Imaging 3-way closures by combining a deconvolution imaging condition with vector offset output RTM
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Summary
In the Gulf of Mexico (GOM), steeply dipping three-way closures are familiar subsalt targets. However, they are generally poorly imaged due to low illumination caused by complex salt geometry in the overburden. The weak underlying signal is masked by excess noise coming from migration artifacts, residual multiples or converted waves. As a result, the signal-to-noise ratio (S/N) is low in these areas.

This paper presents a specialized reverse time migration (RTM) technique, which combines a deconvolution imaging condition together with vector offset output to address this issue. Synthetic and real data examples are used to show that this technique can enhance the subsalt signal amplitude and reduce noise, thereby providing a cleaner subsalt image and decreasing subsalt exploration risk.

Introduction
During the last 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 (WAZ) acquisitions and tilted transverse isotropic (TTI) reverse time migration.

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 current technology. The target dips, marked by the blue dotted lines, could be as steep as 70 degrees. Due to 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 towards the subsalt (yellow lines in Figure 1). Only a limited amount of energy is reflected back to be recorded at the surface; therefore, the amplitude of the target section is weaker than the surrounding area.

Several methods have been proposed to compensate for the amplitude differences due to illumination. The most commonly-used technique is typically applied post-migration and is a global scalar derived from the source side wavefield illumination. Unfortunately, it only provides a smooth and angle-independent scalar, resulting in a mild compensation that fails in the case of complex structures because it cannot handle the rapid variations of illumination.

More accurate techniques have been proposed, such as the least-square migration (LSM) (Nemeth et al., 1999). 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, each of them including at least one migration and one demigration. Some other techniques can be seen as simplifications of LSM, such as the migration deconvolution (Hu et al., 2001; Yu et al. 2006) where the inversion is applied to discretized grids. The illumination-based weighting of RTM angle gathers (Gherasim et al., 2010, Shen et al., 2011) 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 the hybrid normalization proposed by Cogan et al. (2011), which is a balanced...
option between the global compensation mentioned earlier and shot-by-shot wavefield illumination compensation. Contrary to the global compensation, the shot-by-shot compensation can adapt to rapid variations of illumination. Its problem is that it equally boosts both the noise and signal travelling 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.

This paper proposes to combine, in one RTM migration, a modification of the conventional imaging condition to a deconvolution imaging condition, with vector offset output (VOO) stacking. Its intent is to fully enhance the signal going through poorly illuminated areas, while preventing the weak noise from being boosted by the compensation.

The benefits of the deconvolution imaging condition are demonstrated using the model of the SEG Advanced Modeling (SEAM) synthetic. We then show that the combination of the deconvolution imaging condition with VOO can effectively enhance the signal without boosting the noise on two real WAZ datasets from the Green Canyon and Walker Ridge areas of the GOM.

Deconvolution imaging condition and VOO stack

The standard imaging condition of the common-shot RTM usually corresponds to the cross-correlation of the down-going (D) and up-going (U) wavefields (Claerbout, 1971). The image of shot i, in any given point (x, y, z) of the output, is then

$$I_i(x,y,z) = \sum_{t=0}^{\tau} U_i(x,y,z,t) D^*(x,y,z,t)$$  \hspace{1cm} (1)

where $D^*$ is the complex conjugate of D. Alternatively, we use a modification of Claerbout’s originally proposed deconvolution imaging condition where the reflectivity is estimated by dividing U by D using

$$I_i(x,y,z) = \sum_{t=0}^{\tau} \frac{U_i(x,y,z,t) D^*(x,y,z,t)}{D(x,y,z,t) D^*(x,y,z,t) + \alpha}$$ \hspace{1cm} (2)

where $\alpha$ is a damping parameter. In this case, 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. Its drawback, however, is that it will also enhance the noise (multiples, converted waves, migration artifacts from velocity errors, etc.) if applied by itself; it must be followed by a tool to remove the noise, while preserving primary signal.

With the VOO technique (Xu et al., 2011), the RTM image is separated into vector offset outputs illuminated from different directions. The rectangular output aperture of every migrated shot is divided into a number of sectors (typically 9), one for each vector offset range, as illustrated in Figure 2. Therefore, it provides a domain where the imaging signal can be separated from the noise because, for a particular image location, the signal and noise likely originate from different directions.

The stacking of 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 (Figure 3). In this example, sectors 4 and 7 are the primary contributors to the image of
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the right side of the keel, while sectors 6 and 9 house the energy primarily responsible for the imaging of 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.

3D synthetic example

An acoustic modeling simulating a WAZ acquisition using the SEAM model is used to generate input data without multiple. We then run RTM migrations using the true velocity model to compare the effect of different illumination compensations (Figure 4). The global compensation is able to slightly enhance the subsalt energy compared to 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 is free of both noise and multiple, neither could adversely affect the result.

WAZ real data examples

The deconvolution imaging condition is first tested in Green Canyon, in the GOM. The data and velocity model we use are from a WAZ survey that has inline and crossline offsets of 8000m. The target is a potential subsalt three-way closure against a salt weld. Figure 5 shows that the deconvolution imaging condition is able to improve the image of the target by enhancing the signal going through the salt to overcome the power of the noise coming from the basin to its right. On the other hand, the amount of noise in the subsalt area in the center of the image is increased, and the image slightly deteriorated. By combining the deconvolution imaging condition with VOO stacking, the improvement we observe around the target is maintained or improved, while reducing the amount of noise in the center to a level lower than that observed in the conventional RTM.

Another subsalt three-way closure example is from the Walker Ridge area of the GOM. The data and velocity model are also from a WAZ survey acquired with an inline offset of 8000m and a crossline offset of 4000m. Figure 6 shows 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, furthermore, attenuates some noise swinging over the target area.

Conclusions

Our work demonstrates that the combination of 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. The VOO RTM decomposes the output into sectors according to their vector offsets to each shot, which can allow for the separation of the signal and noise. The S/N of the RTM image can then be improved by a weighted stack of the separate sectors based on the azimuth of their seismic events. As shown on the real data example from Green Canyon, applied by itself, the deconvolution imaging condition can also increase the background noise. By combining it with the VOO stacking RTM we can ensure that the signal is enhanced properly while the noise is attenuated.

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Figure 5: WAZ RTM around a potential three-way prospect in the Green Canyon area of the GOM. a) conventional RTM stack with no illumination compensation; b) RTM stack with deconvolution imaging condition; c) RTM stack with deconvolution imaging condition and VOO stacking. Red arrows indicate areas where the noise level is increased. Green arrows indicate areas of signal enhancement.

Figure 6: WAZ RTM around a known three-way closure prospect in the Walker Ridge area of the GOM. a) crossline section of RTM conventional stack; b) crossline section of RTM stack with deconvolution imaging condition and VOO stacking; c) inline section of RTM conventional stack; d) inline section of RTM stack with deconvolution imaging condition and VOO stacking. Green arrows indicate areas of signal enhancement brought by the combination of deconvolution imaging condition and VOO stacking.
References


