G042

Subsalt Imaging Challenges - A Deepwater Imaging Analysis

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SUMMARY

Upon completion of the final reverse-time migration (RTM) imaging for a subsalt prospect in the deepwater Gulf of Mexico, interpreters noted conflicting dip information in a key area of prospectivity. If the conflicting dips were real, they would drastically affect the size of the reservoir and, consequently, the drilling plan. This paper summarizes a modeling and imaging study that used 3D acoustic finite-difference modeling to gain a better understanding of the events on the final RTM image. Based on the results of this study, we conclude that the dipping events are related to noise from residual multiples. The study also shows the role that long-offset and full-azimuth acquisition can have in illuminating complex subsalt targets.
Introduction

Subsalt exploration in deepwater areas can be a high risk endeavor when costs for a single well range from ~USD 100 million to ~USD 300 million and development costs extend into the billions. In basins like the Gulf of Mexico, Brazil, and West Africa, a complex salt canopy degrades the quality of subsalt images, further adding to the drilling risk. The geometry of subsalt horizons against salt walls often determines whether or not a trap will be an economic prospect, so it is critical to get an accurate image in these areas. Unfortunately, these high-dip salt flanks also create low seismic illumination zones in precisely the areas where the imaging is critical. Noise or imaging artifacts in the low-illumination areas can easily be incorrectly interpreted, either creating a lead that isn’t real or indicating that the trap size is non-commercial.

This paper presents a case study detailing seismic modeling and image analysis that was done over one such prospective low-illumination zone in the Gulf of Mexico. The question of what range of dips could be illuminated below salt by the real survey acquisition geometry became the focus of a multistage illumination analysis. The study starts by forming partial images from selected reverse-time migration (RTM) shots, progresses to a ray-traced illumination analysis, and finally, is completed with a 3D acoustic finite-difference simulation of different acquisition geometries.

Figure 1 shows an RTM-migrated seismic section where conflicting dips are seen beneath a steeply dipping salt flank. Initially, prospective sands indicated by the orange arrow approach the salt flank at a low angle, dipping away from the salt face. Directly adjacent to the salt flank, another set of events appear to dip into the salt flank (indicated by the yellow arrow). While the low dips away from salt create a drillable prospect, a roll-over structure represented by the steeper dips against salt maps out as only a marginally economic prospect.

Imaging Analysis

An initial investigation of the RTM image began by looking at the source illumination in the area beneath salt. The source illumination plots showed that most of the transmitted energy was focused away from the area of interest as a function of the salt geometry. Partial RTM images were formed from spatially limited groups of shots with the intent of enhancing the image using only the sources that contributed to the zone of interest.

Shots covering a 9-km² area spanning the deep salt keel from east to west were divided into three segments; shots imaging the keel from the east, from the west, and shots directly above the keel. RTM images were formed by grouping the shots from the three areas and were analyzed for indications of either a low-dip subsalt structure or a roll-over structure below salt. Analysis of these partial images (Figure 2) showed that there was a distinct illumination shadow zone adjacent to and beneath the salt.
and that none of the partial shot combinations improved the image. From the partial images, neither the low-dip termination nor the roll-over interpretation below salt could be ruled out.

**Figure 2** Source illumination pattern for a group of shots above the salt flank (left), and partial RTM image for the same group of shots (right). Green line indicates base salt.

**Ray-trace Illumination**

With the low illumination zone confirmed by the RTM source illumination plots, the imaging analysis continued with an illumination study based on ray tracing through the salt model. Ray tracing has the advantage of carrying offset and azimuth information that can be useful for resolving the acquisition parameters needed to solve an illumination problem. The disadvantage of ray tracing is that rays may not accurately represent wave propagation through complex salt models. Ray tracing was used in this case, knowing that finite-difference acoustic modeling would be done later to confirm the ray-tracing results.

The ray-tracing study was carried out using NORSAR 3D and NORSAR SeisRox software. Specific points of interest on subsalt horizons were chosen to produce azimuth-offset coverage (flower) plots and illumination vector plots. For the specified dip and azimuth on the target horizon, the flower plot (Figure 3a), shows the azimuths and offsets necessary to illuminate that point. In this case, the required offsets fall far outside the range recorded in wide-azimuth (WAZ) geometry.

