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## High-Resolution Multistage FWI and Image-Guided Tomography to Resolve Ultraslow Gas Anomalies

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### Summary

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A combined workflow utilizing high-resolution FWI and tomography is described to resolve velocity model anomalies in an Ireland Atlantic dataset. Shallow anomalies, expected to be related to gas features, distort imaging in their vicinity and in deeper sediments. This can be observed as significant sags in underlying image features and the loss of high frequencies immediately below the anomalies. These are resolved using a combination of dynamic warping and image-guided FWI to insert strong velocity contrasts within the anomalies and high-resolution tomography to fine tune residual moveout errors without damaging the FWI-derived features. Results show significant improvements in imaging of the anomalous regions, as well as underlying features of interest for exploration.

## Introduction

Geologically reasonable, data-driven velocity model building is one of the most critical processes for a seismic imaging project. Often this depends on ensuring that the model is tied structurally to the underlying geology, with model features following the large-scale imaging trends. This assumption breaks down in situations where the velocity is strongly heterogeneous within particular layers or structures, which is especially noticeable when large gas pockets disrupt the imaging with anomalously low velocities and high signal attenuation. When these features are prominent in shallow imaging, the disruption of the signal due to an inaccurate velocity model may propagate down through a significant portion of the imaged depth, despite the true anomalies being located in the shallow sediments.

We present a successful workflow for an imaging project which shows strong velocity and attenuation anomalies in otherwise orderly shallow sediment. The signal in these regions is distorted heavily, leaving little useful kinematic information for reflection tomography. In this case, refraction and reflection-based full-waveform inversion (FWI) (Yoon et al., 2014) model updates provide details of the high-resolution velocity contrasts within this region, and alternating iterations of image-guided tomography (Hilburn et al., 2014a) are then able to resolve the larger scale velocity updates needed to correct for bulk traveltimes errors. This approach leads to a velocity model which is geologically constrained in most areas, with very high-contrast features corresponding well with the imaged anomalous regions. Observed structure below the features is greatly improved, with obvious uplift more than two kilometres deeper than the velocity anomalies.

This hybrid high-resolution FWI and tomography model building approach is detailed, and the associated case study is then discussed to demonstrate the effectiveness of this job flow.

## Method and Theory

The FWI process produces high-resolution model updates based on comparisons of observed and modelled common shot gathers. A multistage FWI job flow was created to help avoid some of the inherent difficulties or inaccuracies of this method (Mao et al., 2016). When focusing on refracted diving wave data in the early steps of model building, the current model may be significantly different from the true model, leading to the likelihood of cycle-skipping errors. This can be mitigated by conditioning data with a dynamic-warping algorithm for diving wave FWI passes, to better match corresponding events while generating large-scale model updates (Ma and Hale, 2013). As model building proceeds, higher-resolution updates are encouraged by the gradual incorporation of additional reflected data, with updates conditioned by an image-guided smoothing scheme for phase-only reflection FWI.

In practice, this multistage FWI process yields high-resolution model features with realistic contrasts across imaged structural interfaces. However, common-image gathers (CIGs) may still show significant residual moveout (RMO), suggesting that the long-wavelength features of the velocity model still need consideration. This leads to the need for additional iterations of model building which are performed with an advanced tomographic job flow.

Tomography utilizes differential RMO across offsets in CIGs to suggest model updates to best focus imaged events. The tomographic suite for this project combines offset-dependent nonparameterized moveout picking with image-guided inversion to encourage data-driven high-resolution updates (Hilburn et al., 2014b). Image-guided tomography enforces structural conformance in model updates, automatically respecting imaged layers and faults. This is an ideal counterpart to the above FWI workflow because it can provide background, low frequency updates at early iterations, but also helps generate the necessary high-resolution velocity contrasts required to isolate strongly anomalous regions.

