Hybrid target-oriented salt interpretation in the Gulf of Mexico
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Abstract

The top-down method for salt interpretation starts with the search for salt-sediment interfaces, which begins at the shallowest depths and progressively moves deeper. This search is typically conducted on intermediate seismic products such as sediment flood, salt flood volumes, overhang sediment flood, and overhang salt flood depth migrations. However, with this approach, poorly imaged subsalt areas become known only after spending considerable time interpreting intermediate salt features. We evaluated a new method for streamlining this traditional approach to salt-model building wherein a reference salt geometry was obtained earlier in the salt interpretation process. Having a reference seismic volume helped to identify poorly imaged subsalt targets much sooner. A hybrid of model-based and data-based interpretations was then performed for the poorly imaged subsalt areas, whereby interpretation was completed by proposing geologically viable models that were continuously verified by their impact on geophysical (seismic) data. In poorly imaged areas, we looked bottom-up, rather than top-down, to establish a salt geometry that best fit the geologic model as well as the geophysical data. Our hybrid target-oriented approach is useful for not only reducing the interpretation cycle time but also for improving images beneath the salt.

Introduction

The Gulf of Mexico is one of the most prolific petroleum basins in the world. Large subsalt discoveries have increased the importance of accurately imaging and interpreting salt geometries for superior subsalt images. Exploration, development, and production in salt basin provinces such as the deepwater Gulf of Mexico have been challenging because seismic imaging of structures below complicated salt bodies requires special consideration through accurate definition of their salt geometries.

Headway has been made in developing methods for integrating migration and interpretation tools for a faster turnaround as well as establishing a feedback process whereby migration results can be efficiently used to update the model for a better final image (Mosher et al., 2007; Foss et al., 2008; Ahmed et al., 2012; Chopra and Marfurt 2012; O’Briain et al., 2013). Li et al. (2009) and Zhang et al. (2009) show how changing salt geometry based on regional geologic knowledge of the area can lead to a better subsalt image. Ritter (2010) explains the importance of identifying geobodies that may have significantly different velocities than surrounding sediments, such as overpressured shale and carbonate carapaces, based on subsalt images and common image gathers. Herron (2013) discusses the need for special consideration when interpreting depth-imaged data and how some of the structural features present can possibly be velocity model artifacts that may require additional migration iterations. Wang et al. (2008, 2009), Ahmed et al. (2012), and O’Briain et al. (2013) highlight the benefit of using polygonal shapes instead of using multiple single-valued top and base surfaces to define complicated salt geometries. Similar to the top-down approach, geometries defined by polygons in each inline or crossline section are interpolated to create a 3D salt body. In addition, Wang et al. (2008) suggest demigrating a depth-migrated image with a preliminary salt model to a subsurface datum chosen below the top of salt (TOS). This demigrated data can be used to test various salt scenarios using faster migration algorithms such as beam migration because choosing a subsurface datum reduces the amount of wave propagation required for remigration with an updated model. O’Briain et al. (2013) clarify how to partition the reverse time migration (RTM) image into vector offset outputs (Xu et al., 2011) and then interactively stack individual tiles to locally optimize the stacked image for better subsalt imaging. Having the individual vectors can help in understanding the illumination direction

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and differentiate noise from true signal. Xu and Jin (2005) outline a procedure to conduct target-oriented visibility analysis, which takes into account several factors, such as the overburden velocity, acquisition geometry, dip information, and reflectivity. It also identifies “geophysically invisible” interfaces that cannot be imaged despite improving the accuracy of migration algorithms or the velocity model. Rosenberg (2000) conducts a related study that analyzes the effects of salt shape and volume on the subsalt image.

