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Technologies Improve Subsalt Imaging

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SANTA CLARA, CA.–The increased exploration and development focus on complex deepwater targets worldwide is giving rise to new challenges for subsalt seismic imaging. For example, the rich oil reserves of the Gulf of Mexico are buried in deep and ultradeep waters up to 30,000 feet from the surface.

The U.S. Minerals Management Service estimates that the Gulf holds 37 billion barrels of "undiscovered, conventionally recoverable" oil, which at $100 a barrel, would be worth $3.7 trillion. However, these reserves are very difficult to find and reach because of the extreme depths. Technological advances in seismic imaging represent an opportunity to overcome this obstacle by providing more accurate models of the subsurface.

These challenges are being met with various wide-azimuth (WAZ) acquisition programs, which are in turn, spawning new workflows and new technologies for imaging WAZ data. These new technologies are compute-intensive, not only because of the increased data volumes of wide-azimuth marine acquisition, but also because of the high-fidelity algorithms that are being employed to meet the imaging challenges.

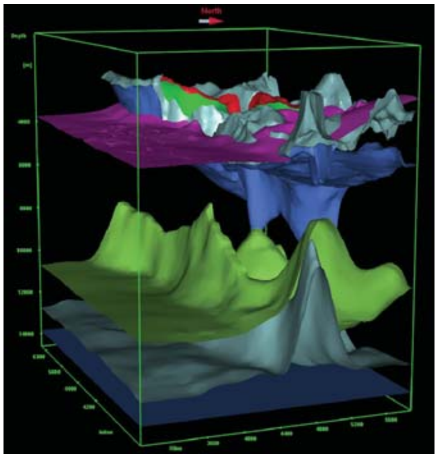
Among these technological advances, reverse time migration (RTM) yields the best possible images. RTM is based on the solution of the two-way acoustic wave equation. This technique relies on the velocity model to image turning waves. These turning waves are particularly important to unravel subsalt reservoirs and delineate salt flanks, a natural trap for oil and gas. Because it relies on an accurate velocity model, RTM opens new frontiers in designing better velocity estimation algorithms.

In many ways, the same hurdles that have always confronted exploration seismologists are still being faced in this new arena–namely accurate and efficient imaging, and determining the correct velocity model. While one may be hopeful that these hurdles are more easily overcome by acquiring more data, and while WAZ acquisition does introduce more information and resolution than was available in the past, the increased data volumes and increased complexity of the data itself are driving the development and deployment of new and innovative techniques for velocity model building and imaging.

To this end, the collaborative Kaleidoscope project was established between 3DGeo and Repsol, leveraging the resources of the Barcelona Supercomputing Center and relationships with Stanford University, IBM and the Spanish Research Council to model WAZ seismic data, and to experiment with optimal imaging strategies using both conventional wave-equation migration and RTM. A unique new velocity estimation technology has been developed that is consistent with wave-equation migrations and based on wavepath tomography that offers not only superior model building capability, but the ability to detect subsalt drilling hazards.

FIGURE 1

Geologic Model with Salt Bodies and Other Structures



Simulated WAZ 3-D Migration

Numerical modeling of wave propagation based on a Gulf of Mexico geological model is a powerful tool to investigate the proper imaging algorithms and survey acquisition geometries required for exploration and development. Using the modeling results, a comparison of the migration results of several algorithms shows that the best results are obtained when more information is incorporated in the imaging process (e.g., turning and/or prismatic waves). In practice, selecting a migration algorithm is based on computational and geophysical considerations. For instance, the complexity of the subsurface tells us whether turning waves are needed. The ability to estimate an accurate velocity model helps decide which method will produce the best results. Finally, computing resources could present challenges when large data sets need to be migrated, especially for advanced compute-intensive imaging techniques such as RTM.

For this example, a geologic model is used that covers 1,150 square kilometers and reaches 15 kilometers in subsurface depth. To image the deepest geologic structures, the required trace length is 18 de-

