Least-squares RTM with ocean bottom nodes: potentials and challenges

Yan Liu, Yi Chen, Hongda Ma, Chao Peng (CGG);*
Gopal Mohapatra, Wisley Martins, Gregory Duncan (Hess), Steve Checkles (Formerly Hess)

Summary

Stampede field is a faulted subsalt four-way reservoir in Green Canyon, Gulf of Mexico. Interference from the complex overburden, which carries large velocity errors and creates non-uniform illumination for the subsalt, has remained a challenge to subsalt imaging. Before correcting the velocity error, least-squares reverse time migration (LSRTM) does not produce a desirable subsalt image, even when using newly acquired ocean bottom node (OBN) data. With an improved OBN full-waveform inversion (FWI) model, combined with the benefits from the full-azimuth and long-offset coverage of OBN data, LSRTM greatly improves the subsalt image. However, further improving LSRTM is still challenging due to the remaining velocity uncertainty and un-modeled physics, as well as residual multiples and converted waves.

Introduction

Reverse time migration (RTM) is the most commonly used imaging technology for complex structures. It forms the subsurface image by reversing the forward wave-propagation effects from the data with an adjoint modeling operator (Baysal et al., 1983; Etgen et al., 2009; Zhang and Zhang, 2009). However, it is difficult for RTM to perfectly represent the reflectivity of the subsurface due to approximation of the inverse of wave propagation effects with an adjoint operator. Therefore, RTM images often suffer from migration artifacts, uneven amplitudes, and limited resolution, especially for areas with complex structures where velocity uncertainty is large.

Least-squares migration (LSM) was proposed to handle these problems by deriving a more accurate estimation of the inverse of the forward modeling operator. Theoretically, the estimation needs to be performed iteratively to solve an inverse Hessian matrix. In reality, iterative LSRTM is often computationally expensive and susceptible to noise and migration artifacts. Single-iteration image-domain LSM methods (Guitton, 2004; Lecomte, 2008; Fletcher et al., 2016; Wang et al., 2016) are proposed to reduce the computational cost and make LSRTM more practical. Among various single-iteration image-domain solutions, the Curvelet-domain Hessian filter (CHF or CHF-LSRTM) based scheme (Wang et al., 2016) tries to obtain matching filters for different structural dips and frequencies to better compensate frequency and angle dependent illumination. Extending CHF from the stack domain to the surface offset gather (SOG) domain can further compensate for uneven illumination across offsets.

Stampede field is located in the Green Canyon area of the deep-water Gulf of Mexico (GOM). After the discovery in 2005, production started in early 2018. While improved imaging has been achieved from various streamer acquisitions and processing efforts, it is still challenging to obtain a better image in areas with complex overhangs and base of salt (BOS) inclusions (Mohapatra et al., 2013; Mohapatra et al., 2016). In 2018, Hess engaged Fairfield Nodal to acquire OBN data over Stampede field (Figure 1). The OBN data has full-azimuth coverage and maximum offsets of more than 25 km. It also contains good low frequency signal down to 1.6 Hz (Yao et al., personal communication, 2019). With good data quality and coverage, we explore the potential of LSRTM with OBN data to resolve the imaging challenges at Stampede field. Single-iteration, SOG-based CHF was applied for LSRTM imaging at this area.

Improved subsalt imaging from OBN LSRTM

The entire Stampede field is covered by a 15,000 ft thick salt canopy. Above the north part of the field, the BOS becomes rugose with a difficult-to-solve inclusion geometry. As a result, OBN data was acquired in this area aiming to improve the imaging for field development and production purposes. The acquired OBN data has a nominal node spacing of 350 m x 350 m and a nominal shot spacing of 50 m x 50 m with a north-south shooting direction. The nodes at the center area have maximum offset between 16 km and 18 km for all azimuths. At the boundary area, the nodes have maximum offset of 8 km for all azimuths, with maximum offset up to 30 km for limited azimuths (Figure 1).

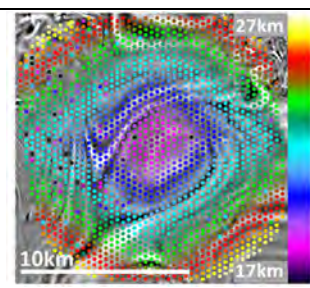

Figure 1: Node map and maximum offset for each node

We first performed OBN Time-lag FWI (TLFWI) (Zhang et. al, 2018) to update the velocity before migration. Figure 2a shows the OBN conventional RTM images after FWI updates. Overall, the subsalt structure was imaged with clear and continuous events. However, migration artifacts make it difficult to determine how far the structure extends below the yellow arrows and whether another fault exists to the left of the major fault. Moreover, the reservoir event above the green arrow has limited resolution and is dimmed.