Over the years, significant improvements in migration and tomography algorithms have enabled us to mimic real-world wave propagation and the physical properties of the earth (through which the waves propagate) in our data processing flow with fewer approximations than before. We have moved from ray-based methods to wave-equation-based methods and from isotropic assumptions to transversely isotropic or orthorhombic velocity models. Still, salt interpretation takes significant resources and time in the model building process. Salt interpretation has become one of the key steps in a standard velocity model building flow (Reasnor, 2007). The salt model has a relatively large impact on the resultant subsalt image, especially when using wave-equation migration algorithms. Further, unlike the sediment velocity update that can largely be automated, salt interpretation tends to be one of the most labor-intensive phases of a depth imaging project. Because detailed and accurate interpretations of the salt must be delivered in a limited amount of time, innovative workflows to reduce cycle time and improve the quality of the subsalt image must be implemented.

Our goal is to make the salt interpretation process more efficient and simultaneously yield better subsalt images. We present a hybrid target-oriented interpretation method that converges on improved interpretations much sooner. In our approach, a reference salt geometry is defined early in the salt interpretation process of model building. Areas that need further investigation are identified based on the quality of the preliminary subsalt image. Rigorous salt scenario testing using geologically credible models is subsequently performed in these problematic areas to achieve a better subsalt image.

**Method**

The top-down salt-model building workflow begins with the shallow depths and moves deeper, picking the TOS and then the corresponding base of salt (BOS) to define the salt body. This is typically done by interpreting the TOS and BOS surfaces on intermediate sediment flood volumes and salt flood volumes, respectively. In theory, the salt model for any salt geometry can be built by this method. With modern-day access to the latest seismic visualization software, faster workstations, and autopicking routines, interpreters have been able to cut down on the cycle time to generate salt models; however, the top-down salt interpretation approach is largely data driven, which introduces some inherent limitations.

Complex structures with overhanging salt features are formed in areas with changes in sedimentation rates, lateral salt movement, and coalescing salt bodies. These structures require several iterations of interpreting TOS and BOS surfaces. Typically, interpreters need to spend a considerable amount of time picking these intermediate horizons, and there is additional downtime spent generating intermediate seismic products such as sediment and salt flood migrations. Furthermore, in areas with considerable salt movement at the allochthonous level, the salt-sediment boundary is not always discernible.

Figure 1 shows an example of a salt geometry in which variable sedimentation rates have resulted in a complicated overhang structure. The top-down approach to salt-model building would ordinarily require eight salt surfaces to completely map all of the overhangs present along the salt flank in addition to multiple iterations of sediment and salt flood migrations. The top-down method of interpretation would take considerable time and effort before we may begin to see the impact of the interpreted salt body on the resulting subsalt image. Also, the halokinetic sequence boundaries appearing as salt wings along the vertical flank are poorly imaged. The potential impact of the thickness and lateral extent of these salt wings cannot be

**Figure 1.** Depth migrated salt image showing that several TOS and BOS surfaces are needed to define the complete salt geometry. The tip of the salt wings marks the halokinetic sequence boundaries (shown by the red arrows).
assessed until we image all eight surfaces required to complete the salt structure.

In areas of complex salt and sediment interactions, intermediate sediment and salt flood volumes can be of very limited use in imaging salt-sediment interfaces. In such instances, incorrect interpretation of a shallow horizon can affect the interpretation of subsequent deeper horizons. This leads to an accumulation of errors in the velocity model and can result in a poor subsalt image. Therefore, spending an excessive amount of time adopting the top-down approach to salt interpretation in areas of geophysical ambiguity may not be prudent and is often counterproductive in generating a good subsalt image.

In light of the above-mentioned issues, which routinely occur in most depth-imaging projects in the Gulf of Mexico, we propose an alternative to the top-down approach for salt-model building that can be adopted for streamlining the salt interpretation process. In our hybrid target-oriented approach, our goal is to define a reference salt geometry at an early stage in the salt interpretation process to identify potentially problematic areas. Figure 2 is a flowchart depicting our method. Traditional top-down interpretation on intermediate interpretation volumes is performed in areas of well-imaged targets, but a hybrid geophysical-geologic method is used in areas of imaging ambiguity.

