Improving subsalt reservoir imaging with reflection FWI: an OBN case study at Conger field, Gulf of Mexico

Feng Lin, Biniam Asmerom, Rongxin Huang (CGG); Brad Kuntz, Carter Gehman, Mehmet Tanis (Hess)*

Summary

Reservoir imaging under the triangular Conger salt remains very challenging even after significant velocity model building efforts in recent years. Continuity and focusing of reservoir reflectors are sub-optimal due to subtle velocity errors from the Conger salt and its neighboring carapace, which are very difficult for conventional methods, such as interpretation-guided salt scenarios and ray-based tomography, to resolve. Diving-wave full-waveform inversion (FWI) has difficulty updating the velocity at this depth due to the limit of maximum offset, and thus penetration depth, of the input data. In this study, we performed reflection FWI (RFWI) using ocean-bottom node (OBN) data for velocity model updates. Our results showed that RFWI can effectively resolve the subtle low-wavenumber velocity errors in the overburden and substantially improve reservoir imaging. We also demonstrated that RFWI using OBN data can result in a better model than using wide-azimuth towed-streamer data due to its full azimuth and much longer offset coverage.

Introduction

The Conger reservoir is a subsalt Miocene play, located approximately 125 miles off the Louisiana coast in the Garden Banks area of the Gulf of Mexico. The Conger field was discovered in 1997, and more than 200 MMBOE have been produced since production started in 2000. Due to the sub-optimal reservoir imaging from legacy streamer seismic data, further field development is facing relatively large risk and uncertainty. In 2013, an ocean-bottom node (OBN) survey was acquired over this area to improve the reservoir imaging and aid production development. Since then, multiple rounds of velocity model building and imaging efforts combining OBN and legacy streamer data have been carried out and, as a result, subsalt reservoir imaging has substantially improved compared to legacy streamer data (Wei et al., 2016; Stieglitz et al., 2016; Wang et al., 2017).

However, subtle velocity errors related to the Conger salt and neighboring carapaces still exist and degrade reflector continuity and focusing at the reservoir level. As we can see in Figure 1a, although the Conger salt is a relatively small triangular body, its base is not well imaged and its flank right next to the low reflectivity carapace (highlighted by the blue ellipse) is poorly defined. Broken reflectors below the wedge of salt, as highlighted by the arrow in Figure 1a, seem to indicate the existence of a fault at the reservoir level. However, well data supports pressure communication between the subsalt portion of the reservoir and the portion outboard of salt, indicating the spurious fault may be an imaging artifact induced by overburden velocity errors. Additionally, a wave-equation-based illumination study shows that the triangular Conger salt actually serves as a focusing prism that illuminates the subsalt area better than the area outboard of salt (Stieglitz et al., 2016). Therefore, weaker amplitudes below the salt are not an effect of illumination but rather velocity errors. Surface offset gathers (SOGs) from reverse time migration (RTM) (Yang at al., 2015) were also generated to evaluate the accuracy of velocities (Figure 1b). The gathers in the carapace and subsalt region either lack enough coherency across offsets to characterize move-out or exhibit chaotic and conflicting curvatures. All of this evidence indicates that velocity errors still exist in this complex area and are the culprits of sub-optimal reservoir imaging.

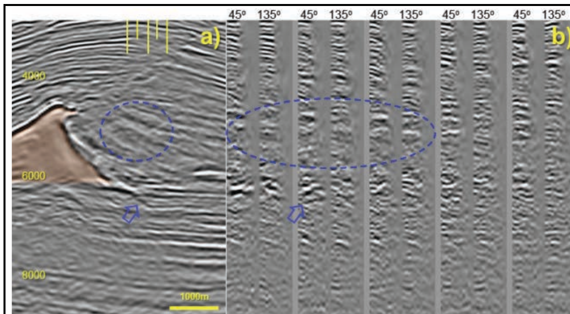

Figure 1: a) 15 Hz OBN RTM stack and b) SOGs of azimuths 45° and 135° at the Conger reservoir. SOG locations are indicated by the yellow lines in a).

