Using Least-Squares Wave-Equation Multiple Migration for Shallow Imaging, a case study on Offshore Brunei OBN data

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Summary

Well drilling and abandonment work offshore Brunei is very challenging due to the presence of complex shallow geological features, such as corals, river channels, gas clouds/chimneys, and small faults. Therefore high-resolution seismic images, which can reveal those features, are desired to help avoid potential geohazards. In this study, Least-Squares Wave-Equation Multiple Migration (LSWEMM) was used to produce 3D high-resolution shallow images. The new results have both high spatial and temporal resolution. The near water bottom geological features are more clearly revealed than on conventional primary images. The resolution of fine channels and small faults is also greatly improved compared to nearfield hydrophone (NFH) images. The new mapping of shallow channels is very helpful for ongoing geohazard assessment work near a planned well. LSWEMM was applied on existing OBN data, hence is much more cost effective compared with an additional survey, such as 3D P-cable acquisition. Moreover, decimation studies show great value in optimizing future OBN acquisition and 2D high-resolution survey design, which could further reduce the cost associated with geohazard assessment work.

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Introduction

Complex shallow geological features, such as corals, river channels, gas clouds/chimneys, and small faults, pose potential geohazards for well drilling and abandonment work. As a result, high-resolution seismic images which capture shallow geological details are highly desirable. Conventional production geohazard assessment mainly relies on 2D High-resolution (HR) seismic data from site surveys. 2D HR images can provide a very high temporal resolution, but are usually too sparse to provide sufficient spatial coverage. Nearfield hydrophone (NFH) imaging has gained significant attention recently due to the fact that it can provide 3D coverage, however the source array separation usually limits the crossline spacing and offset range, hence degrading crossline resolution, fault imaging, and low-frequency content. 3D high-resolution acquisition or source-over-streamer acquisition can alleviate the problem but come with increased acquisition cost. Therefore, a cost-effective 3D shallow imaging method that can produce a good spatial and temporal resolution for geohazards assessment is highly desired.

3D seismic data are usually acquired and processed for deep target exploration. High-density acquisition is required to image shallow targets. Brunei Shell Petroleum (BSP) acquired two high-density shallow water ocean bottom node (OBN) seismic surveys in 2019 and 2020 with shallow to deep targets, offshore Brunei. The processing of primary images show very good uplifts at target depth. However, the primary imaging still suffers in the shallow near surface due to a lack of near-angle primary reflections. With richer near-angle illumination from multiples than primaries, multiple imaging using existing high-density OBN data can produce high-resolution shallow images with very good spatial and temporal resolution. Such images not only can compensate the poor shallow imaging from primary processing for exploration and development purpose but also can be very valuable for geohazard assessment work such as surface/well location assessment and optimization of 2D HR survey design thanks to the very high resolution 3D image which makes shallow geohazard identification and interpreation much easier and more reliable. High-resolution multiple imaging can substantially impact pre-drilling geohazard assessment as well as enable optimization of late-life well abandonment in maturing assets.

Multiple imaging using Least-Squares Wave-Equation Multiple Migration (LSWEMM) for OBN data operates in the common receiver domain and produces images using shot-side multiples. The nature of high-density shotpoint distribution significantly increases the potential subsurface illumination coverage by using the small-angle reflections in the multiples. The least-squares migration/inversion of the LSWEMM method was introduced for better cross-talk attenuation and image resolution (Poole, 2021). In this paper, we will show how we applied LSWEMM to derive a 3D high-resolution image from Brunei OBN datasets and its added value to ongoing geohazards assessment. We will also discuss the impact of different acqusition grids on multiple imaging which may advise future OBN acquisitions.

OBN Acquisition and Shallow Imaging Problem

Two high-density OBN surveys (Intan and Nilam) were acquired in 2019-2020, in a very shallow water with depth varying from 5 m to 65 m. This acquisition was a node-on-a-rope acquisition using center parallel shooting with 75 m x 175 m receiver node spacing for the Intan survey and 75 m x 150 m receiver node spacing for the Nilam survey. Both surveys have a dense shot spacing of 25 m x 25 m.