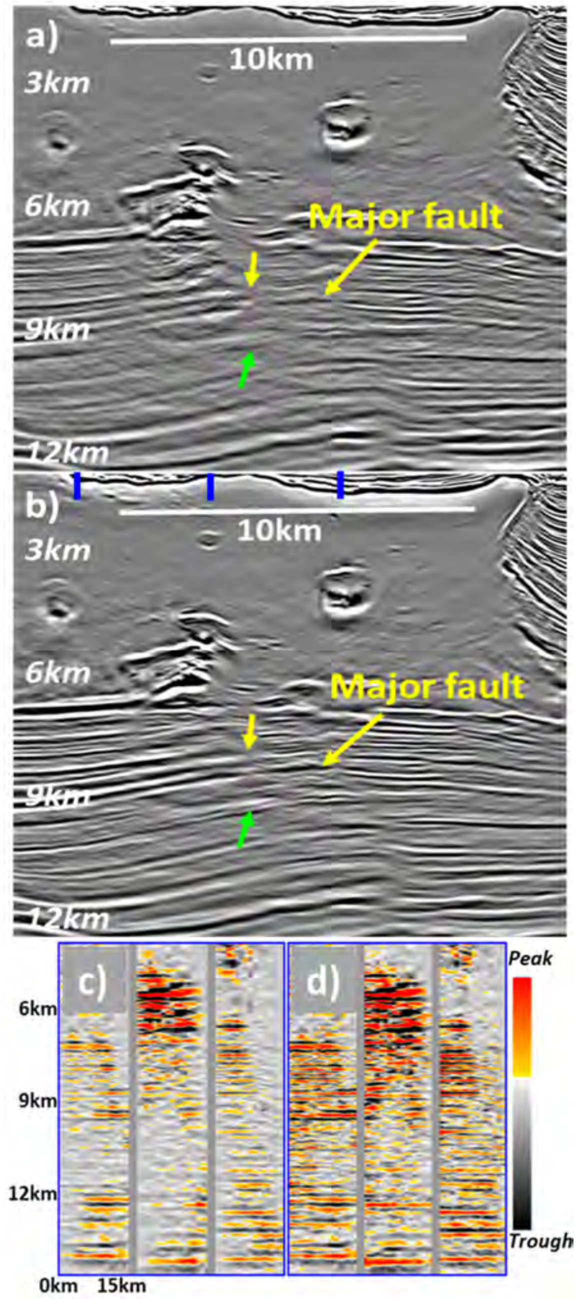

Figure 2: a) Conventional RTM stack; b) LSRTM stack (blue lines indicate gather locations); c) Conventioanl RTM SOGs; d) LSRTM SOGs

In an effort to eliminate the migration artifacts and amplitude distortion, we attempted LSRTM. To correctly compensate for the azimuthal and offset-related illumination differences, the OBN data was separated into different azimuthal and offset groups. SOG-based CHF (Wang et al., 2016) was applied to approximate the inverse Hessian matrix through a demigration/remigration process and compensate for uneven illumination across different groups separately.

After LSRTM (Figure 2b), migration swings were suppressed and migration artifacts were effectively attenuated below the yellow arrows. Meanwhile, the reservoir event showed more balanced amplitudes and improved resolution. Due to the imaging improvements, the structures could be mapped to the major fault with more confidence.

Besides the improvements to the stacked image, SOG-based CHF also compensated for amplitude distortion in the RTM gathers. Conventional OBN RTM SOGs (Figure 2c) showed large amplitude variation across offsets, with generally weaker near offsets, caused by different illumination patterns among offsets and non-uniform fold distribution. After LSRTM, with illumination and fold effects compensated, the amplitudes across different offsets became more balanced (Figure 2d).

What makes OBN LSRTM effective at Stampede?

LSRTM with the newly acquired OBN data greatly improved subsalt imaging at Stampede. It also balanced the amplitudes for the migration gathers by compensating for fold- and illumination-related amplitude distortion. Wang et al. (2016) state that it is difficult for LSRTM to recover events that are not imaged due to poor illumination or an inaccurate velocity model. To understand the importance of an accurate velocity model and sufficient data coverage for effective OBN LSRTM imaging at Stampede, we conducted two experiments.

