# FWI and PSDM of tunnel valleys in the southern part of the Norwegian North Sea

*Hui Fan*, Geokinetics, Inc., Dr. M. Lee Bell, Geokinetics, Inc., Børge O. Rosland, Skagen44, Chantelle Yhap, Geokinetics, Inc.*

**Summary**

Tunnel valleys occur in the Pleistocene and pre-Pleistocene glaciated shallow subsurface of the North Sea. They can be up to 100 km long, 5 km wide, and up to 400 m deep and were formed under the ice sheets of the Quaternary Ice Age. The valley infill is comprised of glaciofluvial deposits, which occurred during ice recession and can be quite different from the surrounding sedimentary structures leading to distortions in the seismic image. The application of joint travel time and full waveform inversion leads to a velocity model for the shallow section that can be employed in pre-stack depth migration. The resulting image is then relatively free of these distortions.

**Introduction**

Tunnel valleys occur in the Pleistocene and pre-Pleistocene glaciated shallow subsurface of the North Sea (see Figure 1). They can be up to 100 km long, 5 km wide, and up to 400 m deep and were formed under the ice sheets of the Quaternary Ice Age (Jørgensen and Sandersen, 2006; Van der Vegt *et al,* 2014). They are thought to have formed primarily by subglacial meltwater erosion and secondarily by direct glacial erosion. The valley infill is comprised of glaciofluvial deposits which occurred during ice recession. Since there have been several advances and regressions of the glaciers, successive generations of tunnel valleys were created with different directions and dimensions that can overprint earlier episodes thus generating a complex near-surface pattern (see Figure 2).

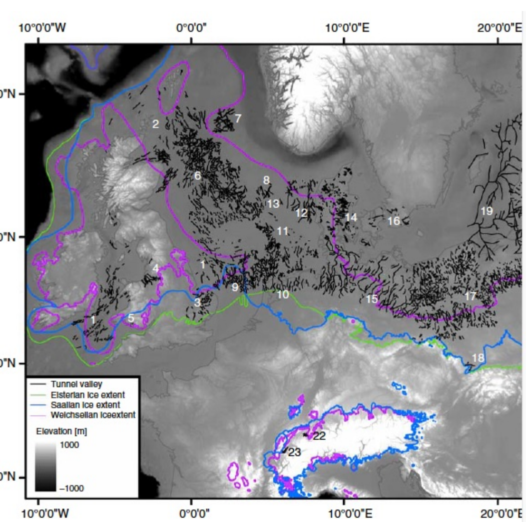


Figure 1: Pleistocene tunnel valleys from Van der Vegt *et al*, 2014.

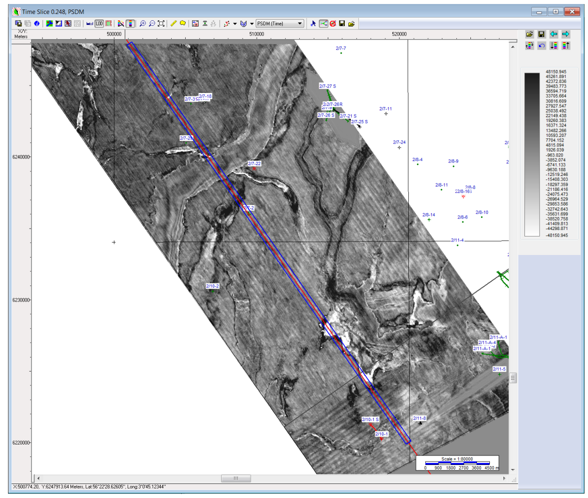

Figure 2: Depth slice of PSDM amplitude cube showing some tunnel valleys in the southern Norwegian North Sea.

The velocities of the tunnel valley infill can be different than the surrounding sedimentary structures, thus making a distortion in the seismic image underneath them. In Figure 3 the disruption in the event continuity beneath a particularly large valley of about 2 km wide and 400 m deep can clearly be seen. A synthetic study conducted by Fan *et al* (2015) using the method described by Zhang and Chen (2014) indicated that utilizing a joint travel time and full waveform inversion could be successful in computing the shallow velocity structure necessary to improve the seismic image beneath tunnel valleys. This methodology was employed on a 2D line extracted from a 3D streamer survey that traversed the tunnel valley of Figure 3 (2D line in red) to correct the image distortion.

