



Tu A2 14

Complex Reservoir De-risking Using Advanced Pre-stack Depth Migration Technology

P. Denman* (CGG), J. Clough (CGG), P. Kurnik (CGG), J. Taylor (CGG), G. Cattini (CGG), A. Holman (CGG), S. Hollingworth (CGG), M. Ackers (Centrica), S. Forsund (Centrica), C. Soufleris (Centrica)

Summary

The North Sea is a mature basin where it is increasingly challenging to make new and economically viable discoveries. Even after discoveries have been made, it is vitally important to have high confidence in the reservoir's extent and spatial location before committing to a development plan. Here we detail the case history of a multi-azimuth pre-stack depth migration re-processing and re-imaging project over the Oda (formerly Butch) discovery in the Norwegian sector of the North Sea. The Oda structure is a complex salt diapir making it crucial to have as much confidence as possible in the position of the reservoir before making a drilling commitment. This study documents how the use of the latest imaging technologies, which include source and receiver deghosting, multi-azimuth full waveform inversion, multi-layer tomography and tomographic uncertainty analysis can aid in de-risking and improving reservoir definition, thereby increasing confidence in development well planning.



Introduction

The seismic imaging of the Oda field was challenging as it is located on the flank of a prominent salt diapir. In order to optimise and enhance seismic illumination, seismic data were acquired in 2012 using conventional narrow azimuth acquisition along three azimuths, N060° (the main azimuth covering the largest area), N015° and N330°. The streamer length was 6,750 m, towed at depths of 7m on the main N060° azimuth and (due to worsening weather) at 9m on the N015° and N330° azimuths. The survey area for the main azimuth was 600 km² and approximately 200 km² for the other azimuths. The current project re-imaged 320 km² of the main survey and the entire area of the other two surveys.

Legacy pre-stack time and depth imaging data provided reasonable positioning of the structure in space, but did not have the resolution and small-scale fault delineation and location required for development well planning (Figure 1a). To improve the understanding of the field, a range of advanced and new processing technologies were utilised including broadband processing, shallow water de-multiple, a high-resolution velocity model derived using multi-layer tomography and full waveform inversion (FWI), along with least-squares Kirchhoff imaging. Tomographic uncertainty analysis of the velocity model was used to further understand the level of accuracy in the imaging. The combination of these technologies gave a final reprocessed volume that has a broader bandwidth and much improved stratigraphic and fault imaging around the reservoir interval (Figure 1b).

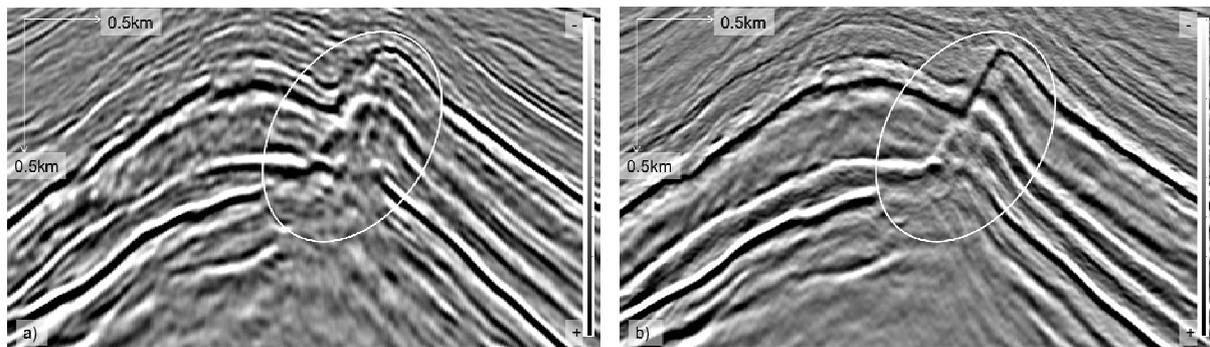


Figure 1 (a) Vintage PSDM image from the main azimuth, and (b) reprocessed PSDM image from the same azimuth. A positive (black) value indicates an increase in impedance, while a negative (white) value indicates a decrease in impedance. The reprocessed image has broader bandwidth with better resolution and well defined stratigraphic terminations along the main fault in the middle of the section.