Full-waveform inversion (FWI) with long offset and full azimuth OBN data provided a reliable velocity model for depth imaging. OBN primary imaging provided good image uplifts at the target depth. However, without near-angle primary reflections in the data, primary imaging still suffered at shallow near surface (<200 m) with imaging problems of amplitude footprints and data holes.

LSWEMM for Shallow Imaging

Subsurface illumination from OBN primary imaging is limited by node density and source distribution. The relatively sparse node spacing leads to the missing of small-angle reflections for shallow events, resulting in limited illumination from primaries for the shallow section. Multiple imaging treats the acquired data as secondary sources, which can significantly increase the subsurface illumination coverage using the small-angle reflections in the multiples (Berkhout and Verschuur, 1994). LSWEMM models the up-going multiple wavefields by convolving the reflectivity with a forward extrapolated down-going wavefield. The modeled up-going multiple wavefields are subsequently forward propagated to the surface to simulate the multiple energy recorded in the acquired data. The reflectivity is then inverted through minimizing the misfit between the modeled up-going multiples with the recorded multiples in a least-squares sense (Poole, 2021). The LSWEMM imaging flow for OBN data is much less complicated than the primary imaging flow. OBN raw P and Z data were run through denoise, up and down wavefield separation and tidal correction to prepare the input. In this study, we applied LSWEMM on the Intan and Nilam high-density OBN datasets to produce high-resolution shallow images, benefiting from rich small-angle illumination from multiples recorded on the OBN data with typically dense shotpoint spacing and a wide shot carpet.

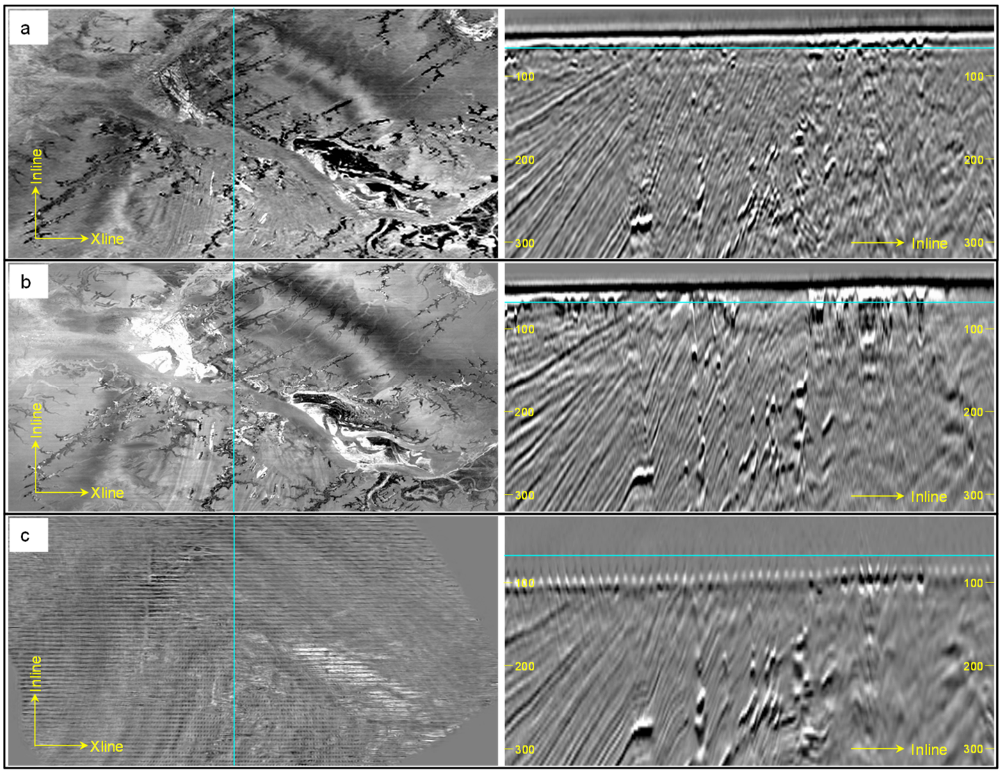

Figure 1 *Comparison of NFH image, LSWEMM image and Primary image from offshore Brunei Nilam OBN data. Left column: depth slices at 64 m. Right column: crossline sections. (a) NFH imaging; (b) LSWEMM imaging; (c) Primary imaging.*

