Application of Image-domain LSRTM for Illumination Study and Optimal Survey Design

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Summary

In complex structures such as subsalt area, the survey design is challenging and critical due to the complicated wave field behavior involved in such structures. We present a wave equation modeling illumination study with the objective to achieve optimum survey design for complex subsalt imaging. Three surveys, narrow azimuth (NAZ), wide azimuth (WAZ) and full azimuth (FAZ) surface acquisition configurations are simulated using wave equation based acoustic forward modeling. The reference model as a set of surfaces following the structure dip are used for reflectivity modeling. Then the simulated data are imaged by reverse time migration. By comparing the remigration image and the reference reflectivity model, the illumination function is computed to approximate the diagonal elements of the Hessian for inversion. The study shows that the FAZ survey provides the best subsalt illumination, the WAZ survey can provide comparable subsalt illumination with some carefully chosen design parameters, while NAZ acquisition has inherent subsalt illumination problems that can only partially be addressed via survey design.

Introduction

Due to wavefield distortion by complex salt geometries, lack of illumination is among the most difficult of subsalt imaging challenges in the Gulf of Mexico. Over the course of interpreting a subsalt area of interest in the Mississippi Canyon region of the Gulf of Mexico with legacy processed data, it was found the existing seismic data was inadequate to derive reliable interpretation. Available data over this area includes legacy NAZ and WAZ 3D surveys. The area of interest is shown in Figure 1 within the green circle. In this area, the salt boundary is not imaged with the existing data, contaminated by strong swing noise present, which could be from poor illumination or converted waves traveling through the salt bodies. The converted wave following the base of salt can be removed during pre and postmigration (Huang, et al., 2013, Wang, et al., 2011). Here we focus on the illumination study of the primary reflection. The difficulty is also demonstrated on a profile in Figure 2 showing poor image quality and the lack of a clear base of salt.

The area of interest lies between and below two salt bodies. Between the two salt bodies, there is a small window for acoustic wave paths to travel without encountering salt. It is suspected that poor illumination from the proximity of salts is most responsible for the difficulty with imaging and a carefully selected acquisition configuration might improve illumination on the subsalt area. A multisurvey illumination study was conducted to confirm this hypothesis. The existing NAZ and WAZ 3D surveys were included as well as a synthetic coil shooting FAZ survey for comparison. A 3D uniform amplitude reflectivity model was built based on a series of horizons and salt bodies, followed by wave equation based finite difference forward modeling. The synthetic modeling was simulated with each of the acquisition geometries. RTM migration is performed on the modeled datasets for each survey to compare the image reflectivity and amplitudes of target depth horizons.

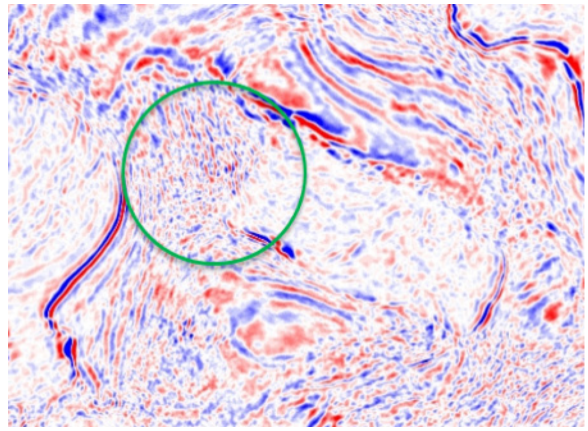

Figure 1. Depth slice of legacy RTM volume at target region inside green circle with imaging challenge. There is no coherent event imaged and the salt boundary is missing.

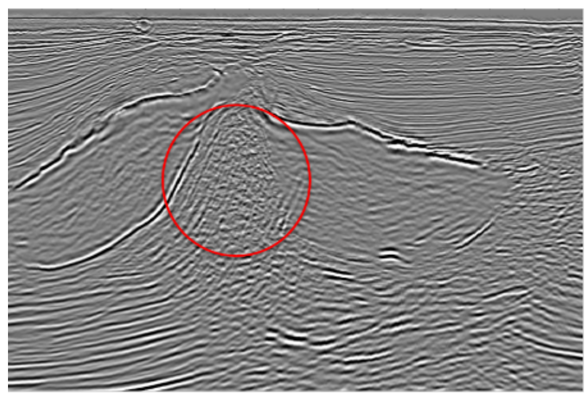

Figure 2. Stack of legacy RTM volume at target area inside red circle with imaging challenge. There is only noise and no coherent event imaged. Base of salt body at right hand side is missing.

