Enhanced imaging with high-resolution full-waveform inversion and reverse time migration: A North Sea OBC case study

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Abstract

In a case study from the Tommeliten Alpha area of the Norwegian North Sea, imaging problems were caused by the presence of gas in the overburden. In particular, a large part of the reservoir is in a seismically obscured area (SOA) caused by the gas. Full-waveform inversion (FWI) and reverse time migration (RTM) dramatically improve the imaging from ocean-bottom cable (OBC) acquisition over the region. The FWI algorithm is pushed to 22 Hz to generate an extremely high-resolution velocity model, and RTM then becomes required to honor the complexity in the resultant velocity model. Consequently, migration is done with the FWI model to generate a high-frequency RTM image to 80 Hz. This image is approximately double the maximum frequency commonly used for RTM in the North Sea and matches that of equivalent Kirchhoff products, but with all the benefits in imaging that RTM brings, providing a subsequent impact on interpretation of the area.

Introduction

Full-waveform inversion (FWI) is an established tool in the velocity model-building process, generating high-resolution velocity models for use in geologically complex areas. Virieux and Operto (2009) give an excellent summary of the process. In general, it currently works best in areas penetrated by diving waves; hence, it is used for shallower targets (shallow, that is, relative to the maximum recorded offset). Reverse time migration (RTM) is a well-known imaging technology for areas of complex geology. It uses the two-way wave equation to improve the handling of velocity complexity and to image steep dips by using reflections, transmissions, diffractions, and prism waves. Leveille et al. (2011) give an excellent summary of the various strengths and weaknesses of different imaging algorithms.

Case-study area

Tommeliten Alpha is a gas-condensate discovery in the Norwegian North Sea (Block 1/9). It was discovered in 1977 in ~ 80 m of water, approximately 25 km southwest of Ekofisk field. Four exploration and appraisal wells have been drilled for evaluation purposes. The reservoir itself consists of two fractured chalk formations (Ekofisk and Tor) at the crest of a broad anticline at a depth of approximately 3000 m. A large part of the reservoir is in the seismically obscured area (SOA) caused by gas in the thin silt and sandstone layers of the middle Pliocene and deeper over a range of 1 to 2 km deep. A combination of the velocity complexity of the gas and its absorption properties causes significant imaging challenges (Ratcliffe et al., 2011).

Geophysical challenges

The objectives for this study were (1) to improve the velocity model in and around the SOA and (2) to improve the PP prestack depth migration. Achieving both goals should assist in interpretation of the area. Because of the shallow to medium depth of the primary velocity anomaly, FWI is an appropriate technology to update the velocity model. RTM is then the imaging process of choice to honor any additional complexity in the velocity model. In our previous work here, the objective was to see the impact of FWI on the structural image (Ratcliffe et al., 2011; Warner et al., 2013; Ratcliffe et al., 2014). Now we use our latest FWI model to migrate to a maximum frequency that allows a more detailed and robust interpretation.

Acquisition details

A high-density, full-azimuth, 4C ocean-bottom cable (OBC) survey was acquired in 2005 to improve the imaging in the seismically obscured area (SOA). The acquisition consisted of three side-by-side receiver swaths with eight parallel cables in each swath (Ratcliffe et al., 2011). The cables were 6 km long and contained receivers every 25 m. The nominal receiver cable separation was 300 m. The 10- × 12-km shooting patch for each swath gave a maximum recorded offset of more than 10 km, with excellent wide-azimuth coverage to 7 km. The 150-m sail-line interval and nominal 25-m flip-flop shooting gave a shot separation of 50 and 75 m in x and y, respectively. Combining all three swaths gave an acquisition consisting of almost 6000 receivers and 100,000 shots, covering ~ 200 km² in area (Figure 1). The OBC nature of the acquisition means data with good signal-to-noise ratio were acquired down to ~ 3.5 Hz.
FWI methodology and results

Our methodology appears in previous publications so is only summarized here; for example, see Warner et al. (2013). We use a 3D acoustic, time-domain, finite-difference algorithm that updates the P-wave velocity via iterative, linearized least-squares inversion. Hence we use only the hydrophone data to drive the FWI. The data processing is kept simple—essentially only low-pass filtering, denoising, and appropriate muting. We inject a ghost-free representation of the source wavelet and use a free surface in the modeling to generate ghosts as well as free-surface multiples (Ratcliffe et al., 2011). This gives appropriate real and modeled data sets for use in the residual calculation. The question of whether to debubble or not is an open one. In this instance, we think the bubble is well represented in the source wavelet, and so we do not debubble the real data. A vertical-transverse-isotropy (VTI) model of anisotropy is adequate in this area and is used here.