Signal processing

Broadband processing, including source and receiver de-ghosting, has now become well established (see, for example, Wang et al., 2013). This was used to improve the bandwidth and spectral shape of the data and hence its temporal resolution compared to the legacy processing. Source de-signature (de-bubbling and de-ghosting) used a modelled far-field signature as the measured far-field was not available.

Compared to the legacy data, broadband processing improved the low- and high-frequency content of the data, hence suppressing wavelet side-lobes, resulting in higher resolution and better interpretability in the reservoir interval. This can be seen in Figure 1b, where the main fault in the section is better defined by a sharper, higher resolution wavelet. Spectral broadening was applied after stack in order to compensate for the Earth absorption effect, helping to improve resolution at target level whilst avoiding the re-introduction of side lobes. The useable bandwidth on the legacy data was 10-40 Hz and this was increased to 5-60 Hz on the re-processed data. Deeper events are clearer and

more continuous and the reduced side-lobe energy makes it easier to track the truncations against the fault on the right as shown by the white oval in Figure 1b.

Velocity model building

A key driver in improving the understanding of the reservoir was to improve the imaging at target level. The presence of near surface channels and shallow gas over the crest of the structure (Figure 2) made it crucial to have accurate shallow velocities to minimise potential wavefield distortions deeper, at reservoir level. Multi-azimuth FWI (Mothi et al., 2013) was a key part of this, with a good starting model required due to the lack of very low frequencies in the data (starting frequency for FWI was 5 Hz). Dip constrained non-linear tomographic inversion (Guillaume et al., 2013) was utilised in the near surface in order to derive an initial estimate of the velocity variations in the channels, which was subsequently used as the FWI starting model. The dip constrained inversion and FWI velocity updates resulted in a high-resolution shallow velocity model, with the channel geometries in excellent agreement with those derived independently by a spectral decomposition process performed on a different high-resolution short-offset dataset, in particular the delineation of the shallow gas and a significant shallow fault (Figure 2).

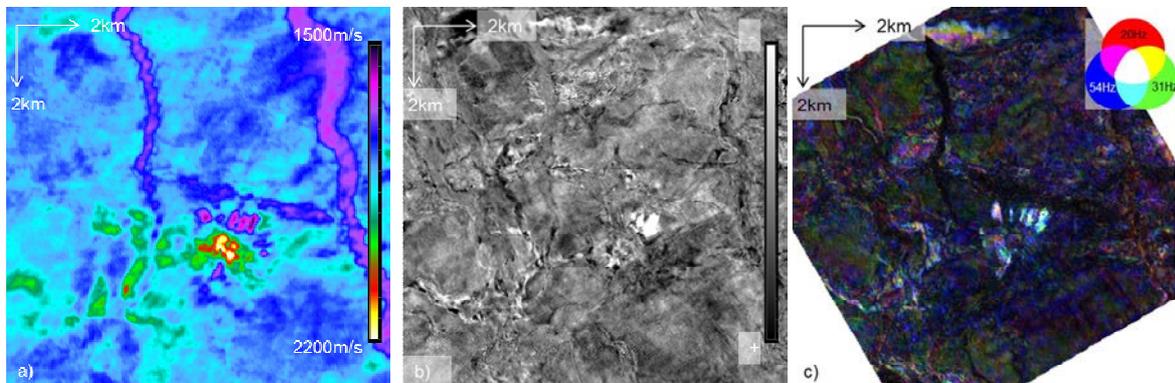


Figure 2 (a) Shallow depth slice through the FWI model at 200m below mean sea level, (b) the same slice through the final PSDM stack volume, and (c) shallow spectral decomposition (RGB blend: 20-31-54Hz) from an independent shallow hazard survey. There are channels and gas pockets clearly defined in (a), (b) and (c).

Once the shallow velocity model had been established using FWI, the velocity model building continued using three passes of multi-layer tomography (Guillaume et al., 2012), which globally inverts for velocity and anisotropy variations, and structurally repositions horizons through integrated map migration. The tomographic inversion also utilises the well information to ensure that the repositioned horizons are calibrated to the corresponding well tops whilst simultaneously updating the anisotropy to preserve etc. The workflow was able to carry key reservoir interpretations through each model update, thereby incorporating client input, making this an integral part of the project.