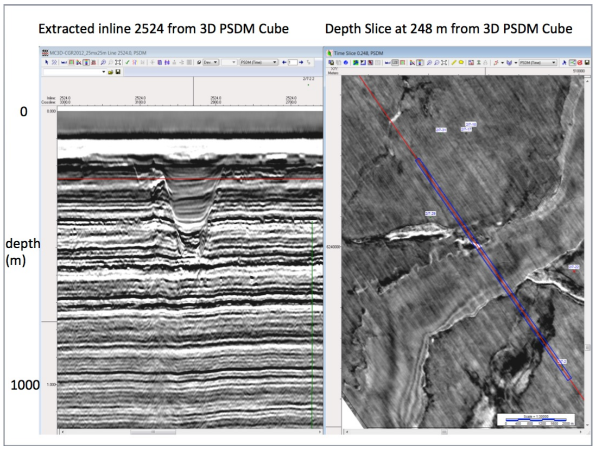


Figure 3: On left, shallow PSDM image of inline 2524 illustrating the distortion due to the anomaly. On right, the red line indicates the 2D line chosen for this study from the PSDM amplitude volume relative to the tunnel valleys.

## Methodology

Joint seismic travel time and waveform inversion (JI) is a method to use both first-arrival travel time tomography (FAT) and early arrival full waveform inversion (FWI). FWI is a nonlinear waveform-tomography method for estimating the near-surface high-resolution velocity. It minimizes the waveform misfit between the predicted and observed early arrivals in seismograms, including the direct wave, refractions, diving-waves, diffractions and reflections. The 2D acoustic wave equation is used to perform the forward modeling. An issue with FWI is the lack of effective preconditioning in the nonlinear inversion. With the inclusion of the travel time in a joint inversion, the matrix of the travel time sensitivity serves this purpose. This significantly speeds up the global convergence of the waveform inversion.

## Application of velocity inversion to a tunnel valley in the southern part of the Norwegian North Sea

The 3D streamer survey is located in the southern part of the Norwegian North Sea, Norway, on Block 2/11. A 2D sail line from the 3D is approximately 40 km long with 903 shots and 3186 receivers and the water depth is about 70 m. The source array is towed at 7 m and the streamer is towed at 20 m. The shot interval is 18.75 m, receiver interval is 12.5 m, record length is 8 seconds and sample rate is 2ms. To improve the interpretability of picking first arrivals for travel time inversion, a common offset sort was used. An example is displayed in Figure 4, which clearly shows the delay due to the anomaly at offset 1995 m.

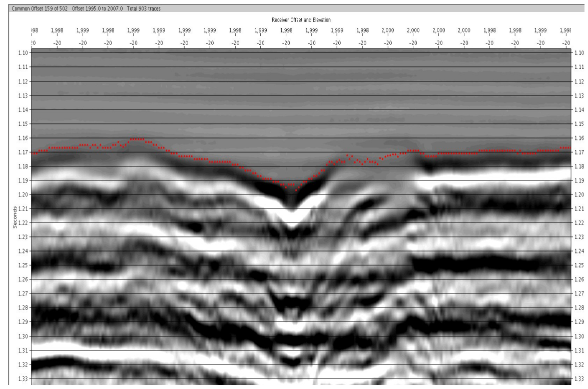

Figure 4: Common offset gather at 1995 m. The picked first arrivals are displayed in red.

After picking first breaks, FAT was used to invert for an initial model. Figure 5 shows the resulting velocities. The largest anomaly representing the biggest tunnel valley can be seen to right of the arrow, but just as in Figure 3, the other tunnel valleys crossing the largest one have an impact on the shallow velocity model as well. The velocity contrast within the anomaly ranges from 1650 m/s to 1820 m/s between the water bottom and 350 m in depth. The background velocity varies from about 1700 m/s to 1850 m/s over the same depth range. Also note the line crosses another, smaller tunnel valley (Figures 2 and 3), which affects the velocity model, somewhat to the southeast (right hand side) of the line.

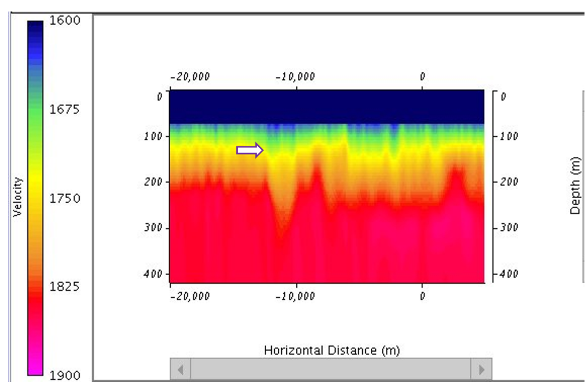


Figure 5: Velocity model generated from First-Arrival Traveltime Tomography. Water velocity is 1490 m/s. The arrow indicates the principle tunnel valley.

