despite the imaging improvements, it is noted that the RFWI update lacked resolution, especially in the vertical direction, and was primarily driven by strong reflectors. Therefore, RFWI was still insufficient in resolving velocity details in the Conger overburden and subsalt. In subsequent re-imaging campaigns, a more advanced FWI algorithm, TLFWI, was applied to the 2013 OBN data. TLFWI was shown to mitigate the negative impact from amplitude mismatch between field data and synthetics, especially in salt environments, through a cost function that prioritizes kinematics over amplitudes, and reduce cycle-skipping by making better use of low frequency signals (Zhang et al., 2018). Compared to RFWI using primary reflections only, TLFWI leverages the full wavefield data, thereby obtaining additional data constraints from diving wave energy and multiples, which help better update both low and high-wavenumber components of the velocity model. As a result, the velocity update from TLFWI was more geologically conformal and captured more details, which led to better-defined overburden complexity and Conger salt body, along with the correspondingly improved reservoir imaging underneath it (Figure 1h).

These advancements in both seismic data and FWI technology have led to great improvements in reservoir imaging at the Conger field. However, structural uncertainty remained, for example, at the center of the field (the yellow arrow in Figure 1h) and towards the northern boundary. An analysis of diving wave illumination (DWI) using the 2013 OBN data revealed that, due to the limited size of the node patch and shot halo, the diving waves diminish rapidly at reservoir level as we move away from the field center (Figure 3d). The lack of diving waves suggested limited updating power from TLFWI and thus potential unresolved velocity errors. These unresolved velocity errors can propagate and distort the shape of the Conger salt, ultimately impacting the reservoirs underneath. In addition to the structural uncertainty, there are also uncertainties in the reservoir amplitude of the vintage least-squares migration images. These remaining challenges in the vintage seismic images highlight the need for further advancements in data and technology.

**New OBN data and imaging technology**

For the aforementioned reason, new long-offset OBN data was acquired over this area in 2020. Compared to the 2013 OBN survey, the 2020 survey employed a larger node patch and shot halo, allowing it to record a maximum inline offset up to ~45 km and a minimum crossline offset of ~12 km. This upgrade substantially boosts not only the diving wave penetration depth and coverage, but also the density of diving wave energy, especially towards the edge and deeper part of the Conger reservoir. To better understand the impact of the data, we conducted two otherwise identical TLFWI applications, differing only in the input data (2013 OBN vs. 2020 OBN). From this comparison, we observed that at shallow depths where diving wave coverage is comparable, the differences between the two FWI updated models are relatively small within the 2013 OBN node patch. Whereas at deeper depths around reservoir level, the inversion differences become larger where the 2020 OBN data shows clearly better diving wave illumination (Figure 3).

With this newly acquired 2020 OBN data, we first performed acoustic TLFWI up to 8 Hz, starting from the smoothed vintage model. After obtaining improved migration stack and gathers from the 8 Hz TLFWI model, well-ties and gather flatness were incorporated to refine the anisotropic parameters. Furthermore, in areas of low diving-wave illumination (e.g., edge of node patch and beyond) where the updating power of TLFWI was limited, the approach of iterative scenarios and TLFWI was used to improve TLFWI initial models and the subsequent TLFWI updated models. With these improved velocity and anisotropy models, a final round of TLFWI was run to 11 Hz for use in migration.
Conger long-offset OBN case study

After achieving an improved velocity model from TLFWI with the 2020 OBN data, and thus better-defined structures in migration images, we took a step further to improve amplitude fidelity, considering that most reservoirs in this area are associated with strong intercepts. Although the velocity model from TLFWI with the long-offset OBN data enhanced reservoir focusing and gather quality, conventional RTM still resulted in stacks and gathers that carry strong amplitude imprints from illumination variations. To improve amplitude fidelity, a 30 Hz surface offset gather (SOG) based LSRTM was carried out with the 2020 OBN data to correct for the illumination variations and thus better reveal geology-related amplitudes. In addition, TLFWI was run up to 15 Hz to generate an FWI Image (Zhang et al., 2020), serving as an important product to assist reservoir interpretation, especially in challenging areas where the value of LSRTM is limited.

