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# Technique Enhances Subsalt Imaging

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HOUSTON–Technology advances such as wide-azimuth/full-azimuth (WAZ/FAZ) acquisition, reverse-time migration (RTM) and iterative salt imaging in model building have greatly improved subsalt image quality.

In the Gulf of Mexico, steeply dipping three-way closures are familiar subsalt targets. However, despite these imaging improvements, some of these targets remain poorly imaged. The fundamental problem is imperfect illumination from limited acquisition. In the poor illumination zones, migration artifacts and coherent noise, such as residual multiples and converted waves, become prevalent and can severely contaminate the images and mislead the interpretation.

A specialized reverse-time migration technique addresses this issue by combining a deconvolution imaging condition with vector offset output (VOO). The effectiveness of RTM in tandem with VOO stacking has been demonstrated on WAZ data from the Walker Ridge area in the Gulf, illustrating how this technique can enhance the subsalt signal amplitude and reduce noise, thereby providing a cleaner subsalt image and decreasing subsalt exploration risk.

In deepwater Gulf of Mexico subsalt oil exploration, the salt-related structures serve as one of the main structural traps for hydrocarbons. Yet, the salt bodies also present the major obstacles for subsalt imaging. Their irregular 3-D shapes and high seismic velocity compared with surrounding sediments can cause severe wave field dissipation and distortion as seismic waves propagate through the complex salt bodies.

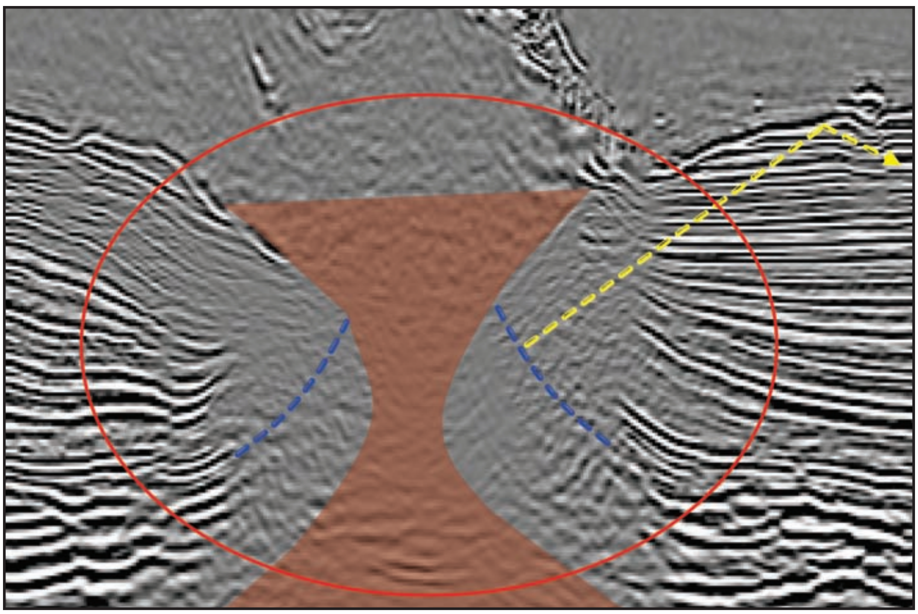
During the past few years, advances in both acquisition and imaging technologies have provided unprecedented breakthroughs for subsalt imaging in terms of image quality as well as velocity model accuracy. Most of the subsalt four-way prospects with gentle dips are well imaged with the latest technologies, such as wide-azimuth acquisition and tilted transverse isotropic reverse-time migration.

However, other subsalt exploration targets, such as the potential three-way traps next to the salt flank or salt keel circled in Figure 1, remain poorly imaged with existing technology. The target dips, marked by the blue dotted lines, could be as steep as 70 degrees. Because of its oblique angle to the base of salt, most of the reflected energy at the target reaches the base of salt at an over-critical angle, and is reflected back toward the subsalt (yellow lines in Figure 1). Only a limited amount of energy may be reflected back to be recorded at the surface. Therefore, the amplitude of the target section is weaker than the surrounding area.

In extreme cases of poor illumination (e.g., where the dipping sediments truncate against the salt flank), the true events can be overwhelmed by noise. To improve the images in illumination shallow zones, illumination compensation must be addressed to enhance the amplitude as well as reduce the noise to enhance the signal-to-noise (S/N) ratio.

