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Salt Exit Velocity Retrieval Using Full-waveform Inversion
W. Huang (WesternGeco), K. Jiao (westerngeco), D. Vigh (westerngeco), J. Kapoor* (westerngeco), H. Ma (westerngeco), X. Cheng (westerngeco) & D. Sun (westerngeco)

SUMMARY
Accurate retrieval of salt exit velocity has been an important part in drilling hazard prediction, and is essential to achieve a clear subsalt image. Subsalt velocity retrieval is in many cases a difficult task to perform as the subsalt signal is often very weak. The common industrial practice to derive the subsalt velocity is to superpose a regional velocity gradient below the salt. However, using regional velocity gradient trend to estimate subsalt velocity ignores the relation between effective stress and velocities, which is extra important in determining the salt exit velocity. Full-waveform inversion (FWI) emerges as an advanced model building tool in recent years; however, the capability of FWI is limited due to lack of low-frequency and large-offset dataset, which are essential to the success of FWI retrieval. In this work, we successfully use time-domain full waveform inversion together with large offset dataset to retrieve the salt exit velocity, which improve the subsalt image and benefit the pore pressure prediction.
Introduction

In the last two decades, subsalt imaging in the Gulf of Mexico (GoM) has been a major focus of oil and gas exploration. Correct retrieval of subsalt velocity has been an important part to achieve a clear subsalt image. Subsalt velocity retrieval is, in many cases, a difficult task to perform as the subsalt signal is often very weak. The common industrial practice to derive the subsalt velocity is to superpose a regional velocity gradient below the salt. However, using a regional velocity gradient trend to estimate subsalt velocity ignores the relation between effective stress and velocities, which is extra important in determining the salt exit velocity. The effective stress just beneath the salt is lower as the salt density is smaller than the surrounding shale; therefore, the salt exit velocity will be lower than the regional trend in general (Mukherjee, 2006). Determining the salt exit velocity is not only important to the quality of the subsalt image, but essential for drilling hazard prediction using pore pressure estimation. Most major GoM deepwater operators have developed company-specific salt exit procedures to avoid the risk by subsalt pressure uncertainty, whereas accurate salt exit velocity can further facilitate the well planning process.

Different approaches have been introduced to derive the salt exit velocity. Mukherjee (2006) estimated salt exit velocity by using effective stress compensation from knowledge of the rock physics. Brown and Higginbotham (2009) utilize base of salt amplitude and wave-equation migration velocity-focusing analysis for subsalt overpressure detection. Li et al. (2011) further extend this method by using a reflectivity inversion. In the reflectivity salt exit velocity inversion, the salt exit velocity is inverted from a simple 1D reflectivity equation, with compensation of transmission and illumination loss handled by 3D wave equation forward modelling (Li et al., 2011). This method is limited due to lack of definition of the thickness of the salt exit zone, where ad-hoc thickness of the salt exit velocity zone has to be assumed. It is realized that a 1D amplitude based method cannot account for the complex salt geometry; however, the derived salt exit velocity model can be an initial constraint for further subsalt tomography. Tomography using ray-based gathers is limited for salt exit velocity determination because of the high velocity contrast between salt and sediment. Recent development of high-quality reverse time migration (RTM) angle gathers can be used for tomography update of subsalt velocity (Xu et al., 2011); however, the efficiency of angle-gather based tomography is related to the available subsalt opening angle, which is quite limited from conventional acquisitions.

One of the other advanced techniques that can offer the ability to resolve the velocity field just beneath the salt is the full-waveform inversion (FWI). FWI is an inversion technique that utilizes residual differences between the observed and wave-equation-modelled seismograms to update the velocity field, which was first introduced in the 1980s (Tarantola, 1984). Successful developments were made to increase the efficiency and accuracy (Vigh et al., 2009). With the development of newer computer hardware, and emerging high-performance algorithms, the application of FWI became possible. Due to the high computational cost of FWI, only recently was it applied to large-scale industrial projects (Huang, et al., 2012)

However, the ability of full-waveform inversion is limited for conventional surveys due to lack of low frequency and large offset. One of the difficulties with FWI is the convergence to the local minima which makes the technique very sensitive to the starting velocity model. To lessen the sensitivity of the initial velocity FWI starts with, low frequencies and long offsets are required (Bunks et al., 1995, Pratt and Shipp, 1999), enabling FWI to update the low frequency wave-number component of the velocity model (Vigh et al., 2011). Recent development of new acquisition technique, e.g. coil acquisition, maximizes the capability of FWI by available low frequency (2Hz) and large offset (14km) datasets. Full-waveform inversion can be a powerful alternative to retrieve the salt exit velocity coupled with the new acquisition data.