Results

Compared to the vintage TLFWI model derived with the 2013 OBN data, the new 11 Hz TLFWI model from the 2020 long-offset OBN data revealed significant kinematic differences in the shale geobody to the north of the reservoir. The entire geobody was slowed down with better-defined lateral variations (Figure 4b vs. 4g). Moreover, thanks to deeper diving wave penetration provided by the 2020 OBN data, TLFWI was able to extend the geologically conformal update beyond 8 km, leading to improved event focusing at deeper depths (Figure 4h). Moving towards the center of the field, the low reflectivity geobodies were also better delineated to the east of the reservoir, and similarly, the geologically conformal update was extended vertically and laterally by the 2020 long-offset OBN data. The improved overburden velocity from the new data re-shaped the Conger salt, leading to better focusing of the salt flanks and the rugose base of salt, as well as subtle weld details that were previously missing or misplaced in the vintage images. As a result of the improved velocity model, the basin boundaries were better imaged and defined, and for the first time, coherent reservoir events were imaged across the Conger field (Figure 4e vs. 4j).

Using the improved velocity field, SOG based LSRTM effectively balanced the illumination, resulting in a reservoir amplitude pattern that correlated better with the modeled well log results. For example, LSRTM successfully corrected the false amplitude observed in the conventional RTM (Figure 5a vs. 5b). However, challenging areas of poor S/N still existed in the LSRTM, as indicated by a gap in the reservoir amplitude map. This problematic area was located under the salt tip of the Conger salt and on the side with a highly steeping salt flank. The SOGs in this gap area revealed that the near offsets did not record meaningful signal, while the far offsets showed reasonable S/N, likely because the latter could better bypass the overburden (Figure 5g). The effect of LSRTM was limited in this area by extremely poor S/N at near offsets, resulting in a sub-optimal stack with a reservoir amplitude gap. Consequently, this introduced uncertainty when characterizing the extent and connectivity of the reservoir (Figure 5b).

In contrast, the 15 Hz OBN FWI Image not only produced a similar amplitude pattern as LSRTM in areas with good S/N,
but also greatly improved the image and amplitude in the gap area where the LSRTM image struggled (Figures 5b & 5e vs. 5c & 5f). This improvement can be attributed to the iterative data fitting of the full wavefield data (e.g., multiples) in FWI from low to high frequencies, as opposed to single-iteration imaging domain LSRTM that uses primary energy only. As a result, the FWI Image provided an amplitude map better matched with the well information and field production history, and greatly reduced the amplitude uncertainty in the gap area that persisted in vintage RTMs and LSRTMs.

Conclusions and discussions

Seismic data and imaging technology always complement each other for subsurface imaging. Better data is needed to support the application and development of more advanced technology, while more advanced technology is crucial to unlock the power of better data. In the past two decades, the Conger field has witnessed the evolution of subsalt imaging in the Gulf of Mexico driven by the advancements in both seismic data and imaging technology. The combination of the newly acquired 2020 long-offset OBN data and the imaging technology of TLFWI and FWI Imaging has produced superior reservoir images compared to any legacy images, not only for structure but also for amplitude.

Looking ahead, considering that the 2020 long-offset OBN data is one of the best seismic datasets currently available, advancements in FWI technology are likely to have a better chance to further improve Conger reservoir imaging. The current TLFWI model, constructed using the 2020 long-offset OBN data, was built based on acoustic approximation.

As a result, a salt halo exists around the salt body due to the unexplained elastic effects in acoustic FWI, potentially undermining the reservoir image near the salt. A recent advancement in TLFWI involves upgrading the modeling engine from acoustic to elastic, enabling better modeling of the elastic effects around salt boundaries. (Wu et al., 2022). As shown in Figure 6, the 8 Hz elastic TLFWI (E-TLFWI) model shows a greatly reduced salt halo, along with higher resolution and cleaner updates when compared to the 8Hz acoustic TLFWI (A-TLFWI) model. These improvements lead to clear uplifts in the corresponding FWI Images (Figure 6c vs. 6d). Moving to elastic FWI or even high-frequency elastic FWI (Buist et al., 2023; Liu et al., 2023) is the next tangible step to further improve the reservoir images at Conger before we reach the new limitations of input data and imaging technology.

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