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Image Guided Full Waveform Inversion (IGFWI) Modelling of Shallow Channel Features in the Moray Firth

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Summary

We present a successful case study of Full Waveform Inversion (FWI) used to resolve velocity heterogeneity due to complex channel systems in the shallow section. These velocity variations produce imaging distortions – pull ups in deeper reflections – that tomography methods cannot handle due to their short spatial wavelength. Therefore, a multiscale FWI approach is used to accurately update the rapid variations in velocity.

The initial model for FWI uses the time interval velocity converted to depth interval velocity, smoothed, calibrated to wells and updated with one iteration of tomography update. A modeled far-field signature is used as the initial source wavelet. Acquisition footprint is addressed by KxKy footprint removal applied on the raw gradient of each iteration. Image Guided smoothing using structural tensors is effective in minimizing leakage of velocities across geological boundaries created by shallow channels and faults .

Introduction

We present a successful case study of the Full Waveform Inversion (FWI) method used for depth velocity model building. The data set is a 3D survey in the Moray Firth, in the North Sea (Figure 1). One of the main challenges in this area is the strong velocity heterogeneity observed in the very shallow section around 100-350 m depth. This is due to channels crosscutting flat layered horizons, these channels contain different velocity fill deposits that produce false pull-ups in deeper reflectors at Quaternary and Tertiary levels (Figure 2) when not accounted for in the velocity model. This was a key motivator to derive a new a high-resolution velocity model for this dataset that would correctly migrate the data without distortions, in this case using FWI.

The key targets in this area are in the Upper Jurassic and Lower Cretaceous, with proven discoveries; Kimmeridge clays are the source rock, Paleozoic is the secondary target.

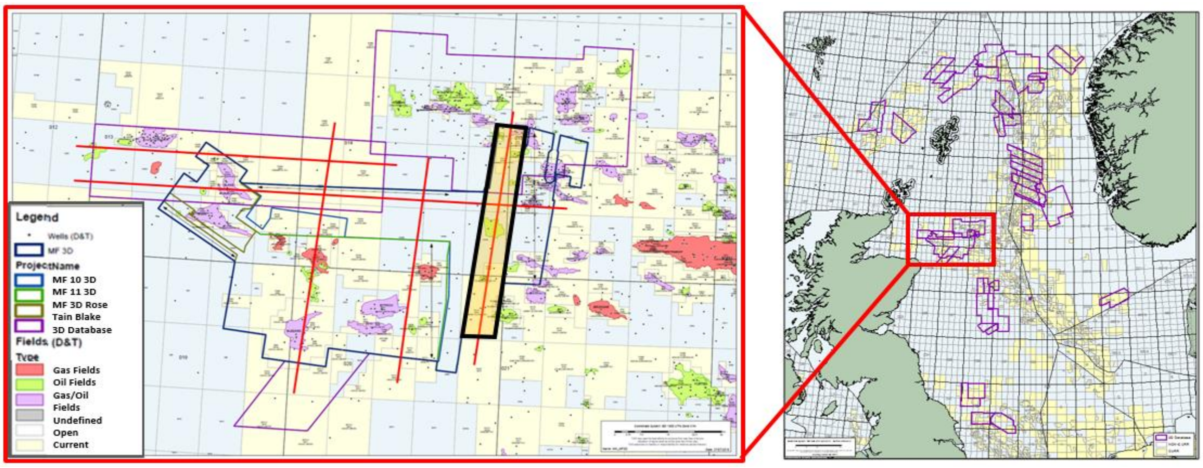

Figure 1 *Right, the map shows the location of the Moray Firth 3D in the North Sea, left is a map for the Greater Moray Firth with gas fields in red, oil fields in green and oil/gas fields in purple, MF11NS FWI cube is highlighted in black.*

