Dirty salt velocity model building with constrained iterative tomography: Methodology and application

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Summary

Subsalt imaging has been a challenge for Gulf of Mexico (GoM) exploration, mostly due to the complexity of salt geometry and high salt-sediment velocity contrast. In addition to these, the presence of inclusions within the salt, also referred to as dirty salt, presents an additional significant challenge in subsalt imaging. Following a systematic study with synthetic datasets, we propose a new method for automatically determining the dirty salt geometry, and a further consolidated constrained iterative dirty salt velocity model building flow. We applied this workflow on a real GoM dataset and demonstrate its effectiveness by presenting an improved subsalt image.

Introduction

A major challenge in seismic imaging is to derive optimal input model parameters, e.g., velocity and anisotropy, for imaging algorithms and workflows. One particular challenge in the velocity model building workflow associated with Gulf of Mexico (GoM) settings is to include salt structures. This includes determining the overall geometry of the salt and the optimal salt velocity for imaging. Salt is however rarely pure halite and often we see inclusions inside salt that affects the imaging quality. Thus, for GoM, development of workflows that can handle geometrical complexities as well as internal heterogeneities of salt bodies is of particular interest for imaging and development of subsalt reservoirs. Current industry efforts aim to address this challenge.

Salt inclusions have multiple geological origins. Salt inclusions (heterogeneities) could be deposited together with the halite, because of fluctuations in the deposition. Layers of clay stone, carbonate and anhydrite inter-bedded in halite are common. Deformation of the inter-bedded layers start as soon as the salt begin to move in response to local differential loading and in this way inclusions may be formed within the salt. Salt bodies may also contain other types of inclusions that were not initially deposited together with the salt. These inclusions can be sedimentary rocks incorporated from the side walls of the flowing salt, igneous inclusions, or sediments trapped between converging salt bodies. When the top of a salt body is near sea-bottom, the top portion may dissolve to form a type of cap rock breccia. Inclusions may also be formed during salt evacuation where salt and sediments are mixed to form salt sutures. Regardless of their geological origin, we often refer to salt with inclusions as dirty salt. Due to their many geological origins, it is difficult to come up with a single method that can determine the structure of these different types of inclusions and incorporate them into the imaging process.

In recent years, the impact of dirty salt has attracted the attention of the seismic imaging community and the industry started to make efforts to tackle this issue. An early attempt to understand how salt inclusions affect the image was presented by Haugen et al. (2008). Ji et al. (2011) proposed a reflectivity inversion method to update dirty salt velocity. While this method is simple, it is based on a strong assumption that the velocity-density relationship obeys Gardner’s relation. Li et al. (2011) proposed to use reverse time migration (RTM) angle gather tomography (Woodward et al., 2008) to update dirty salt velocity. While this approach has advantages over surface offset gather tomography, it only uses inclusion boundary residual moveout (RMO), which may not be practical for real cases because the gather inside salt is normally very noisy. Huang et al. (2012) applied Full- Waveform-Inversion (FWI) to address the dirty salt velocity updating problem. FWI has obvious theoretical advantage over other approaches. However, application of FWI requires low-frequency data, which is still a strong limitation at the current stage. Additionally, current FWI implementation also has a strong assumption regarding density information.

In this study, following Liu et al. (2013), which provided a systematic study with synthetic dataset, we propose a new method to automatically determine the dirty salt geometry, and a further consolidated constrained iterative dirty salt velocity model building flow. We applied this workflow on GoM data and demonstrate its effectiveness by presenting a significant improvement of the subsalt image.

Methodology

In velocity model building workflows associated with salt structures a “top to bottom” approach is often considered. A simplified description of this approach follows: First, determine the velocity model for the shallow sediment section without considering the salt structure (sediment flood model). After this, from the image obtained using the sediment flood model, interpret top of salt (ToS). Then
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flood velocity model with salt velocity below ToS interpretation (salt flood model). Then, from image obtained using the salt flood model, interpret base of salt (BoS). After interpretation of BoS, assign subsalt sediment velocities to the velocity model below BoS. For complex salt structures the salt flood/sediment flood technique may be repeated to account for all complexities. For salt structures with salt inclusions the workflow becomes even more advanced. Exactly when in the model building workflow to address salt inclusion velocity determination may vary from case to case. This will depend on the quality of the image obtained at various stages in the velocity model building.

For salt inclusion velocity determination there are two major components to consider 1) How to detect inclusions (geometry) inside salt and 2) Which velocity to assign to the inclusions. Using both synthetic and real data we developed several methods to handle various dirty salt scenarios.

Detection of the correct geometry of an inclusion may be challenging. Besides inclusions, the seismic image inside salt may also be affected by multiple energy, migration artifacts and various types of noise. Some pre-processing may be required before inclusion detection. One alternative is manual interpretation of the inclusion. This is often a tedious and time-consuming approach so we will here concentrate on more automated methods. A straightforward automated method is detection based on image amplitude; using top and base of salt to define the zone of interest, amplitudes within the salt higher than a certain threshold amplitude are picked and defined as inclusions. The amplitudes themselves can be used as indications as to which velocity we should assign to the inclusions. This method works quite well for smaller inclusions as illustrated in Figure 1.