The availability of data acquired along three different azimuths offered the possibility of investigating the presence of, and solving for, orthorhombic anisotropy. Indeed, some small differences in event moveout were observed between the three azimuths. However, these differences were not significant enough to warrant a detailed analysis and it was decided that, in this phase of the project, the imaging process would capitalize from the benefits of the multi-azimuth illumination only.

A major factor in the project was ascertaining the level of uncertainty in the final positioning and extent of the reservoir. Tomographic uncertainty analysis (Messud et al., 2017) was used to derive a standard deviation like uncertainty attribute for the positioning of the key primary events around the discovery through the perturbation of both the velocity and anisotropy models. The uncertainty values for the Top Chalk horizon are shown in Figure 3. The highest uncertainty is on the steepest flanks of



the structure. This information is useful for determining the 3D spatial extent and positioning of the reservoir. Further uncertainty analysis may be investigated using other methods (for example, Birdus et al., 2015).

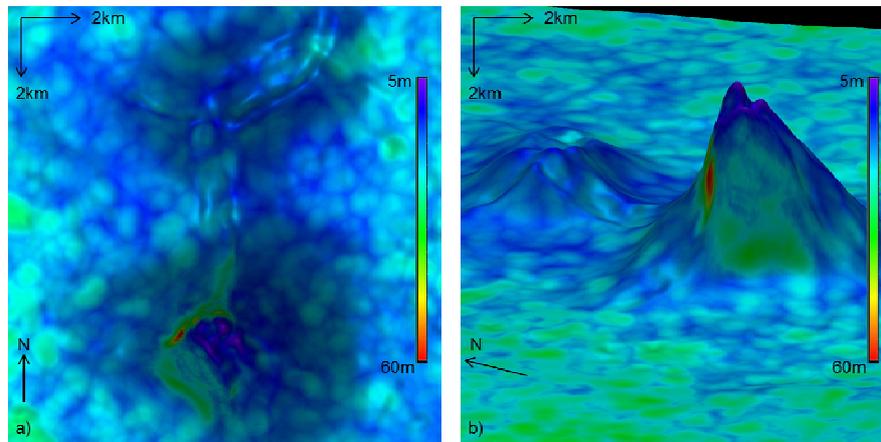


Figure 3 (a) Top down view of the uncertainty analysis of the Top Chalk horizon, and (b) a side-on 3D view of the surface. The greatest uncertainty in depth occurs on the steepest flank of the structure where it reaches a maximum value of 60 m (expressed in terms of standard deviation in relation to the depth of the Top Chalk horizon in the final velocity model).

Imaging for reservoir de-risking

Prior to imaging, the data was regularised using 5D regularisation to improve the data quality and fold on the near offsets, which are historically poor quality on narrow-azimuth shallow-water acquisitions. This regularisation helped to reduce the level of migration artefacts through the reservoir level. The data were imaged first using standard single-arrival Kirchhoff imaging. As there were variations in the illumination of each azimuth, these were combined using a multi-azimuth stack to produce an optimised image with the best imaging contributing from each individual azimuth to aid structural interpretation.

