Next Generation Shallow Water Resolution: Primary Wave Imaging and High Frequency Visco-acoustic Full-waveform Inversion

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Summary

With many production reservoirs located at a depth greater than 1km, the near surface is often overlooked during seismic processing. Therefore, valuable information relating to shallow geohazards, shallow gas, faults and changes to lithology are lost or unused. We present a new processing methodology to improve the spatial resolution of the near surface seismic image. Careful treatment of source and receiver deghosting was required to handle azimuthal variations and spatial aliasing. A dense 5D interpolation was used to increase crossline sampling and nominal fold in the near surface, allowing for a better signal to noise ratio. At the migration stage, a one-way wave equation migration was considered to capture high frequencies (~200 Hz) and steep dips while limiting migration noise. A velocity model update was performed using guided-wave inversion, visco-acoustic full-waveform inversion and a 32 Hz joint reflection and refraction full-waveform inversion to produce high spatial resolution. The resulting seismic image has high spatial resolution and broad bandwidth making shallow features highly resolved. The derived velocity model is sufficiently highly resolved to be considered as a tool to aid in seismic interpretation and sediment classification. This comprehensive workflow was essential to overcome the challenges imposed in shallow water acquisition.

Introduction

The near surface image produced from a towed streamer geometry has limitations in a shallow water marine environment. This is because the distances between the source and the nearest receivers, and the distance between the cables, are both large in comparison with the water depth. There are also large azimuthal variations between the source and outer streamers compared with the inner streamers. Historically, processing sequences for towed streamer surveys have been designed for deeper targets and do not address the issues of near surface imaging. Furthermore, the lack of near surface clarity can cause ambiguity of geohazards, such as gas pockets, and shallow channel features. Recently, there has been a shift in focus towards shallower targets. New acquisition designs such as TopSeis (Vinje et al., 2017) mitigate the zero offset issue but would require surveys to be re-acquired. Therefore, a comprehensive workflow for conventional towed streamer data was developed which combines careful pre-processing with high resolution velocity model building. This includes guided-wave inversion (GWI), visco-acoustic full-waveform inversion (FWI) and joint reflection/refraction FWI.

The main objective of this seismic data processing is to use the primary wavefield to significantly improve the resolution of the near surface image compared with the vintage pre-processing, and to produce a high-resolution velocity model with sufficient spatial resolution to aid interpretation or sediment classification alongside the seismic image. This objective is achieved through the construction of a depth velocity model using guided, reflected and refracted waves, and the application of careful signal processing designed to mitigate the lack of near offset receivers, and poor sampling across the towed streamer array (between the cables). The data we present here is a marine variable-depth streamer (Soubaras and Dowle, 2010) and variable-depth source acquisition over the Quad 22 block of the North Sea, shot narrow azimuth with 150-8000 m offset and a shot spacing of 25 m. The receiver spacing is 12.5 m along the length of the 10 cables, with each cable separated by 100 m. The processed area was approximately 180 km^2 with a depth of 1 km.

Signal Processing

Designature, source deghosting and receiver deghosting

Deghosting is a key stage in the processing sequence which results in broader bandwidth from notch recovery, sharper primary wavelets and a higher resolution image. The shallow water environment creates strong azimuthal variations in the source signature from the front of the outer cables. This means a simple designature operator will introduce strong artefacts, such as ringing, and fail to correct for the outer offset signature. Where we have shallow channel features with strong crossline dip, even a 2D inline operator will break down, especially on the outer cables. Therefore, a 3D tau-px-py iteratively reweighted inversion scheme was utilized which was highly constrained by simultaneously solving for the source signature, source ghost and receiver ghost. The 3D estimate of the source signature was created using notional sources derived from near field hydrophone data (Poole et al., 2015). Since the ghost modelling must satisfy both the source and receiver ghosts, the process is less sensitive to noise and more robust against mis-modelling.

5D Regularisation

An important challenge faced in shallow water acquisition is the distribution of missing near offsets. This results in selecting a first offset class of ~175-200 m often with a nominal 75-100 m offset class width used for common-offset migration. The large offset class increment and relatively large azimuthal variations within the offset class results in only two or three traces of usable reflection fold in the very shallow after migration. In addition, the crossline sampling is generally poor, which further degrades the crossline spatial resolution. To overcome these issues, a 5D interpolation (Poole, 2010) was performed on a dense 6.25 m × 6.25 m grid with 37.5 m offset class bin sizes. By using the offset dimension in regularization, better populated further offset classes can be used to improve the interpolation in the poorer populated near offsets. Reducing the offset class increment increases the useable fold of traces in the shallow (in this case they are doubled) and so the primary coherency is greatly improved on stack. The denser crossline sampling dramatically improves the crossline spatial resolution with shallow channel features now becoming much more continuous and well defined.