Because of its ability to image turning waves, RTM allows for the interpretation of several surfaces in one step. For example, instead of only interpreting TOS on the sediment flood stack (as in the top-down process), we can often simultaneously interpret the secondary TOS. Similarly, we interpret the primary BOS and the secondary BOS using the salt flood. In areas containing obvious overhangs, oftentimes, the secondary BOS is not immediately apparent as a mappable event on the seismic data. In such areas, however, we can still interpret a regional BOS by referring to surrounding areas that are free of overhangs and where the salt is relatively tabular or uncomplicated.

In areas of complex geology, intermediate salt features are often poorly imaged. Not only is interpreting these features an arduous task, but it can also potentially hinder the subsalt image more than benefit it if there is a large amount of uncertainty in the interpretation, which is often the case. Conversely, in our hybrid target-oriented approach, our model starts with a less complicated salt geometry for the reference volume and then adds complexities where needed, based on the resulting subsalt image. It becomes imperative in such areas to have a hybrid (or integrated) geologic and geophysical approach in which (1) a range of geologically sound salt models is proposed because geophysical data alone are ambiguous and (2) the proposed geologic models are tested and compared by their impact on resultant subsalt image. In this sense, we look bottom-up in poorly imaged areas and establish an interpretation that is geologically viable and produces the best subsalt seismic images. As a result, our approach is more holistic and integrated compared to a simple top-down salt interpretation.

Figure 3 shows an area where the hybrid target-oriented method was applied. We interpreted up to three pairs of TOS and BOS that we designated as the reference salt body. By omitting all the intermediate steps of overhang sediment flood and overhang salt flood migrations, we obtained a reference salt body stack (Figure 3a) much earlier in the salt interpretation phase than is typical. With this reference seismic volume, we were able to quickly identify areas with poor subsalt imaging (Figure 3b, red box) and areas with good subsalt imaging (Figure 3a, green box). This enabled us to jump to rigorous salt scenario testing in the poorly imaged areas much sooner.

This approach can produce a better final subsalt image in two distinct ways. First, it helps focus most interpretation effort in areas with poor subsalt imaging by isolating them from adjoining areas with good subsalt imaging. Second because scenario testing can begin much earlier in the interpretation process, many more scenarios using geology-based salt movement models can be rigorously tested, resulting in a better optimal salt model and subsalt image. Because several iterations of salt geometry testing and assessment may be required before obtaining a final salt geometry, the ability to identify the areas warranting special attention (provided in our method) is very important early in the model building phase. In tandem with these scenario tests, we can continue with the top-down velocity model building flow in the well-imaged areas. Figure 4 shows salt scenario testing for the poor subsalt area, revealing the step-change improvements in the subsalt.

**Application**

We started with a reference salt geometry based only on sediment flood and primary TOS flood volumes.
This reference salt geometry is free from salt-body complexities that are frequently imaged poorly. The salt geometry in poor subsalt areas is then updated based on plausible salt movement histories, indirect hints from surrounding sediment behavior, and adding incremental complexity. We do this until we obtain an optimum interpretation that simultaneously fits the seismic data and geologic/salt flow model and also yields a better-focused subsalt image.

In the examples that follow, we illustrate the importance of understanding regional salt tectonics and the various ways salt and sediment can interact to construct geologically viable scenarios as part of our hybrid target-oriented interpretation approach. All data migrations are in the depth domain because that is required in areas with complex salt structures. The cartoons represent template models for the corresponding scenario tests and are not actual geologic restorations for any given seismic data example. The models and corresponding data migrations are in 3D, though for sake of better illustrations for the paper, we have shown representative 2D slices for each model. The corresponding seismic data are also 2D slices displayed from the 3D migrated cube to better correlate them with the respective model. The changes in salt geometry were made using a top-down approach for salt interpretation, in which starting at the shallowest depth, progressively deeper horizons are picked until complete salt geometry is defined.