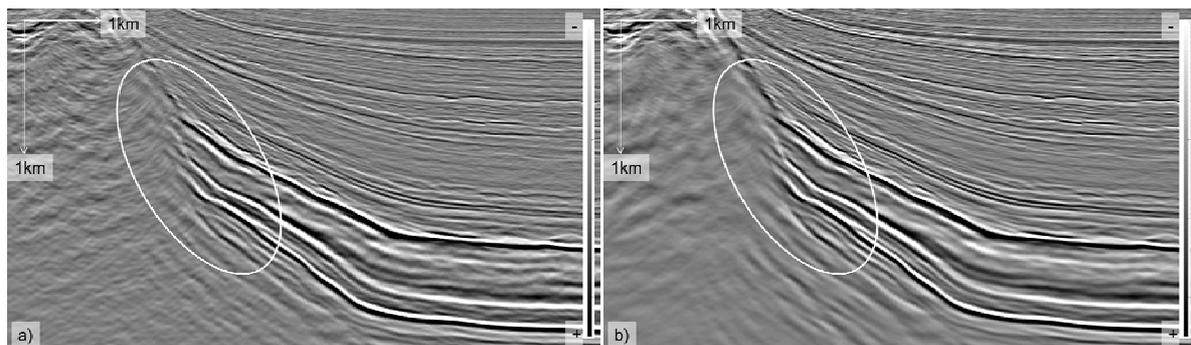


Figure 4 (a) A standard Kirchhoff image of a key flank of the structure, where the chalk and salt layers are contaminated by migration noise in the white oval, and (b) least-squares Kirchhoff image of the same structure, which has significantly reduced migration noise allowing the steep flank to be imaged more clearly. A positive (black) value indicates an increase in impedance, while a negative (white) value indicates a decrease in impedance.

Kirchhoff images are often limited by migration artefacts and illumination issues. This can be seen in Figure 4a where the stratigraphic terminations against the salt flank appear to be severely contaminated by migration noise highlighted by the white oval. In order to overcome these limitations and improve the imaging and resolution of the reservoir, a range of different algorithms and



approaches were evaluated, including, Full Gaussian Beam, Reverse Time Migration (RTM) and least-squares Kirchhoff migration. Figure 4b shows the result of least-squares Kirchhoff imaging using a Hessian migration deconvolution approach (Casasanta et al., 2017), which is significantly less affected by migration noise than the standard Kirchhoff image in Figure 4a. As the main reservoir was on the flank of the structure, the primary focus of the image was not limited by the single arrival nature of a Kirchhoff image. The multi-arrival aspect of RTM could help improve the imaging in the areas of dip change, where the milder dips are truncated by the salt flank.

Conclusions

We have outlined the case history of multi-azimuth PSDM re-processing of the Oda discovery which aimed to improve the resolution of the reservoir and de-risk the field development well planning by minimising the uncertainty of the reservoir size and position. The inclusion of numerous advanced seismic imaging techniques provided a cleaner, broader-bandwidth dataset with improved image resolution. Combined with the uncertainty analysis, this dataset should provide further clarity in de-risking the planning of future development wells in the area.

Acknowledgments

The authors would like to thank the partners of licence PL 405 (Centrica, Suncor Energy, Faroe Petroleum and AkerBP) for permission to publish this paper and the CGG sub-surface imaging team who were involved in the project.

References

- Birdus, S., Ganivet, V., Artemov, A., Teakle, R. and Phythian, P. [2015] Estimation of Uncertainties in Fault Lateral Positioning on 3D PSDM Seismic Image - Example from the NW Australian Shelf. *77th EAGE Conference and Exhibition*, Extended Abstracts, Tu N118 06.
- Casasanta, L., Roberts, G., Perrone, F., Ratcliffe, A., Poole, G., Wang, Y. and Yie, X. [2017] Practical benefits of Kirchhoff least-squares migration deconvolution, *submitted to 79th EAGE Conference and Exhibition*.
- Guillaume, P., Hollingworth, S., Zhang, X., Prescott, A., Jupp, R., Lambaré, G. and Pape, O. [2012] Multi-layer tomography and its application for improved depth imaging. *82nd SEG Annual Meeting*, Expanded Abstracts, 1-5.
- Guillaume, P., Reinier, M., Lambaré, G., Cavalié, A., Iren Adamsen, M., and Munch Bruun, B. [2013] Dip-constrained non-linear slope tomography: an application to shallow channel characterization. *75th EAGE Conference & Exhibition*, Extended Abstracts, Tu 02 09.
- Messud, J., Reiner, M., Prigent, H., Guillaume, P., Coleou, T. and Masclat, S. [2017] Extracting seismic uncertainties from tomographic velocity inversion and their use in reservoir risk analysis. *The Leading Edge*, in press.
- Mothi, S., Schwarz, K. and Zhu, H. [2013] Impact of full-azimuth and long-offset acquisition on full waveform inversion in deepwater Gulf of Mexico. *83rd SEG Annual Meeting*, Expanded Abstracts, 924-928.
- Wang, P., Ray, S., Peng, C., Li, Y. and Poole, G. [2013] Premigration deghosting for marine streamer data using a bootstrap approach in tau-p domain. *83rd SEG Annual Meeting*, Expanded Abstracts, 4221-4225.