Impact from velocity model
In the first experiment, we performed OBN LSRTM with a legacy model. The legacy model (Figure 3a) was built using a top-down salt model building process with tremendous efforts made in salt scenario testing. Most of the salt scenario work was conducted within the dashed circle area. The OBN RTM image from the legacy model had strong migration swing contamination and dimmer amplitudes compared to the nearby well-imaged area, as indicated by the yellow arrow in Figure 3b. The distorted subsalt events raise doubts as to the validity of this faulted structure.

10.1190/segam2019-3216736.1

After LSRTM (Figure 3c), the image had more uniform amplitude, but, at the same time, migration artifacts were boosted. On the left side above the arrow, migration swings were amplified and masked the seismic events. Overall, the benefit was limited in restoring subsalt structures.

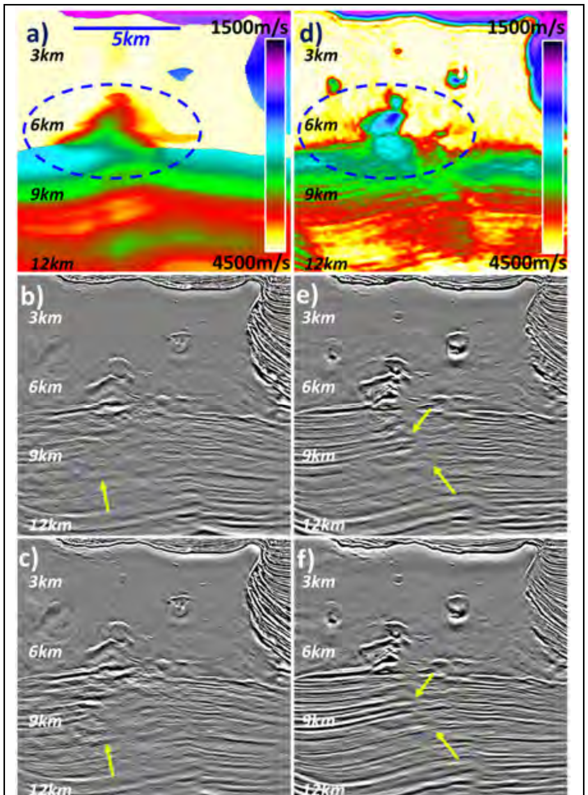

Figure 3: OBN RTM and LSRTM with different velocity models: a) legacy model, b) conventional RTM with legacy model, c) LSRTM with legacy model, d) OBN FWI model, e) conventional RTM with OBN FWI model, f) LSRTM with OBN FWI model

After OBN FWI, the model had more detailed salt boundaries, as highlighted by the dashed circle in Figure 3d. Conventional OBN RTM (Figure 3e) started to show interpretable subsalt events with the updated model, indicating the velocity error had been reduced by OBN FWI. However, un-canceled migration swings still lead to structural discontinuity between the two arrows. After LSRTM (Figure 3f), the swings were effectively attenuated and subsalt events were clearly extended. Amplitudes were compensated without boosting noise. This experiment indicates least-squares migration output is only as reliable as the underlying velocity.

The complexity of the salt and intra-salt sediment velocities at Stampede field is typical of many GOM areas. Any misinterpreted salt or biased intra-salt velocity can easily break the LSRTM assumption, which is that the provided velocity is accurate. With OBN FWI, the velocity error can be largely reduced, leading to improved performance of LSRTM.

Impact from full-azimuth and long-offset coverage

To gain more insight into the value of the full-azimuth and long-offset coverage of OBN data, the second experiment was designed to investigate whether similar imaging uplift could be achieved using limited azimuths and offsets, such as from a wide-azimuth (WAZ) acquisition. In this experiment, we discarded the OBN data that was outside the azimuth and offset range of a typical WAZ data set. The remaining OBN data only covered 1/3 of the full azimuths and had a maximum offset of 9 km. We then compared conventional RTM and LSRTM images from the limited OBN data set and the complete OBN data set (full azimuth, 15 km maximum offset). The OBN FWI model was used for all migrations. It is worth mentioning that the limited OBN data set is still considered to be more ideal than towed-streamer data as it contains less cable and ambient noise.

