Reflections on Full Waveform Inversion

FORCE Seminar organised by the Geophysical Network Group

25-Oct-21

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12:00	**Intro**
10 min	*Moderator*
12:10	**Resolving geological challenges in the North and Barents Sea with Time-Lag FWI and FWI Imaging**
30 min	*Krzysztof Ubik, CGG*
	(20-25 minutes + 5-10 minutes Q&A)
12:40	**Estimating the Earth Model with Simultaneous Inversion of Velocity and Reflectivity**
30 min	*N.Chemingui, Ø.Korsmo, PGS*
13:10	**Journey of the decade from streamer to sparse node regional studies**
30 min	*Denes Vigh, Schlumberger*
13:40	**10 min break**
13:50	**High-frequency FWI for interpretation**
30 min	*Tom Rayment, DUG*
14:20	**Extracting more value from the Utsira OBN survey by leveraging long offsets and reflection FWI**
30 min	*Simon Baldock, TGS*
14:50	**10 min break**
15:00	**FWI in the Real World: Past, Present and Future**
30 min	*Carlos Calderon, Ion*
15:30	**Discussion and Questions**
20 min	*Moderator, 20 min*
15:50	**Closing remarks**
16:00	**End**

Resolving geological challenges in the North and Barents Sea with Time-Lag FWI and FWI Imaging

Krzysztof Ubik

Abstract

The traditional workflow for velocity model building in the North Sea relied heavily on ray-based tomography, which was able to define good regional parameters for the velocity, anisotropy and viscosity. Over the last decade more advanced velocity model building workflows based on full-waveform inversion (FWI) have been successful in this area. These latest techniques include multi-parameter FWI, inverting simultaneously for velocity, anisotropy and viscosity, as well as the recently developed Time-Lag FWI (TLFWI; Zhang et al., 2018) and FWI Imaging (Zhang et al., 2020).

TLFWI is designed to better utilise the entire recorded wavefield including diving waves, reflections and multiples. Using the entire wavefield further improves the models in terms of details, as well as benefiting from deeper updates, beyond the diving wave penetration, with additional illumination from the multiples. Using the full wavefield in FWI brings increased risk in modelled and recorded data amplitude mismatch, and cycle skipping. TLFWI can mitigate these risks through a travel time-based cost function, hence driven mostly by kinematics.

Pushing the maximum frequency in the FWI beyond the typical values used in a velocity model building project (>15 Hz) generates high-resolution details in the velocity model. These details may not have a great impact on conventional migration images however it can give additional insights through the estimation of reflectivity from the FWI velocity model itself. These FWI Images are obtained by generating various spatial derivatives of the high-resolution FWI velocity model, and benefit from the additional illumination of the data (diving waves, reflections and multiples) that were used to derive the velocity model and the effects of the least-squares data fitting process.

Figure 1 shows an example of shallow velocities from a Central North Sea OBN project where 40 Hz TLFWI improves the resolution and captures the shallow low-velocity anomalies (panel c and d). These are potentially related to gas trapped within the complex faulting system above the salt diapir (panel d). The updated model also captures diagonal low-velocity features of the regional trend of glacier channels (panel c).

Figure 2 compares the conventional OBN RTM image (panels a and b) with the FWI Image (c and d). In addition to improved imaging, we observe the impact of the extra illumination from the multiples, which help in healing the acquisition footprint, filling in acquisition holes and extending the image to a broader area. Since FWI is an iterative least-squares fitting process of the full wavefield, we also benefit from improved signal to noise and balanced illumination like a least-squares migration.

In the full version of the presentation, I will show FWI Imaging of high-resolution TLFWI velocity models from several projects from the North Sea (Central North Sea, North Viking Graben) and the Barents Sea. Results will be presented from 3 different acquisitions (OBN, standard tower streamer and source-over-streamer) and will demonstrate the benefits of FWI-Imaging in challenging geology, including salt diapirs, high-amplitude absorbing bodies, and shallow hazards.

References

Zhang, Z., Mei, J., Lin, F., Huang, R., and Wang, P. [2018] Correcting for salt misinterpretation with full-waveform inversion. SEG Technical Program Expanded Abstracts 2018 (pp. 1143-1147).

Zhang, Z., Wu, Z., Wei, Z., Mei, J., Huang, R., and Wang, P. [2020] FWI Imaging: Full-wavefield imaging through full-waveform inversion. SEG Technical Program Expanded Abstracts 2020 (pp. 656-660).