Method

The illumination analysis for wave equation migration is based on a least-squares approximation in the image domain. The image-domain least-squares migration gives the linear approximation equation in the following form,

$$\mathbf{I} = (\mathbf{L}^T\mathbf{L})^{-1}\mathbf{L}^T\mathbf{d}$$

Here d is the data, L is the modeling operator, L^T is the migration operator, and I is the linearized inversion image. Here $(L^TL)^{-1}$ is an operator that has both the focusing effects and amplitude compensation. For illumination study, it is simplified as amplitude term only, which can be calculated as a ratio between the reference image and the remigrated image (Claerbout and Nichols, 1994; Rickett, 2003).

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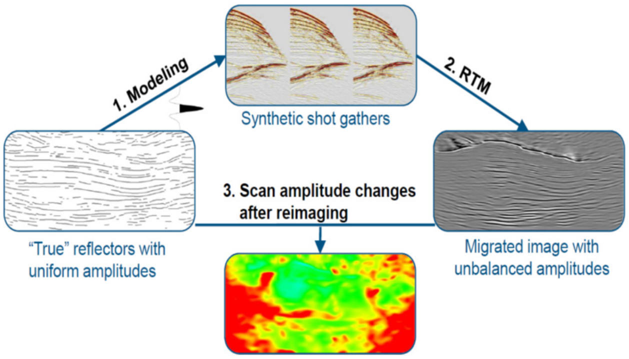

Figure 3. The flow for computing illumination function.

To perform a 3D acoustic forward modeling requires a 3D velocity model, a reflectivity model and an acquisition geometry. The existing VTI models were used in the forward modeling and associated RTM. There are different choices for the reflectivity model, such as the enhanced stacking image or the delta function of surfaces. The flow for computing the illumination function is presented in Figure 3. He et al. (2018) stated that during the modeling the interference effects from the stacking image could cause amplitude issues in AVO analysis while the spike-valued surfaces preserved the modeling amplitude to be constant through all incident angles. Thus, the illumination calculation is more accurate with a better amplitude-preserved modeling procedure.

Here, to create the reflectivity model, a series of fourteen reflector horizons are interpreted based on events in the legacy RTM stack image, including five horizons within the area of interest. A 3D uniform amplitude reflectivity model is generated from these horizons and shown in Figure 4. Three surface acquisition configurations are simulated: a NAZ 3D with north-south shooting direction, a WAZ with 45° northwest-southeast shooting direction, and a simulated FAZ using circular acquisition geometry. The NAZ and WAZ 3D were based on existing seismic acquisitions available in the area of interest.

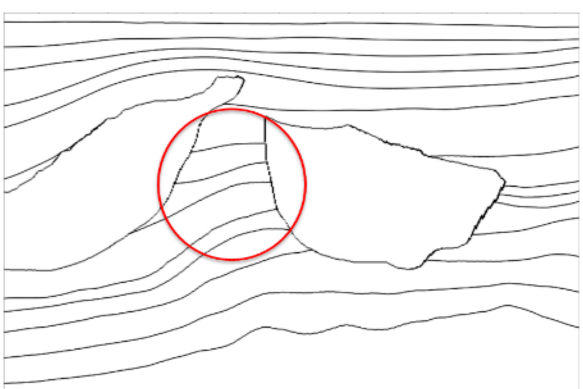

Figure 4. Reflectivity model showing reflectors at target region. Five reflectors with varied dips were added to target region.