Comparing with our early published works, the key changes in methodology are: (1) the source wavelet comes from the data directly rather than from the gun signature; (2) we use a smoothed 3D VTI anisotropy model rather than a blocky version; (3) we open the mute to include more pre- and postcritical energy rather than highlighting only transmitted arrivals; and (4) we use the undecimated acquisition, which is needed as we push to higher frequencies. In addition, our FWI algorithm has been upgraded for increased accuracy and efficiency by using, among other things, the wave equation and finite-difference scheme described in Zhang et al. (2011).

Figure 2 summarizes an inline of the FWI velocity model through the central gas-charged area: (Figure 2a) starting model obtained from an industry-standard tomography process, (2b) 22-Hz FWI model, (2c) 22-Hz FWI model with RTM overlay, and (2d) 22-Hz FWI model with RTM overlay and color map that highlights the reservoir depth at ~3 km. The increase in resolution and change in shape of the gas-charged area are clear differences. Also note the observed slowdown in the deeper region. We lose confidence in the FWI result at a depth of ~4 km, as indicated by the appearance of artifacts in the raw result, and hence we merge back to the starting model at this depth.

In the last two frequency bandwidths of the FWI (with maximum frequencies of ~16 and 22 Hz, respectively), we see the appearance of a “semicoherent” noise in the updates, in addition to the extra resolution gained from the FWI. Although this noise is weak, it does degrade the quality of the update and corresponding cost-function decrease. We currently do not interpolate the shot and receiver samplings in the FWI, and we think this noise is caused by aliasing related to the raw acquisition geometry.

RTM methodology and results

We previously used RTM as a quality-control tool of structural improvements in the imaging (stack power, reflector continuity, and so forth) because of changes in the velocity model. An appropriate maximum imaging frequency for this goal is 40 Hz, which is a fairly standard number for RTM in the North Sea but is approximately half the maximum frequency used in equivalent Kirchhoff migrations in this region. Of course, Kirchhoff techniques do not handle significant complexity in the velocity model, whereas RTM does. We now push the maximum RTM imaging frequency to 80 Hz, thus generating a data set with the same frequency content as the Kirchhoff migration, allowing better interpretation of data.

In terms of preprocessing, we use PZ summed data for the RTM imaging, as is typical in OBC processing. This is different than the P-wave-only data used to drive our FWI. Prior to PZ summation, standard processing had been applied to these data—designaturing, denoising, and trace editing. After PZ summation, we interpolate and apply a 3D tau-p deconvolution and mute as a denoising process. We are careful to honor the 80-Hz sampling requirements for preprocessing and RTM. For the usual efficiency reasons in OBC data, we invoke reciprocity and migrate receiver gathers. All the migrations use the 3D VTI anisotropy model derived from tomography.

Figure 3 shows an 80-Hz RTM inline section in and around the gas-charged area, with Figure 3a migrated...
with the starting velocity model and Figure 3b migrated with the FWI velocity model. Figure 4 shows the top reservoir horizon interpreted from the 80-Hz RTM seismic volumes, with Figure 4a derived from the starting velocity model and Figure 4b derived from FWI velocity model. Figure 5 shows depth slices at 1280 m migrated with the FWI velocity model, Figure 5a with 40-Hz RTM and Figure 5b with 80-Hz RTM. Figure 6 shows a zoom of the shallower part of central inline sections migrated with the FWI velocity model for (Figure 6a) 40-Hz RTM and (Figure 6b) 80-Hz RTM.

The comparisons in Figures 3 and 4 show the dramatic uplift in imaging achieved by using the FWI velocity model — the anisotropy model and input seismic data in these migrations are the same, so uplift comes from the different velocity models. Figures 5 and 6 highlight the improvement in the image from the 40-Hz to 80-Hz RTM. Figure 7 compares frequency-amplitude spectra in the upper part of the migrated volume of Figure 6.

