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Full Waveform Inversion Around the World
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SUMMARY
An accurate earth model is key to any successful depth imaging project. FWI is an advanced velocity model building process that uses the full two-way wave equation and overcomes the limitations of existing methods that use a ray-tracing approach to distribute velocity errors within the model.

Full-waveform inversion (FWI) has long been considered by the industry to be the next logical step in deriving detailed velocity models. The availability of low-frequency, long-offset data sets and increased compute power has now allowed FWI to become the preferred method for building detailed velocity models.

In this presentation, we will show examples of imaging improvements obtained with FWI velocity models from different geological environments around the world.
Introduction

The industry has moved to using two-way wave-equation migrations, commonly known as reverse time migration (RTM), especially in areas of complex geology, and it has become increasingly obvious that an accurate velocity model is required to obtain full benefits from these migration algorithms.

Full-waveform inversion (FWI) has long been considered by the industry to be the next logical step in deriving detailed velocity models. The availability of low-frequency, long-offset data sets and increased compute power has now allowed FWI to become the preferred method for building detailed velocity models.

An accurate earth model is key to any successful depth imaging project. FWI is an advanced velocity model building process that uses the full two-way wave equation and overcomes the limitations of existing methods that use a ray-tracing approach to distribute velocity errors within the model.

In this presentation, we will show examples of imaging improvements obtained with FWI velocity models from different geological environments around the world.

Method and theory

Full-waveform inversion, based on the finite-difference approach, was originally introduced in the time–space domain (Tarantola 1984; Pica et al. 1990; Sun and McMechan 1992). Inversion can also be implemented in the frequency domain (Pratt et al. 1998; Pratt and Shipp 1999; Ben-Hadjali et al. 2008).

Recently, 3D FWI has been applied on real data sets in marine (Plessix 2009; Sirgue et al. 2009; Vigh et al. 2009, 2010; Kapoor et al. 2011, 2012) and land (Plessix et al. 2010) environments. These works demonstrate that FWI can be used for velocity updates if the acquired data have enough low frequencies and long offsets. Particularly, the shallow part of the model could be significantly enhanced by use of FWI and can result in a more improved depth image over all.

One of the difficulties with FWI is convergence to the local minima. To avoid converging to a local minima, one requires a starting velocity model that bridges the gap between the low frequencies and long offsets acquired in the data. Generally, the starting model is a smoothed version of a tomography-derived legacy model calibrated with well logs, VSP, gravity, magnetotelluric (MT) and other measurements that may be available. Note that tomography-derived models are not immune from convergence to local minima, hence, the need to smooth such models.

**Figure 1** Full-waveform inversion workflow.
We have implemented a 3D time-domain tilted transversely isotropic (TTI) anisotropic acoustic version of full-waveform inversion using the two-way wave equation with an elastic correction factor to model seismic data using an initial best guess of the earth model. This can be a depth model from a previous processing effort and/or calibrated to well logs and any other seismic or non-seismic measurements.

The modeled seismic data are compared to the real prestack seismic measurement, and errors are backwards propagated into the velocity model, iterating to a final detailed model (Figure 1).

**Examples**

We will present results of FWI projects around the world from the Gulf of Mexico to offshore Australia, the Middle East, and the North Sea (Figure 2).

*Figure 2 Map showing full-waveform inversion projects from different geologic basins around the world.*

Following are some of the examples of detailed velocity models built with FWI from different geologic challenges around the world as shown in Figure 2.

**Delineation of North Sea channel systems on OBC data:**

*Figure 3 Comparison of velocity models from tomography (left) and FWI (right) from a North Sea project. Notice the velocity detail added by FWI.*

(From Houbiers et al. 2012)

This project result shows the shallow velocity feature caused by a channel has been accurately determined with FWI, whilst with the previous model, it had been manually inserted and the central feature has had its rapidly varying velocity estimated.
We will show in our presentation the comparisons of the improvements in image quality obtained by using the FWI velocity model.

The input in this project was an OBC data set with ~4-Hz low frequency and 8.2- x 4.2-km maximum inline and crossline offsets.

Offshore Australia high-frequency FWI for a detailed velocity model on narrow-azimuth marine data:

![Initial starting model vs. FWI model](image)

**Figure 4** Comparison of initial starting model (smoothed version of tomography model) and FWI model. The velocity detail added by FWI includes both high- and low-velocity channels that conform to the geology of the area.

This project shows the capability of FWI to start with a low-frequency model and iterate to a high-frequency detailed velocity model.

The input in this project was conventional narrow-azimuth marine data with ~ 4-Hz low frequency and 7.3-km maximum offset.

**Conclusions**

Although FWI on real 3D data sets is a challenging task (Vigh et al. 2009), it is now becoming the preferred method of building velocity models and can address a wide variety of geologic challenges. Modern acquisition designs incorporating low frequencies, long offsets, and all azimuths facilitate the implementation of FWI.

Need a starting velocity model that bridges the gap between the low frequencies and long offsets acquired in the data

Starting from low frequencies, FWI can iterate to high-frequency models.

Adequate QC between iterations is required to ensure convergence.

Current applications are acoustic, but elastic FWI is becoming a possibility.
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References


