Optimizing seismic repeatability at Ringhorne, Ringhorne East, Balder and Forseti with QC driven time-lapse processing

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Summary

Time-lapse (4D) seismic data at Ringhorne, Ringhorne East, Balder and Forseti in the Norwegian North Sea are used to monitor gas and water movement within the reservoirs and improve reservoir simulation models, enabling cost-effective field operations. The structural complexity of the reservoirs, their proximity to the high-impedance Cretaceous chalk, and a modest predicted 4D signal required significant effort in seismic acquisition and processing to achieve a successful final product. The 4D repeatability of the data was significantly improved at the processing stage through the use of robust quality control measures (QCs) analyzed in collaboration between CGGVeritas seismic processing specialists, ExxonMobil geophysicists and business unit geoscientists. Analysis was followed by targeted seismic processes which removed as much of the 4D noise as possible while retaining the true 4D signal amplitudes and the 4D resolution. The final result is a 4D dataset of outstanding quality.

Field Backgrounds

**Ringhorne:** The Ringhorne Jurassic and West (Ty) fields were discovered in 1997 and 2003, respectively, with first production occurring in 2003. There are two commercial hydrocarbon units in the Ringhorne field. The Lower Jurassic fluvial and shallow marine Statfjord reservoirs form in a structural horst-block trap on a basement high. The deep water Paleocene Ty sands stratigraphically pinch out onto the Ringhorne high. The Ty sand is a low reflectivity sub tuning thickness reservoir which directly overlays the regionally extensive Cretaceous chalk. The reservoir is being produced via natural water drive. The Jurassic sands are found in three fault blocks underlying the chalk and are produced by a combination of natural water drive and water injection.

**Ringhorne East:** Ringhorne East is similar to Ringhorne Jurassic. The producing sands are from the sub-chalk shallow marine Statfjord formation. The trap is a downthrown closure to the Ringhorne horst, with a deeper OWC. The field was discovered in 2003 and came on production in 2006. It is produced via natural water drive. There is very little structural relief to the reservoir.

**Balder:** The Balder field was discovered in 1967 but reservoir complexity and poor seismic imaging resulted in a delay of initial production until 1999. The main reservoir sands are Paleocene Heimdal distal deepwater turbidites that pinch out onto the margin of the Utsira High. These sands were extensively remobilized in the Eocene resulting in formation of a mounded topography controlled by deeper structure, and extensive injection of sands as sills and dykes through the higher Paleocene and Eocene shales. The field has a high level of interconnectivity and a common OWC and GOC. Production is supported by water drive from the regional Paleocene aquifer, limited water injection, gas injection and minor gas expansion.

**Forseti:** Forseti is geologically similar to Balder. It is a laterally extensive remobilized sand with limited structural relief. The field was discovered in 1997 and came on production in 2002. It is currently produced via natural aquifer drive.

Introduction

The Ringhorne, Ringhorne East, Balder and Forseti fields are located in the Norwegian North Sea, on the Utsira high. The fields are characterized by significant 4D imaging and detectability challenges due to weak to moderate 3D and 4D seismic responses sitting close to the ultra high-impedance Cretaceous chalk. In this paper we focus on the processing challenges and solutions applied to the 4D co-processing of two streamer vintages and the corresponding OBC vintages around the Balder FPSO. Using QC maps that spatially highlight the repeatability of the data we were able to identify the dominant residual non-repeatability effects leading to large 4D noise bursts on migrated data in close proximity to zones of interest. This allowed us to fine-tune processing parameters and choose additional processing algorithms in order to better recover the 4D signal and reduce noise. The analysis was carried out in collaboration between the 4D processing experts from CGGVeritas and ExxonMobil as well as with the asset geoscientists. Interpretation was performed throughout the processing and those results were fed back to influence processing decisions. This close collaboration allowed for maximum 4D signal enhancement without loss of amplitude reliability or resolution.
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Table 1: Geometric repeatability achieved in the 2009 streamer acquisition relative to the 2001 baseline for four offsets.

<table>
<thead>
<tr>
<th>Offset</th>
<th>Mean</th>
<th>Median</th>
<th>Mode</th>
<th>P10</th>
<th>P90</th>
</tr>
</thead>
<tbody>
<tr>
<td>325m</td>
<td>32.42</td>
<td>15.91</td>
<td>9.15</td>
<td>6.97</td>
<td>63.66</td>
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<tr>
<td>1000m</td>
<td>37.8</td>
<td>20.97</td>
<td>9.09</td>
<td>7.49</td>
<td>67.56</td>
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<tr>
<td>1800m</td>
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<td>23.6</td>
<td>9.78</td>
<td>7.85</td>
<td>112.31</td>
</tr>
<tr>
<td>2745m</td>
<td>64.23</td>
<td>28.01</td>
<td>9.05</td>
<td>8.01</td>
<td>210.63</td>
</tr>
</tbody>
</table>

Seismic Acquisition

The baseline 3D seismic survey was acquired in 2001, after two years of production at Balder, but prior to any production at Ringhorne, Ringhorne East or Forseti. Coverage holes associated with the Balder FPSO and a neighbouring drilling rig were filled with an OBC patch and an interleave streamer patch, respectively, in 2002. Monitor surveys were shot in 2006 (Ringhorne only) and 2009. In 2009, the 2002 OBC patch was repeated and the 2002 interleave section was acquired, but this time as part of the standard race track shooting. Both monitor surveys employed common 4D acquisition strategies such as matching baseline source positions, overlapping streamers to improve coverage, infill data to optimize repeatability, and feather matching.