**Interpretation**

Comparing the 80-Hz RTM images in Figure 3, we see that the FWI velocity model has helped to solve the velocity pushdown effect below the gas-charged area. It is also clear that the reflections at the chalk-reservoir level are focused better and are more continuous in the image generated using the FWI model compared with the one generated from the starting model.

Figure 4 presents interpretation of the top of the reservoir. The Ekofisk horizon has been autotracked with the same parameters on the 80-Hz RTM data migrated with the starting model (Figure 4a) and on the 80-Hz RTM data migrated with the FWI model (Figure 4b). The reduction of the SOA is evident and is limited now to the very crest of the reservoir. For one area (indicated by the meshed horizon on Figure 4b), autotracking required manual editing, but the quality of the newly imaged data enables further shrinkage

**Figure 3.** Comparison of VTI RTM inline sections in and around the gas-charged area: (a) 80-Hz RTM migrated with the starting model and (b) 80-Hz RTM migrated with the FWI model. The improvement in image quality in the central SOA as a result of migrating with the FWI model is clear.

**Figure 4.** Comparison of top reservoir horizon interpreted from 80-Hz RTM seismic volumes, (a) migrated with the starting model and (b) migrated with the FWI model. These displays show the reduction in extent of the SOA as well as the large change of the anticline structure at depth when migrating with the FWI model. Yellow lines (L1 and L2) denote the sections in Figure 8 where arrows correspond to the three faults picked in Figure 8b. Circles represent locations of the four existing wells from Tommeliten Alpha.

**Figure 5.** Comparison of VTI RTM depth slices at 1280 m, both migrated with the FWI model, for (a) 40-Hz RTM and (b) 80-Hz RTM. These displays show the uplift in resolution going from 40 to 80 Hz in the RTM.
of the SOA. The difference in shape of the reservoir between the two images is also noticeable; the image from the FWI model gives a more realistic four-way dip structure.

Several faults are visible on the top reservoir maps. Their extent and orientation toward the crest of the structure are impossible to assess on the interpretation from the volume that used the starting model (Figure 4a), but they become detectable on the volume that used the FWI model (Figure 4b). Focusing on the two cross sections through the top reservoir horizon, we can see in Figure 8 that images obtained from migration using the FWI model allow tracking and interpretation of these faults through the SOA. This provides key information for understanding the structural development of the Tommeliten Alpha field.

We see that three of the four wells drilled in the Tommeliten Alpha field are in the SOA with the data migrated using the starting velocity model (Figure 4a). However, on the data migrated using the FWI model, these wells are now located outside the SOA (Figure 4b), enabling well ties and depth calibration.

In addition to the observed improvement in resolution as we increase the maximum frequency of the RTM, Figure 6 shows that we can see more small-scale features and thin formations. The broader-bandwidth RTM gives more character to the data that allows an interpreter to make unambiguous correlations of seismic reflectors from the shallower Eocene-Oligocene section through to the chalk reservoir. The shallower depth slice in Figure 5 highlights the cleaner and sharper definition of the gas-charged area. We observe enhanced imaging of other shallow glacial features (iceberg scours and boulders), although they are not shown here for reasons of space. Overall, these images demonstrate the importance of improved processing and imaging techniques to help identify any shallow drilling hazards.

Conclusions

We have shown the uplift in imaging quality from an OBC data set acquired over the Tommeliten Alpha area of the Norwegian North Sea. Improvements come from the combination of a high-resolution velocity model generated by FWI (to 22 Hz) and high-frequency imaging with RTM (to 80 Hz). Both of these maximum-frequency limits are approximately twice the current industry standard for these processes. To the best of our knowledge, this is the first time this combination of velocity model and imaging maximum frequencies has been applied to a 3D production data set. The final results highlight a dramatic improvement in imaging and resolution compared with results obtained from the starting model with the typical maximum imaging frequency for this part of the world.

References


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Figure 8. Comparison of 80-Hz VTI RTM sections zoomed to top-reservoir horizon depth for (a) line L1 migrated with the starting velocity model, (b) line L1 migrated with the FWI velocity model, (c) line L2 migrated with the starting velocity model, and (d) line L2 migrated with the FWI velocity model. Labels L1 and L2 refer to the yellow lines in Figure 4.