Application of full-waveform inversion for salt sediment inclusion inversion
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Summary
Since the 1990s, subsalt imaging in the Gulf of Mexico (GOM) has been a major focus of oil and gas exploration. Due to the high velocity contrast between salt and sediment, defining salt geometry has been the key to successful subsalt imaging, and efforts have been made to implement new methods to correctly determine salt geometry. While salt boundary definition is heavily dependent on manual picking, other methods have been proposed for inversion of sediments inside salt. In this paper, we demonstrate that full-waveform inversion can be a powerful and accurate alternative to unravel the complexity of sediment inclusion contained within the salt.

Introduction
In early industrial imaging applications, it was commonly assumed that salt bodies are homogeneous, with constant velocity and density. While treated as homogeneous media, salt bodies in nature are far from homogeneous; rocks and sediment residuals may be deposited inside the salt body during the salt evolution process. The salt body with sediment inclusions is generally called dirty salt or variable salt. The major reason why salt bodies are treated as homogenous is because of the processing simplicity and lack of effective methods to retrieve the velocity of the sediment inclusions.

The sharp velocity contrast between salt and sediment make it necessary to have a clear definition of the salt geometry from inside and out. Manual salt-body picking has been an important step in most seismic imaging projects in the GOM; such picking requires high-level understanding of salt tectonics to derive the correct salt geometry. Salt body extraction from seismic images can be a slow and tedious process, and significant manpower is required. Efforts have been made to extract salt bodies automatically, and it has been shown that automated salt picking could be possible with human intervention to a lesser extent. While omnipresent in the salt bodies in the GOM, sediment suture velocity updates drew attention only very recently. A detailed study demonstrating the effect of sediment inclusions on subsalt imaging was first presented by Haugan et al. (2008). It was shown that the complex structures and/or velocity changes will affect the wave propagation in such a way that subsalt image will get distorted and/or defocused (Haugan et al., 2008). Although manual-picking can be possible for large sediment inclusions (Schoernann et al., 2010), it is unpractical to manually-pick large surveys. Automatic sediment inclusion inversion is in high demand for most industrial imaging applications, especially for GOM projects, where a large number of salt bodies exist.

Various approaches have been proposed for automatic inversion of dirty salt since 2010. Ji et al. (2010) first introduced the reflectivity-based dirty salt inversion, which uses a simple 1D reflection assumption. The 1D reflectivity-based dirty salt inversion gained attention due to its simplicity and effectiveness. However, the simplicity may sacrifice the accuracy of the obtained velocity. Although reflectivity-based inversion can give the rough location and magnitude of inclusion, the 1D assumption fails in most realistic geological environments, especially in the GOM where complex salt geometry exists. Reflectivity-based practice utilizes the reflection amplitude where the impedance difference is big, capturing the surface structure for bigger sediment blocks. Li et al. (2011) demonstrated that large sediment inclusion velocity updates can be done by tomography updates on reverse-time migration (RTM) angle gathers. Using angle gathers to update inclusion velocity could be a superior method to that of manual picking for large sediment sutures; however, most sediment inclusions are smaller than the size shown (1.5 km) in Li et al. (2011). Other amplitude-based techniques exist for sediment inclusion velocity updates, where the amplitude envelope inside the salt is used to scale the sediment inclusion velocity; however, the scaling is generally ad-hoc. The limitation of these approaches motivated us to seek more robust inversion techniques for dirty salt inversion. One of the most advanced techniques that offer the ability to resolve sediment inclusion velocity anomalies is full-waveform inversion (FWI). FWI is an inversion technique that...
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that utilizes residual differences between the observed and wave-equation-modeled seismograms to update the velocity field, and was first introduced in the 1980s (Tarantola, 1986). Successful developments were made to increase the efficiency and accuracy (Vigh and Starr, 2008). With the development of newer computer hardware, the emerging high-performance algorithms make the application of FWI possible. However, due to the high computational cost of FWI, only recently was it applied to large-scale GOM projects. The FWI is unlimited relative to both 1D reflection and angle-gather based techniques in the sense that there are almost no geological constraints for both the matrix salt body and sediment suture, e.g. salt geometry and size of the sediment inclusion.

In the following section, we first apply our FWI to synthetic datasets. Then, we show real GOM examples to demonstrate the ability of FWI to unravel sediment inclusion.

