Long offset ocean bottom node full-waveform inversion and multi-azimuth tomography for high-resolution velocity model building: North Sea, Utsira High

Adriana Citlali Ramirez, Simon Baldock, Dhiman Mondal, Jan Gromotka, Matt Hart, TGS*

Summary

Efficient acquisition of large-scale, azimuth-rich ocean bottom node (OBN) data, with long offsets and high fold is now a reality. Such data provide an opportunity to apply advanced model building techniques to derive high resolution velocity models. As offsets increase the risk increases of cycle skipping and other instabilities being introduced into the model. Here, an iterative diving-wave full waveform inversion (DWFWI) workflow is used to provide stable, detailed model updates for OBN data. The technique is demonstrated on long offset OBN data from the Utsira High in the North Sea. We show that by making use of long offsets we can resolve the velocity model using DWFWI with confidence in the frequency range of 2-8 Hz. The process of progressively increasing the offset in DWFWI allows stable velocity model updates and can model sand injectites, shallow gas anomalies and deep geological structures. The model is then updated with multi-azimuth tomography.

Introduction

Ocean Bottom Node (OBN) acquisition has become increasingly cost effective in recent years due to the fast deployment of nodes and reduced operational cost, particularly at shallow water depths, using the node-ona-rope method. It is now possible to efficiently acquire, azimuth-rich node data, with long offsets and high fold using multi-vessel and multi-source acquisition. These data provide an opportunity to use advanced techniques to derive high resolution velocity models, which lead to improved images of the subsurface (Huang et al., 2019). Although multi-azimuth tomography is frequently combined with full waveform inversion (FWI), examples of FWI on long offset OBN surveys from the North Sea are not common. Here, we describe the application of FWI to the first, large scale, long offset (up to 17 km) node survey in the Norwegian Continental Shelf (NCS).

The data used in this study form part of the 1584 sq. km multi-component Utsira OBN data set. The survey was shot over two seasons utilizing two source vessels in 2018 and three in 2019, in both cases all vessels were configured with triple sources. The geometry for the survey is a 50 m receiver station interval with a 300 m receiver line spacing. The source lines are parallel to the receiver lines with a shot interval of 25 m and a source line spacing of 50 m. A subset of 120 km^2 of data were processed by TGS from deblended receiver gathers through to up-down deconvolution (Ziolkowski et al., 1998). The survey location is shown in Figure 1b. The processed dataset has a maximum offset of 7 km in the inline direction and 6 second record length and is the data used for migration and evaluation of the migrated FWI results. For initial velocity model building and FWI a deblended hydrophone only dataset with 20 km maximum inline offset and 13 second record length is used.

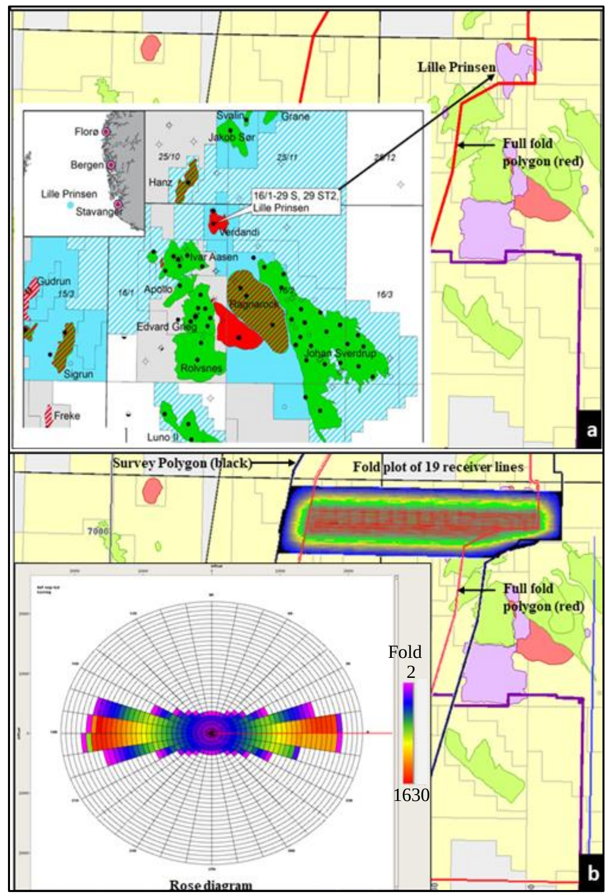

Figure 1: (a) Location map of Lille Prinsen over the survey area indicated by the black arrow; (b) Fold map of 19 Receiver lines with a rose diagram showing the approximately inline offset of 20 km and cross line offset of 3 km available for processing.