For larger inclusions however, the method picks up top and base, and not always the full extent of the inclusion. Post-stack impedance inversion is a theoretically straightforward method but has issues of instability in practice. We therefore developed a detection method where amplitude-based detection is followed by a logic process simulating ink injected from the salt boundary. The ink flows inside the salt boundaries, coloring the clean salt with ink while leaving salt inclusions untouched. This process identifies salt inclusions from clean salt. Amplitudes may still be used to assign velocities to the inclusions. Alternatively, the detection process may also be used to generate a mask to be used in a tomographic update of the salt inclusions. The ink injection method is illustrated in Figure 2.

After the salt inclusions have been identified and incorporated in the structural framework of the velocity model, the task of assigning proper velocities can start. The simpler approach here is to scan for velocities, picking the velocity that gives the best image. Another straightforward approach is to use the image amplitudes to define the velocity of the inclusions. This method can be used for smaller inclusions or, as further described herein, to assign initial velocity for larger inclusions which will be further updated using tomographic methods. Li et al. (2011) proposed using RMO information at the boundary of the inclusion to update dirty salt velocity with tomography in the 3D angle domain. This might be effective when RMO information at the boundary of the inclusion is available and has good quality. However, due the noisy background inside a salt body, in most real cases, we cannot obtain inclusion boundary picks of sufficient quality for tomography. As suggested by Liu et al. (2013), we thus seek the possibility of using more information, such as BoS and subsalt RMO information in a bounded dirty salt tomography, constraining velocity updates to only the inclusions. In this approach, defining the salt inclusion mask becomes important and here we utilize the “ink injection” method described earlier. Figure 3 illustrates the gradual improvement in imaging achieved from including more RMO information in tomography. We see from the

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Figure 2: Illustrating use of the “ink injection” method for detection of inclusions. The top and base of the inclusion is detected (in middle) on the salt flood image (left) using the amplitude detection method. The “ink injection” further distinguishes salt from inclusion (right).
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element that unbounded tomography using BoS RMO information may improve image focus, correct positioning is however still a problem. Bounded tomography improves both image focus and positioning, but when using only BoS RMO information we are not able to account for inclusions close to the BoS. Including both BoS and subsalt RMO information enables velocity update of inclusions close to the BoS and we are able to obtain good image focus as well as correct positioning of subsalt events.

Often, dirty salt velocity updating is considered as the last step of imaging in the velocity model building workflow. However, in some cases, dirty salt could substantially distort the BoS boundary, and thus further impact the subsalt imaging quality. Therefore it is important to do an initial dirty salt velocity update to avoid severe BoS boundary distortion before subsalt velocity model building. At this stage, we determine the inclusion geometry automatically with the ink injection method, and also assign an initial velocity to the inclusion with tomography of combined input of inclusion boundary and BoS common-image gathers. After the first iteration of subsalt velocity model building, the RMO of both BoS and subsalt are available for dirty salt velocity updating, and consequently, we can further improve dirty salt velocity updating, BoS and subsalt imaging quality. The following is the summary of this iterative dirty salt velocity update workflow: 1) Salt flood RTM imaging, 2) Inclusion geometry determination, 3) Initial dirty salt velocity update with inclusion and BoS RMO, 4) Subsalt RTM imaging and velocity update, 5) Next iteration of dirty salt velocity update with both BoS and subsalt RMO, followed by subsalt imaging and velocity update. 6) Repeat 5) if necessary.

Synthetic example and GoM application

First we tested this workflow with a more realistic 2D synthetic model, which was designed with high complexity inclusion geometry. The inclusions have significant differences in size, position, orientation, velocity contrast with surrounding salt, and boundary geometry. The purpose of this design is to test the validity of the proposed workflow in various dirty salt scenarios. Figure 4a shows the true model. Figure 4b is the RTM image with the true model. Figure 4c is the RTM image with the clean salt model. Figure 4d is the RTM image with the dirty salt updated model, which shows substantial image quality improvement.

Figure 3: Illustrating gradual improvement in image when including more RMO information in tomography. Upper left: Image obtained using clean salt model. Upper right: Image obtained using unbounded tomography with only BoS RMO information. Bottom left: Image obtained using bounded tomography (updating inclusions only) with only BoS RMO information. Bottom right: Image obtained using bounded tomography with both BoS and subsalt RMO information.

Figure 4: a) Dirty salt velocity model, b) RTM image with true velocity model, c) RTM image with clean salt velocity model, d) RTM image with updated velocity from bounded dirty salt tomography.
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We further applied this constrained iterative dirty salt velocity model building workflow to real GoM data. We selected data from a wide-azimuth survey in the Walker Ridge and Amery Terrace areas in GoM where the dirty salt was clearly a challenge. After the sediment flood to determine supra-salt velocity and salt flood to image the BoS, salt inclusion geometry was determined with ink injection, and initial inclusion velocity was assigned with tomography using a combination of inclusion boundary and BoS RMO. In a second iteration when subsalt picks were available, a further velocity update was applied to the salt inclusions. Figures 5 and 6 demonstrate the examples of subsalt image improvement, showing the validity of this workflow.

Conclusions

We proposed a new workflow for automatic determination of dirty salt geometry, and a further consolidated constrained iterative dirty salt velocity model building flow. We applied this workflow on real GoM data and demonstrate its effectiveness by presenting a successful improvement of the subsalt image.

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