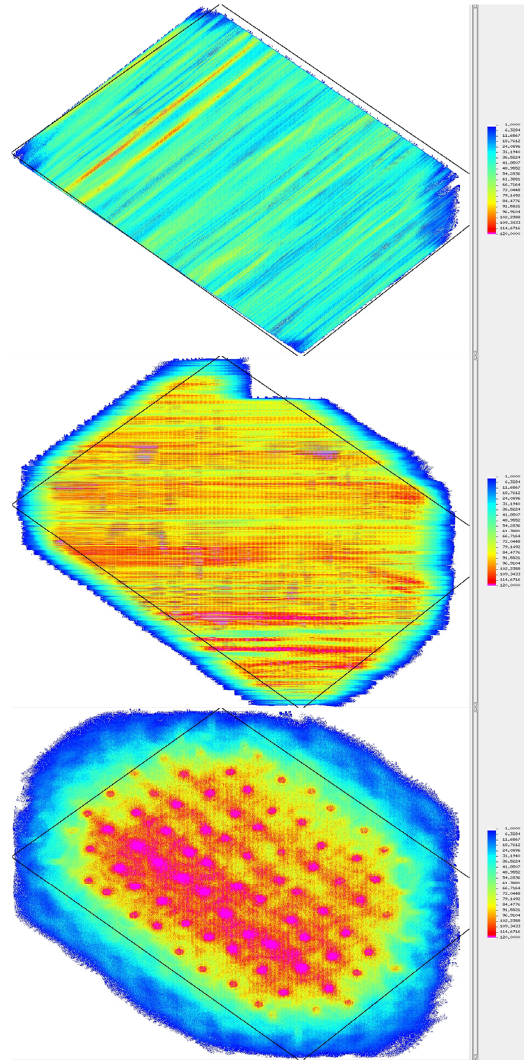

Figure 5. Fold coverage for NAZ, WAZ and FAZ surveys.

The NAZ acquisition configuration is as follows: north-to-south shooting direction, 62.5 m shot spacing, 180 m shot line spacing, 6 streamers with 80 m streamer separation, and 9000 m streamers each with 720 receivers. The WAZ survey is acquired at 45° northwest to southeast, 37.5 m shot spacing, 600 m shot line spacing, 10 streamers of 120 m streamer separation and 7000 m length, each with 558 receivers. The FAZ survey is designed to be a circular acquisition with circle center spacing of 3000 m, two streamer vessels of fourteen streamers each with 100 m streamer separation and 8000 m length with 640 receivers per streamer. Figure 5 shows the comparison of fold coverage for NAZ, WAZ and the circular shooting for all offsets. The footprints of the different acquisition geometry are observed. WAZ and the circular shooting surveys are observed with the better coverage than NAZ. The fold is the most for the circular shooting. As illumination is primarily determined by acquisition configuration and limited by sediment and salt geometry, a comparison of the resulting subsurface illumination provided by each acquisition configuration will provide the extents and limits of each.

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The surface seismic acquisition is simulated using an acoustic finite-difference (FD) modeling algorithm followed by reverse time migration (RTM) to migrate the synthetic data with the same velocity model used in the forward modeling. The spike-valued surfaces are fed into the modeling as reflectivity to generate flat AVO reflections. The data is recorded with different acquisition configurations. RTM is used preferentially as the imaging algorithm as it has the capability to image the subsalt better than other imaging methods. The same velocity model is used to eliminate the effect of velocity errors in the study. The reflectors in the sediment are imaged well, as expected. The layers in the subsalt area are not imaged in the poor illumination area. Illumination of the target reflectors is analyzed on the RTM image. To eliminate other factors which may affect imaging quality or evaluation of illumination, surface multiples are excluded in the acoustic forward modeling of the synthetic data.

The RTM image amplitude of the reflectors along the reflector horizons are extracted to study the illumination of the target region. As the amplitude of the RTM images is normalized, the amplitude of a reflector image is a direct measure of reflector illumination. The stronger the amplitude, the better the illumination.

Results

Figures 6, 7, and 8 show the RTM images of the NAZ, WAZ, and FAZ forward modeled data, respectively. With adequate illumination, we expect each reflector to be imaged with uniform amplitude. The results of the migration instead show clear amplitude differences, indicating distinct differences in illumination between the three acquisition configurations. In Figure 6, imaging of the reflectors from the NAZ configuration show broken reflectors, as indicated by the red arrow, while in Figure 7 and 8, the reflectors at the target region are fully imaged with the WAZ and FAZ configurations. The illumination of the reflectors at the area of interest is insufficient with the existing NAZ configuration. The steep dip salt flank diffracted the wavefield away from the surface receivers, which leads to the poor illumination of the primary reflection and the imperfect cancelation of the swing noise. Additionally, with the comparison of the images from the WAZ and FAZ configurations, it is noted that both provide images with comparable quality. For the particular subsalt geology in the area of interest, the WAZ acquisition configuration achieves similar illumination although FAZ has a better coverage in azimuth. It could be that the WAZ acquisition covers enough signal from the primary reflection. The redundant information from FAZ does not contribute much to the imaging process. Actually, from the experience of processing both datasets, the rich azimuth and long offset information from the FAZ acquisition may be helpful during the model building process but provides very limited benefits during the final imaging step.

