A Robust FWI Method for Model Updating in High Contrast Bodies

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Summary

We present a robust method for Full Waveform Inversion (FWI), enabling the recovery of long-wavelength features of a velocity model. By using both transmitted and reflected waves the dynamically weighted FWI gradient enables high-resolution model building deeper than those achieved by diving waves alone. This reduces the dependency on long offset data acquisition.

The FWI approach uses a sophisticated regularization scheme to stabilize the inversion space. This methodology, which forms an extra constraint on the objective function, overcomes some of the limitations of the inversion in the presence of high contrast bodies. The implementation uses the split Bregman method, making it efficient and accurate.

We demonstrate the benefits of using the new gradient and regularization scheme by presenting the results on an intra-volcanic reservoir velocity model build from the Faroes-Shetland Basin.

Introduction

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Theory

FWI is a methodology that seeks to find a high-resolution, high-fidelity model of the subsurface that is capable of matching individual synthetic seismic waveforms with an original raw field dataset. This is achieved iteratively by determining and minimizing a residual; the difference between modelled and recorded data. The model update is computed as a scaled representation of its gradient. This is conceptually presented in Figure 1.

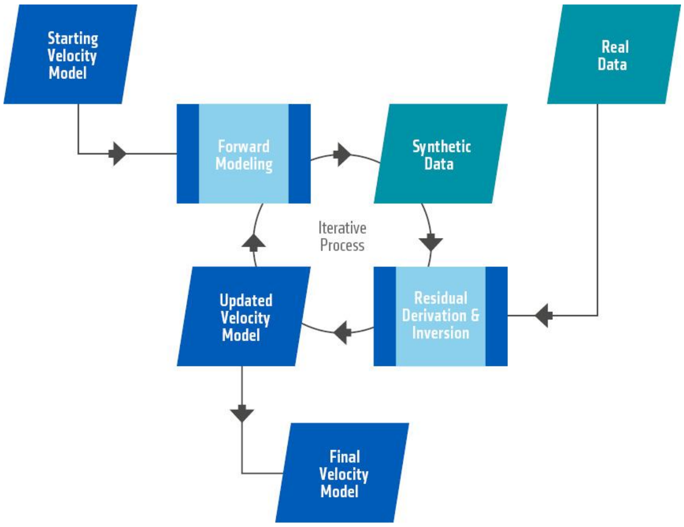

***Figure 1**. Conceptualized overview of the Full Waveform Inversion scheme.*

In conventional 'transmission FWI', diving waves only allow an update of features to the deepest turning point for the maximum acquisition offset. FWI requires reflected energy if a deeper update to the model is required for the same maximum offset. Using a conventional gradient computation, reflections only allow the reconstruction of the high wavenumber features of the model.

Zhou et al. (2015) proposed a method producing long wavelength velocity updates at greater depths by decomposing the gradient into separate wavenumber components. Our approach is a further development of this concept, and was first introduced by Ramos-Martinez et al. (2016). This method computes a gradient where the high wavenumber migration isochrones, corresponding to reflections, are removed preserving the low wavenumber energy from the two-way wavefield extrapolation back-scatter. Using impedance-velocity parameterization, we apply the inverse of the dynamic weights of Whitmore and Crawley (2012) to remove the high wavenumbers in the velocity sensitivity kernel. This eliminates the migration isochrones that dominate the gradient in heterogeneous media.

Furthermore, it enables an update by low wavenumber components to the velocity model beyond the penetration depth of diving waves. The velocity kernels are presented in Figure 2.

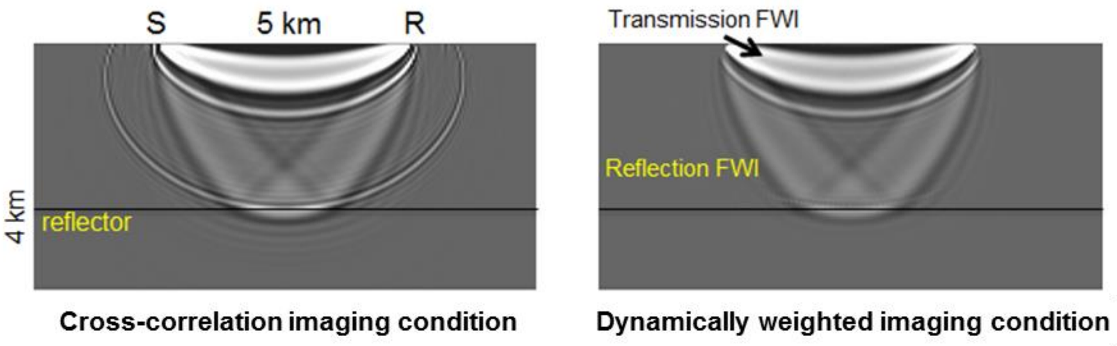

Figure 2*. Velocity kernels of a source-receiver pair for both transmission FWI and reflection FWI that use the conventional cross-correlation imaging condition (left) and the new dynamically weighted imaging condition (right).*

The band-limited nature of the seismic data and the limitations of the acquisition geometries mean that FWI is an ill-posed problem. A regularization process is required to build a geologically plausible model (Qiu et al. 2016). We use a variable weighted L^1 norm of the total variation of the model defined by Qiu et al. (2016) as:

$$\min_m \|F(m) - u\|_2^2 + \lambda\|\nabla_m\|_1 \qquad (1)$$

Where F is the modelling operator, m is the velocity model, u is the recorded data. The first term forms the traditional representation of the FWI misfit function. The additional regularization is formed by λ, the regularization parameter. The second term uses an L^1 norm to pursue a sparse representation of the high contrast boundaries of the model. Our L^1 norm implementation solves the slow convergence problem by using split Bregman iterations. The main advantages of this are the preservation of sharp edges with effective noise removal during inversion.