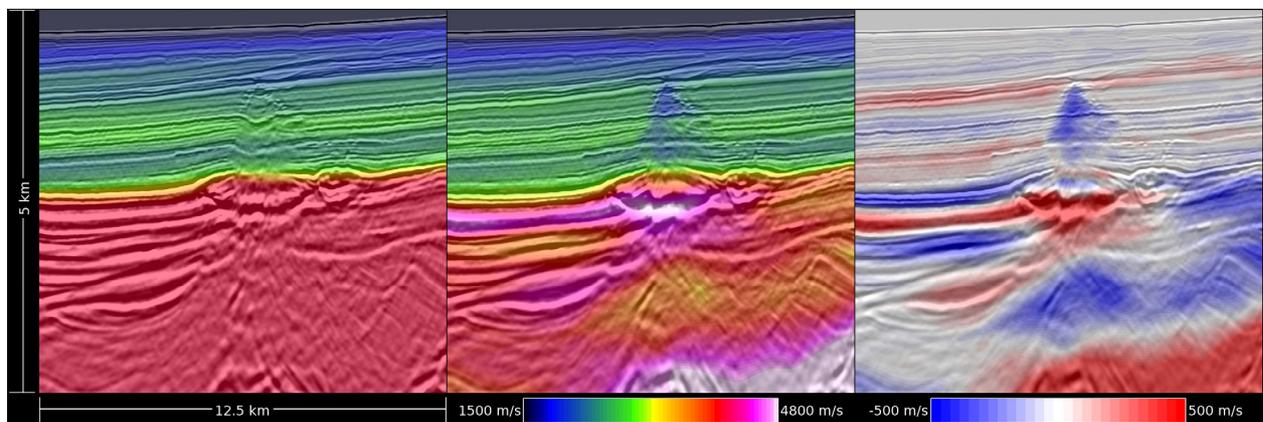
Multistage FWI and tomographic updates work best when each approach can focus on its strengths. A typical workflow proceeds as follows:

- Iteration 1: Low-resolution tomography yields major velocity features, correcting significant signal mismatch in modelled and observed common shot gathers to aid subsequent FWI.
- Iteration 2: Diving wave dynamic warping FWI generates a higher resolution update, beginning to isolate anomalous regions within layers while being cautious to avoid cycle-skipping errors.
- Iteration 3: The simplified CIG RMO is now more easily picked for image-guided tomography, which is run with a resolution similar to that of the dynamic warping FWI to obtain approximately correct depths around shallow anomalous features.
- Iteration 4: Image-guided phase-only reflection FWI adds high-resolution details through the anomalies, better separating their low velocities from the surrounding sedimentary trend.
- Iteration 5: High-resolution image-guided tomography fixes any relative traveltme errors remaining and helps define the velocity anomalies from reflection data.

This process of alternating FWI and tomographic updates while increasing the update resolution may proceed until the desired convergence is reached in the image. Due to the need for properly focused CIGs, the final iteration of model building should always be a corrective tomographic update.