Acknowledgements

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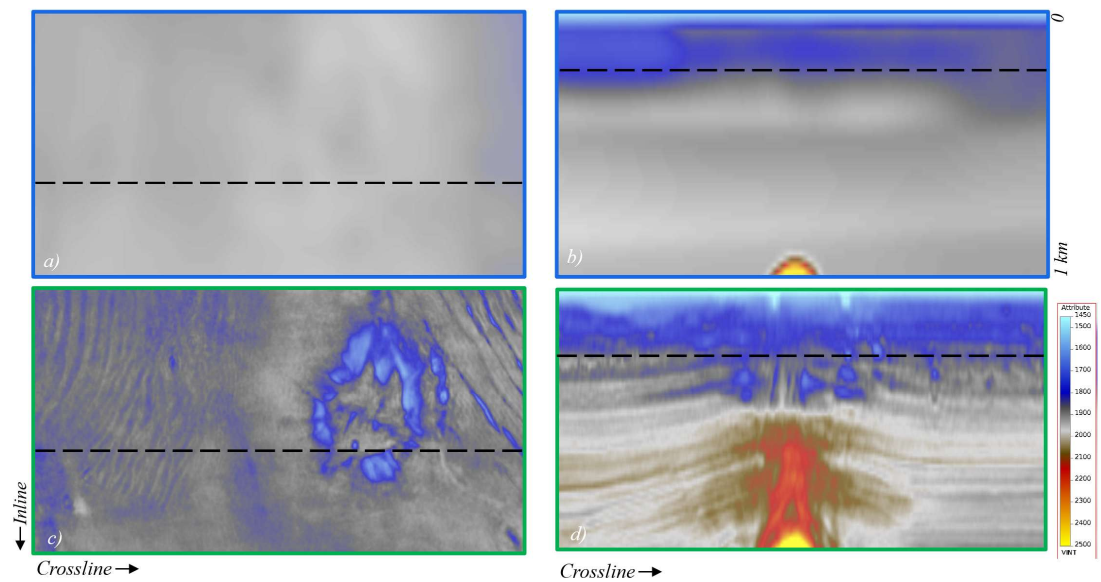

Figure 1: Shallow water TLFWI update example: a) and b) depth slice at 360 m and cross-section, respectively, of 2020 towed-streamer velocity model; c) and d) depth slice at 360 m and cross-section, respectively, of 40 Hz TLFWI model.

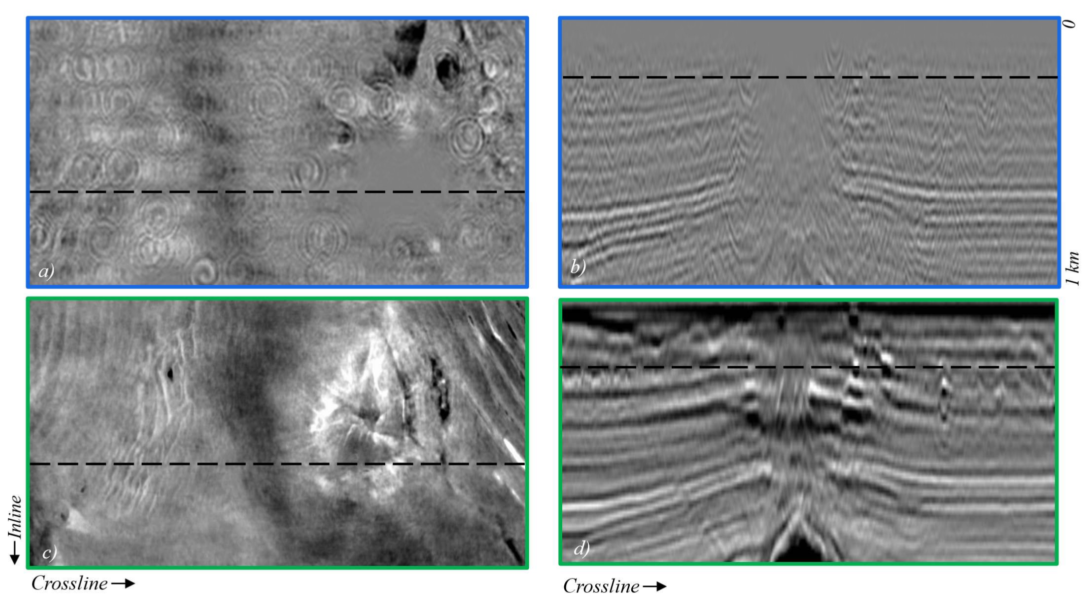

Figure 2: Shallow water FWI Imaging example: a) and b) depth slice at 360m and cross-section, respectively, of conventional RTM Image; c) and d) depth slice at 360m and cross-section, respectively, of FWI Image derived from 40 Hz TLFWI velocity model.