**FIGURE 1**

**Example WAZ RTM Illumination Issues In Gulf of Mexico Subsalt Target**



### Illumination Methods

Several methods have been proposed to compensate for the amplitude differences resulting from illumination. The most commonly used technique typically is applied post-migration and is a global scalar derived

FIGURE 2

Section in an RTM Impulse Response (Left) and Shot Migration Division into Nine Sectors (Right)

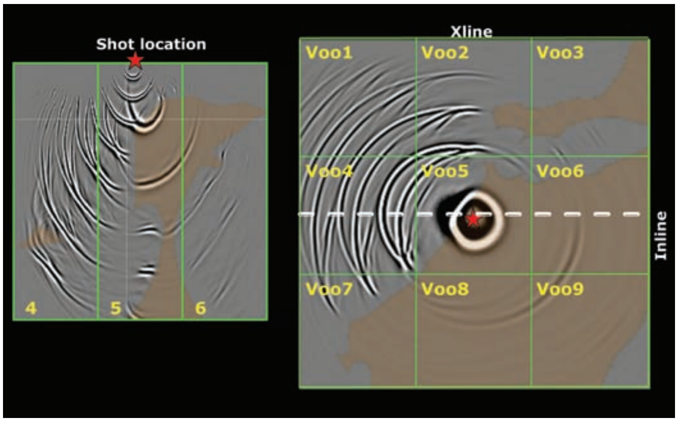
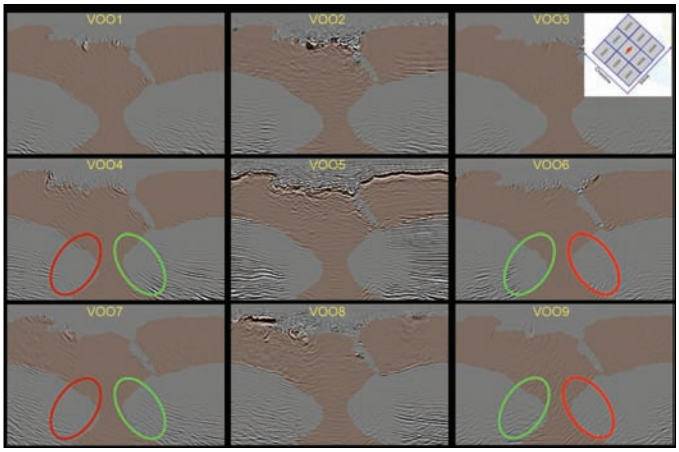



FIGURE 3

Example of VOO Image Sectors Around Salt Keel




from the source-side wave field illumination. Unfortunately, this approach only provides a smooth and angle-independent scalar, resulting in a mild compensation that fails to adequately account for amplitude variations in the case of complex structures.

More accurate techniques have been proposed, such as least-squares migration (LSM). In LSM, the optimized image is obtained iteratively by minimizing the mismatch between the demigrated and field data. In this case, the imperfect illumination issue is solved directly at the core of the inversion process. However, LSM is very computationally intensive because it requires multiple inversion iterations, with each of them including at least one migration and one demigration.

Some other techniques can be seen as simplifications of LSM, such as migration deconvolution, where the inversion is applied to discretized grids. The illumination-based weighting of RTM angle gathers is another further simplified technique. It makes use of the subsurface angle- and azimuth-dependence of illumination. It can be used to provide a balanced section and to improve the S/N of angle stacks. However, this method is still expensive, since it requires RTM output of angle gathers from both synthetic and real data, and may be limited for use with very specific targets.

A much less expensive method is a hybrid normalization technique that provides a balanced option between global compensation and shot-by-shot wave field illumination compensation. Contrary to global compensation, shot-by-shot compensation can adapt to rapid variations of illumination. However, the problem is that it equally boosts both the noise and signal traveling through poorly illuminated areas, often resulting in a noisy image. The hybrid method applies a scalar on the shot-by-shot compensation in order to limit the noise enhancement. It can result in a less noisy image, but at the expense of applying only a mild compensation of the signal amplitude. In addition, since the S/N can vary greatly in a survey, controlling the limitation scalar can be difficult.

The new technique proposes to combine–in one RTM migration–a modification of the conventional imaging condition to a deconvolution imaging condition, with vector offset output stacking. The intent is to fully enhance the signal traveling through poorly illuminated areas while preventing the boosted noise from contaminating images by VOO stacking.

The benefits of the deconvolution imaging condition were demonstrated using the model of the Society of Exploration Geophysicists Advanced Modeling (SEAM) synthetic. Applying this technique to the Walker Ridge study area showed that combining the deconvolution imaging condition with VOO can effectively enhance the signal without boosting the noise.