**Figure 3** (a) Surface offset-azimuth coverage for a low-dip subsalt reflector adjacent to salt. (b) Illumination density plot for the actual WAZ geometry from a subsurface point below salt.

Information regarding the possible dips and azimuths that could be illuminated with a certain acquisition geometry and velocity model can be obtained with illumination vector analysis (Lecomte, 2008). Figure 3b shows that the illumination below the salt is patchy for the WAZ geometry. There is evidence
of illumination of very low dip (0°-10°) as well as an illumination pattern consistent with the steeper (30°-50°) dip west of the salt flank. The base salt geometry has a strong influence on the transmitted rays.

Similar to the partial migration image analysis, ray tracing shows more evidence for an illumination void in the area below salt where the two different interpretations are possible. The ray-tracing flower plot in Figure 3a suggests that improved illumination would require significantly longer offsets and NW-SE azimuthal coverage.

Ray tracing through salt bodies is inherently ambiguous because the sharp impedance contrast between salt and sediments results in failed rays. For these cases, wave-propagation-based illumination is preferred.

**Finite-difference Modeling**

Acoustic 3D finite-difference (FD) modeling, followed by common-shot wave-equation migration (WEM) was proposed as a robust method to analyze subsalt illumination and image quality. Using the unsmoothed velocity model and inserting the low-dip subsalt horizons, FD modeling would show what the image should look like if the interpretation was correct. Comparing the migrated synthetic image to the real data would help to understand which interpretation was more likely.

For the FD modeling, the final sedimentary velocity model was interpolated to a 25-m x 30-m x 10-m grid and the density volume was extracted using Gardner’s equation (Gardner et al., 1974). Subsalt horizons interpreted from the real data were added to the density model. A regular grid of constant-density spheres was added to the density model to evaluate illumination for the full range of dips.

Three different acquisition geometries were simulated with 3D finite-difference modeling: (1) Areal or node geometry, 400-m node (receiver) spacing where each node is surrounded by sources spaced 50 m apart with a maximum inline/crossline offset of 14 km, (2) same node geometry with a maximum absolute offset of 8 km, and (3) a typical four-source, two-recording-vessel WAZ geometry.

The results of migrating the modeled data for the three acquisition geometries lead to a significant conclusion: the westward dips that form the roll-over structure are present with all three geometries, despite their absence in the original model (Figure 4).

*Figure 4* Density model (a), WAZ simulated data (b), 8-km areal simulated data (c), and 14-km areal simulated data (d). Black arrow indicates west dip events observed on simulated data.
This supports the theory that the dips are not real data, but are multiples or poorly cancelled migration energy. The modeled data also show that imaging the low-dip subsalt horizons requires both long offsets and full-azimuth data to get a consistently improved image. As a final test, a fourth data volume was generated using the areal geometry with an absorbing surface, eliminating surface-related multiple energy (Figure 5). As this volume shows, without the surface-related multiples included, there is no contradicting dip energy present in this area.

Figure 5 14-km areal geometry data with multiples (a) and without surface multiples (b).

Conclusions

Acoustic finite-difference modeling confirms the results of the partial migration and ray-tracing analysis. A steeply dipping base salt geometry creates an illumination void beneath the salt. Interpretation of false events in the low-illumination area can significantly change the economics of a prospect. Modeling with and without a free-surface boundary demonstrates that the dips interpreted as the roll-over structure were consistent with events that disappeared when modeling without multiples. Future studies of this type would benefit from recently published techniques that combine the directional information from ray-tracing and the robustness of wavefield propagation, e.g. Lapilli et. al. (2010). Illumination and imaging improvements would be expected from the acquisition of long-offset/full azimuth data. Targeted dual-coil acquisition (Moldoveanu and Kapoor, 2010) over the existing WAZ data could be an efficient way to acquire the needed azimuths and long offsets.

Acknowledgements

We are grateful to WesternGeco for computer resources and permission to publish this paper.

References