In following sections, we first outline the FWI inversion scheme we used for this work, and then we further present the application of FWI in determining the salt exit velocity for a GoM coil shooting dataset.
Inversion scheme

The FWI inversion used for this work is implemented in the time domain using the acoustic wave equation:

\[
\frac{1}{v^2} \frac{\partial^2 P}{\partial t^2} = \left[ \frac{\partial}{\partial x} \left( \frac{1}{\rho} \frac{\partial P}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{1}{\rho} \frac{\partial P}{\partial y} \right) + \frac{\partial}{\partial z} \left( \frac{1}{\rho} \frac{\partial P}{\partial z} \right) \right] + S ,
\]

(1)

Where \( P \) is the pressure field, \( \rho \) is the density, \( V \) is the interval velocity and \( S \) is the source term (Vigh et al. 2011).

A time-domain implementation is used to minimize the misfit function, which is given by:

\[
E = \frac{1}{2} \sum_s \sum_r \left[ dt[P_{cal}(x, y, z, t) - P_{obs}(x, y, z, t)]^2 \right]
\]

(2)

Where \( P_{obs} \) is the observed data and \( P_{cal} \) is the data calculated using the acoustic wave equation. The misfit function \( E \) is minimized iteratively by calculating the gradient \( \nabla_v E \). The gradient \( \nabla_v E \) is used to update velocity field by following equation:

\[
V_{n+1} = V_n - \alpha \nabla_v E
\]

(3)

Where \( \alpha \) is the step length and \( V_{n+1} \) is the updated velocity field. The step length \( \alpha \) is achieved by conjugated gradient method.

Gulf of Mexico Data example

FWI was performed on a dual-coil dataset around Sigsbee Escarpment. Dual-coil shooting involves two recording vessels with their own sources and two separate source vessels, all sailing in large (12 to 15 km) diameter interlinked circles, which is shown schematically in Figure 1. The trace density of this design is approximately 2.5 times that of current wide-azimuth survey designs, and the resulting very high fold will improve the signal-to-noise ratio to further improve the imaging of weak subsalt reflections. The extra large offset by a coil survey delivers rich refraction information that can benefit the model building process by FWI. One of the other attribute of coil data that further maximizes the capability of FWI is its rich content of low frequency (2.5 Hz) data. Figure 2 shows a comparison between the observed coil-shot data and FWI modelled shot filtered to 2.5 Hz.

Starting with a ray-based tomography velocity model and a regional gradient-trend-derived subsalt velocity, we executed 15 iterations of FWI update at 2.5 Hz to retrieve the velocity model. Figure 3 presents the initial and final resolved velocity model, which shows a low velocity zone beneath the salt after the FWI update. The lower velocity further indicates a possible over-pressure zone under the salt. Reverse time migration was performed according to the two different velocity models and the resulting images are shown in Figure 4. Significant uplift in the subsalt image quality is observed due to combination of sediment and salt exit velocity update by FWI.

Conclusion

An accurate salt exit velocity is important for a high-quality subsalt image, and is essential for pore-pressure prediction. We first introduce the inversion scheme used in this study. We then apply the FWI practice to a GoM project, where an accurate salt exit velocity and a high quality subsalt image were achieved. It can be concluded that, equipped with extra large offset and low-frequency datasets by advanced acquisition techniques, full-waveform inversion can successfully address the difficulty of salt exit velocity. With a corrected salt exit velocity, the subsalt seismic image is more focused and coherent. The accurate salt exit velocity model by FWI provides a more robust basis for pore-pressure prediction, which can benefit the drilling process.
Figure 1 Schematic plot of a coil survey, indicating a shot gather from near offset and a shot gather from far offset.

Figure 2 (a) observed near-offset shot (b) FWI-modelled near-offset shot (c) Observed far-offset shot (d) FWI-modelled far-offset shot.

Figure 3 Velocity model (in feet) comparison between initial and FWI updated (a) Initial velocity model (b) FWI inverted model indicating a low-velocity zone beneath the salt.
Figure 4 (a) RTM image using the initial velocity model (b) RTM using the velocity model by full-waveform inversion.

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Reference