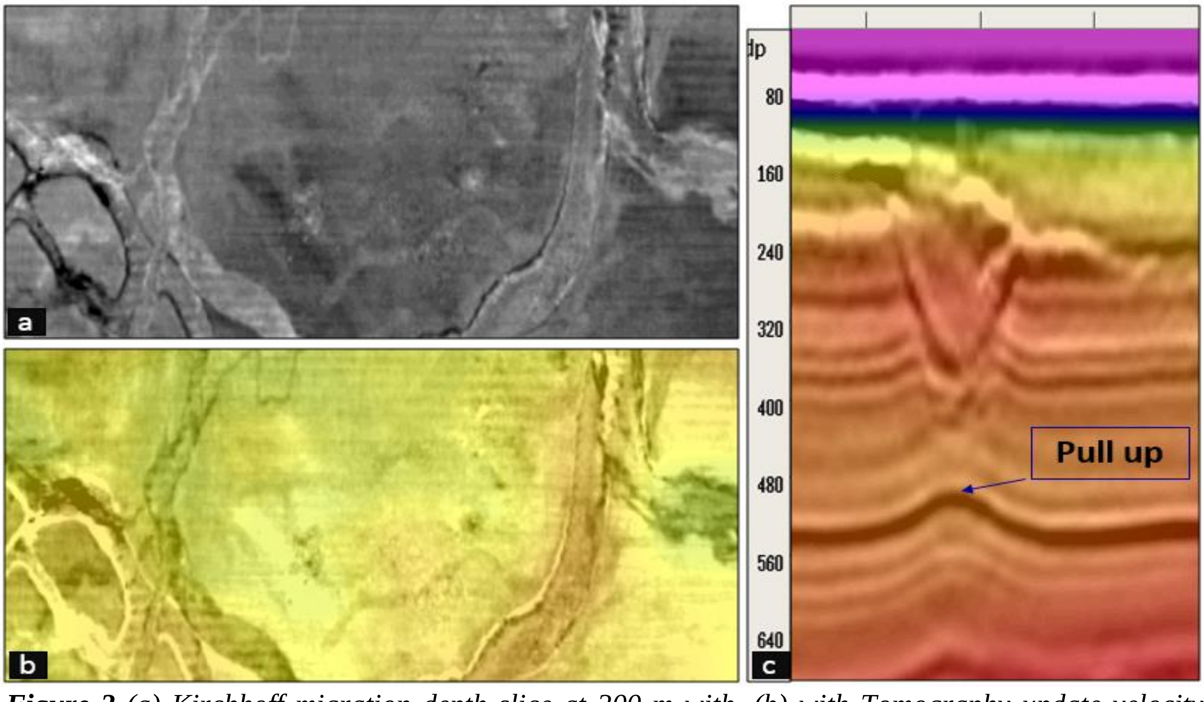

Figure 2 *(a) Kirchhoff migration depth slice at 300 m with, (b) with Tomography update velocity model and (c) example of inline across the channel with Tomography velocity overlay highlighting false seismic pull ups.*

Full Waveform Inversion FWI

FWI (Pratt et al., 1998; Virieux and Operto, 2009) is an inversion method based on finite-difference modelling, which aims to minimise the differences between recorded data (observed gathers) and modelled data. If the shift between observed data and modelled data is too large, FWI will not be able to converge due to cycle skipping between the observed and synthetic data. For this reason, a multiscale inversion is implemented: we start with a low fequency FWI update of 6-10 Hz to update the broader velocity outline of major structures, this is followed by increasingly high resolution velocity updates of 8-12 Hz and 10-14 Hz.

The input to FWI is shot gathers after minimal noise attenuation to attenuate strong bursts of swell noise. A frequency analysis is performed to ascertain the lowest reliable frequency that can be used for FWI. A pass of debubble is applied, in addition reflections from high velocity formations, such as chalk, which cross the diving waves at further offsets, are removed.

A modelled far-field signature is used as the initial source wavelet, which is then updated after the first iteration of FWI. The initial model for FWI uses the existing time interval velocity converted to depth interval velocity, smoothed and calibrated (Figure 3) to wells and updated with one iteration of tomography update.

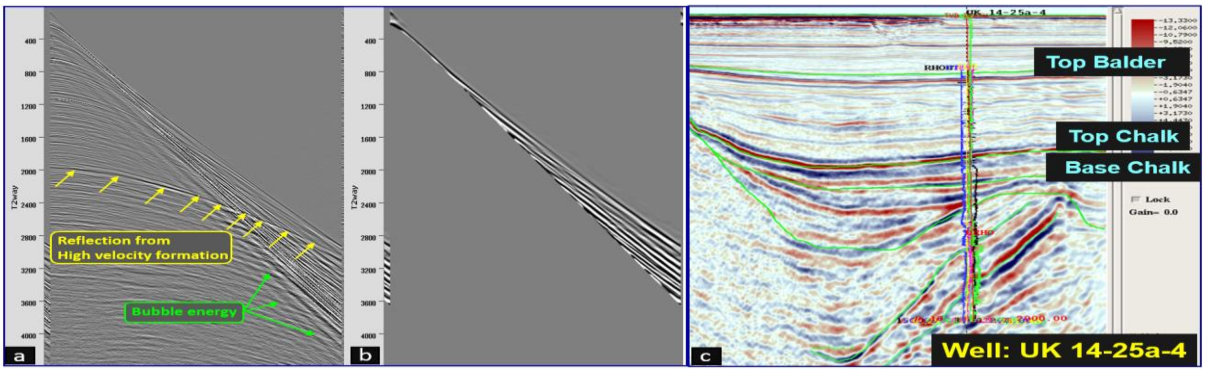

Figure 3 *(a) Input field-recorded gather after noise attenuation; (b) precondition with a 10 Hz filter; (c) Kirchhoff migration with one Tomography update after well calibration.*