Estimating the Earth Model with Simultaneous Inversion of Velocity and Reflectivity

Yang Yang, Jaime Ramos-Martinez, Dan Whitmore, Guanghui Huang, Nizar Chemingui and Øystein Korsmo (PGS)*

Summary

The main goal of seismic inversion is detailed estimation of subsurface properties, primarily velocity and reflectivity. The classical inversion workflow consists of two sequential steps based on scale separation of the earth model- building the long wavelength velocity field, and imaging the reflectors associated with geological boundaries. Over the past decade, Full Waveform Inversion (FWI) has emerged as the most robust tool for velocity estimation. Similarly, Least-Squares Reverse Time Migration (LSRTM) has become the method of choice for seismic reflectivity inversion. In principle, as a non-linear inversion, FWI is capable to recover a complete earth model where both reflector locations and interval velocities are estimated simultaneously. However, excluding the high wavenumbers when updating the reference model is a critical requirement on a reflection-inclusive FWI. Failure to build the correct background model leads to inaccurate earth models that simply resemble seismic images.

We introduce a new inversion solution to simultaneously invert for both velocity and earth reflectivity. The core of the inversion workflow is a novel wave-equation modeling relation that is parameterized in terms of velocity and vector reflectivity and capable of modeling the full seismic wavefield. A key aspect of the inversion is the separation of the low- and high-wavenumber components of the gradient, enabling the sensitivity kernels to update the velocity and the vector reflectivity, respectively. The estimation problem is essentially a multi-parameter inversion where the crosstalk trade-offs between the two parameters are minimized through scale separation. Our solution is equivalent to performing Full Waveform Inversion (FWI) and Least-Squares Reverse Time Migration (LSRTM) in a single framework using the full vector-acoustic wavefield. The new approach reduces the turnaround time of seismic inversion by combining velocity model building (FWI) and imaging (LSRTM) into a single process, with minimal data pre-processing.

With field examples, we demonstrate how our unique solution for vector-reflectivity modeling combined with our special FWI kernels enable us to address the long-standing challenge of building full-bandwidth earth models.

Journey of the decade from streamer to sparse node regional studies

Denes Vigh, Schlumberger

Full-waveform inversion (FWI) is a high-resolution model building technique that uses the entire recorded seismic data content to build the earth model. Conventional FWI usually utilizes diving and refracted waves to update the low-wavenumber components of the velocity model. However, updates are often depth-limited due to the limited offset range of the acquisition design. To extend conventional FWI beyond the limits imposed by using only transmitted energy, we must utilize the full acquired wavefield. Analyzing FWI kernels for a given geology and acquisition geometry can provide information on how to optimize the acquisition so that FWI is able to update the velocity model for targets as deep as basement level.

Recent long-offset ocean-bottom node acquisition helped FWI succeed, but we would also like to be able to utilize the shorter-offset data from wide-azimuth data acquisitions to improve imaging of these data sets by developing the velocity field with FWI. FWI models are heading towards higher and higher wavenumbers, which allows us to extract pseudo-reflectivity directly from the developed velocity model built with the acoustic full wavefield. This is an extremely early start to obtaining a depth image that one would usually produce in much later processing stages.

High-frequency FWI for interpretation

Tom Rayment, DUG

Full waveform inversion is now a routine feature of modern velocity model building workflows. In addition, the use of FWI as an imaging solution has attracted much attention in recent years and a range of options are now available for this purpose. In this presentation, we will discuss the advantages and disadvantages of these solutions, present a novel approach that simultaneously inverts for velocity and reflectivity and discuss the future of this exciting new technology.

Extracting more value from the Utsira OBN survey by leveraging long offsets and reflection FWI

Simon Baldock, Adriana Citlali Ramírez, Matt Hart, Jan Gromotka and Eddie Cho

The North Sea has been extensively explored for about 60 years. Exploration in this mature area continues to this date and is mainly focus on ILX (infrastructure-led exploration) with the goal of capitalizing on existing infrastructure. ILX provides the possibility of low-cost production and delaying infrastructure decommissioning. With these goals in mind, in the area between the Utsira High and the South Viking Graben, new seismic data was acquired by TGS and AGS in 2018-2019: the Utsira ocean-bottom node (OBN) survey. It was the first large-scale (more than 2000 sqkm.), densely sampled OBN survey ever acquired for exploration purposes. The regional volume was processed with a modern technology that included up-down deconvolution demultiple and 5Hz full waveform inversion (FWI) using a standard offset range (6.7 x 3km split spread).