The main objective and challenge for depth domain processing in the Utsira High is to estimate a high-resolution velocity model for depth migration. The area contains shallow channels, complex overburden, sand injectites and gas anomalies of short wavelength. A second objective is to improve the imaging of deeper reflectors beneath the

complex overburden. We demonstrate that FWI on full azimuth data can resolve the shallow anomalies and improve deeper imaging; using the longer offsets and multi-azimuth tomography further complements the FWI model.
Here we present the stages of velocity model building using data from a long offset OBN survey over the Utsira High in the North Sea (Figure 1). The survey area is located approximately 200 km west of Stavanger, 10 km north-west of Johan Sverdrup and 5 km north-east of Ivar Aasen field. The water depth varies from 105-120 m.

Theory and Method

Diving wave FWI (DWFWI) is an inversion method based on finite-difference (FD) modelling, which works to minimize the differences between observed seismic and synthetic data by updating the velocity model (Pratt et al., 1998; Virieux and Operto, 2009). The velocity model update methodology used in this survey is as follows:

- Calibrate initial velocity model to checkshots
- Estimate delta and epsilon at selected well locations
- Debubbling and wavelet extraction
- Frequency analysis to evaluate lowest frequency which can be used for DWFWI
- Cycle skipping QC
- Iterative FWI updates
- Multi-azimuth tomography update

The initial velocity is derived from an underlying grid of 2D data. This velocity is smoothed and calibrated with the available checkshots. The calibrated model is then used to run prestack Kirchhoff depth migration (PreSDM) using common mid-point (CMP) gathers after up-down deconvolution. A focusing analysis (Cai et al., 2009) is used to derive the anisotropic parameters delta (δ) and epsilon (ε). The long offset deblended hydrophone data is then prepared with a pass of debubble. Further data conditioning is avoided to preserve the diving wave energy. An initial wavelet is extracted from the near offsets of the debubbled data and matched to FD modelled data to optimize the inversion.

Diving wave analysis with raytracing (Figure 2) shows that with increasing offsets we get deeper updates, however, the reliability of updates will depend on the accuracy of the velocity model. However, note that raytracing uses a high frequency approximation that is not correct for FWI, in particular, the depth reach of a low frequency wavelet may be different to that predicted with raytracing. With an offset limit of 7 km the velocity updates will be limited to the first 1-2 km in depth, while with offset of 17 km, diving waves will penetrate to depths 3-4 km or more. One of the key challenges of DWFWI is cycle skipping caused by inaccuracies in the initial velocity model. The risk of cycle skipping will increase with frequency and with travel time hence longer offsets will be more at risk of cycle skipping than near offsets (Figure 2b).

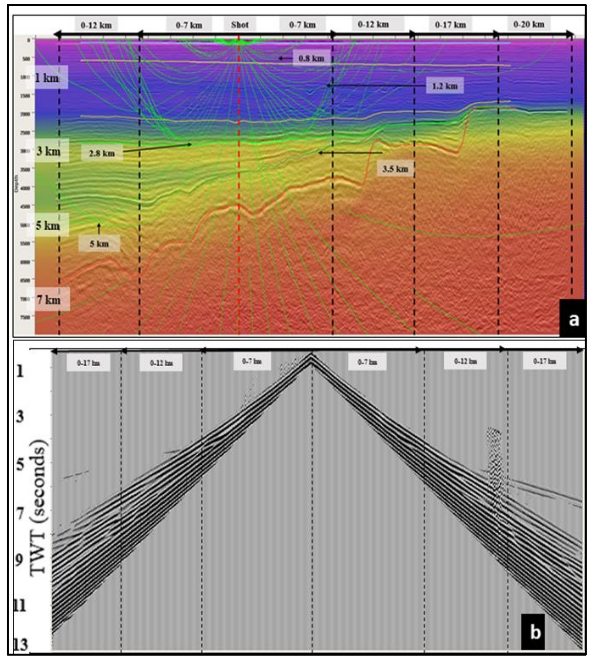

Figure 2: (a) diving wave analysis; (b) input observed seismic gather of long offset.