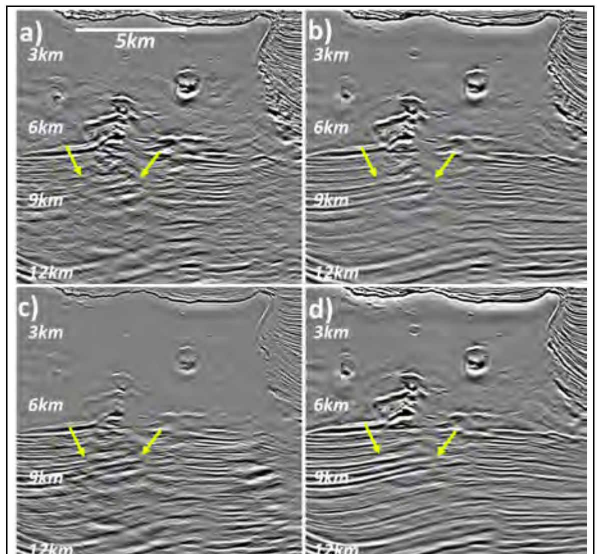

Figure 4: Conventional RTM: a) limited OBN input data, b) complete OBN input data; LSRTM: c) limited OBN input data, d) complete OBN input data

Due to insufficient illumination, the conventional RTM image migrated with the limited OBN data had obvious missing events and contained strong migration artifacts, particularly at locations right below the arrows in Figure 4a. When migrated with the complete OBN data, events were more continuous along the reflectors at the same locations (Figure 4b). The missing azimuth and far offset data is important for filling the gaps that cannot be successfully imaged with the limited portion of the data, as shown by this

10.1190/segam2019-3216736.1

comparison. This also reiterates the importance of full azimuth and longer offsets for subsalt imaging. Moreover, when the conventional RTM image was degraded by the limited OBN data, LSRTM lacked the power to attenuate the illumination-related artifacts below the yellow arrows in Figure 4c. In contrast, the advantages of LSRTM were more prominent when using the complete OBN data set (Figure 4d). Subsalt event continuity was further improved with more consistent amplitudes, and swing artifacts were well suppressed from shallow to deep sections.

The key to the CHF-LSRTM method is to estimate the inverse of the Hessian matrix through a matching filter between the raw migration image and the remigration image. The input for remigration comes from synthetic data from Born modeling, considering the raw migration image as the reflectivity. Therefore, any missing or very weak events in the raw migration image due to data limitations could also result in degradation of illumination compensation from LSRTM. In other words, OBN data helps to enhance the performance of LSRTM by improving the quality of the raw migration image.

These two experiments demonstrated the importance of velocity accuracy and sufficient data coverage for effective LSRTM. The velocity inaccuracy in the legacy model was the major issue preventing us from previously applying LSRTM, and has now been addressed by OBN TLFWI. Meanwhile, full-azimuth and long-offset coverage from OBN data improved the performance of LSRTM.

Challenges for OBN LSRTM

While we achieved subsalt improvement from OBN LSRTM at Stampede field, we noticed the image is still not completely satisfactory. Two major issues were observed from the current result. After extracting the RMS amplitude along a geological event at around 9 km depth, the amplitude became compensated overall after LSRTM (Figure 5b) compared to conventional RTM (Figure 5a). However, a further investigation showed that the amplitude extraction from LSRTM after filtering below 8 Hz was more uniform than that from above 8 Hz. This frequency-dependent subsalt amplitude pattern indicates there could be un-compensated absorption effects. Since the acoustic Born modeling applied in LSRTM is a simplified form to represent wave propagation through the earth to model part of the physics, un-modeled physics, such as absorption, transmission loss, and elastic effects, cannot be compensated by LSRTM.

Another issue is that, even after OBN LSRTM, residual swing still exists to the left of the arrows and beneath the rugose BOS (Figure 2b). It was observed from a synthetic study that the residual swing is likely related to inter-bed multiples due to the reflections between the salt-sediment boundaries above it. This highlights the other limitation of LSRTM. Usually, unwanted energy, such as multiples and converted waves, is hard to fully attenuate in the subsalt. Any of that residual unwanted energy in the data will not be modeled by LSRTM and will remain in the final image.

