

## Salt interpretation for depth imaging – where geology is working in the geophysical world

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### Summary

Accurate salt interpretation involves an integration of geology and geophysics. In the practice of salt interpretation and model building in depth imaging, we see two problems that could happen: exclusive geophysical interpretation without geological input and insufficient geological interpretation without understanding how the geophysical data are processed and without evaluating the limit and uncertainty of some geological data. Here we present two before-after examples to show why these problems can happen, how the final imaging products can be improved through integrating geological and geophysical data in salt interpretation/modeling for depth migration, and why the cross-training of geological, geophysical and interpretation skill sets are key factors in improving depth imaging products.

### Introduction

Seismic interpretation and modeling is an integration of geological, geophysical and engineering data. In depth imaging, expertise from both geophysical processing and geological interpretation are becoming key factors in bringing out high quality imaging products. However, in depth imaging processing practice we could sometimes detect the knowledge gaps between seismic processing, geological and interpretation skills for the salt velocity modeling. Two problems - exclusive geophysical interpretation and insufficient geological interpretation - are the direct results of the gap.

The first problem, exclusive geophysical interpretation which means geophysical reflection is the only concern for interpretation, is usually caused by lack of geologic data or without knowledge of regional geology and salt tectonics. Because salt is one of the most impressive geological features shown in the seismic data in the Gulf of Mexico, it is easy to believe that salt should always be homogeneous and salt boundaries should always have strong reflections in seismic sections. This philosophy for interpreting salt worked well when exploration was focused on shallow and less complex areas. However, since exploration moved to deep and complex area this method has become outdated. In these more complex areas, salts can be deformed by many geological events and consequently are not homogeneous. Additionally acoustic impedances of salt and sediments can be very close and consequently reflections from salt boundaries can be very weak.

The second problem, insufficient geological interpretation which means geological data are the only concern for

interpretation, can be caused by not understanding how the seismic data were acquired and processed or by not considering the limit of geologic data, as represented by the seismic data. The purpose of interpretation for depth migration is to build a correct velocity model to reflect the strong velocity contrast between sediments and salt as seen in the Gulf of Mexico. The highly mobile salt bodies are assumed to have constant velocity and density. Often in exploration frontiers geologic data are very sparse, making it impossible to provide large area with well controls. In addition, too detailed geologic interpretation beyond the limits of seismic resolution will not help seismic imaging.

We will present our salt model building process at first, and then we will use two before-after examples to illustrate the importance of integrating geology and geophysics, and the benefits and the limits of geologic data to salt interpretation for depth imaging.

### Salt model building process

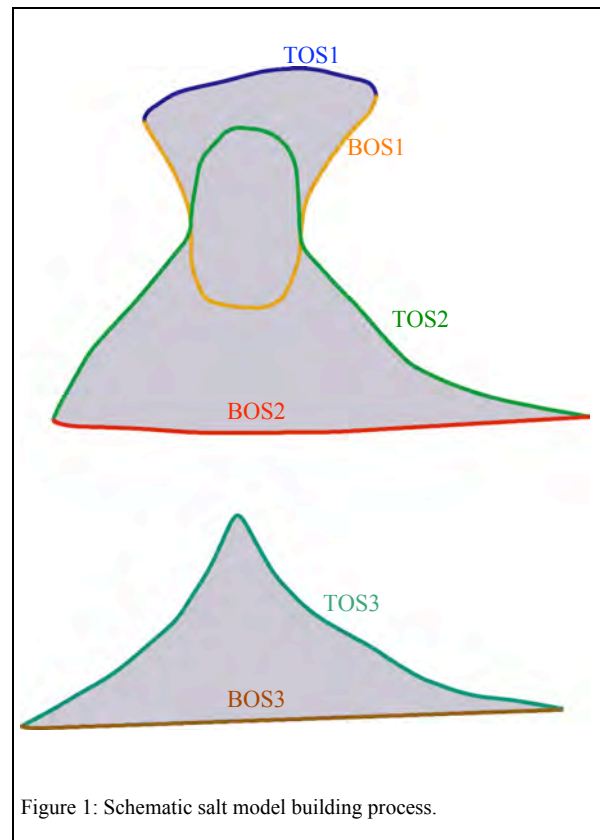


Figure 1: Schematic salt model building process.

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Figure 1 shows a simplified cartoon of a salt model building process for a shallow salt with overhang, and a detached deep salt feeder and base below.

The model building workflow is as below.