Velocity Model Building

In shallow water, reflection tomography can be problematic due to a limited amount of usable offsets, as energy quickly becomes post-critical. This creates difficulty for move-out picking and leads to unresolved complex structures. As a result, the inaccurate complex overburden distorts deeper events and affects imaging quality down at the target level. In this study, two key technologies were used to overcome such difficulty: GWI, deriving the water column velocity and the very shallow sediment velocity, and FWI, deriving the velocity down to about 500 m.

GWI extracts useful information from the dispersive energy in water column reverberations, i.e. multiples. The method originates from surface wave inversion, inverting for a velocity model using the multiple modes of the phase-velocity dispersion curves (Miao et al., 2017). Here the dispersion curves are analyzed on a 50 × 50 m grid using super-shot gathers of 1000 m aperture. A 1D model was used as input, and three modes were used in the inversion within a frequency band of 2-45 Hz. The updated model is kept within the depth of penetration of the guided wave and used as the starting model for FWI. An input model with more accurate water and shallow sediment velocity helps FWI converge faster. Using the GWI incorporated velocity and vintage anisotropy as input, preserved-amplitude FWI (Qin and Lambaré, 2016) and a diving-wave FWI update up to 32 Hz were ran, generating a high-resolution model that could assist interpretation (Figure 1).

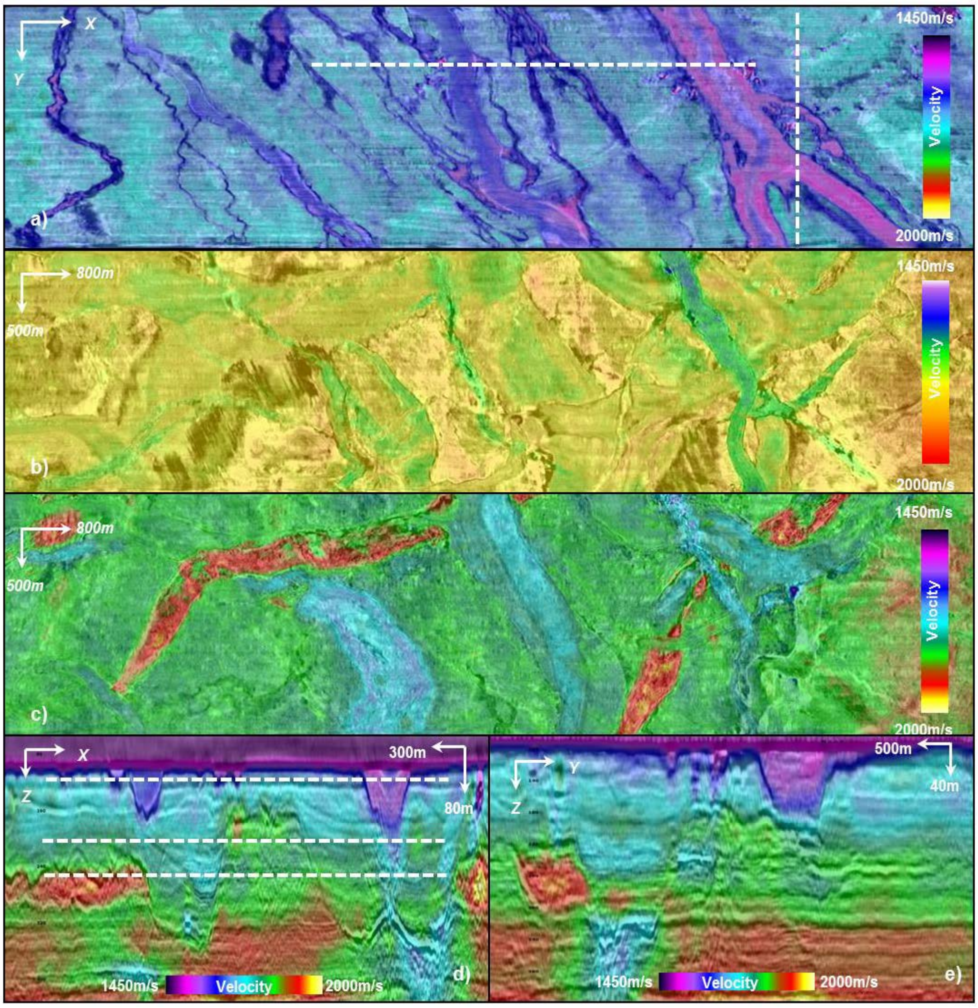

Figure 1 *a-c) depth slices of the model at 115 m, 185 m and 250 m, respectively; d) one inline; e) one crossline. The dotted lines show the location of the corresponding depth slices and inline/crossline sections.*

Two gas charged bodies were observed (Figure 2, yellow oval) during the FWI update. Traditional acoustic FWI does not honour the dissipation term in waveform propagation, and disregarding the phase rotation will lead to erroneous velocity compensating for Q anomalies. Therefore visco-acoustic FWI (Q-FWI) was performed. A background Q = 150 model was used as input to Q-FWI and the updated Q model correlates nicely with the gas sheet (Figure 2c). The updated Q model is honored in a subsequent V_P only FWI and also used in Q-compensating depth imaging (Figure 2b).