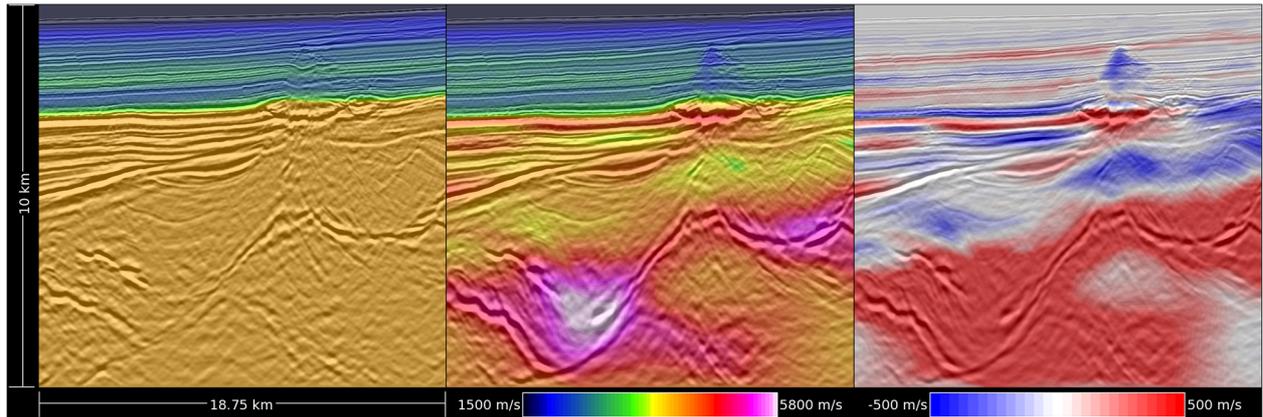
### Examples

The project chosen to demonstrate this workflow is the 2017 narrow azimuth 3D Crean survey off the western coast of Ireland, covering about 6500 km<sup>2</sup>. Initial imaging in this area reveals a neatly structured shallow sedimentary region, which persists down to a thick chalk layer at 3.5 km in depth. As can be seen in Figures 1, 2, and 3, this shallow region is contaminated by several anomalies characterized by significant sags in underlying layers due to severely compromised events in migrated gathers, suggesting very sharp velocity contrasts. The imaging impact of the largest of these anomalies can be observed more than two kilometres below its upper bounds. Image-guided tomography has been shown to be a robust and detailed model building method for these kinds of imaging issues (Hart et al., 2015), but early iteration reflection data around the anomaly is so poor that diving wave FWI is necessary to begin to construct the velocity contrasts needed. FWI has previously shown its ability to recover strong velocity contrasts in low-velocity, poorly-illuminated regions (Yoon et al., 2014).

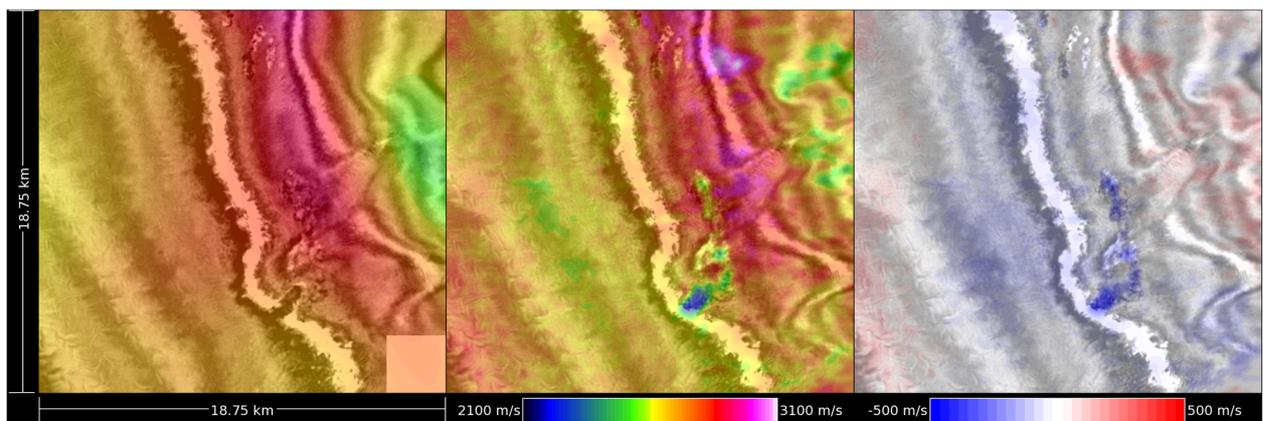


**Figure 1** Zoomed inline slices of: initial imaging and velocity (left), final imaging and velocity (center), and final imaging and total velocity update (right).

