Resolving Celtic Sea imaging anomalies through a multistage FWI and tomography workflow

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Summary

The Crean survey in the Celtic Sea demonstrates a variety of interesting geological and kinematic features which necessitate a novel and adaptive processing flow, particularly in regard to velocity model building. Prominent shallow anomalies related to gas pockets and channels distort the deeper sediments which are of primary interest for exploration.

Imaging challenges are addressed first through appropriate preparation of data with deblending, regularization, and multiple attenuation. A subsequent iterative model-building workflow uses interwoven passes of increasingly high resolution full-waveform inversion and image-guided tomography to generate a geologically reasonable, data-driven velocity model.

The final imaging results resolve the shallow anomalies and yield great uplift in their underlying sediments, allowing for more reliable interpretation and production planning.

Introduction and Survey Description

The 2017 3D Crean survey was acquired in the Porcupine Basin within the Celtic Sea off the western coast of Ireland (Figure 1). Approximately 5,500 km^2 of new data in the region was acquired using a triple-source acquisition configuration. The new acquisition was merged with approximately 960 km^2 of legacy data, and the entirety was reprocessed together.

Large-scale rotated fault blocks, which offset Middle Jurassic strata and are covered by the synrift Upper Jurassic sequences, typify the geology of the Porcupine Basin. Hydrocarbon plays such as the Paleocene basin-floor "Avalon" and Lower Cretaceous Drombeg prospects have been defined within the postrift succession. The Cretaceous chalk layers have been identified as potential hydrocarbon traps, particularly along the western flank of the basin. In the north, tilted fault blocks extending across the Porcupine High in the west and the Celtic Platform to the east, offer an insight into the continuation of the faulting within the Lower Cretaceous sections.

Of particular interest for this project are the multitude of shallow anomalies which manifest as disruptions in the imaging. On the northern side of the survey, a series of channels with typically high infill velocities, conflicting with the regional trend, distort imaging of deeper sediments. A similar effect causes imaging disruption on the southern edges of the region where shallow gas pockets lead to significant signal attenuation and anomalously low velocities. Both of these types of features are distinguishable on poststack sections and should be able to be isolated by appropriate model building tools which rely on structural constraints.

The Crean survey provides a variety of imaging challenges and opportunities due to the triple-source acquisition, the complexity of the velocities around the interval of interest, and the disruptive shallow velocity anomalies. To meet these challenges, the proposed workflow proceeds as follows: source deblending, regularization, multiple attenuation, then concluding with multistage full-waveform inversion (FWI) and image-guided tomography (IGT) model building.

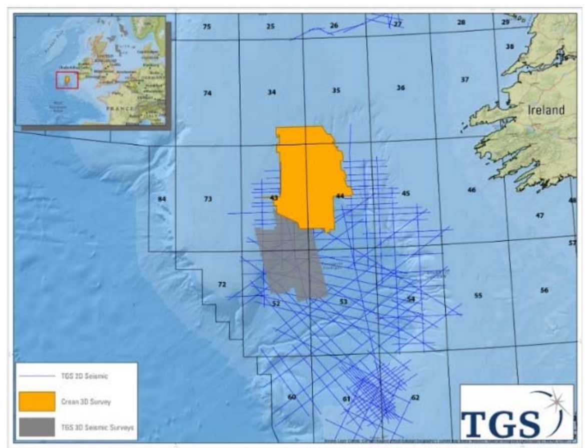

Figure 1: Crean survey area in the Celtic Sea.

Data Preparation

The high-resolution model building flow needed for this project depends on several vital time processing steps in the preparation of input data.

To encourage higher-resolution results this survey utilizes three sources rather than two, which necessitates a reduction in the shot interval. Due to the increased temporal shot density, shot records display overlaps between the shot of interest and shots occurring both before and after. The multidomain coherency-based deblending workflow presented by Baldock et al. (2018) separates these shots with minimal residual noise.