An additional observation can be made concerned the dependence of illumination on dip. The horizons interpreted for the study were designed to cover a range of dips. The RTM images of the modeled data clearly demonstrate poorer illumination with increased dip. It is also apparent that the base of salt image associated with higher dips are broken or missing. It is known that longer offsets and larger apertures in both forward modeling and the corresponding migration can improve imaging of higher dips. It is noticeable that the circular shooting gives more swing noise than the other two surveys, which is due to the irregular surface coverage.

To attain overall illumination of the target area, we compare amplitude maps extracted from a reflector horizon, which are displayed in Figure 9, 10 and 11 with high amplitudes displayed in pink and weak amplitudes in blue. High amplitudes indicate good illumination. The target region is indicated by the black circle. The blue area at the right of the circle corresponds with salt. The salt body boundary is clearly imaged. In general, the WAZ (Figure 10) and FAZ (Figure 11) amplitude maps show higher amplitudes than the NAZ (Figure 9), which is consistent with the stacked sections shown earlier.

The use of the FAZ acquisition configuration allowed for an upper limit to the illumination that could be expected at the target region. The similar level of illumination observed in the WAZ and FAZ modeling demonstrates that existing data is sufficient for imaging this target and additional data will provide limited uplift. Likewise, the results from the NAZ modeling demonstrates that the existing NAZ data is insufficient. It is left for future study to determine whether a different NAZ acquisition azimuth would suffice to image the area of interest or if a WAZ acquisition is required.

According to the results of this illumination study, the WAZ survey is able to provide reasonable illumination of this target region. Difficulty in imaging the area of interest may result from an error in salt geometry or sediment velocity. While outside the scope of this study, this assumption was confirmed via additional updates of the sediment velocity and salt geometry, which demonstrated significant uplift of the target region.

Conclusions

We present a multisurvey illumination study with a 3D acoustic forward modeling approach. Illumination functions are computed by image-domain demigration and remigration. The results show that the legacy WAZ or a FAZ acquisition configurations can better illuminate the target region than that of the legacy NAZ acquisition. In addition, for the target region, the WAZ acquisition configuration provides illumination comparable to FAZ acquisition. While it is possible that a different NAZ acquisition azimuth could provide better illumination of the target, this study does confirm that the existing NAZ is insufficient and the existing WAZ data provides enough coverage to image the target.

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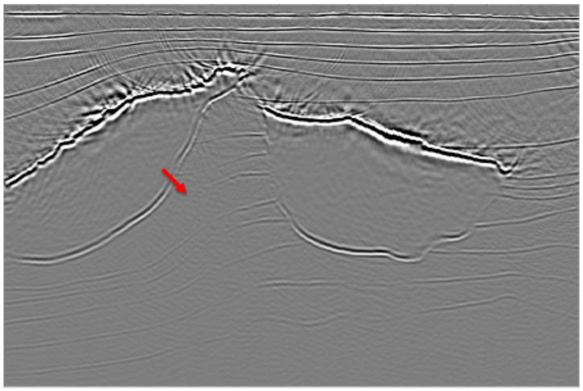

Figure 6. RTM image at target region with NAZ synthetic data. Reflector indicated by the red arrow cannot be imaged in NAZ surface acquisition configuration.

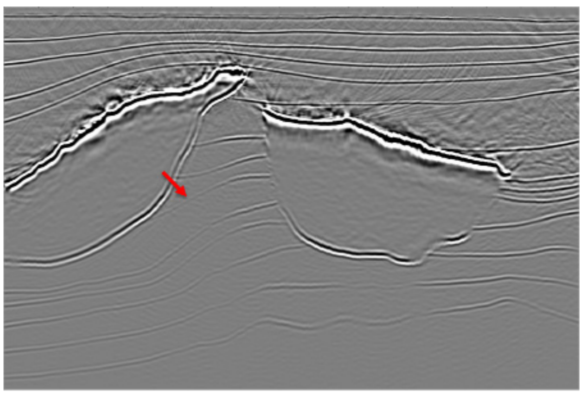

Figure 7. RTM image at target region with WAZ synthetic data. Reflector indicated by the red arrow is imaged in WAZ surface acquisition configuration.