1. Sediment migration volume - To pick first top of salt (TOS1) (blue horizon) ;  
=> TOS1 Salt flood migration - Salt velocity is applied below TOS1 for migration;
2. TOS1 salt flood volume - To pick first base of salt (BOS1) (orange horizon) .  
=> Use TOS1 and BOS1 to close first salt body, then apply sediment velocity below BOS1 for migration;
3. BOS1 volume - To pick second top of salt (TOS2) (green horizon);  
=> Salt flood below TOS2, as step 1;
4. TOS2 salt flood volume - To pick second base of salt (BOS2) (red horizon);  
=> Sediment flood below BOS2, as step 2;
5. BOS2 volume - To pick third top of salt (TOS3) (greenish blue horizon)  
=> Salt flood below TOS3, as step 3.
6. TOS3 salt flood volume - To pick third base of salt (BOS3) (brown horizon) and complete the salt model building process!!  
=> Sediment flood below BOS3 and migrate.

The salt model building workflow is to start from shallow to deep, picking top of salt and then base of salt to define salt body step by step and one by one. In theory no matter how complex the salt geometry is and how many overhangs there are, salt model can always be built with this method, if iterations and time are not limited. The key is to interpret surfaces which can separate salt velocity zones and sediment velocity zones. For illustrative purposes, we present two real world examples of depth imaging projects.

### Example I: Integrating geology and geophysics for salt interpretation

Figure 2 shows Reverse Time Migration (RTM) with a previous derived salt model in the Gulf of Mexico. In this model a shallow event was picked as the base of the major salt bodies. There are several reasons interpreters chose this shallow event as BOS. First, this event is the first strong reflection below the TOS, and the reflections between this event and the TOS is chaotic as typical salt characteristics on the seismic. Second, the event on the saltflood gathers is flattened which means it is appropriate to use salt velocity between the TOS and this event (Figure 3). Third, poor signal below the shallower event, this event being stronger than the deeper reflection, the deeper event being close to multiple of water bottom in the saltflood volume, and interpreters' concerns about possible subsalt prospects being destroyed on the seismic by having too much salt in the model encouraged interpreters to pick the shallow event

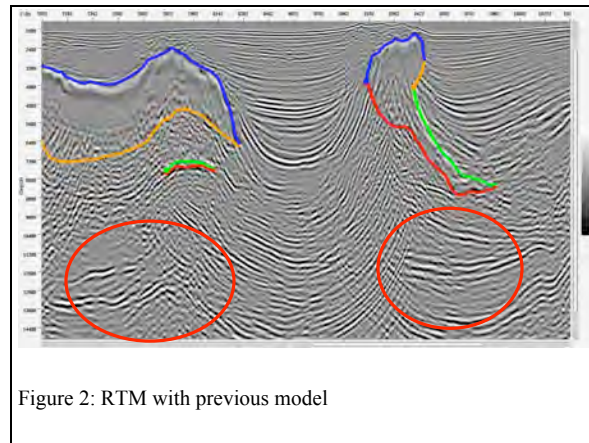


Figure 2: RTM with previous model

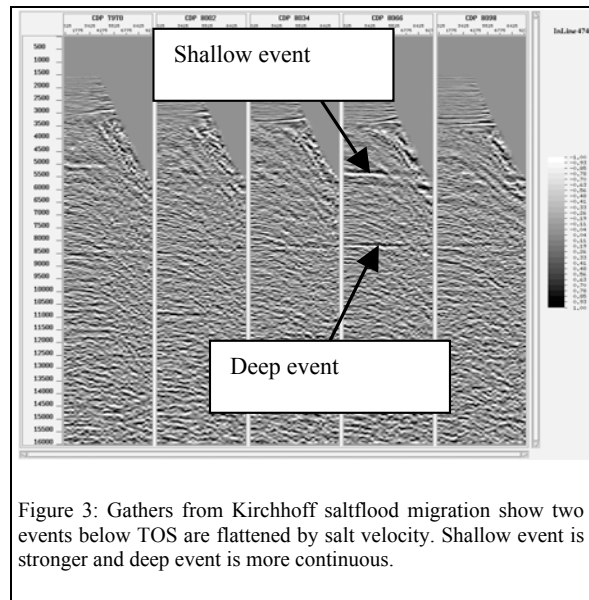


Figure 3: Gathers from Kirchhoff saltflood migration show two events below TOS are flattened by salt velocity. Shallow event is stronger and deep event is more continuous.

as base of the main salt body and interpreted the deep event as salt weld. After migration with this model, some questionable images appear, which might indicate a different velocity model with thicker salt may be more accurate. First, regional geology study shows that in this area sediment supply is from north to south (right to left in Figure 2) as is the regional dip. However, we see subsalt formations were pulled up and don't follow the regional dip. Second, subsalt events are highly distorted and look like intense deformations happened to these formations, which is not likely considering the nature of the formations from a regional geological history viewpoint. Generally, sedimentary sections in the Gulf of Mexico from Late Jurassic to present were deposited under stable tectonic conditions, only modified by salt and growth-faulting (Salvador, 1991). There is no evidence to support that the