Following deblending, the data is regularized using a 4D antileakage Fourier transform approach (Whiteside et al.,

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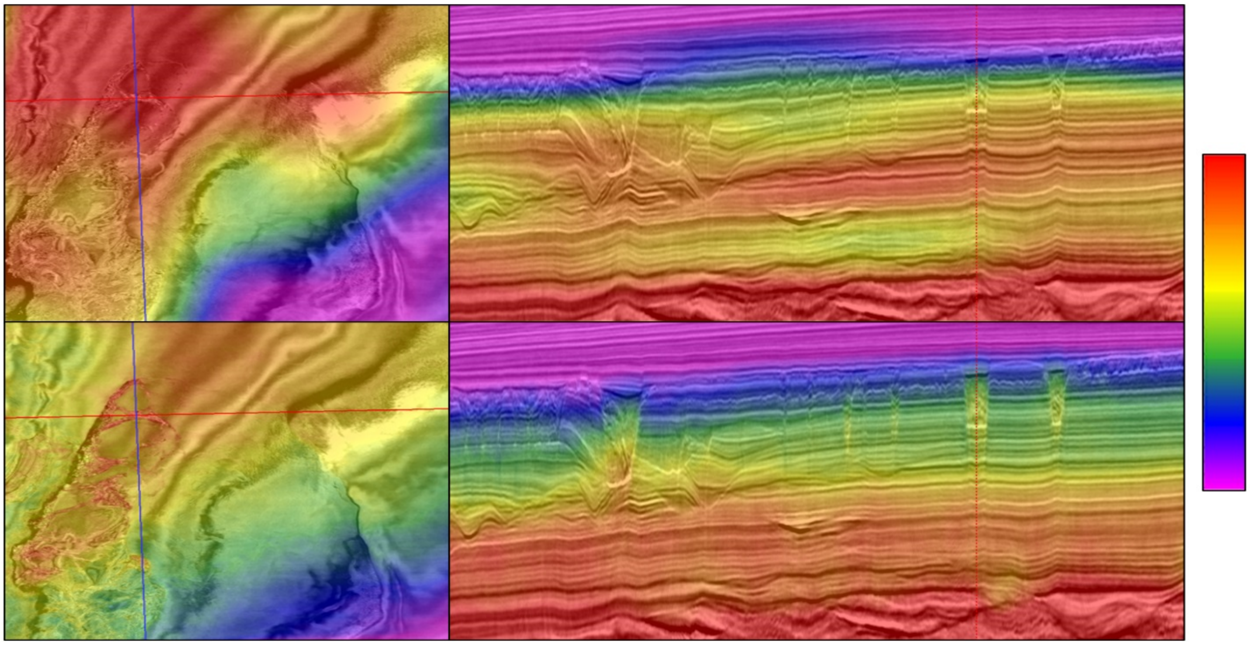

Figure 2: Shallow channels with high infill velocities are prominent in the northern extent of the survey, distorting initial imaging (top). Associated imaging anomalies are greatly reduced after appropriate high-contrast details are added to the velocity model (bottom).

2014). This regularization scheme offers good dip and diffracted energy preservation by using an iterative matching-pursuit process to incrementally isolate the dominant plane wave components of the data in order to reconstruct missing traces. The 4D approach allows for the use of information from neighboring offset or spatial traces to fill data coverage gaps, yielding a data and geologically-consistent fully populated dataset.

For this type of narrow-azimuth streamer data, multiple attenuation is best performed once the regularization process has filled gaps in the input data. Surface-related multiple elimination creates a predicted multiple model by convolving 3D shot and receiver gathers in order to remove undesirable multiples associated with additional free surface reflections at the water surface.

These processing steps lead to an input dataset for model building which is effectively free of surface-related multiples and has a consistent gather distribution, ideal for FWI and high-resolution tomography.

Model Building

FWI is often seen as the pinnacle of high-resolution model building techniques, while traveltime tomography has been the model-building workhorse for the seismic industry for many years. In actuality, these two processes must both be carefully utilized to ensure their strengths are emphasized and their weaknesses are compensated appropriately. FWI can reliably add velocity model contrast by isolating minute differences in shot gathers from refracted or reflected energy, while tomography does an excellent job of resolving bulk moveout errors and reducing travel time errors to ensure the correct depth positioning and focusing of reflectors. These facets of the two major model building methods are complementary to one another if arranged properly in the overall model building workflow.

IGT is an ideal counterpart to a multistage FWI approach, as it allows for easily controllable resolution and geological adherence of the velocity updates (Hilburn et al., 2014). The image-guided interpolation scheme of Hale (2009) conditions IGT inversion results to encourage structural conformance, with user-specified edge and layer preservation. This is ideal for this survey, as not only can the final details of the model be generated in a data-consistent manner, but the early iterations can run with relaxed parameterization to respect only regional, low-resolution structural information. At early stages in the model-building process, large-scale velocity updates are needed to correct for the bulk of the observed velocity errors, in order to provide a model and gathers appropriate for higher-resolution updates. These initial low-resolution updates should honor the largest model features, such as major velocity contrasts and changes in geological regime.