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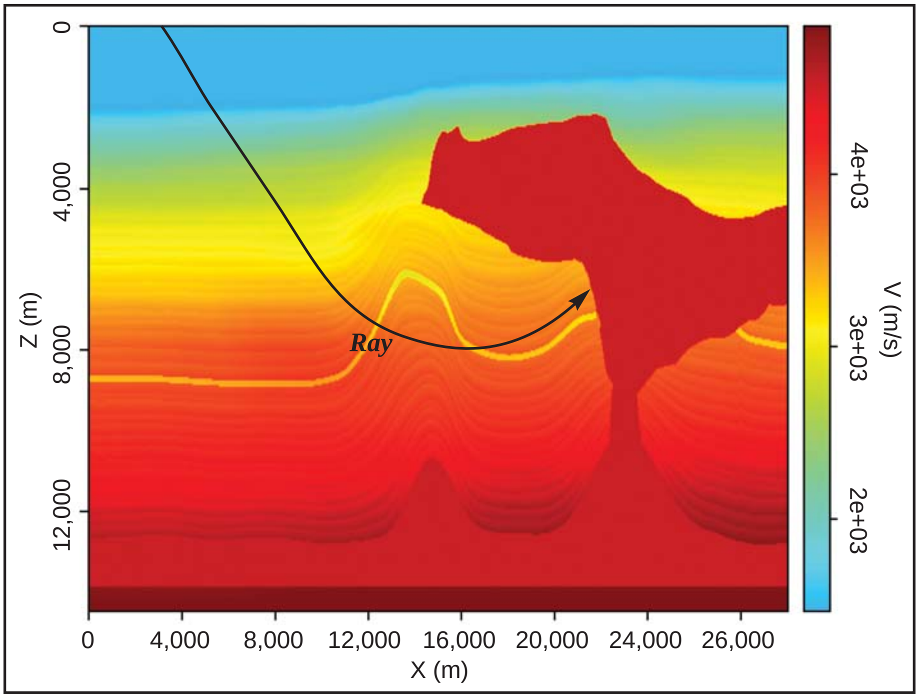
FIGURE 2

Velocity Model Showing an Overturning Ray



grees. Each of the 4,047 modeled shot gathers covers ±240 square kilometers, resulting in a 32-terabyte data set, which can be subsampled to simulate a narrow-azimuth acquisition or used in full to simulate a wide-azimuth towed-streamer acquisition geometry. The data can be used to benchmark imaging algorithms, evaluate processing workflows, design multiple elimination strategies, and design field data acquisition, including wide-azimuth and rich-azimuth alternatives. The combined data set can even be used to compare the performance of computer architectures.

Figure 1 displays the geological model used for this study, with salt bodies shown in blue. The geology behind the Repsol model addresses both complex and common problems typically found in subsalt exploration in the Gulf of Mexico. These problems include imaging salt feeders, steeply dipping subsalt reflectors, reflectivity changes in the subsalt section, faults and welds, and rugose top of salt–all of which give rise to multibranching and multipathing of seismic wave fronts. In addition, steep dips of the base of salt and complex salt shapes create illumination challenges that must be compensated by the imaging algorithm. In the near future, we plan to improve the model to benchmark anisotropy algorithms and reservoir characterization in full 3-D.

Data Imaging

After modeling, the data were migrated with advanced imaging techniques suited for handling complex wave field propagation. We decided to focus on three migration techniques. All of them use shot profiles for input data. The first migration technique utilizes a one-way propagator for the wave field propagation (SPM one-way). This propagator, which incorporates a Fourier finite-difference operator with optimized coefficients, is accurate for steep dips. The second migration technique is a two-pass migration, where the down-going wave field is saved and used as a source for the up-going wave field (SPM two-way). This technique has the ability to migrate overturning waves. Third, we used a two-way propagator based on the full 3-D acoustic wave equation. This last technique is known as RTM. All of the techniques have pros and cons.

SPM one-way is a fast algorithm that can image complex structures as long as the energy does not overturn. This limitation is overcome in SPM two-way and in RTM. However, having a limited sensitivity to steep dips, SPM one-way has the advantage of being less sensitive to velocity errors.

The two-way algorithm, based on the one-way propagator (going either up or down), is limited in its ability to correctly propagate events traveling close to 90 degrees in complex areas. This can produce events that are not positioned correctly in depth. Because SPM two-way can model up- and down-going events, artifacts similar to those seen with RTM will be created. These artifacts come from the cross-correlation of undesired events, such as head waves. Fortunately, these events can be attenuated by either looking at different images formed by the