Figure 1 shows the LSWEMM result and its comparison with legacy passive NFH image and OBN primary image. The left column of Figures 1a, 1b, and 1c show a depth slice at 64 m for NFH, LSWEMM, and OBN primary imaging, respectively. The OBN primary image suffered from amplitude footprints and data holes at this depth due to limited near-angle illumination. Both NFH and LSWEMM imaging provided better overall lateral resolution than the OBN primary imaging, with many river channels being clearly defined. LSWEMM imaging had the highest lateral resolution, with much better delineation of small channels. The right column of Figure 1a, 1b and 1c show crossline sections of the NFH, LSWEMM and OBN primary image, respectively. The comparison shows that the primary imaging suffered from illumination issues and uncancelled migration swings within the first 200 m while NFH imaging and LSWEMM provided much higher resolution shallow images. The NFH image had more high frequency content but poor fault imaging, while the LSWEMM image was more broadband with better low frequencies, producing better fault imaging and better delineation of shallow structures. However, LSWEMM still suffers from certain cross-talks, caused by multiples more than one order apart correlating with each other.

Dense acquisition is the key factor that makes LSWEMM work on the Intan and Nilam OBN datasets. To understand the impact of acquisition on multiple imaging, we performed several acquisition grid decimation tests. Figure 2a, 2b & 2c show the LSWEMM results of different node spacing and Figure 2a, 2d, 2e & 2f show the LSWEMM results of different shot spacing. The comparisons show that OBN multiple imaging is not very sensitive to node spacing due to the large output coverage from each receiver line, although coarser nodes caused slight image degradation with lower S/N. However, the shot grid proved critical for OBN multiple imaging. Multiple imaging quality degrades quickly with increased shot spacing. For areas with similar complicated shallow geology and water depth around 40 m, a dense shot grid smaller than 50 m x 50 m should be considered for multiple imaging. Such observations are very useful for new acquisition design. Good image resolution still can be achieved while reducing the node spacing, which will heavily reduce the acquisition cost and can be an important factor when acquiring in areas with lots of infrastructure.

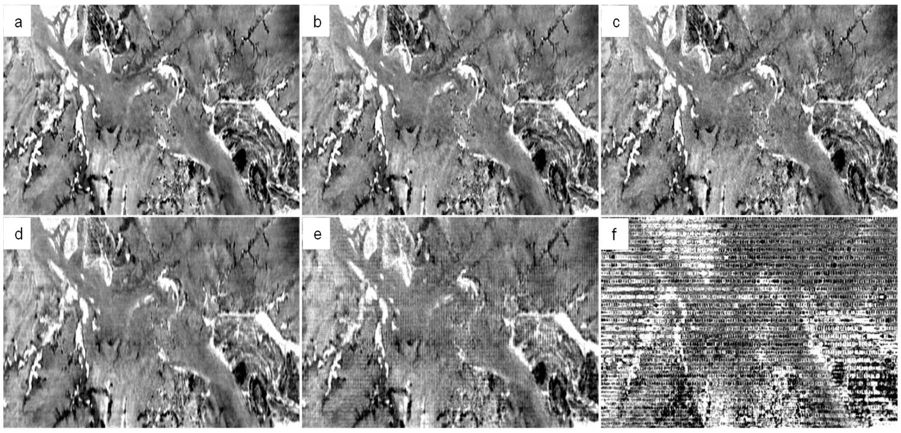

Figure 2 *Acquisition Grid Decimation Test. Receiver Grid Decimation Test: (a) 75 m x 150 m; (b) 150 m x 150 m; (c) 150 m x 300 m. Shot Grid Decimation Test: (a) 25 m x 25 m; (d) 25 m x 50 m; (e) 50 m x 50 m; (f) 50 m x 100 m.*