Application examples

The application was made to data acquired from the FSB11-12 dual sensor streamer survey in the Faroes-Shetland Basin, the extent of which is shown in Figure 3. The survey was acquired in 2011 and 2012, with the majority of the original seismic processing occurring during the second season of acquisition.

The dataset contains a number of challenges for building an accurate high-resolution velocity model. Shallow thin wedges of fast sediment and associated inter-bed multiples; sand injectites; gas chimneys; shallow channels and a deeper reservoir encased in high contrast flood plain basalts all make traditional tomographic model building difficult.

The main reservoirs in the area are both post and intra-volcanic sediments of Eocene age. The intra-volcanic reservoirs are variable in distribution and are considered to be progressing from a shallow marine to fluvio-deltaic environment. This has resulted in a variation in sand presence and thickness of units across the area. Intermittent periods of volcanic activity produced varying quantities of basaltic lava and volcaniclastic material, which are inter-leaved with the siliciclastic deposits.

There are structural imaging variations in the datasets in this area, probably due to differences in the velocity fields caused by a complex overburden and the thick volcanic section. This has led to increased uncertainty in the depth conversion over this region. The emphasis of the velocity model building stage of the re-processing was to accurately account for the complex overburden and attempt an intra-volcanic update to reduce depth uncertainty and generate an enhanced image.

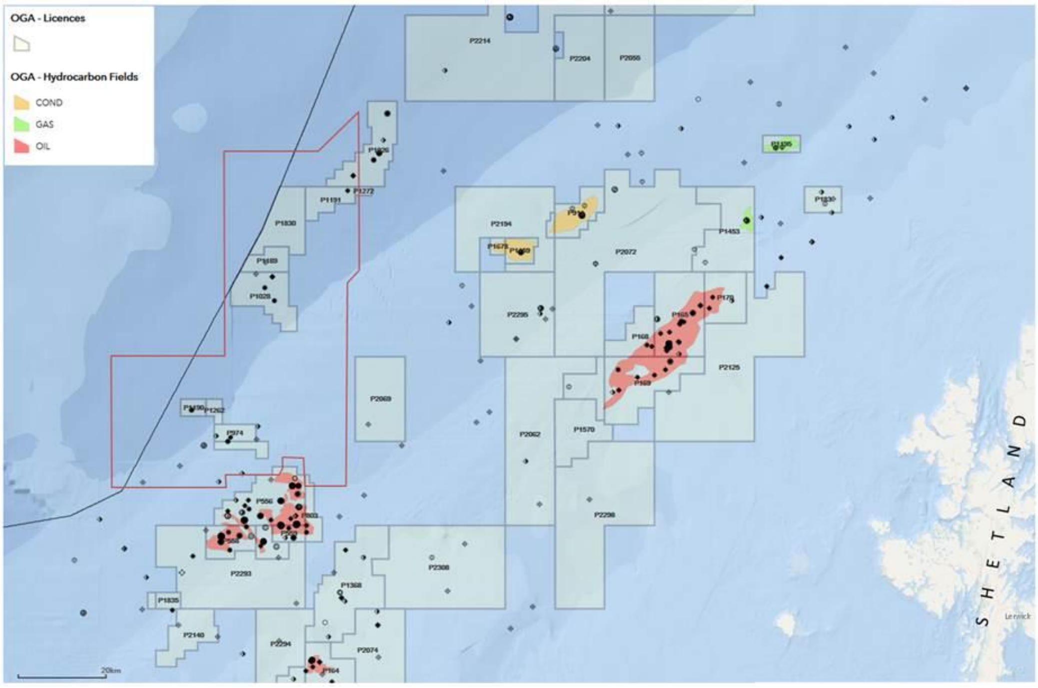

Figure 3. *Map showing location of the combined FSB11-12 survey in the Faroes-Shetland Basin.*

Despite FWI accurately accommodating the shallow challenging aspects of this data, we focus on the results obtained for the intra-volcanic reservoir section. The top and base basalt layers encasing the reservoir occur at approximately 2500m to 3000m respectively. Several high velocity near surface layers limit diving wave penetration, limiting the ability of classical FWI schemes to produce meaningful model updates. Furthermore, the high contrast basalt layer enclosing the reservoir inhibits traditional reflection tomography through a lack of data to constrain the inversion.