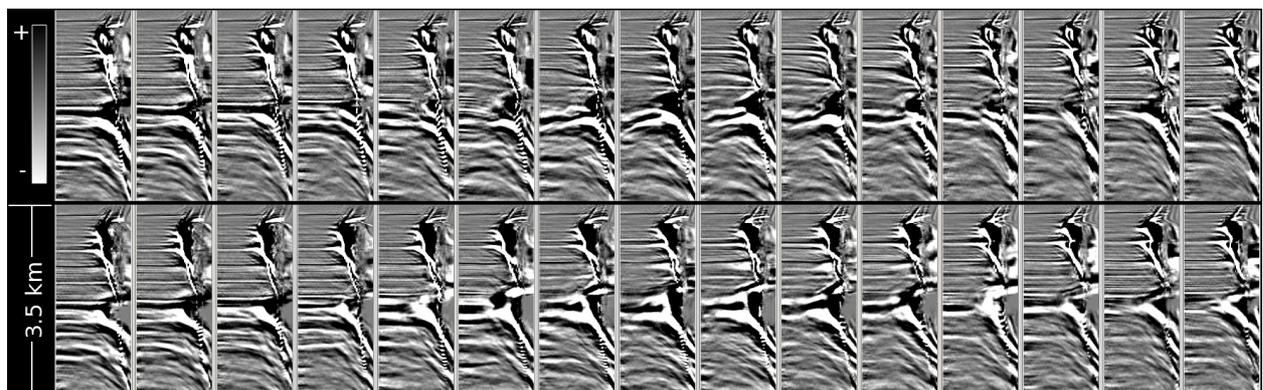
The five-iteration model building workflow presented above is followed, with alternating passes of tomography and FWI. Initial long wavelength model updates are provided by iteration 1 tomography. Iteration 2 consists of relatively low-resolution diving wave FWI updates, with an emphasis on isolating the boundaries of the anomalous velocity regions whose upper bounds are well imaged. The tomographic update in iteration 3 improves overall gather event flatness. The pass of reflection FWI for iteration 4 nearly finalizes the character of the model around the anomaly, minimizing phase differences across the high contrast model boundaries. Finally, iteration 5 is a tomographic update to correct any minute residual moveout errors around and below the anomaly, to begin the process of updating the deeper velocity model.



**Figure 2** Inline slices of: initial imaging and velocity (left), final imaging and velocity (center), and final imaging and total velocity update (right).



**Figure 3** Depth slices at 2.6 km of: initial imaging and velocity (left), final imaging and velocity (center), and final imaging and total velocity update (right).



**Figure 4** Common-image gathers around the shallow anomaly before (top) and after (bottom) the hybrid FWI-tomography approach.

Initial CIGs in Figure 4 demonstrate complex RMO which produces unreliable picks around the anomalous region due to the inaccuracy of the smooth initial velocity model. The progression from low to high frequency updates, provided by alternating tomography and FWI application, brings events into better focus, with each model update providing an improved starting point for the subsequent steps. The final gathers are well-focused across the offset range.

The overall imaging improvement, shown in Figures 1, 2, and 3 with the velocity model updates, is driven by the ultraslow velocities generated within the upper section of the anomaly, which are typically

500 m/s slower than surrounding velocity trends and tie strongly to the imaged anomaly. Despite this anomalous update being largely constrained to the region shallower than 3 km, the impact of the changes is easily seen to a depth of at least 4.5 km. Structure through and below the chalk layer is now much more geologically plausible, and event continuity is greatly improved despite the dominant low frequencies. The final pass of tomography has just begun to resolve the deeper structure, a process which is only reliable due to the detailed model building conducted in the shallow regions.

## Conclusions

The hybrid high-resolution FWI and tomographic model building workflow presented within relies on the strengths of each approach to help mitigate the weaknesses of the other. FWI generates critical velocity model contrasts by isolating the relative shot gather differences for various portions of the same events. This is crucial early in the model building process when refracted energy is more easily considered than reflections from areas of poor signal. Tomography is unable to independently find these contrasts in areas of very poor signal, particularly around strongly anomalous velocity features, but does a good job of correcting overall RMO to enhance event focusing. A sequence of alternating FWI and tomographic passes highlights these benefits while reducing the uncertainties associated with each method's shortcomings.

This job flow is applied to an offshore Ireland dataset which demonstrates strong velocity inhomogeneities in shallow sediments, disrupting the image around and beneath these anomalies. The combined high-resolution update produces useful events from poorly imaged regions by improving continuity and focusing. The strong contrasts in the velocity model at the edges of the anomalies are necessary to successfully solve the complicated moveout observed in these events. Final imaging results are geologically simplified despite the high level of detail inserted into the model.

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