LSWEMM for Geohazard Assessment

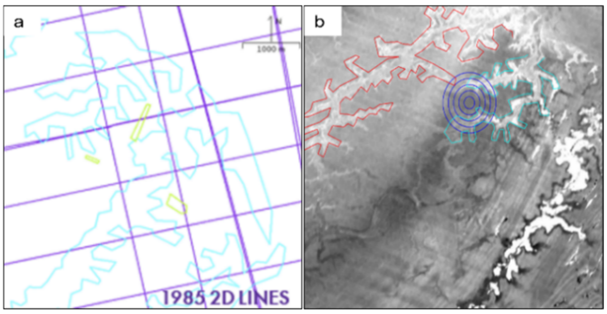

Figure 3 *Shallow geohazard interpretation for 2D HR acquisition optimization. (a) Sparse 2D HR lines (purple) and avoidance polygons (cyan); (b) Depth slice at 56 m from LSWEMM with avoidance polygons (red and cyan) overlaid near well location (blue).*

The high spatial resolution of shallow images can be very useful for geohazard assessment, such as mapping of channels and hydrocarbon accumulations and surface assessment for well locations. For shallow water, 2D HR seismic is usually acquired to provide a detailed shallow image. However, 2D HR lines are sparse and limited in shallow geohazard identification and channel interpretation where 3D high-resolution image is required (Figure 3a). LSWEMM data provides a high-resolution 3D image, which is very valuable in mapping shallow channels, corals and other seabed features. Figure 3b shows an example of interpreted avoidance polygons around such channels which were used to help optimize the new 2D HR acquisition for an ongoing geohazard assessment work near a planned well. LSWEMM, which provides high lateral resolution, can be very useful for 2D HR survey design optimization and can help further optimize the geohazard mapping, thus adding great value to geohazard analysis.

Figure 4a shows a successful well relocation example using 3D NFH data, which clearly tells that the original proposed well location A (highlighted in yellow) was located at the edge of a channel. The updated well location (highlighted in red) was selected at a safe distance away from the edge of channels as well as other potential shallow geohazards, thanks to the high spatial resolution shallow image. Figure 4b shows that, with much better delineation of channels and other geological features, the LSWEMM image can be used to further optimize the surface location of wells and can be very valuable for future well location assessment work.

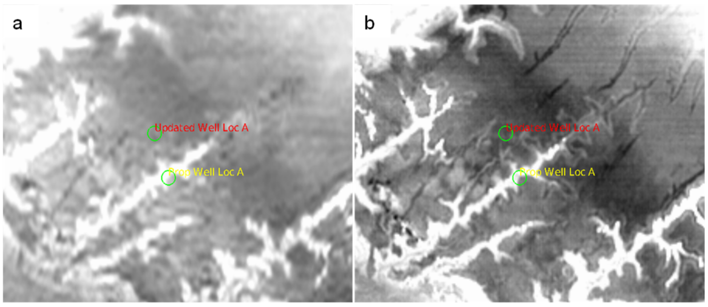

Figure 4 *Geohazard surface location assessment for proposed well. (a) Depth slice at 56 m from NFH imaging; (b) Depth slice at 56 m from LSWEMM imaging. Proposed (yellow) and updated (red) well locations are overlaid.*

The above cases show that geohazard assessment can benefit from the very high spatial resolution of LSWEMM. However, due to resource limitations, LSWEMM was only run up to 90Hz on the OBN datasets. Hence LSWEMM lacks the very high frequencies to match the super high temporal resolution of 2D HR data (125-500 Hz). NFH has high frequencies up to 250 Hz. LSWEMM and NFH data can be merged (Damianus, et al., 2022), with good low frequencies from LSWEMM and good high frequencies from NFH, to generate a 3D high-resolution cube which can be used for geohazard assessment together with 2D HR data. Such a 3D high-resolution dataset may potentially change the requirement for 3D HR acquisition to save cost and time.

Conclusions

We have shown that LSWEMM can produce high-resolution shallow images from high-density OBN datasets. The results can fill the gaps left by OBN primary imaging and 2D HR data, thus adding significant value to the pre-drilling geohazard assessment and optimization of 2D HR survey design around proposed well locations. Given the promising result from this case study, we have applied LSWEMM to our OBN surveys, which has impacted the geohazard assessment in those areas.

Acknowledgments

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