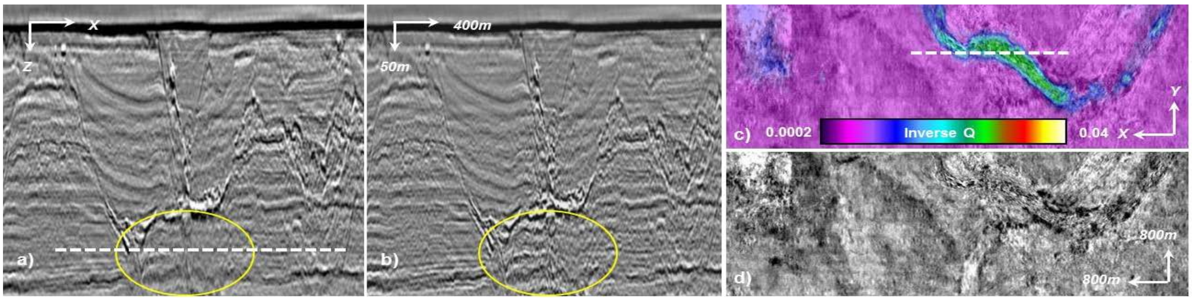

Figure 2 *a) Kirchhoff depth imaging, b) Q-compensating Kirchhoff depth imaging, c) depth slices at 398 m showing the inverted Q-FWI model overlain with seismic, d) depth slice of seismic only.*

The migration algorithm is an important step to a highly resolved near surface image. The Kirchhoff method has inherent limitations with regards to ray multi-pathing and requires smooth models for stability. Wave equation based approaches such as Reverse Time Migration (RTM) are far more accurate in their treatment of multi-pathing but are expensive due to the high frequencies needing to be migrated here (up to 200 Hz). Also, turning-wave noise is strongest in the shallow section of a RTM image. A natural compromise between Kirchhoff and RTM is a one-way wave equation migration, which can be used efficiently up to high frequencies, does not require a smooth velocity model, and shows little contamination by turning-wave noise in the shallow (Figure 3).

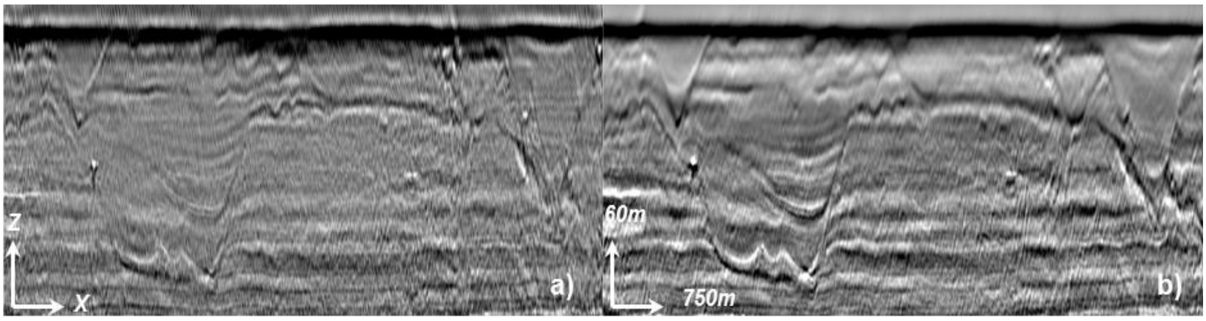

Figure 3 *Depth migration comparison of: a) Kirchhoff migration, and b) one-way wave equation migration. Both migrations used the same input velocity model and underlying seismic data.*

Results and conclusions

The legacy stack was not processed with the shallow target in mind; the uplift with the new processing workflow is clearly shown in Figure 4. This new workflow has produced exceptionally well resolved shallow features with spatial variations of less than 10 m being revealed. The new high-resolution processing has well-defined shallow channel features in the inline and crossline direction with no residual ghost. The new demultiple flow targeting the water layer multiples has been more effective at suppressing multiples compared with the vintage. Careful treatment of the receiver motion correction has preserved the diffractions during interpolation. The acquisition footprint attenuation has also been improved compared with the vintage and has suppressed noise which would normally distort shallow crossline sections. Comprehensive pre-processing and model building workflows have been used to overcome imaging challenges imposed due to a shallow water towed-streamer acquisition. Careful consideration of the high frequencies and sampling were essential for both the final seismic image and the velocity model building. While FWI can produce high frequency model updates on its own, the GWI model used as input to the FWI update improved its convergence and reduced cycle skipping. The inclusion of Q to be iteratively updated as part of the FWI improved the accuracy of the velocity model by placing phase distortions due to attenuating bodies into a Q-model.