A 4D feasibility study conducted prior to acquiring the 2006 monitor survey suggested that impedance changes resulting from water displacing oil in Ringhorne would be 7-8%. While above what is normally considered the detectable limit for 4D application, the proximity of the reservoirs to the high impedance chalk adds a number of complications. A relatively low amplitude change of 20% (relative to the chalk reflectivity) and potential side-lobe interference from the chalk required that the 4D data be highly repeatable. Pre-project modelling at Ringhorne East, Forseti and Balder had similar implications.

A post-survey assessment of the geometric repeatability achieved during the 2009 acquisition is summarized in Table 1. The median value for source and receiver mispositioning between the two surveys (dS+dR) is less than 30m for all offsets. This is similar to the quality of the successful 2006 survey, but covering a much larger area.

4D Co-processing

To maximize repeatability and to preserve and resolve differences due to production, the 2009 streamer data were co-processed with the 2001 baseline following very closely the successful sequence applied between the baseline and 2006 monitor over Ringhorne. Key elements of this sequence are 3D projection filtering for swell noise removal, deterministic wavelet matching, relatively mild initial pre-stack demultiple, and deterministic 3D amplitude and time-shift corrections. We then perform a 4D binning which uses a cost function that looks at both acquisition repeatability and trace similarity. Traces with dS+dR greater than 200 meters are rejected automatically. Data are then regularised to bin center, followed by 4D amplitude corrections and time-alignments. This last step follows the philosophy of “match the error” in order to minimize 4D noise. In particular, the time alignment reduces the 4D migration noise that can result from non-subtracting migration swings coming off the rugose and high amplitude chalk, which has the potential to mask the true 4D amplitudes.

Prior to migration the OBC infill data are processed independently of the streamer. The sequence has similar 4D elements as the streamer data, in particular, deterministic wavelet matching to base streamer, 4D binning, global spectral matching of monitor OBC to base OBC followed by 4D sailline static correction. As with the streamer 4D processing, OBC traces which have dS+dR above 200 meters are dropped, empty bins are filled with interpolated traces and the data are regularised to bin center. Prior to migration we perform a statistical 4D amplitude and time-alignment of the OBC to the base streamer data.

At significant processing steps we perform 4D QCs, relying mostly on time-shift and RMS ratio or difference maps of 4D binned and stacked data. Figure 1 shows a key example of such a QC consisting of the RMS energy of the quadrature difference of the survey (without the OBC data) just prior to migration. Marked on this map are several noise bursts. These were investigated in more detail in order to locally reduce the observed 4D noise by additional or amended processing steps.
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Identified issues, processing solutions, impact

The map in Figure 1 shows a number of areas which contained significant amounts of 4D noise prior to migration. We identified three separate causes for these noise issues; a) localized areas with residual multiples b) two saillines from the monitor survey with anomalous amplitude levels that had not been picked up from the acquisition report and c) relatively poor acquisition repeatability leading to badly repeated ray paths. It was important to find ways to mitigate this noise without significantly delaying final data delivery. After some testing, simple and effective solutions were a) deconvolution before stack for attenuating residual multiples b) the application of global match operators to the two sequences with anomalous amplitude levels and c) harsher 4D binning cutoff where we remove and replace traces with dS+dR above 90 meters but only within polygons around the areas affected.

The impact of these solutions after migration is shown on Figures 2 and 3. The cross-sections in Figure 2 show the combined effect of deconvolution before stack to remove multiples and harsher dS+dR cutoff for removing poorly repeated traces which are subsequently replaced via interpolation. This leads to fewer migration swings from the chalk cutting thorough the 4D signal. We were also able to obtain (prior to migration) more robust 4D sailline statics between the two vintages after the additional multiple attenuation. We found that limiting the 4D time-shift calculation window to a short 80 ms interval centered on the chalk was surprisingly robust and delivered time-shifts that reduced the 4D noise not just at chalk level but also in the shallower part of the data. The improved alignment of the data at the chalk horizon reduces the post-migration 4D noise significantly. The combined impact of all these changes on 4D data quality can be seen in Figure 3, where RMS amplitudes from the post migration 4D difference cube are compared to what was obtained prior to applying solutions a), b) and c) and improving the 4D sailline statics.

Discussion & Conclusion

The North Sea is a mature area for time-lapse and processing sequences handling the complexities of various fields are well developed. 4D QCs are particularly apt at identifying acquisition and processing weaknesses (at a level often overlooked in 3D processing) and this paper shows several examples. The timely creation of these QCs as well as the use of robust repeatability measures showing true acquisition and processing issues is clearly critical. They allow the implementation of processing solutions which, as is the case here, do not have to be particularly complex. We applied effective and relatively quick solutions followed by impact analysis post migration. This is the domain in which the interpreters from the asset teams can best review the effect on the 4D signal and resolution. Our additional processing resulted in significant reduction of 4D noise while the 4D signal and resolution were completely preserved.
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Figure 3: RMS amplitude of the quadrature difference between monitor and baseline. Each map is labeled with the reservoir interval extracted. Top row is from initial migration of the data. Bottom row is final migration after improving multiple suppression and 4D sailline statics solution, fixing a couple anomalous saillines and dropping poorly repeated trace pairs. Note the significant reduction in 4D noise in the bottom row.

Acknowledgements

We thank ExxonMobil E&P Norge, ExxonMobil Production Company, Statoil Petroleum AS, Petoro and CGGVeritas for permission to publish this paper.
REFERENCES