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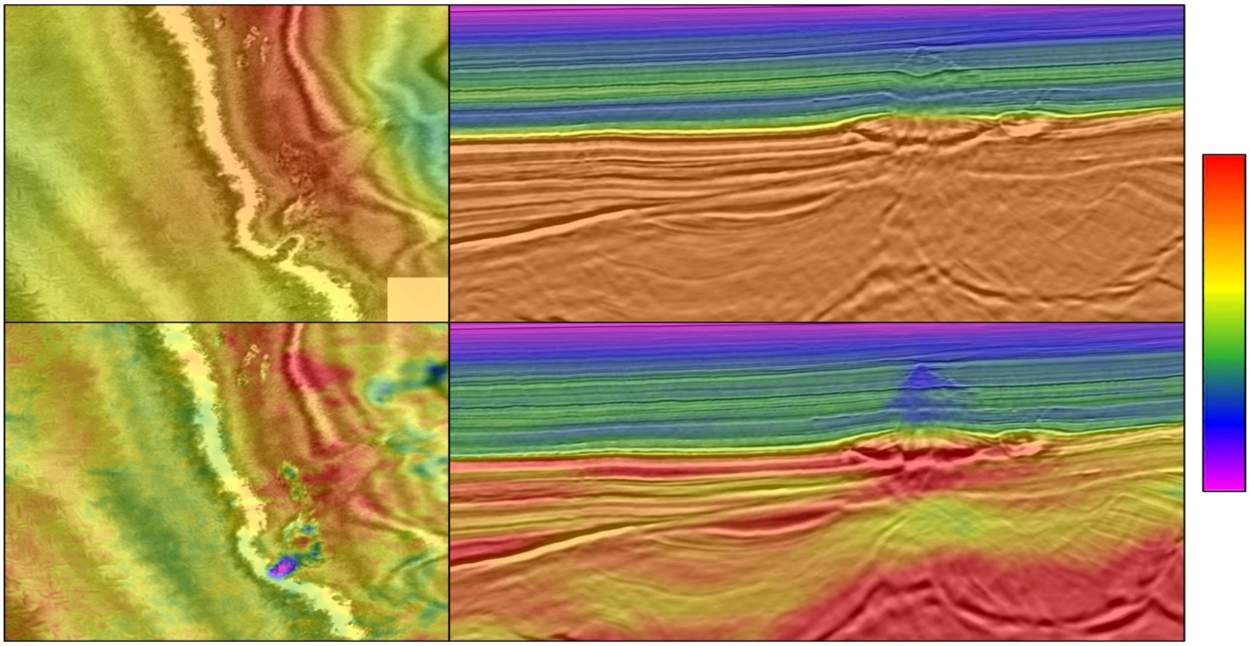

Figure 3: In the southern reaches of the survey area, shallow gas clouds cause imaging disruption on initial images (top). Significantly lower velocities than the neighboring sediments are required to correct the distortions around and below these features (bottom).

However, at later stages, it is also necessary to be able to insert high-resolution details while respecting the details of the underlying structure.

Due to the sensitivity of FWI to its initial model, multistage FWI flows are becoming more commonplace and robust. Mao et al. (2016) describe the workflow applied for this project. In the early stages of model building, when the current model is likely to be significantly different from the true model, cycle-skipping errors are likely to lead to erroneous FWI results if not appropriately considered. To mitigate this possibility, initial low-resolution diving wave FWI shot gathers are conditioned by dynamic warping (Ma and Hale, 2013) to ensure events are properly correlated between the modeled synthetic traces and the field data. As the low-frequency model components are correctly accounted for and added, the cycle-skipping issue is largely resolved, and the input data to FWI is modified to incorporate additional reflected data to generate high-contrast details in the model. At this point, an image-guided conditioning scheme, similar to that described above for image-guided tomography (IGT), is applied to ensure the model updates are correctly positioned with regard to imaged features. This conditioning is used in conjunction with a phase-only reflection FWI engine in the final stages, for generation of fine model detail.