To extract more value of Utsira OBN, new model building work, Re20, has been done by TGS focusing on 698 sqkm in the northern area. Re20 has used dynamic-matching full waveform inversion (DM-FWI) with ultralong-offset (17km. split-spread at an average bathymetry of 110 m.) diving wave energy and a second pass of reflection DM-FWI. The data-driven model building work was enhanced by tomography and anisotropy updates, using miss-ties to wells, surfaces, and interpreter's geological input. In this presentation, we will present the results of this work that had led to an interpretable model with high-level of detail (Figure 1).

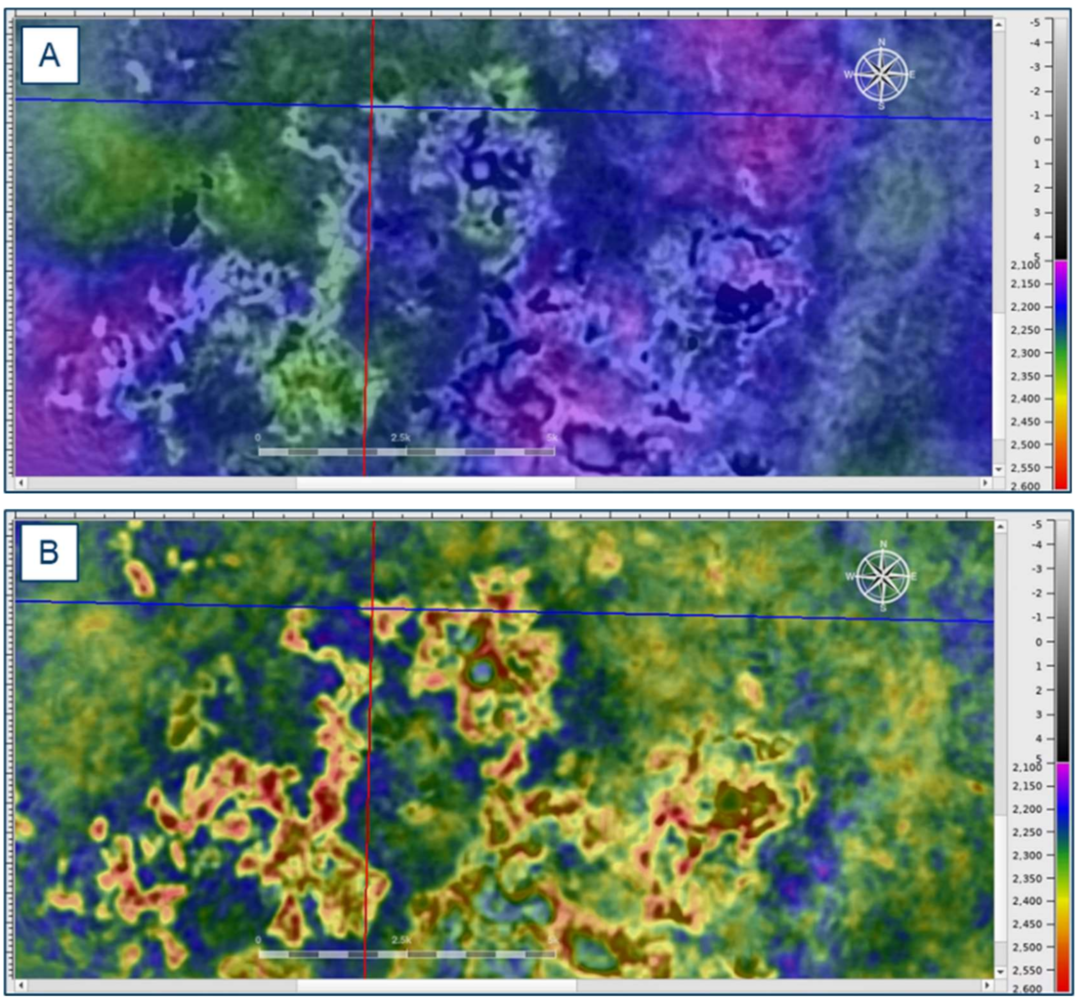

Figure 1: A) Depth slice at 1910 m showing sand injectite features, data is the final legacy with final velocity model overlaid; B) As for A) but showing the second pass DM-FWI model overlain on an intermediate QC migration.