A reservoir embedded in a high contrast medium provides an opportunity to showcase the combination of the reflection velocity kernel and total variation regularization FWI. Several wells penetrate the volcanic section to the south-west. The well log profiles were used to insert a single velocity value for the volcanics in the model. The pre-stack data migrated with the starting velocity model (Figure 4a) shows under-corrected gathers in the reservoir section.

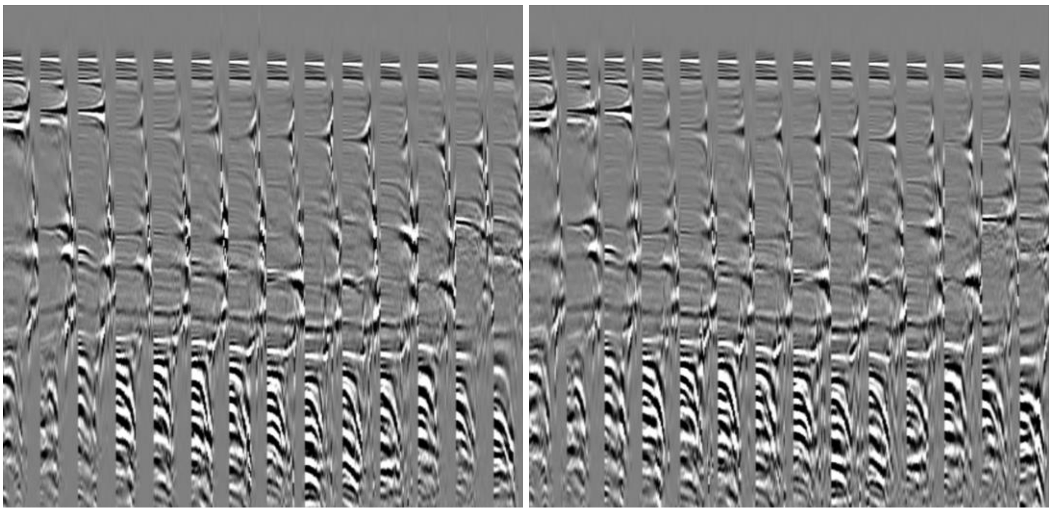
Figure 4a/b. *CDP gathers corrected with the starting and FWI velocity model. The gathers on the right side show a clear improvement in the volcanics, but also additionally in the vicinity of a gas chimney.*

Figure 5a shows the difference of the model update from FWI, whilst Figure 5b highlights the spatial variation in the update within the volcanic section and shows a specific slowdown in the reservoir interval. The gathers (Figure 4b) migrated with the FWI model show a significant improvement in gather flatness.

The combination of a reflection velocity kernel and total variation regularization on the updated model have facilitated an update in the intra-volcanic reservoir; a high contrast body inhibiting model building using traditional tomographic inversion.

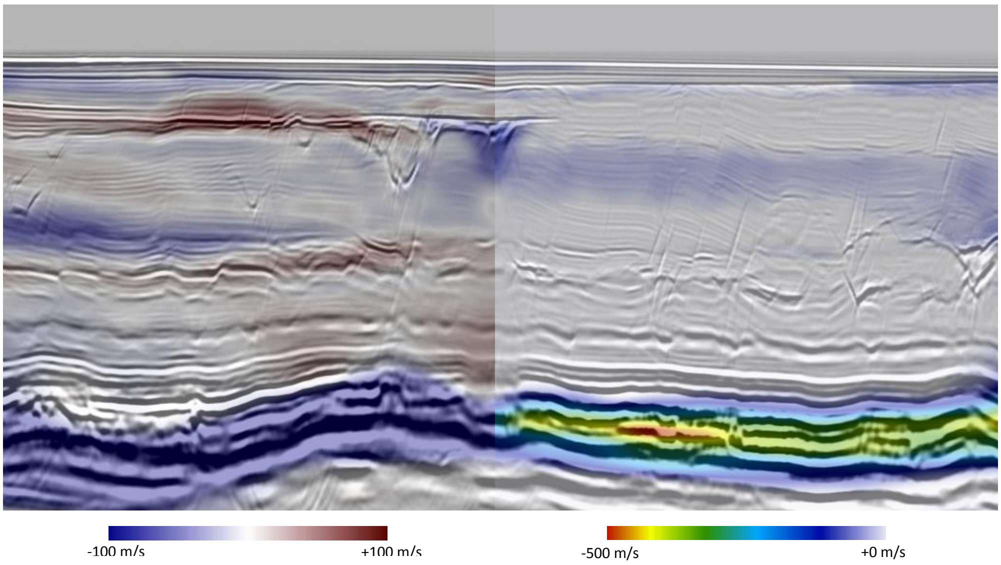

Figure 5a/b. *Velocity difference after FWI. On the left side the difference highlights the overall change in the velocity. The right side shows the difference highlighting the overall change in the volcanic layer. The largest update (blue) coincides with the known reservoir location.*

Conclusions

We have presented an example of a solution to recover long-wavelength features with FWI. The approach uses both reflected and transmitted wave modes to create high-resolution velocity models. The FWI gradient enables a reliable deep update where diving waves do not penetrate. Additionally, it uses a regularization scheme that overcomes some of the limitations of the inversion in the presence of high contrast geobodies and cycle skipping.

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