In order to combine the multistage FWI process with IGT, care needs to be taken to apply each technology when it is most appropriate. For this survey, a five-iteration workflow is utilized to arrive at geologically and data-consistent results:

1) Long-wavelength tomography generates major velocity model features to stabilize FWI results.
2) Diving-wave dynamic-warping FWI runs with a higher resolution than initial tomography to begin resolving anomalous shallow features. Cycle-skipping errors must be carefully avoided at this point.
3) A pass of marginally higher-resolution IGT is better able to resolve travel time errors due to the FWI removal of shorter wavelength details in the residual moveout between neighboring gathers.
4) The second pass of FWI uses the high-resolution phase-only reflection scheme to better separate the shallow low-velocity anomalies from the sedimentary model trend. Deeper sediments are also updated as possible.
5) A final pass of high-resolution IGT corrects for any unresolved traveltime errors while helping define sharp contrasts in the velocity model which correspond to imaged features.

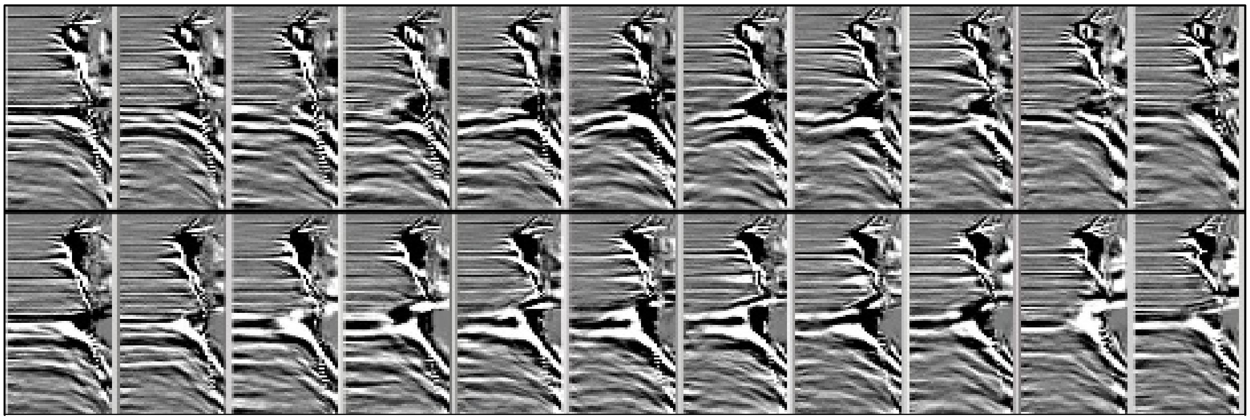

Figure 4: Representative gathers before (top) and after (bottom) velocity updates around the most prominent gas feature demonstrate the uplift obtained through high-resolution model building in these anomalies.

Results

Model building and related imaging results are shown in Figures 2, 3, and 4, detailing the application of the five-iteration model-building sequence described in the preceding section.

In the northern section of the survey, anomalously high velocities derived in channel features reduce the upward deflection of underlying structure, as seen in Figure 2. Despite the lack of imaged boundaries for many of these channels, the updates create very strong lateral contrasts that consistently improve deeper imaging and help define the subtle kinematic features of the channels themselves.

Conversely, the shallow disruptions in the southern region required anomalously low velocities to repair the sagging structure underneath, consistent with their expected relation to gas clouds in these strongly-attenuating features. Figure 3 demonstrates the uplift achieved with derivation of model updates that are strongly constrained within the imaged bounds of the anomalies.

Common image gathers for representative examples of the gas-associated anomalies are shown in Figure 4. As can be seen, the initial gathers display complex moveout with events that are frequently broken due to the high contrast updates required to correctly account for the channels and gas pockets. A simpler black-box type of model-building workflow would struggle with events of such complexity. However, final gathers have been largely corrected for the moveout discrepancies, with events that are properly focused across the offset range. Gathers around the northern channels follow this same trend.

Conclusions

The Crean survey poses many processing challenges due to its triple-source acquisition, complex geological and velocity trends, and shallow gas clouds and channels which manifest as strong imaging and kinematic anomalies.

A time processing sequence highlighted by source deblending, regularization, and multiple attenuation yields clean, spatially consistent data for depth processing. The velocity model-building workflow then utilizes increasingly high-resolution passes of image-guided FWI and tomography to isolate strong contrasts across layers of rapidly changing properties, as well as at the boundaries of the shallow-velocity anomalies.

The final imaging results resolve the deeper sediments of exploration interest following correction for the model heterogeneities at gas pockets and channels which initially contaminated the underlying image. Complex, broken events on common image gathers are now better focused, and stacked event continuity is greatly improved.

The novel challenges associated with this survey are properly considered and rectified by the advanced processing methods presented.

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