FWI in the real world: Past, present & future.

Ian F. Jones and John Brittan, ION.

Over the past decade, full waveform inversion (FWI) has emerged as the leading technology for resolving small-scale parameter anomalies in Earth models, and as a direct consequence, has facilitated improving the reliability of imaging and reduced associated exploration risk. Most recently, it has also emerged as a potential technology to provide direct, high-resolution images of the subsurface. In this talk, we'll illustrate the evolution of FWI from its original inception as a means of subsurface parameter inversion to directly deliver elastic parameters, to the current state of the art which only offers the significantly lesser objective of merely obtaining a better model for migration and, on occasion, a direct image itself. We'll then look-back to the original vision of Tarantola and assess the time scale required for the industry to achieve elastic parameter inversion without the intermediate step of migration. We will review the fact that FWI is not a 'single thing' but rather a blend of several algorithmic variants used in conjunction with diverse methodologies and show how moving from conventional open-loop approaches to more integrated closed-loop methods will enable us to better image and understand our reservoirs and thus lead to an associated reduction in exploration and development risk. In addition to all this, we now have the 'wild card' of 'machine learning', and if training these systems can be made generic, then perhaps they will offer a complimentary or even alternative route to address the huge non-unique inverse problem that we aim to solve in our inversions.

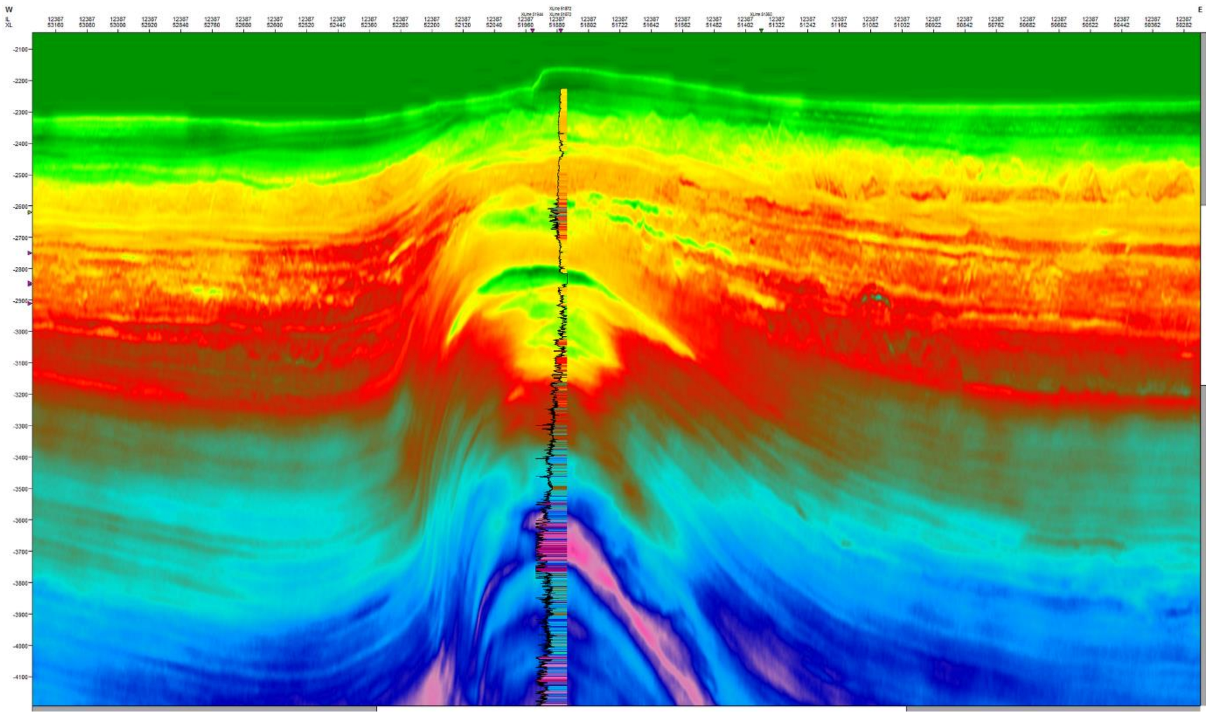

Figure 1. The FWI derived Earth model overlain with a velocity log from a well on the seismic line. This model was derived using a combination of least-squares and extended domain FWI and shows the potential of the method to derive highly resolved subsurface parameter fields.