Figure 4 shows how the same starting salt geometry (an allochthonous salt sheet) can evolve into two different salt structures, depending on the sedimentation rate during the salt rise. To interpret the area shown in Figure 6a, we first considered a simple salt flow model (Figure 5, model 1) in which a minibasin is subsided into a salt sheet, creating a smooth flank without any overhanging structure. This model assumes uniform sedimentation throughout the minibasin formation. However, we observed that horizons immediately below the minibasin flank in Figure 6a are not continuous, which suggests a model artifact. Next, we considered a different possibility of salt flow in which sedimentation was not uniform during minibasin formation (Figure 5, model 2). When the
sedimentation rate was reduced, the salt was able to extrude laterally before the sedimentation rate increased again, leaving an overhanging salt structure that was poorly imaged on the seismic. The improvement can be seen in Figure 6b. We used the sediment truncations against the flank as a guide to interpret the overhanging salt because the salt-sediment interface was not properly imaged. The images with our modified salt geometry reveal the subsalt underneath the flank more clearly than the images with our original salt geometry.

Figure 7a shows another example of a subsiding minibasin. In this case, the salt thickness and salt intrusions along faults have been poorly imaged because salt was evacuated, and the basin subsided. First, we assumed a simple model of minibasin subsidence (Figure 8, model 1); in the absence of extensional faults, the minibasin subsided, which created a smooth flank. We also assumed there was some remnant thickness at the bottom of the basin. This model shows that the subsalt horizons, especially at the Top Cretaceous (enclosed in the red box), is fragmented. This may be an artifact of the model we used. Next, we changed the salt geometry based on the illustration shown in Figure 8, model 2 in which the minibasin subsidence occurred in an extensional environment resulting in remnant salt (indicated by the red arrows) along the extensional faults.

In Figure 7b, we assumed that most of the salt on the right side of the dome structure was welded and contributed to the bright reflectivity observed in the

Figure 5. Two alternative models of evolution of an allochthonous salt sheet in response to minibasin subsidence. Model 1 — The uniform sedimentation rate during minibasin subsidence creates a smooth flank. Model 2 — The reduction of the sedimentation rate during minibasin subsidence allows for lateral salt extrusion. The subsequent rise in the sedimentation rate results in an overhang structure.

Figure 6. Depth migrated salt scenarios based on the two alternative models shown in Figure 5. (a) The model with a smooth minibasin flank shows a distorted subsalt image directly under the flank (red box). (b) The model with the overhang structure better images the subsalt directly underneath (green box).

Figure 7. Depth migrated salt scenarios based on the two alternative models shown in Figure 8. (a) The scenario with the smooth minibasin flank shows a distorted subsalt image directly under the flank. (b) The scenario with salt intrusions along the faults results in a more continuous subsalt image. The red arrows point to bright reflections, which are salt intrusions along the extensional faults.
minibasin from the above-mentioned extensional faults containing remnant salt that were formed during the salt rise. On the left side of the dome structure, there is some thickness of salt that had not been properly imaged. We changed the salt geometry according to this model and observed that the top Cretaceous, which had been fragmented and discontinuous, became a smooth horizon. This verified that the structure seen in Figure 7a is actually a model artifact.

Another situation often encountered in the Gulf of Mexico salt provinces occurs when multiple allochthonous salt bodies coalesce to form a bigger salt structure. In such cases, distinguishing between the reflections within salt that are caused by the presence of impurities inherent to salt and the reflections that indicate remnant sediment bodies trapped in between two salt masses becomes difficult. Figure 9a shows an example of a salt sheet moving toward the right from a deep feeder on the left side; several internal reflectivities within the salt (marked by red arrows) were dismissed as salt impurities to show a simple model case (Figure 10, model 1). However, the image of structure immediately below the flank (a Cretaceous event) is distorted. We modified the model according to Figure 10, model 2 where we assumed that there is remnant sediment, and the two salt bodies have not coalesced completely. The lower salt body had almost welded underneath the upper salt sheet. As seen in Figure 9b, adding this complexity to the salt geometry gives more continuous and better imaged subsalt horizons.