Resolving the velocity errors in this complex area is by no means a trivial task. It is very difficult to define the salt body accurately with manual interpretation and salt scenario testing, partly because the salt boundaries are not very well imaged to begin with. Ray-based tomography also breaks down in this area due to poor gather quality and complex gather move-out. Recently, for the first time in the industry, full-waveform inversion (FWI) keying on diving waves from low-frequency and long-offset OBN data was shown to be able to automatically invert velocities for complex salt bodies and greatly improve the subsalt images (Shen et al., 2017). However, in the Conger field, the complex overburden right above the reservoir is beyond the reach of diving waves due to the large velocity gradient in the shallow sedimentary basin and the limited maximum offset of the 2013 OBN survey. What else can we do to improve the velocity model with this data set?

10.1190/segam2018-2996264.1

Recently, reflection FWI (RFWI) has been shown to provide low-wavenumber velocity updates beyond the diving-wave penetration depth and has produced greatly improved images (Vigh et al., 2016; Gomes and Chazalnoel, 2017). As Mora (1989) pointed out, the gradient derived from reflection energy can be divided into two different components: the high-wavenumber component, known as the migration term, generated by incident and scattered wavefields propagating in opposite directions, and the low-wavenumber component, known as the tomography term or “rabbit ears”, generated by incident and scattered wavefields propagating in the same direction. Usually, the migration-term gradient has a much stronger magnitude than the tomography-term gradient, but it is this weak-amplitude tomography-term gradient that carries the important low wavenumber kinematics information of the velocity model. A key component of RFWI is to extract this tomography-term gradient from the total gradient and use it to update the velocity. This can be done by up-down wavefield decomposition (Liu et al., 2011; Tang et al., 2013; Irabor and Warner, 2016) or by Born modeling of the source-side and receiver-side scattered wavefields separately (Xu et al., 2012). The decomposition approach can produce artifacts around high-dip reflectors due to its inability to differentiate the propagation directions at these locations, while the Born-modeling-based approach is free of these artifacts at the cost of extra wavefield propagation. Therefore, we decided to use Born-modeling-based RFWI for our study (Z. Zhang, personal communication, 2018).

RFWI update at Conger

The input data used for RFWI here is an OBN data set acquired in 2013 in the north-south direction. The nominal node spacing is 400 m by 400 m, while the nominal shot spacing is 50 m by 50 m. The maximum crossline offset was limited to 10 km during acquisition, and the maximum offset of the survey (mostly driven by the inline shots) can reach up to about 18 km. The down-going wavefield after designature, source deghost, and demultiple was used for RFWI inversion, and we muted off the energy above the water bottom reflection. The source wavelet for RFWI was automatically inverted from the direct arrivals from all nodes with offsets less than 2 km. The starting model was the best model available, which was after several iterations of ray-based tomography, diving-wave FWI, and salt scenario tests using both streamer and OBN data. Most of the shallow sediment velocities were reasonable after these updates, and the main velocity uncertainties come from the Conger salt and the low reflectivity carapace.

We performed RFWI from 4 Hz to 7 Hz with a frequency step of 1 Hz. The RFWI velocity updates led to promising improvements on the stack images, as shown in Figure 2. The low reflectivity carapace above the Conger salt was better resolved, with several reflectors being brought out after RFWI. As a result, the top of salt event right next to the carapace was also better imaged and defined, especially at the salt wedge. The improvement at the overburden velocity healed the broken bright reservoir reflector beneath the edge of the Conger salt and in general resulted in better focused reflectors and better defined structures in the deeper region. Migration swings were also reduced in the stack image with an improved velocity model from RFWI. As expected, velocity updates in the overburden are mostly low-wavenumber with small values within a range of ±50 m/s, which is less than 2% of the initial velocity

