Th-07-05

Improving Gather Picking for Tomography in Complex Velocity Models, a Case Study on Shale Diapirs

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SUMMARY

We present a case study demonstrating that in a complex geological setting travel time tomography can produce high resolution velocity fields without resorting to the use of simplified blocky velocity models to represent the complex velocity field where there is poor seismic imaging. We developed a strategy to enhance the travel time picking which allows the reliable use of small spatial smoothing in the tomographic inversion and produces a stable complex velocity field which significantly improves the deeper imaging.

The study area overlies the Vema Dome (offshore Norway) containing irregular structured shale diapirs in the shallow section. These diapirs are possibly cored by diatomaceous oozes deposited during the Paleocene and Miocene periods which results in rapid large velocity changes.
Introduction

We present a strategy for generating a stable broader wavenumber velocity field using tomographic inversion in a complex geological setting. It is focused on producing more reliable travel time picks to permit reduced spatial smoothing as a pre-conditioning of the tomographic inversion. The case study area is in the region of the Norwegian Sea overlying the Vema dome where the seabed is significantly distorted by the surface expression of shale diapirs and seismic imaging below is degraded as shown in Figure 1. These shale diapirs are geobodies with very irregular topography, rapid changes in internal velocity structure and large velocity contrast with the surrounding host rocks. The structure of these geobodies must be adequately incorporated into the velocity model in order for a pre-stack depth migration (PreSDM) image to reveal the deeper structures of interest.

Case study area geological background

The overburden in the area is characterized by shale diapirism, cored by coccolith diatomaceous oozes deposited during the Paleocene and Miocene periods (Hovland et al., 1998), which gives rise to rugged seabed topography. At water depths of over 1km, the seabed features associated with the shale diapirism rise to a height of about 70m above the surrounding seafloor level and there are multiple levels of this shale diapirism in the shallow section extending down to 1300m below the seabed.

![Figure 1](image-url)

*Figure 1* Starting (Kirchhoff) and Final (Beam) PreSDM stack showing the nature of the diapiric disturbance, and the diatomaceous oozes bodies. The effect on deeper image (inside dashed orange box) is clearly observed in the dimming below the oozes structures. This zone has been greatly improved in the final stack due to the update in the velocity model.

Model building methodology

The reliability and resolution of travel time tomography is dependent on accurate travel time picks of events in common reflection point (CRP) gathers. The quality of these picks is influenced by many factors including the complexity of the subsurface velocity field and the accuracy of the velocity model used in a migration to produce the CRP gathers. In geological settings which contain high amplitude large wavenumber variations in the subsurface velocity field, an inaccurate starting velocity model will result in CRP gathers which contain no coherent events in and below the areas of complex
velocity. The lack of coherent events then prevents accurate travel time picking, which leads to leaking of surrounding velocity updates into the area of complex imaging.

The standard industry strategy to resolve this problem is to iterate velocity updates from shallow to deep which progressively reduces the velocity error at depth (Jones 2012). We started with this strategy but after a review of the CRP gathers from the first iteration of the shallow section it was clear that there were insufficient coherent events to pick reliable travel times below the top of the shale diapirs. So as our first alternative solution we tried to impose a blocky velocity model for the shale diapir into the background velocity model. This blocky model was derived from a suite of constant velocity floods below the top of the shale diapir. Unfortunately this still did not result in coherent events below the shale diapirs, as it became apparent that the diapirs had a complex internal velocity field that could not be adequately represented by a blocky velocity model.

To capture the internal velocity structure of the diapirs we have developed a strategy to enable updating of the velocity model using the CRP gathers in and below the diapirs. As part of this strategy we recognize that for a fixed velocity error the sensitivity of constructive interference in imaging a CRP is frequency variant with low frequencies being less sensitive to velocity errors than high frequencies (Jones 2010). Therefore we begin by harshly frequency filtering the data, altering the resolution of the tomographic inversion and adapting the CRP travel time picking to produce reliable picks throughout the volume being updated as shown in Figure 2. As the velocity model becomes more accurate the frequency constraints are relaxed increasing the spatial sampling of reliable CRP travel time picks. This permits the reduction of spatial smoothing required to stabilize the tomographic inversion which broadens the wavenumber content of the resultant velocity model.