Another challenge for DWFWI is poor signal to noise ratio (S/N) at low frequencies. A phase analysis is performed on selected receiver stations to find lowest frequency with good S/N ratio, indicated by stable phase behavior at a given frequency (Figure 3). It is seen that the S/N ratio is poor below 2 Hz and thus a starting bandwidth of 2-4 Hz is selected for the first DWFWI update.

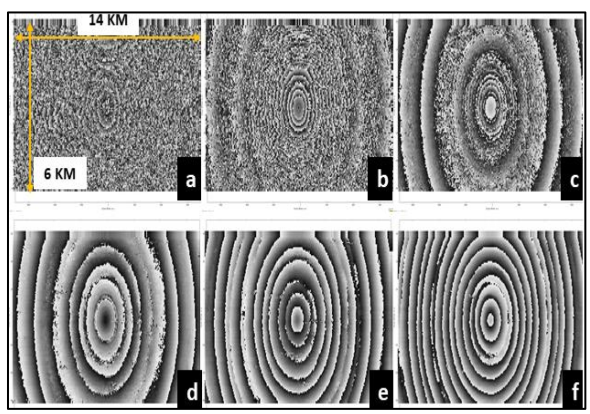

Figure 3: Frequency map on a receiver station (a) 1.5 Hz; (b) 2 Hz; (c) 2.5 Hz; (d) 3 Hz; (e) 3.5 Hz and (f) 4 Hz.

10.1190/segam2020-3428806.1

In order to address these challenges, DWFWI proceeded in an iterative manner. First starting with low frequencies and near offsets then iteratively increasing offsets for the same frequency band, before moving onto the next frequency band. In this case the DWFWI update is executed by progressively increasing the offset of input gathers from 0-7 km, to 0-12 km and finally by 0-17 km as shown in Figure 2b. Therefore, the velocity update is optimized from shallow to deep at each step to provide a stable velocity model update. In all stages and every iteration of DWFWI δ, ε, and density (ρ) are kept fixed, and an anisotropic wave equation with free-surface boundary condition is used.

The misfit curves of the DWFWI are monitored at every iteration and the difference between the observed and synthetic is checked if it is within a half cycle of the wavelet to avoid cycle skipping. It is observed that with the increasing noise content at longer offsets, the velocity update will not be reliable beyond 17 km. Hence, the maximum offset used in this survey for DWFWI is 17 km.

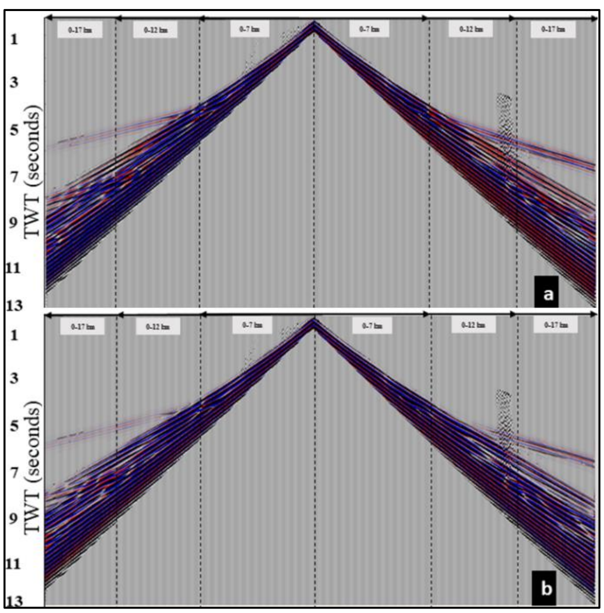

Figure 4: (a) FD modelled gather (coloured) with 2-4 Hz 7 km DWFWI model;(b) FD modelled gather (coloured) with 2-4 Hz 17 km DWFWI model overlaid on observed seismic (wiggle, positive black).