Acknowledgments

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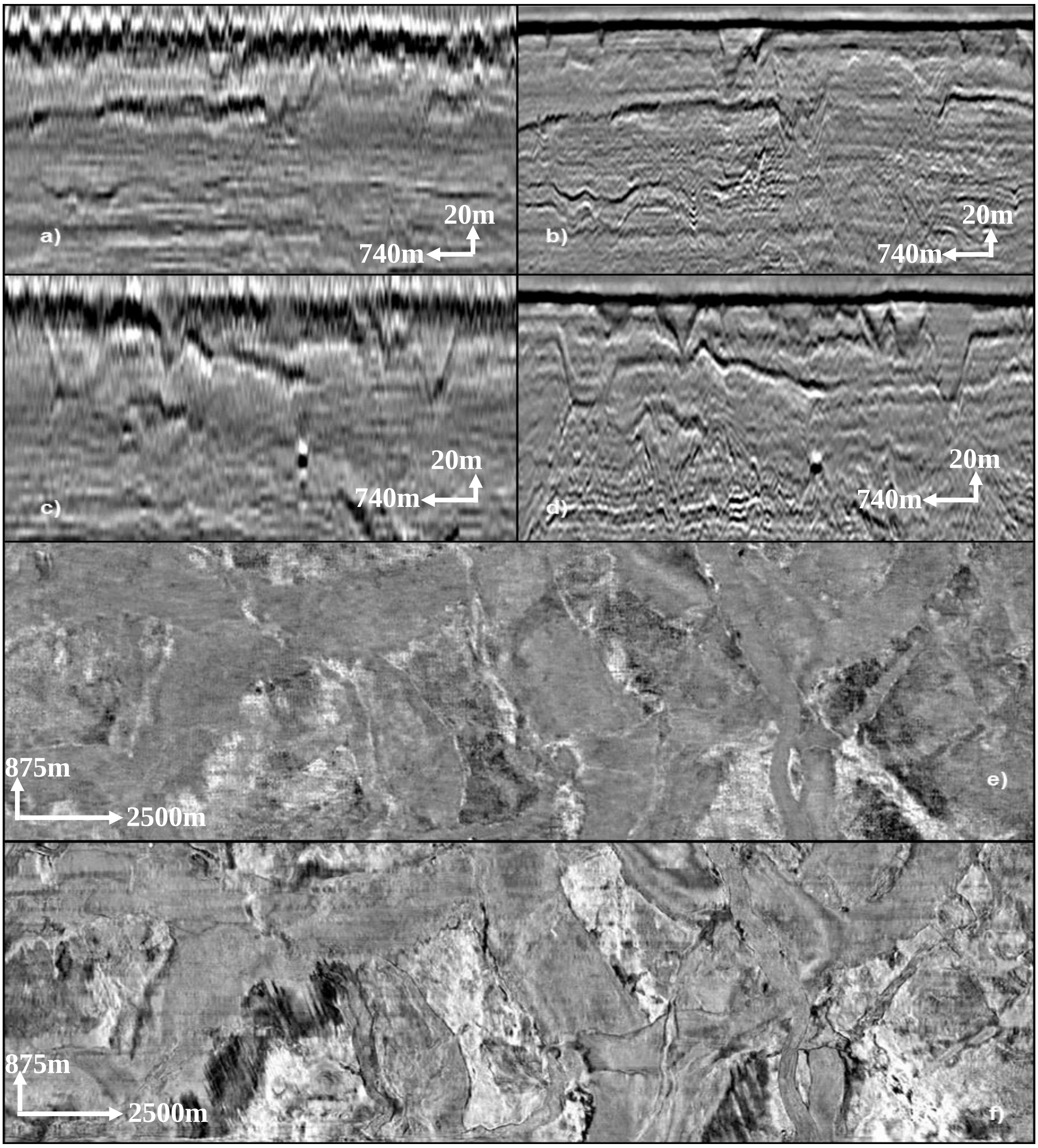

Figure 4 *a) vintage crossline, b) high-resolution crossline, c) vintage inline, d) high-resolution inline, e) and f) depth slices at 180m (~50m below seabed) for vintage and high-resolution processing, respectively.*

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