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discontinuity was caused by salt and faulting. Third, Kirchhoff migration (Figure 4), which is more tolerant to velocity model inaccuracy, shows some subsalt events are more continuous and dip basinward, but wave equation migration (Figure 5), which is more sensitive to an inaccurate velocity model, shows poor subsalt images and has pull-up artifacts. Fourth, on saltflood gathers there is a deeper and more consistent event (Figure 3) which is flattened by salt velocity. Above this event, chaotic reflection shows typical salt characteristics, giving the idea that maybe the deeper event is BOS. Other information supporting a velocity model with a thicker salt include: Bouguer residual gravity data are with minimum values at this location, indicating a thick low-density geologic unit which is more likely to be salt in this location; and regional geology research indicates thick salt is more possible.

After considering information regarding regional geology and salt tectonics and observing Kirchhoff, wave equation and RTM images, we realized that the shallow event picked as BOS represents a suture of two periods of salting. The interpretation of the real base of salt was changed to be the deeper event. The salt was re-picked and the final RTM was run with the new model shown in the Figure 6. In the

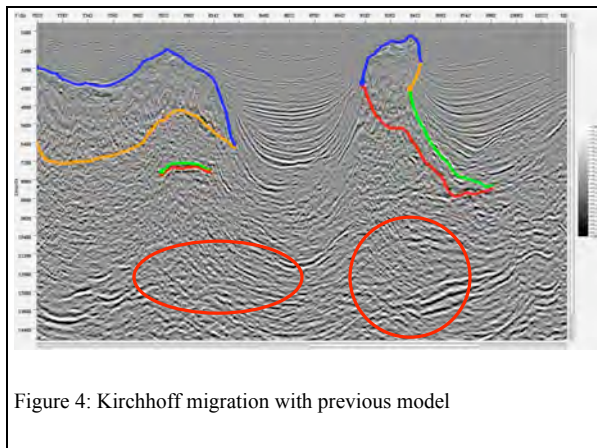


Figure 4: Kirchhoff migration with previous model

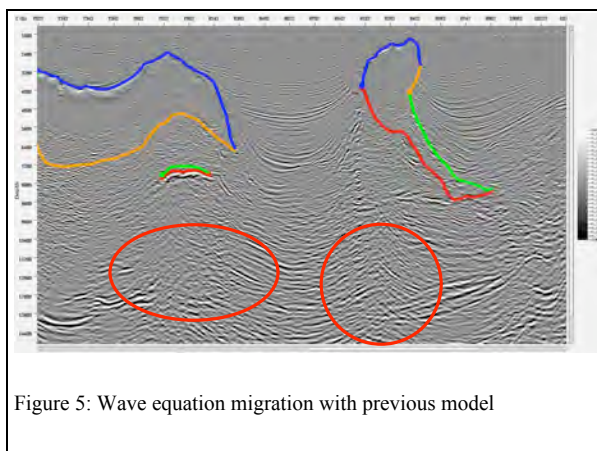


Figure 5: Wave equation migration with previous model

new RTM volume, subsalt events are more continuous and the seismic images are more geologically reasonable.