![Figure 2](image)

**Figure 2** Synthetic residual move-out curves (red pick lines) overlain on CRP gathers before and after pre-conditioning from the same model-building iteration.

To summarise the steps taken to produce the velocity field:

1. Water column velocity profile based on averaged full water column velocity measurements.
2. Gather conditioning, frequency filtering e.g. 5 to 30 Hz, relaxing filtering with progressive iterations, noise reduction on gathers.
3. Limiting angle range of CRP gathers to control picking and to avoid reduced accuracy caused by varying amplitude response of events with reflection angle.
4. Automatic quality control of CRP picking, rejecting unreliable picks.
5. Removing CRP picks that are not part of laterally continuous reflectors.
6. Varying the travel time grid for migrations and tomographic inversion grid, from sparse to dense with increasing iterations and varying with depth.
7. Reducing smoothing required to stabilize the tomographic inversion from 400m to 150m.

Overall, seven iterations of full volume hybrid gridded tomography were employed to update the background velocity field including the anisotropic parameters. CRP gathers were output on a 25m *
25m grid for each iteration supported by ray tracing on a 40m*40m*40m mesh for Kirchhoff migration. Starting from a smoothed version of an initial PreSDM model, the initial tomographic cell size was 200m*200m*55m, but reduced to 75m*75m*65m for the iterations designed to resolve the shale diapirs. Anisotropic control was provided via calibration against the available well data. For shallow updates Kirchhoff migration was used to produce input gathers to tomographic inversion, whilst for deeper updates beam migration was used.

Figure 3 Starting and final velocity models with PreSDM stacks from Figure 1 overlain, showing detail of shale/ooze geobody. CRP gathers for the region in the orange box are shown in the Figure 4.

Figure 4 Starting and final CRP gathers from the boxed region of Figure 3. There are many more flat coherent events in the final CRP’s in the region inside the dashed yellow box below the shale/ooze diapir structures.
Results

The final velocity model is a detailed representation of the shale and diatomaceous ooze diapirs (Figures 3 and 5) and has enabled the final PreSDM to image the deeper seismic events as highlighted in Figure 1. Figure 3 illustrates the internal velocity structure of the geobody representing the shale and diatomaceous ooze diapir, the interval velocities range from 1600m/s in the upper ooze layer, to 2600m/s in the deeper part of the body. To complicate the velocity model further this geobody is surrounded by a velocity trend reversal as the background velocity field above the geobody is about 2300m/s but only 1900m/s below. As shown in Figure 4, the improvement in the continuity of events on the CRP gathers and the flatness of those events demonstrates that the complex velocity structure caused by the shale and diatomaceous ooze diapirs has been adequately captured in the model.

![Starting and Final velocity model overlain on a depth slice at 1815m showing the spatial variation in the final velocity model that correlates with the diapiric structures.](image)

Conclusions

We have developed a strategy to produce stable travel time picks on CRP gathers in an area of initially poor imaging. This has allowed us to perform ray based tomographic inversions which have successfully resolved the internal structure of complex shale and diatomaceous ooze diapirs. This velocity model is spatially consistent with the geology and has been used in a PreSDM to significantly improve imaging below the diapirs.

Acknowledgements

Our sincere thanks to BG Norge and the PL599 partners, Idemitsu Petroleum Norge AS, PGNiG Norway AS and Noreco Norway AS for permission to show these results, and to Fugro and ION-GX Technology for permission to publish this work. We are also very grateful to James Selvage (BG Group) for many useful discussions on how to overcome the many challenges on this project and to Ian Jones (ION) for his hands-on support in producing this paper.

The underlying data is proprietary to and a trade secret of Fugro (“Data Owner”). The use of this data is restricted to companies holding a valid use license from Data Owner and is subject to confidentiality terms of that license.

References