Acquisition Footprint Removal

This NAZ data set exhibits a strong acquisition footprint. Considering the challenge of trying to provide a high-resolution model in the first 400 m, it is necessary to prevent the footprint being imprinted on the FWI velocity update. To do this, KxKy footprint removal was applied on the gradient stack image of each FWI iteration prior to the application of image-guided smoothing. Additional KxKy footprint removal was applied on the total δv. The effect of footprint is further mitigated by using source-side illumination compensation and image-guided smoothing (Figure 4).

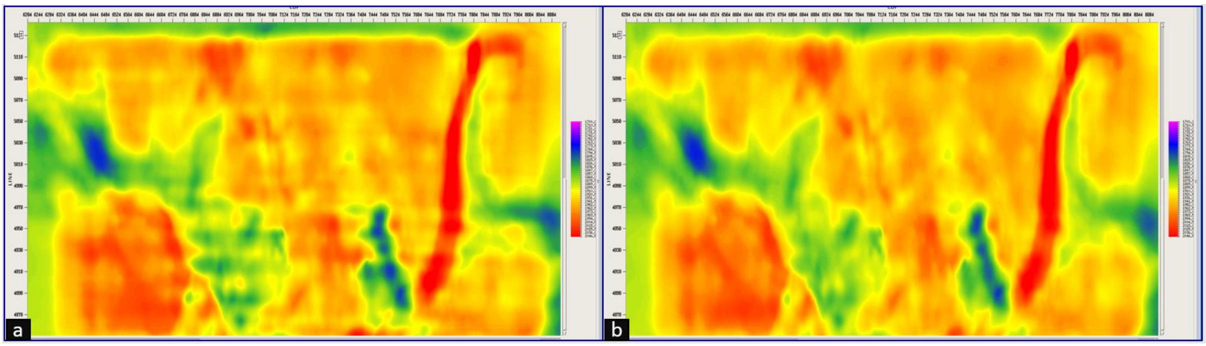

Figure 4 *(a) 8-12 Hz IGFWI model and (b) 8-12 Hz IGFWI model with KxKy acquisition footprint removal. KxKy filter removed the horizontal strips.*

Image Guided FWI (IGFWI)

The crosscutting nature of the channels imparts a significant degree of structural complexity to the FWI target zone. In order to ensure that this complexity is honoured by FWI, image-guided smoothing is applied to the gradient at each iteration. Image-guided smoothing (Mao et al., 2016) uses structural tensors to constrain smoothing to the main geological boundaries. This minmizes the possibility of leakage of rapid velocity changes across structural features such as faults or channels. Through the use of IGFWI, the complex channel systems are updated by FWI without prior knowledge or interpretation.

Result

The multiscale FWI approach used on this project is able to accurately update the rapid velocity variations associated with the shallow channel system. Due to their short spatial wavelength, conventional tomographic updates are unable to resolve the channels with sufficient precison.

Figure 5 shows the data migrated after 1 pass of tomography, the velocity model is also overlain on the seismic. Figure 5a shows a depth slice at 300 m. The complex, crosscutting nature of the channel systems is visible. On the right hand side of the slice two north-south trending channels can be seen to cross. Figure 5b shows an inline from the same migration. Looking at the strong reflector beneath the channel a pull up can be observed, indicating that the velocity in the channel needs to be increased. Above and to the right of the intersecting channel, a broader shallower channel can be identified.