Figure 4 shows the overlay of modelled and observed data. Modelled data that matches well with the observed data is displayed in blue on the overlay, while modelled data with mismatch with observed data is displayed in red. Figure 4a shows the results of the 2-4 Hz update using 0-7 km offset to update the model. (Figure 4a). The modelled data out to 7 km offset matches the data well, while from 7-17 km the match becomes increasingly divergent. Figure 4b shows the results of the 2-4 Hz update after updates using 0-12 km and 0-17 km. The modelled data at the further offsets now matches well with the observed seismic data.

After 2-8 Hz DWFWI update, the up-down deconvolved data is then split into six azimuth sectors for multi-azimuth tilted transverse isotropy (TTI) tomography inversion to prepare the final velocity model.

Results

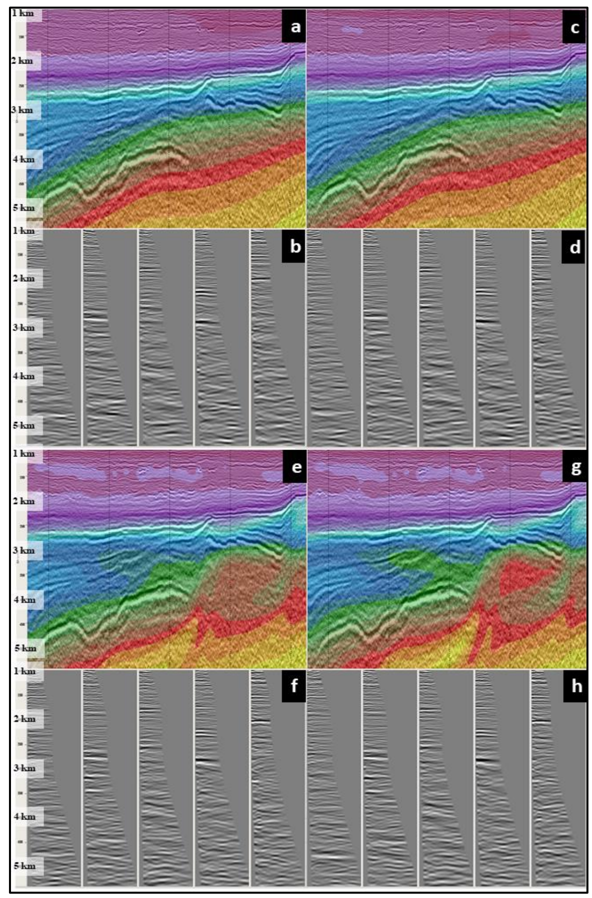

Figure 5 PreSDM stack and gathers (5-35 degree). (a) and (b) using calibrated model; (c) and (d) using 7 km 4 Hz DWFWI model; (e) and (f) using 12 km 4 Hz DWFWI model; (g) and (h) 17 km 4 Hz DWFWI model.

Figure 5 shows the results of iteratively increasing the maximum offset for the 2-4 Hz frequency band. The black dashed lines on the velocity model which is overlaid on the corresponding inline stack shows the Kirchhoff pre stack depth migration (PSDM) gather location. The display range of depth is 1000-5500 m and the velocity on this figure is

1489 to 6000 m/s velocity, covering the deeper zone of interest. The iterative velocity update from shallow to deeper depth can be seen in the progression from left to right on this section. The gathers are flatter in the shallow, and focused and migrated to the right depth for the deeper updates after the final update. In addition, the velocities at depth become increasingly conformable to geological structure as longer offsets are used in the updates.

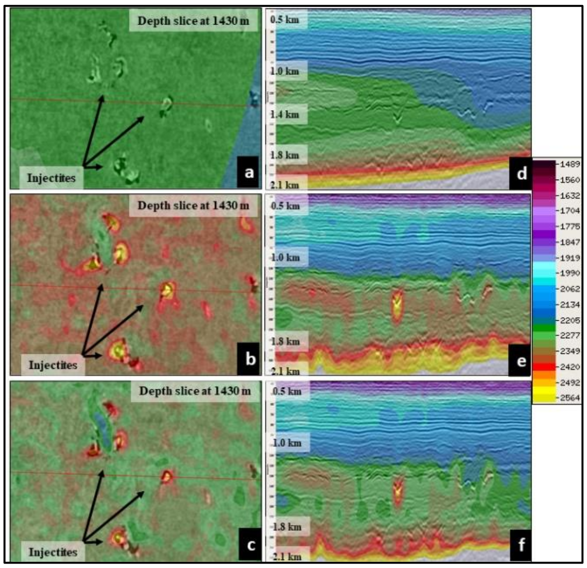

Figure 6: (a), (d) depth slice and inline stack using calibrated model; (b), (e) depth slice and inline stack using 2-8 Hz DWFWI model; (c), (f) depth slice and inline stack using tomography updated model.