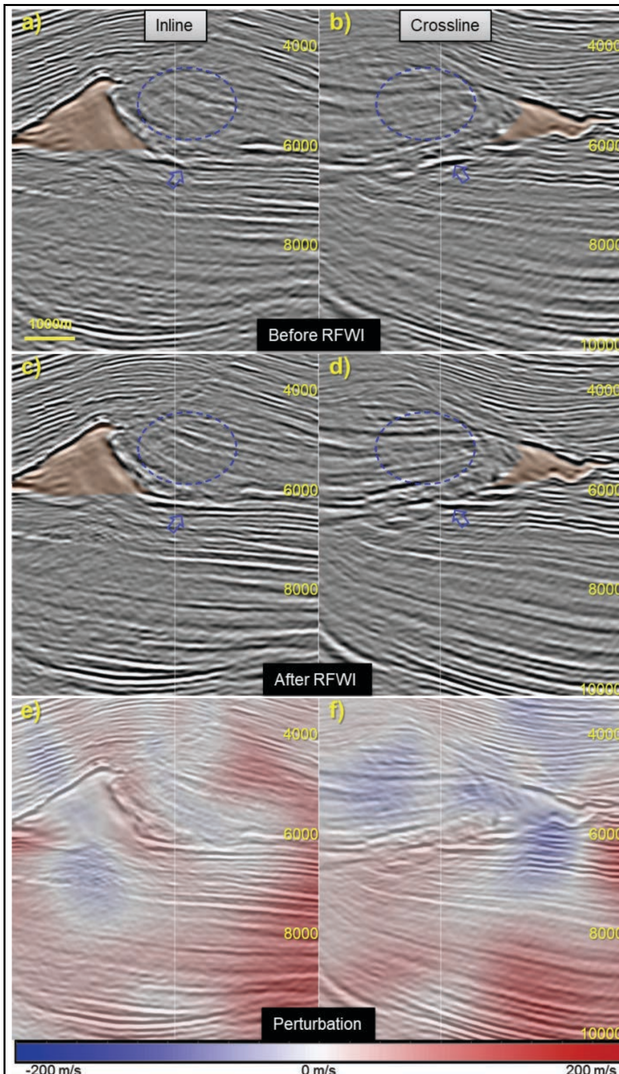

Figure 2: 15 Hz OBN RTM inline and crossline sections: a) and b) before RFWI update; c) and d) after RFWI update; e) and f) overlay RFWI perturbation on c) and d).

(Figures 2e and 2f); however, their impact on the reservoir imaging is still quite significant. The gather response is also improved (Figure 3). Events in gathers were better focused and were mostly flat within the carapace and at the reservoir level after RFWI. All of these indicate that 3D low-wavenumber velocity errors can have a critical impact on imaging, and RFWI is capable of correcting these subtle low-wavenumber kinematic errors effectively, which has proven difficult for conventional methods such as interpretation-guided velocity updates or ray-based tomography.

WAZ RFWI vs. OBN RFWI

The success of RFWI in improving Conger imaging is attributed to the full-azimuth and long-offset constraints provided by OBN data. Yet OBN acquisition is still quite costly and unavailable in most areas. So we ask the questions: Will RFWI using wide-azimuth (WAZ) data also improve the results? How much benefit can RFWI gain when using full-azimuth and long-offset OBN data instead of WAZ data? We used a WAZ data set that overlaps with the OBN coverage to carry out an experiment to explore