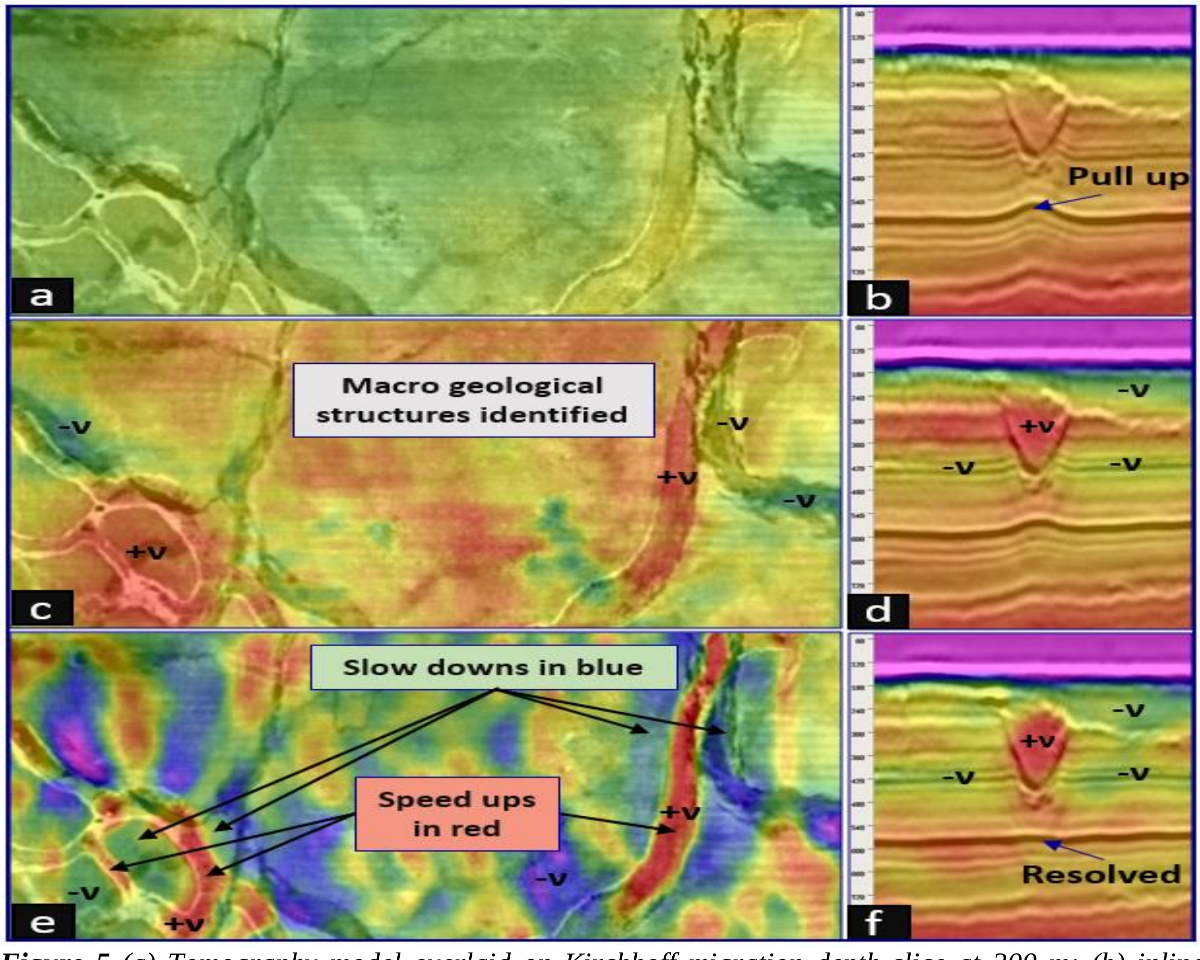

Figure 5 *(a) Tomography model overlaid on Kirchhoff migration depth slice at 300 m; (b) inline across the channel with Tomography velocity; (c) first FWI run with 6-10 Hz update velocity overlay; (d) inline across the channel with 6-10 Hz FWI velocity overlay; (e) FWI velocity from 6-8 Hz to 8-12 Hz and to 10-14 Hz overlay, (f) inline across the channel with FWI velocity till 10-14 Hz overlay.*

Figures 5c and 5d show the data migrated with the model output from the 6-10 Hz FWI update. This velocity model is also overlain on the seismic. The first pass of FWI provides an accurate baseline for later updates. The channels and macro geological structures are now identified. The velocity within the channel is increased and that of the crosscutting channel slowed down. These velocity variations go some way to address the imaging distortions, but are yet not optimum, as some pull up still remains.

The higher frequency FWI updates of 8-12 Hz and 10-14 Hz result in a high-resolution velocity model with clearly defined boundaries to the crosscutting channels. Figures 5e and 5f show the data migrated with the model from the 10-14 Hz FWI update (also overlain on the data). The velocity heterogeneities are now well described and follow the geology. Looking at the channel on the right edge, it is now clear that this represents quite a complex channel sytem where a fast narrow channel is underlying a shallower wide channel that is filled in with lower velocity sediments Elsewhere, FWI identifies small isolated gas pockets in the shallow section and compensates for distortions beneath them.

Conclusions

Full Waveform Inversion (FWI) has been used to successfully resolve imaging distortions due to strong velocity heterogeneity in the shallow section associated with shallow channels. KxKy Acquisition footprint application on δv was used to address acquisition foot print in the velocity model. IGFWI preserved localised details in the high-resolution velocity model where smoothing is constrained along geological layers.

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