### Deconvolution, VOO Stacking

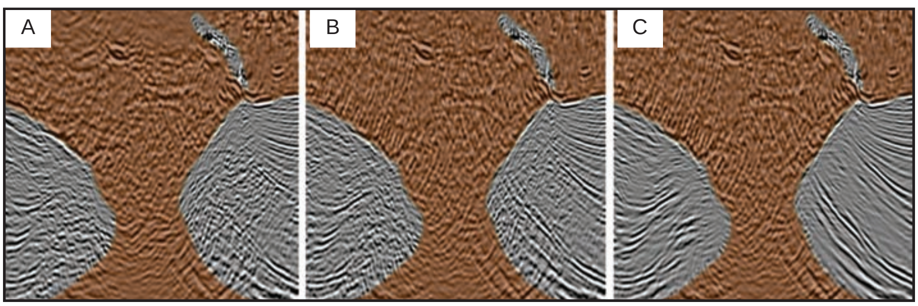
The standard imaging condition of the common-shot RTM usually corresponds to the cross-correlation of the source (S) and receiver (R) wave fields, based on the kinematics of Claerbout's 1971 imaging principle. Using a modification of this principle, the illumination compensation is applied directly at the imaging condition stage, ensuring that individual shots are well balanced prior to the summation process. Therefore, it has the ability to adapt to rapid variations of illumination.

The drawback, however, is that it will also enhance the noise. Multiples, converted waves and migration artifacts from velocity errors, etc., can be boosted significantly, along with the signal, if the deconvolution imaging condition is applied by itself. It must be followed by a tool to remove the noise while preserving primary signal.

Based on the idea that in the subsurface imaging space, signal and noise can have different output offsets to the shot location, dividing the migration output into vector offset domain provides an opportunity to separate the noise from the true image contribution. Compared with conventional migration, which migrates a common-shot data to a rectangular aperture area and stacks all migrated shots to obtain a full stack, the vector offset output scheme

FIGURE 4

WAZ RTM Around Potential Prospect in Walker Ridge Area



proposed divides the aperture area for one shot into multiple vector offset tiles, according to the shot location.

In practice, the rectangular output aperture of every migrated shot is divided into a number of sectors (typically nine), one for each vector offset range, as illustrated in Figure 2. At left is a section in an RTM impulse response, and at right is a top view of the division of the shot migration into nine sectors according to their vector offsets from the shot location. The white line represents the depth location of the section to the right.

Stacking all the VOO sectors gives the same image as the traditional full stack. But given the local geological structure, we are able to selectively combine migration outputs from only the vector offsets that contribute to the signal at a given location. Reflectors that are flat or have gentle dips should have image contributions in all aperture vector offset tiles, except when constrained by the actual acquisition geometry.

For dipping reflectors, however, the contributing energy often is distributed into certain tiles according to the actual 3-D structure orientation (azimuth and dip). Subsalt reflectors with high dips, typically migrated from large aperture, tend to concentrate more locally. The migration artifacts exist in all vector offset outputs, and noise from residual multiples may focus in different tiles from the true images as a result of different propagation from the primaries.

Figure 3 shows a real WAZ example from Walker Ridge of the nine VOO sectors of the image around a salt keel. Green circles show the locations of signal contributing to the image, while red circles represent the noise contribution that should be unselected from the stack image. Sectors 4 and 7 are the primary contributors to the image of the right side of the keel, while sectors 6 and 9 house the energy primarily responsible for imaging the left side of the keel.

On the other hand, sectors 4 and 7 contain only noise on the left side of the keel, and sectors 6 and 9 contain noise on the right side of the keel. By weighting the stack of the different vector offsets based on the dip and azimuth of their seismic events, this method can reduce the noise contamination from shots not contributing to the image of a particular area.

**Testing The Technique**

In order to test the technique, the deconvolution imaging condition was applied to synthetic data using the Society of Exploration Geophysicists Advanced Modeling synthetic. An acoustic model simulating a WAZ acquisition using SEAM was used to generate input data without multiples. RTM migrations then were run using the true velocity model to compare the effect of different illumination compensations. The global compensation is able to slightly enhance the subsalt energy, compared with no compensation, but is too mild and many weak amplitude anomalies remain.

Alternatively, the deconvolution imaging condition RTM is able to boost many weak anomalies to the level expected from the reflectivity model. This demonstrates the benefits of the deconvolution imaging condition over a more conventional illumination compensation approach. However, since the synthetic data for this test are free of both noise and multiple, neither could adversely affect the result.