Figure 6 shows sand injectite features on the PSDM inline stack and depth slice at 1430 m. After 2-8 Hz DWFWI update clearly identifies velocity anomalies in the complex overburden and multi-azimuth tomography further improved the image.

Figure 7 show the results of DWFWI and tomography on a gas anomaly at very shallow depth of 400 m at eastern edge of the survey. Although, due to the shallow depth, the anomaly exists only at short offsets, the full azimuth nature of the OBN data will help to define the spatial extent of the anomaly.

Conclusions

Long offset azimuth rich OBN data provides high fold data, a means to expand the subsurface illumination limits, the opportunity to use advanced processing to improve imaging and to build high resolution velocity models. A process of iteratively increasing the maximum offset in each frequency band of DWFWI allows for stable velocity model updates. The multi-azimuth TTI tomography inversion with up-down deconvolved data further improved the model. The application of this technique to azimuth-rich long offset OBN data acquired over the Utsira High in North Sea provided uplift to the velocity model building at both shallow and deep depths. Velocity anomalies associated with sand injectites and shallow gas pockets were incorporated into the shallow update, while deeper geological targets benefited from the use offsets up to 17 km.

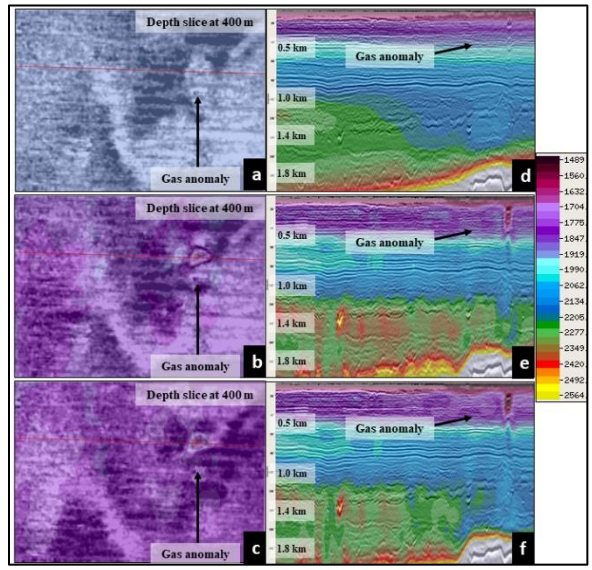

Figure 7: (a), (d) depth slice and inline stack using calibrated model; (b), (e) depth slice and inline stack using 2-8 Hz DWFWI model; (c), (f) depth slice and inline stack using tomography updated model.

Acknowledgements

We would like to thank TGS and AGS for permission to present this work. We appreciate the helpful technical discussions from Yong Ren and Yi Huang.

REFERENCES

Cai, J., He, Y., Li, H., Wang, B., and Guo, M., 2009, TTI/VTI anisotropy parameters estimation by focusing analysis, Part I: Theory: 79th Annual International Meeting, SEG, Expanded Abstracts, 301–305, doi: https://doi.org/10.1190/1.3255480.

Huang, Y., Mao, J. and Sheng, J., 2019, FWI Salt Model Update with Sparse Nodes: A Feasibility Test on OGO FAN Survey: 81st EAGE Conference and Exhibition, doi: https://doi.org/10.3997/2214-4609.201901234.

Virieux, J., and Operto, S., 2009, An overview of full waveform inversion in exploration geophysics: Geophysics, **74**, WCC1–WCC26, doi: https://doi.org/10.1190/1.3238367.

Ziolkowski, A., Taylor, D. and Johnston, R., 1998, Multiple wavefields: Separating incident from scattered, up from down, and primaries from multiples: 68th Annual International Meeting, SEG, Expanded Abstracts, 1499–1502, doi: https://doi.org/10.1190/1.1820196.