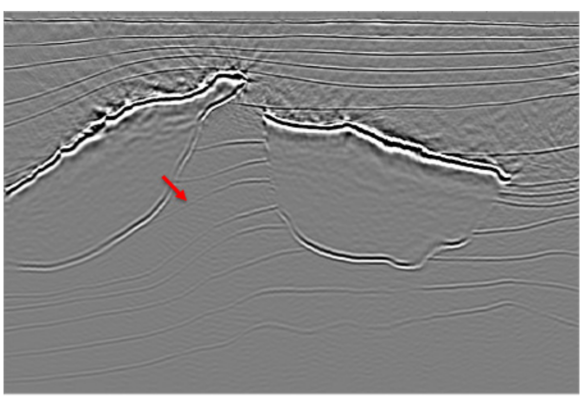

Figure 8. RTM image in target region with FAZ synthetic data. Reflector indicated by the red arrow is imaged similar to WAZ surface acquisition configuration.

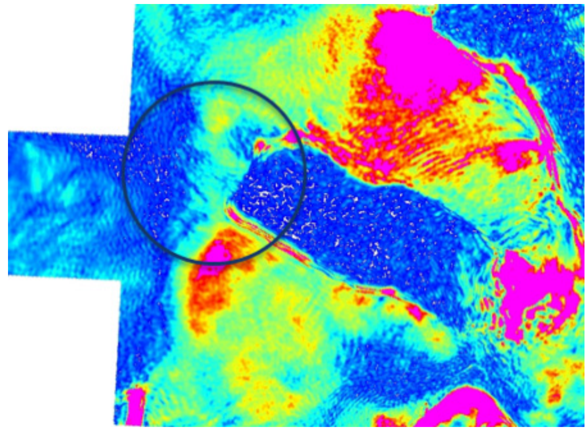

Figure 9. Amplitude map extracted from RTM image of NAZ data. Target region is inside black circle in which salt body in blue is shown at right. The target region is poorly illuminated.

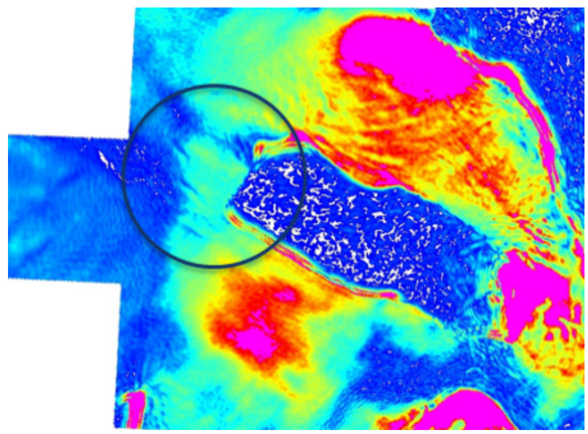

Figure 10. Amplitude map extracted from RTM image of WAZ data. Target region is reasonably illuminated shown inside black circle.

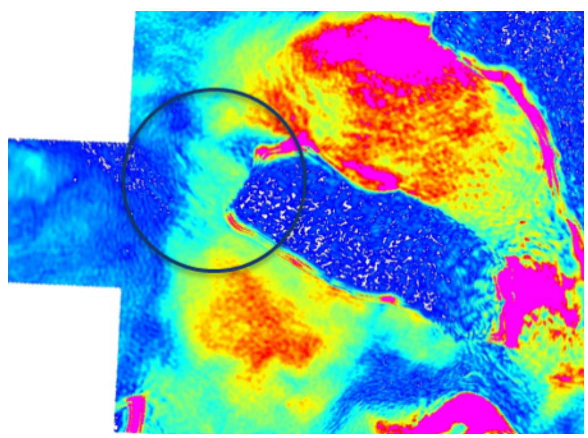

Figure 11. Amplitude map extracted from RTM image of FAZ data. Target region is reasonably illuminated shown inside black circle.

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