Before applying JI, the seismic data is filtered and muted, creating a window of 250 ms within which the inversion is performed. The final waveform velocity model after 10 iterations is exhibited in Figure 6. The impact of the smaller tunnel valley to the southeast is more obvious after the JI. As a QC an overlay of the predicted waveform window from the model is superimposed on shot 1071 can be seen in Figure 7.

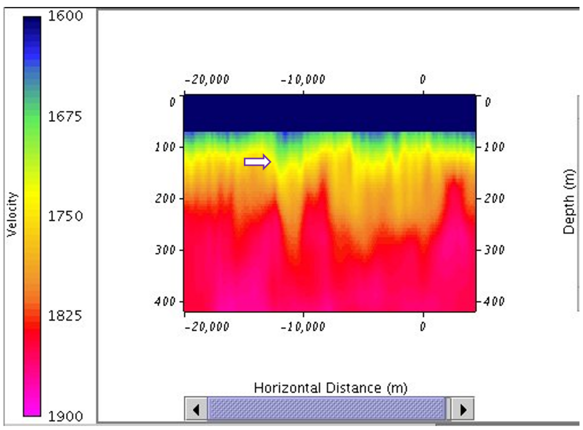


Figure 6: Joint seismic travel time and waveform inversion velocity model. Again the arrow indicates the principle tunnel valley.

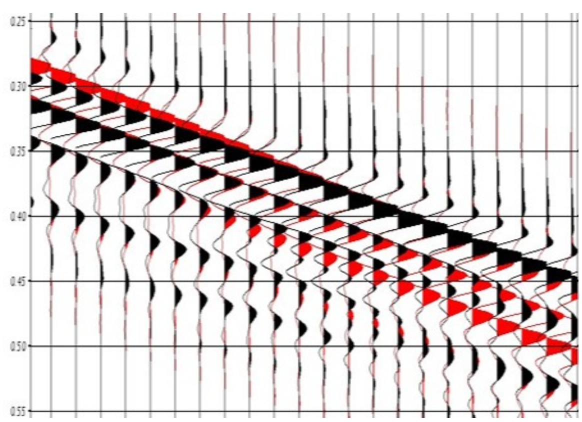

Figure 7: Overly of synthetic data (red) with input seismic data (black).

## PSDM using the inverted shallow velocity model

Figure 8 is the result of a conventional approach with pre-stack Kirchhoff depth imaging using smoothed interval velocities derived from the PSTM velocity analysis. Figure 9 uses the velocities from Figure 6 of the joint inversion.

Although the velocities in the tunnel valleys on this line are subtly different from the surrounding formations, the improvement on the section by incorporating them in the model can be clearly seen by comparing Figures 8 and 9. The structure under the anomalies at, for example, events at 500 and 600 ms has had its distortion substantially removed.

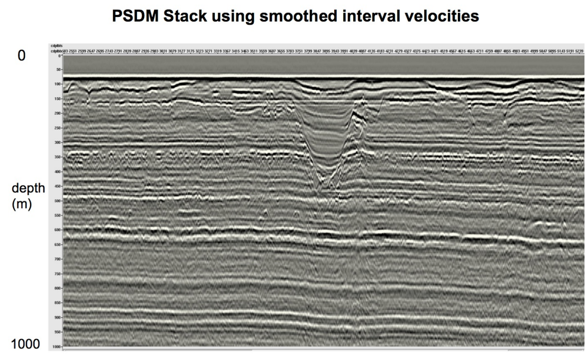


Figure 8: PSDM image using smoothed interval velocities from PSTM.

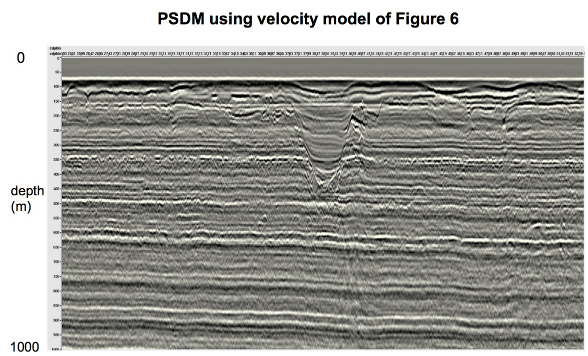


Figure 9: PSDM using the interval velocities from Figure 6 as a result of the JI.