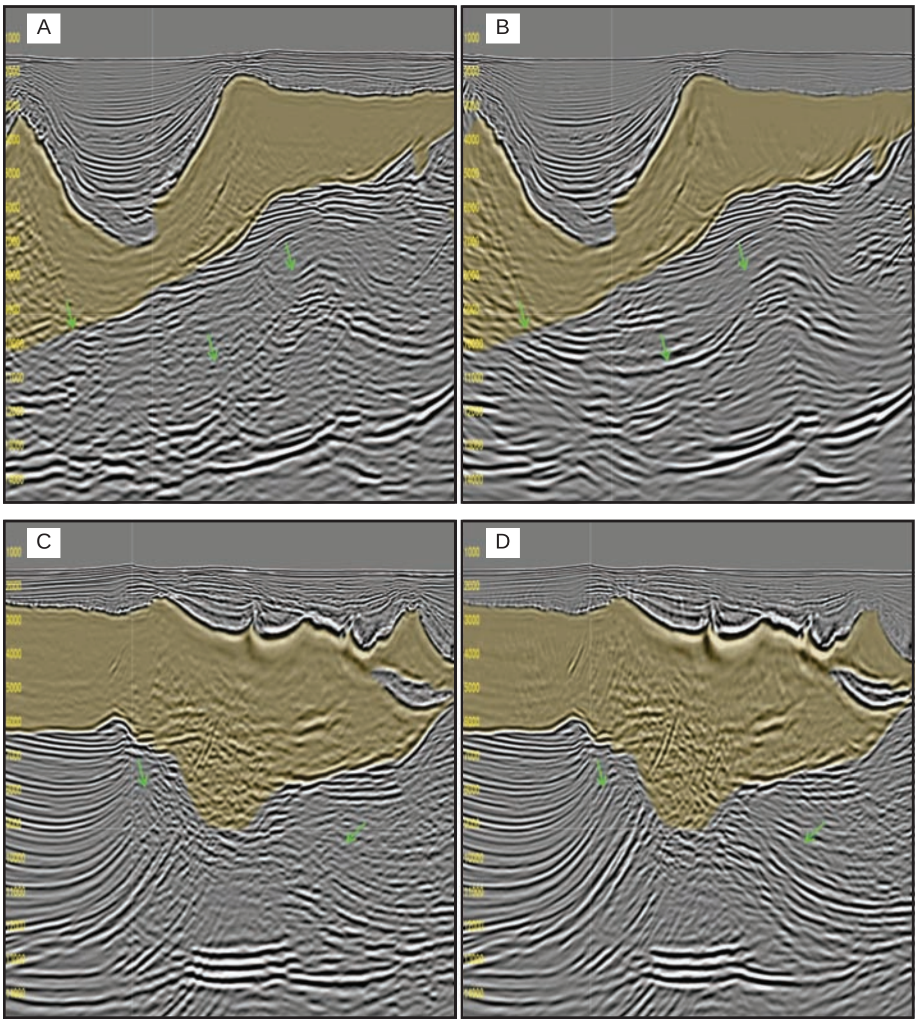
The next step was testing the combination of the deconvolution imaging condition and VOO in the Walker Ridge study area in the Gulf of Mexico. The data and velocity model are from a WAZ survey acquired with an in-line offset of 8,000 meters and a cross-line offset of 4,000 meters.

Figure 4 shows WAZ RTM around a potential prospect in the Walker Ridge area. The panel at left (a) is the conventional RTM stack with no illumination compensation; the center panel (b) is the RTM stack with deconvolution imaging condition; and the panel at right (c) is the RTM stack with deconvolution imaging condition and VOO stacking.

These results show that the deconvolution imaging condition is able to boost the energy of the target dips on both sides of the salt flanks by enhancing the signal traveling through the salt. The dips are dominated by noise with contradicting dips on the conventional RTM images. However, the amount of noise near the

**FIGURE 5**

**WAZ RTM Around Three-Way Closure in Walker Ridge Area**



salt keel still is severely degrading the images, even with enhanced signals. By combining the deconvolution imaging condition with VOO stacking, the image improvement observed around the target is maintained or improved while reducing the amount of noise in the center to a level lower than that observed in conventional RTM.

Figure 5 is another subsalt three-way closure example from the Walker Ridge area. The images show the comparison of the combined deconvolution imaging condition and VOO stacking RTM with the raw conventional RTM. Once again, the combination enhances signal that was not imaged with the conventional RTM and attenuates some noise swinging over the target area.

In this example, the top left panel (a) shows the cross-line section of the RTM conventional stack; the top right panel (b) is the cross-line section of the RTM stack with deconvolution imaging condition and VOO stacking. The panel at bottom left (c) shows the in-line section of the RTM conventional stack, and the panel at bottom right (d) is the in-line section of the RTM stack with deconvolution imaging condition and VOO stacking. The green arrows indicate areas of signal enhancement brought by combining deconvolution imaging condition and VOO stacking.

This work demonstrates that combining the deconvolution imaging condition and VOO stacking in one RTM migration can mitigate the critical illumination issues commonly seen when imaging three-way closures under complex salt structures. The deconvolution imaging condition can fully balance the amplitude of each migrated shot prior to stacking and is more effective than the conventional post-migration approach, as shown on the SEAM synthetic example.

By decomposing the output into sectors according to their vector offsets to each shot, VOO RTM can allow signal and noise to be separated. The S/N of the RTM image then can be improved by a weighted stack of the separate sectors, based on the azimuth of their seismic events. As shown on the first real data example from Walker Ridge, applied by itself, the deconvolution imaging condition also can increase the background noise. By combining it with the VOO stacking RTM, the signal is enhanced properly while the noise is attenuated. ❐

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