Synthetic modeling

We first examined the applicability of FWI to retrieve sediment inclusions with variable inclusion size. A 2D synthetic prestack dataset was created by forward modeling that uses a 20 Hz Ricker source wavelet and a velocity model with checkerboard pattern sediment inclusions. The forward modeling geometry is similar to that of real acquisition geometry: 12.5 m detector distance, 25 m between shots, and 8 km cable length. The initial 2D clean salt velocity model was extracted from the SEG advanced modeling (SEAM) model. As shown in Figure 1(a), three checkerboard patches were added inside the clean salt model, corresponding to 50 m x 100 m, 250 m x 500 m, and 500 m x 1000 m for individual elementary square sizes, which is proposed to examine the minimum retrievable size of sediment inclusion at different source frequencies and to examine the performance of our FWI.

The velocity for checkerboard sediment inclusion is set to be 15% smaller than that of salt velocity. Figure 1(b) shows the starting model for FWI update, which is a smoothed version of the initial clean salt model. A density model was generated according to the Gardner et al. (1974) equation, which is given by

$$\rho = 0.23V^{0.25}$$

where $V$ is velocity in m/s and $\rho$ is the density in g/cm$^3$. To make the FWI inversion more realistic, we assume that we do not have any prior knowledge of the density, which is the case for most real data seismic imaging projects. A constant-density model, $\rho = 1$ g/cm$^3$, was used in the FWI inversion.
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FWI inversion was performed progressively from 2 Hz, to 4 Hz, to 6 Hz, to 8 Hz. The updated velocity models for 2 Hz and the final 8 Hz inversions are shown in the bottom row of Figure 1. With 2 Hz FWI inversion, it is possible to capture most of features of the 500 m x 1000 m checkerboard patch, while the high-resolution details of the 250 m x 500 m patch are missing. When we apply the checkerboard patches to the clean salt, a set of small overhang-like structures are created at the left side of the salt flank, as shown in Figure 1(a). The small overhang structure is inverted at 2 Hz because of the relative size of the structure: around 1.0 km. When updated progressively to 8 Hz, most of the fine structure of the 50 m x 100 m checkerboard patch shows up; however, to achieve even more detailed velocity, it is necessary to use a higher frequency. In the final 8 Hz updated velocity model, the square shape structure of 500 m x 1000 m and 250 m x 500 m is very sharp. It is also observable that the inverted velocity at the left and right sides of the salt body is distorted compared to the real velocity, which is due to the boundary effect. RTM images with different velocity models are also presented in Figure 3. The imaging quality of the fault structure in the subsalt section is improved progressively from an initial clean salt model to an 8-Hz FWI-updated velocity model.

A more realistic variable salt model that mimics a realistic variable salt scenario is presented in Figure 2(c). Similar forward modeling and FWI inversion procedures are used. This random sediment inclusion model, which has a random variation with an average scale length of 250 m, is generated according to the random salt generation outlined by Frankel et al. (1986). The variable salt model has a velocity perturbation of ± 15% of salt velocity, and the velocity of the sediment inclusion could exceed that of the salt. From the profile in Figure 2(d), it is clear that, while the initial model is far from the exact model, FWI retrieved the large velocity variations inside the salt.

GOM field data examples

Having validated our algorithm with synthetic tests, we applied our FWI codes to a project in the Green Canyon area of the GOM. Figure 4 shows the velocity model together with reverse-time migration (RTM) images from real data. The left column shows the migrated images with a clean salt model, and the right side shows the images with a FWI-updated salt model.

From Figure 4, it is clear that there are significant uplifts in both the RTM images. The base of salt body and subsalt section is more continuous and focused by using the FWI-updated salt velocity.
Conclusion

The applicability of FWI to resolve sediment inclusion inside salt bodies is demonstrated in this paper. We first applied our FWI codes to two synthetic models. One model was part of the SEAM model and has checkerboard-like sediment inclusions; the other had random variable salt velocity. Both tests demonstrated the ability of FWI to resolve the sediment inclusions inside the salt. Apparently, the accuracy of the retrieval of different sizes of sediment inclusions is dependent on the incident wavelength. In general, our FWI code is capable of resolving small-size inclusions, as small as 100 m with 8 Hz FWI inversion.

As a straightforward extension of the synthetic test, we applied our FWI to real GOM data. While realistic data are more challenging for FWI inversion, e.g., computational cost and different sources of noise, our high-performance FWI code is capable of sediment inclusion retrieval for real GOM projects.

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Figure 4: Column (a) Initial velocity model overlay on RTM images; Column (b) FWI updated velocity model overlay on RTM images
REFERENCES