## Discussion and Conclusions

We were able to demonstrate that the application of the joint inversion of travel time tomography and early arrival full waveform inversion could produce a velocity model that removes the depth distortions that tunnel valleys can introduce, even when the velocity contrast is subtle. It has been pointed out by Furre *et al* (2014) that tunnel valleys can be gas charged which could significantly increase the velocity contrast.

On further investigation we arrive at the very interesting Figure 10. Displayed in four panels we see a shallow depth slice on the left hand side, the SW inline next, a NE inline next to that, and a crossline along the tunnel valley on the right hand side. The inline we analyzed is on the left middle; the inline 750 m to the NE is in the right middle and clearly shows more distortion. The most interesting, however, is the crossline, which shows significant distortion to the SW in particular, indicating yet a much stronger velocity anomaly.

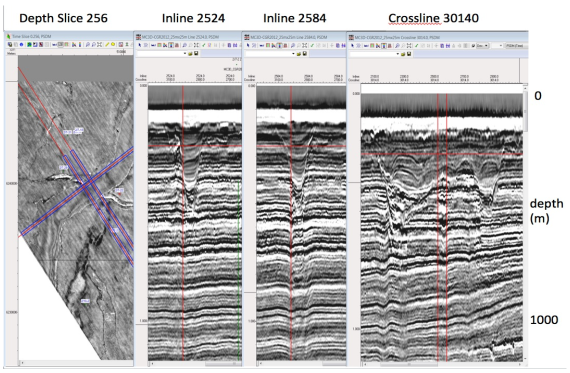


Figure 10: From the left, the first panel shows a shallow depth slice showing the two inlines and one crossline displayed. The next panel displays the inline to the SW that was analyzed in this paper. The third panel displays a neighboring inline 750 m to the NE and the fourth panel shows a crossline down the axis of the tunnel valley. Note the strong velocity distortion to the SW.

Given the strong local variation in velocity that can be seen in this figure, the next step should be to do a 3D joint inversion. In this way the inhomogeneity of the velocity variation can be properly captured in the model and the depth image will reflect the geology more accurately.

**Acknowledgements**

We wish to thank Concedo ASA (www.concedo.no), Skagen44 AS (http://www.skagen44.no/en), and Geokinetics, Inc. (www.geokinetics.com) for their permission to show these results. We also wish to thank GeoTomo, LLC. (www.geotomo.com) for their advice and assistance.

## EDITED REFERENCES

Note: This reference list is a copyedited version of the reference list submitted by the author. Reference lists for the 2016 SEG Technical Program Expanded Abstracts have been copyedited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

## REFERENCES


Fan, H., L. Bell, Y. Deng, and J. Zhang, 2015, Imaging shallow complex structures in North Sea with joint traveltime and waveform inversion: 2015 SEG Depth Model Building: Full-waveform Inversion Workshop, 40–43, http://dx.doi.org/10.1190/FWI2015-010.

Furre, A. K., P. Ringrose, A. Cavanagh, A. D. Janbu, and S. Hagen, 2014, Characterisation of a submarine glacial channel and related linear features: Near surface geoscience 2014 — First applied shallow marine geophysics conference, EAGE, 14–18 September 2014.

Jørgensen, F., and P. B. E. Sandersen, 2006, Buried and open tunnel valleys in Denmark — Erosion beneath multiple ice sheets: Quaternary Science Reviews, **25**, 1339–1363, http://dx.doi.org/10.1016/j.quascirev.2005.11.006.

van der Vegt, P., A. Janszen, and A. Moscariello, 2012, Tunnel valleys: Current knowledge and future perspectives, *in* M. Huuse, J. Redfern, D. P. Le Heron, R. J. Dixon, A. Moscariello, and J. Craig, eds., Glaciogenic reservoirs and hydrocarbon systems: Geological Society, Special Publications 368, 75–97, http://dx.doi.org/10.1144/SP368.13.

Zhang, J., and J. Chen, 2014, Joint seismic traveltime and waveform inversion for near surface imaging: 84th Annual International Meeting, SEG, Expanded Abstracts, 934–937, http://dx.doi.org/10.1190/segam2014-1501.1.