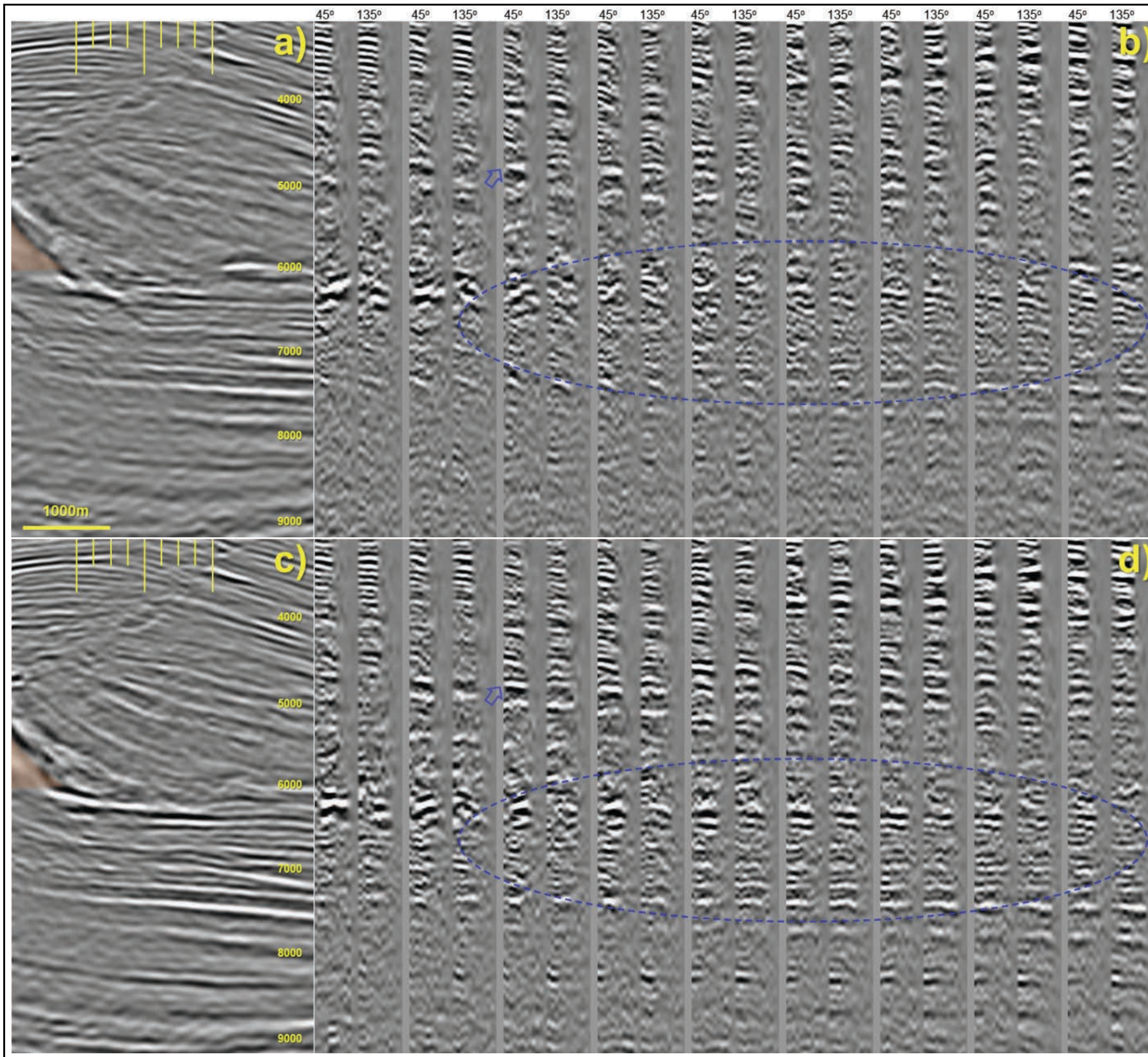

Figure 3: 15 Hz OBN RTM stack and SOGs of azimuths 45° and 135° from: a) and b) initial model; c) and d) after RFWI update. Gather locations are indicated by the yellow lines in a) and c).