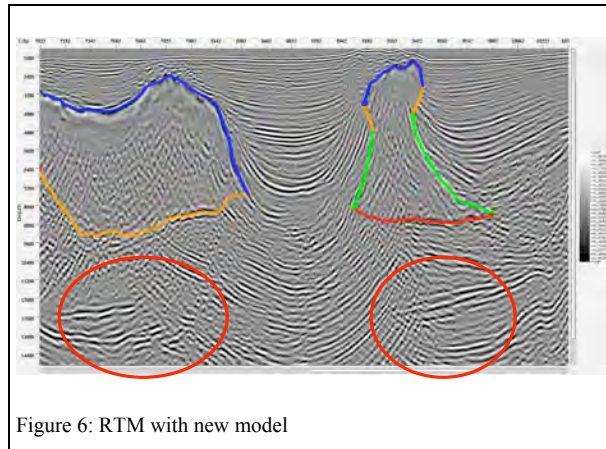


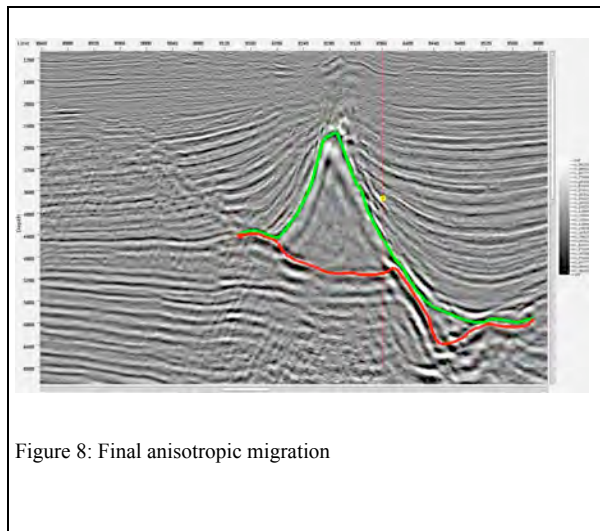
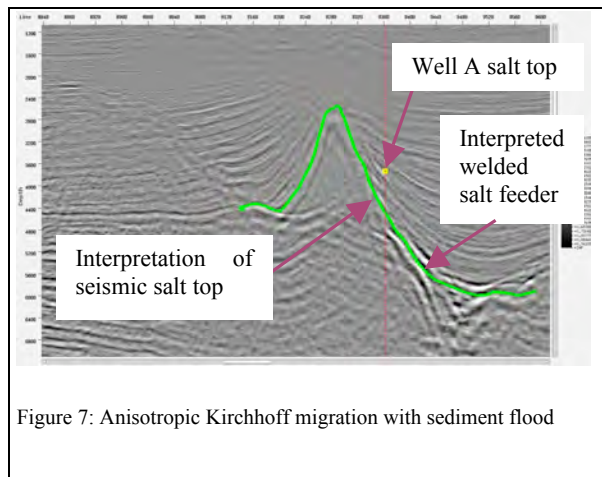
Figure 6: RTM with new model

### Example II: Risk of applying uncertain geologic data to salt modeling

Figure 7 shows an anisotropic prestack depth migration which was migrated using a velocity model that was calibrated with checkshots. The data are from Gulf of Mexico. Well A was drilled along the salt flank and hit salt at depth of 3752 m (Figure 7), which is shallower than TOS picked from the seismic. It was suggested that the interpreted TOS should be moved up to tie with the well top, and the events below the well top should be interpreted as artifacts, because the well top was believed to be more accurate. However, a study of more salt tops from other wells in this area shows that most salt tops already tie very well with TOS picked from seismic. Further research found that Total Depth of Well A is only 14 meter deeper than the salt penetration point, and there is no evidence to indicate Well A was drilled into a main salt body. Detailed salt mapping from the main salt body to the salt feeder and the weld (Figure 7) indicates that the TOS picked from seismic is consistent with salt tectonic history. It is most likely that, when the salt moved, surrounding sediments were faulted and fractured, allowing small amount of salt to invade into the sediments to form numerous distal salts surrounding the main salt body. The salt encountered by Well A is only one of the distal salts.

It is not reasonable to apply salt velocity to the area where salt only accounts for a small percentage of rocks. Final anisotropic migration using the salt model with picks on seismic salt top provides excellent salt and subsalt images (Figure 8) and further proves the salt model is accurate.

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### Challenges of interpretation in the depth imaging

Interaction of interpretation and processing teams takes place throughout the whole velocity model building and depth migration workflow. Inaccurate interpretation will significantly decrease the quality of depth migration products. From Kirchhoff and Wave Equation to Reverse Time Migration, we see migrations are increasingly more sensitive to velocity model accuracy. With the advancement of computer technology and migration algorithm, interpreters in depth imaging face even greater challenges to deliver high quality models within very tight timeframes.

As salt model builders of depth migration projects, interpreters need to know how the seismic data are processed, and need to understand the principles of geology. The benefits of interpretation teams' early involvement in processing project can be maximized and the risks can be minimized, with the interpreters being the bridges between geophysics and geology and between data processing and exploration. The practical value of seismic data is that it can be used to predict "ahead of the drill bit" what to expect in a new subsurface exploration venture, and seismic images should represent real geological features; at the same time, geologic data will be more helpful to depth imaging if the limit and uncertainty of data are well evaluated and understood. To achieve these goals, interpreters need to work seamlessly with processors and explorationists from project design to final data delivery to help to make depth migration more practically valuable.

### Conclusions

As exploration targets are moving to deeper depth and into more complex geological area like sub-salt, plus the advance of fast turn-around in depth migration, the interpretation for depth imaging is becoming even more challenging than ever before. Trainings in seismic processing, migration algorithms, geological knowledge and salt tectonics and interpretation skills are key factors in ensuring a better velocity model building and therefore superior migration products.

### Acknowledgments

We would like to thank TGS-NOPEC for permission to use the data in this paper. Thanks to Laurie Geiger, Zhiming Li and Bin Wang for editing and giving us suggestion to improve this paper.

#### **EDITED REFERENCES**

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