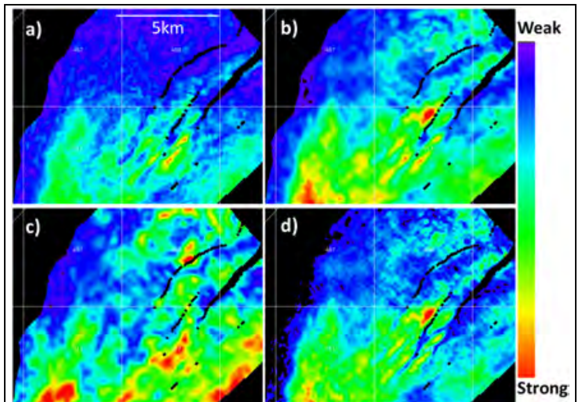

Figure 5: Amplitude extraction along geological event at 9 km depth: a) Conventional RTM, b) LSRTM, c) LSRTM filtered to 0-8 Hz, d) LSRTM filtered to 8 Hz and above

According to the observed issues from our current results, OBN LSRTM still cannot fully resolve the subsalt imaging and amplitude issues. To further address these challenges, we need to include more physics in the LSRTM method and obtain data with less contamination from unwanted energy.

Discussion and Conclusions

At Stampede field, LSRTM improved the subsalt image using OBN data. First, OBN FWI helped to largely reduce the velocity uncertainty for a geologically complex area, which was important for the success of LSRTM. Second, with full-azimuth and long-offset coverage, OBN LSRTM had more accurate illumination compensation than streamer data could provide.

Nonetheless, we consider being able to resolve the velocity error and obtain better data coverage as just a starting point to performing and evaluating LSRTM. There are many issues that require additional efforts to push LSRTM to its full potential. Better data/technique to build more accurate velocity models, further research on un-modeled physics, and a robust algorithm for better attenuating unwanted energy will lead to further improvement of LSRTM.

Acknowledgments

We thank Hess, Equinor, Chevron, and CGG for permission to publish this paper. We also thank Tony Huang and Ping Wang for insightful discussions and Yuan Yao for the Stampede OBN FWI work.

10.1190/segam2019-3216736.1

REFERENCES

Baysal, E., D. D., Kosloff, and J. W. C., Sherwood, 1983, Reverse time migration: Geophysics, **48**, 1514–1524, doi: https://doi.org/10.1190/1.1441434.

Etgen, J., S., Gray, and Y., Zhang, 2009, An overview of depth imaging in exploration geophysics: Geophysics, **74**, no. 6, WCA5–WCA17, doi: https://doi.org/10.1190/1.3223188.

Fletcher, R. P., D., Nichols, R., Bloor, and R. T., Coates, 2016, Least-squares migration — Data domain versus image domain using point spread functions: The Leading Edge, **35**, 157–162, doi: https://doi.org/10.1190/tle35020157.1.

Guitton, A., 2004, Amplitude and kinematic corrections of migrated images for nonunitary imaging operators: Geophysics, **69**, 1017–1024, doi: https://doi.org/10.1190/1.1778244.

Lecomte, I., 2008, Resolution and illumination analyses in PSDM: A ray-based approach: The Leading Edge, **27**, 650–663, doi: https://doi.org/10.1190/1.2919584.

Mohapatra, G., D., Smith, J., Goode, and G., Harris, 2013, An imaging journey over Stampede field, Gulf of Mexico: Improvements and challenges: 83rd Annual International Meeting, SEG, Expanded Abstracts, 4001–4004, doi: https://doi.org/10.1190/segam2013-0433.1.

Mohapatra, G., A., Nabasir, and S., Strauss, 2016, An integrated approach to Stampede field development, Deepwater Gulf of Mexico: Offshore Technology Conference.

Wang, P., A., Gomes, Z., Zhang, and M., Wang, 2016, Least-squares RTM: Reality and possibilities for subsalt imaging: 86th Annual International Meeting, SEG, Expanded Abstracts, 4204–4209, doi: https://doi.org/10.1190/segam2016-13867926.1.

Zhang, Y., and H., Zhang, 2009, A stable TTI reverse time migration and its implementation: 79th Annual International Meeting, SEG, Expanded Abstracts, 2794–2798, doi: https://doi.org/10.1190/1.3255429.

Zhang, Z., J., Mei, F., Lin, R., Huang, and P., Wang, 2018, Correcting for salt misinterpretation with full-waveform inversion: 88th Annual International Meeting, SEG, Expanded Abstracts, 1143–1147, doi: https://doi.org/10.1190/segam2018-2997711.1.