10.1190/segam2018-2996264.1

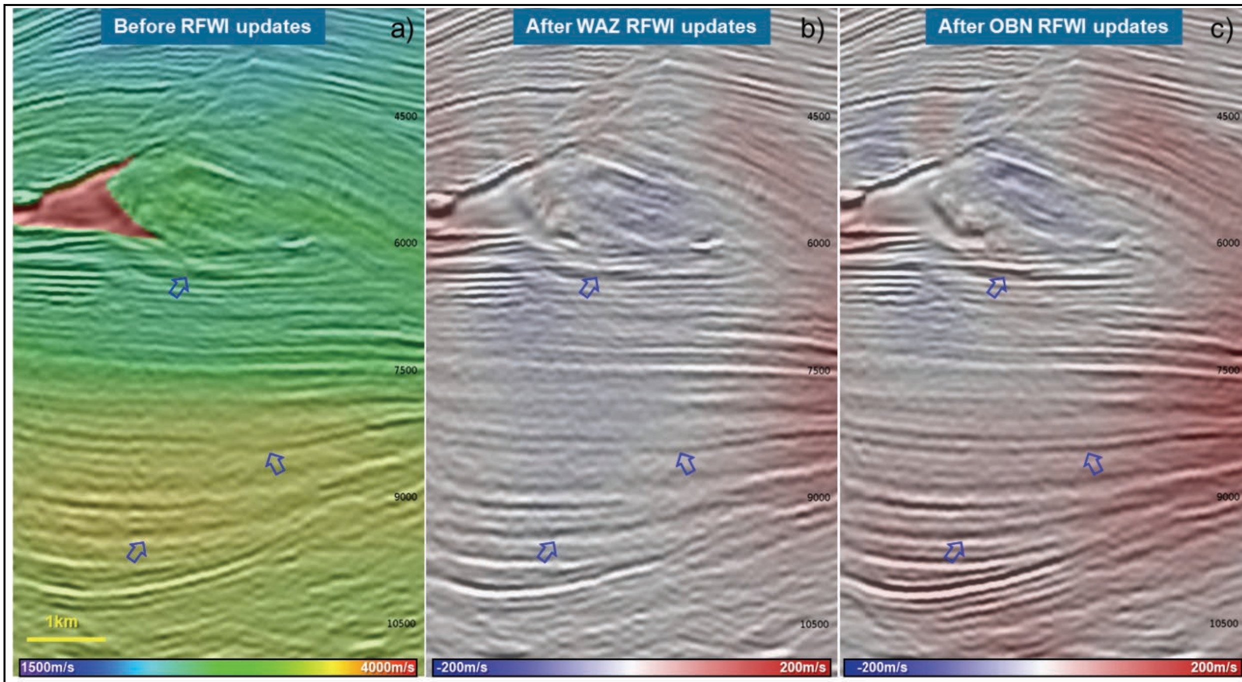

Figure 4: 15 Hz OBN RTM: a) initial migration stack and initial model; b) WAZ RFWI migration stack and perturbation; c) OBN RFWI migration stack and perturbation.

these questions.

The WAZ data set was acquired between 2007 and 2009 in the northeast-southwest direction. Its maximum crossline offset is about 4 km and maximum offset is about 9 km, compared to 10 km maximum crossline offset and 18 km maximum offset in the OBN data. The WAZ data used for RFWI was also after designature, source and receiver deghost, demultiple, and with the same data and wavelet preparation procedure. RFWI was run on the WAZ data starting from the same initial model and for the same frequency range of 4 Hz to 7 Hz.

As shown in Figure 4, the WAZ RFWI update also improved the image below the salt and deeper sediments. Broken subsalt events were healed and deeper events were better focused. However, the uplift from WAZ RFWI was less than that from OBN RFWI. OBN RFWI had better event continuity below the salt and more focused events at the deeper section. It is not a surprise that OBN RFWI can update the velocity better and result in better images over WAZ RFWI from shallow to deep. The full-azimuth acquisition is expected to better resolve the complex velocity in the carapace and salt. Longer offsets also result in larger reflection angles at deeper reflectors and help constrain the deeper model better.