In the last example, we demonstrated that some of the impurities and inclusions present within salt bodies need to be mapped to generate a better subsalt image. Salt is highly inhomogeneous with a myriad of internal impurities. Dirty salt inversion (Ji et al., 2011) can be used to account for some of these impurities in the salt model, but in cases in which these inclusions have a reasonable thickness to them, they need to be considered during interpretation and salt body definition.
Figure 11a and 11b demonstrates how sedimentary inclusions are formed within salt bodies. We illustrated two common examples, but there are numerous other ways that these sediment inclusions form. Figure 11, model 1 shows a small sediment body trapped between two coalescing salt tongues, and Figure 11, model 2, shows the case of a roof of a rising diapir breaking and disbanding to form several sediment inclusions. In the seismic example based on these models, Figure 12a shows a salt body that has some internal reflectivity, but we cannot immediately determine whether there is any thickness to it. In a top-down method of salt interpretation, sediment inclusions are often overlooked owing to uncertainties in their shapes and sizes. A thicker inclusion may get misinterpreted as dirty salt unless we look bottom-up — from the poor subsalt image to its potential cause in the salt geometry above it. In this case, we observed that horizons immediately below the BOS are pushed down, which suggests that there is an extra thickness in the salt. The top and base are reasonably well defined. In Figure 12b, we tried a lens-shaped sediment inclusion along the base. The inclusion made the subsalt image more continuous compared to Figure 12a.

Conclusions

As seismic processing technology advances, salt interpretation for imaging subsalt targets requires advancement as well. The top-down salt interpretation focuses on finding the salt-sediment interface on intermediate seismic volumes in the model-building phase. Here, we present a hybrid target-oriented salt interpretation technique in which well-imaged and poorly imaged subsalt areas are treated separately. For well-imaged areas, interpretation is still performed in the top-down fashion, which is a quick process if the geologic features are not too complex. However, for poorly imaged and complicated subsalt areas, a corresponding salt model cannot be easily deduced based solely on geophysical seismic data; a hybrid approach integrating geophysical data and geologic knowledge is needed to arrive at a realistic salt model. By taking into account the seismic data and the salt model in the neighboring areas in conjunction with regional salt tectonics and the salt flow history, several realistic salt-model scenarios can be proposed and tested for subsalt image quality. This scenario testing can proceed in an iterative fashion by starting with simplistic salt geometries for the poorly imaged areas and progressively adding complexities to the salt structure until diminishing returns are observed in the subsalt image quality.

In theory and often in practice, our hybrid target-oriented approach can expedite the salt interpretation in geologically complex areas. However, this method does have some limitations. For one, it relies heavily on quick evaluation of results. The bottom-up evaluation requires the eyes of a skilled geophysicist with salt interpretation experience. Furthermore, designing realistic geologic scenarios requires knowledge of regional tectonic and structural histories. The fact that salt can behave like a fluid in the subsurface means that the possible geometries it can assume are numerous unless indirect clues are taken from nearby well-imaged salt bodies and surrounding clastic sedimentary rocks. Finally, even after the poorly imaged areas are identified and separated early in the imaging project, not all
horizons become immediately clear. However, the time savings inherent in the hybrid target-oriented approach make the interpretation process more efficient by focusing the interpreter’s time and energy in areas where they are most required.

Judiciously combining the top-down approach to salt modeling in areas with simple salt geometry along with our hybrid target-oriented approach in more challenging areas reduces the time spent in the salt-modeling phase of a depth-imaging project and also results in better quality imaging. By combining geophysical data with geologic know-how, a feedback loop can be created wherein results from geophysical data are continually assessed based on regional geology and salt tectonics, and an optimal salt model can be established within a reasonable time frame. Adopting such an approach can prove beneficial by streamlining the salt-modeling workflow thereby reducing cycle time and by yielding a better subsalt image in areas with complex geology and salt movement where geophysical data alone fall short in defining the salt geometry.

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References


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