Discussion and Conclusions

At Conger we observed that long-wavelength, subtle velocity errors can critically affect the imaging of the reservoir. We demonstrated that RFWI using OBN data is able to resolve such velocity errors associated with carapace and salt, thus improving reservoir imaging at the Conger field. After RFWI, focusing of the events was improved and the structure was clearer at the complex carapace and salt areas, and at the subsalt level. RTM surface offset gathers were also improved substantially after velocity updates. By comparing WAZ RFWI to OBN RFWI, we showed that long-offset and full-azimuth OBN data provides more constraints and is more favorable for RFWI at complex regions. On the other hand, the RFWI update lacks vertical resolution due to the intrinsic low wavenumber of the transmission component and the contribution being dominated by a few strong reflectors. A better scheme overcoming such limitations should further reduce the velocity uncertainty at the Conger field.

Acknowledgments

We thank Hess, Anadarko, Shell, and CGG for the permission to publish this paper. We are grateful to Zhigang Zhang for his insightful discussion and suggestions during this work.

REFERENCES

Gomes, A., and N. Chazalnoel, 2017, Extending the reach of full-waveform inversion with reflection data: Potential and challenges: 87th Annual International Meeting, SEG, Expanded Abstracts, 1454–1459, https://doi.org/10.1190/segam2017-17731403.1.

Irabor, K., and M. Warner, 2016, Reflection FWI: 86th Annual International Meeting, SEG, Expanded Abstracts, 1136–1140, https://doi.org/10.1190/segam2016-13944219.1.

Liu, F., G. Zhang, S. A. Morton, and J. P. Leveille, 2011, An effective imaging condition for reverse-time migration using wavefield decomposition: Geophysics, **76**, no. 1, S29–S39, https://doi.org/10.1190/1.3533914.

Mora, P., 1989, Inversion = migration + tomography: Geophysics, **54**, 1575–1586, https://doi.org/10.1190/1.1442625.

Shen, X., I. Ahmed, A. Brenders, J. Dellinger, J. Etgen, and S. Michell, 2017, Salt model building at Atlantis with full- waveform inversion: 87th Annual International Meeting, SEG, Expanded Abstracts, 1507–1511, https://doi.org/10.1190/segam2017-17738630.1.

Stieglitz, T., M. Scott, D. Walker, C. Shi, W. Martins, K. Brad, and P. Pujiyono, 2016, Illumination, imaging, and 4D analysis of the Conger Field (GB 215): 86th Annual International Meeting, SEG, Expanded Abstracts, 3935–3939, https://doi.org/10.1190/segam2016-13847556.1.

Tang, Y., S. Lee, A. Baumstein, and D. Hinkley, 2013, Tomographically enhanced full wavefield inversion: 83rd Annual International Meeting, SEG, Expanded Abstracts, 1037–1041, https://doi.org/10.1190/segam2013-1145.1.

Vigh, D., K. Jiao, X. Cheng, D. Sun, and W. Lewis, 2016, Earth-model building from shallow to deep with full-waveform inversion: The Leading Edge, **35**, 1025–1030.

Wang, Z., R. Huang, Y. Xuan, Q. Xu, S. Morton, and B. Kuntz, 2017, Improving OBS-streamer 4D imaging by least- squares migration: 87th Annual International Meeting, SEG, Expanded Abstracts, 5819–5823, https://doi.org/10.1190/segam2017-17739944.1.

Wei, Z., Y. Xuan, R. Huang, C. Theriot, D. Rodenberger, M. Chang, S. Morton, and M. Zouari, 2016, Application of deghosting for spectral matching in OBS-streamer 4D processing: 86th Annual International Meeting, SEG, Expanded Abstracts, 5506–5510, https://doi.org/10.1190/segam2016-13872129.1.

Xu, S., D. Wang, F. Chen, Y. Zhang, and G. Lambaré, 2012, Full waveform inversion for reflected seismic data: 74th Annual International Conference and Exhibition, EAGE, Extended Abstracts, W024, https://doi.org/10.3997/2214-4609.20148725.

Yang, Z., S. Huang, and R. Yan, 2015, Improved subsalt tomography using RTM surface offset gathers: 85th Annual International Meeting, SEG, Expanded Abstracts, 5254–5258, https://doi.org/10.1190/segam2015-5848366.1.

10.1190/segam2018-2996264.1