FIGURE 3A

SPM One-Way Migration Result

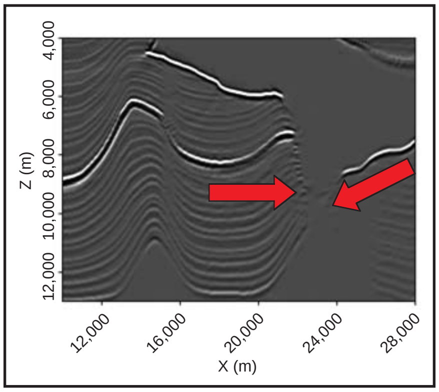


FIGURE 3B

SPM Two-Way Migration Result

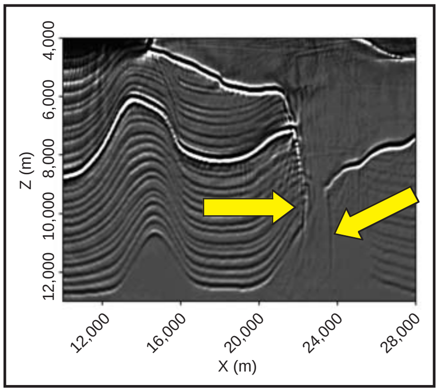


FIGURE 3C

RTM Migration Result

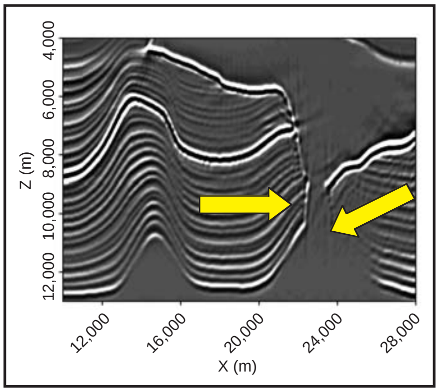


FIGURE 4A

Close-Up of Velocity Model

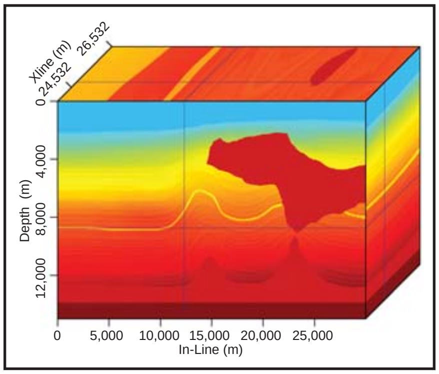


FIGURE 4B

SPM One-Way 3-D Migration Result

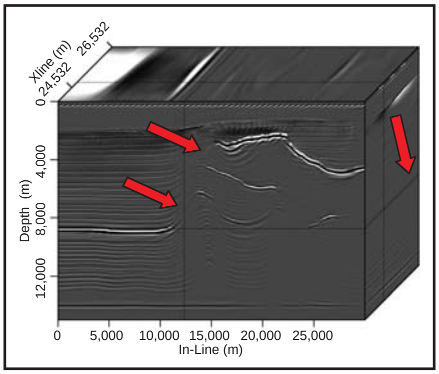
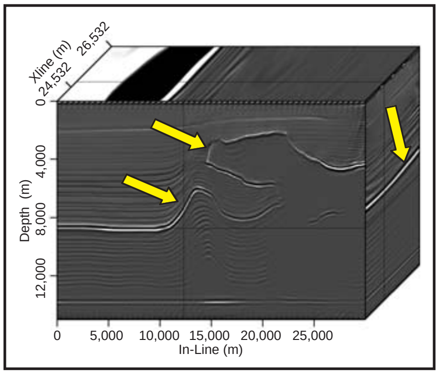


FIGURE 4C

RTM 3-D Migration Result



cross-correlation of up- and down-going events in the receiver and source wave fields separately, or by adapting the operator to exclude these artifacts.

Figure 2 shows the velocity model for an in-line through the 3-D Repsol model. A ray (in blue) shows that the steep flanks on the deep root of the salt body can only be imaged with overturning events. Figure 3A shows the SPM one-way result. The propagator is accurate enough to image the steep flank at z = 4,000 meters, but the deep salt root is not imaged.

Figures 3B and 3C show the imaging results for the SPM two-way and RTM techniques, respectively. The SPM two-way image shows the deep root pretty well, but not with the same accuracy as the RTM. The difference stems partly from the accuracy of the SPM propagator close to 90 degrees. A better propagator may result in a better image, but would also significantly increase cost. The noise level is slightly higher in the SPM two-way result because of the presence of internal multiples that are not properly imaged.

To test 3-D RTM and the effect of azimuth coverage in imaging, Figure 4A displays a volume extracted from the 3-D velocity model for narrow-azimuth acquisition. This volume embeds the 2-D section of Figure 2. As pointed by the red arrows, the SPM one-way result in Figure 4B shows missing reflectors that the RTM in Figure 4C is able to image properly. Note that the deep salt root visible in Figure 3C is not imaged in this narrow-azimuth result; the reason for this is simple and symptomatic of 3-D. Because of limited migration aperture, some parts of the model are not imaged. This illustrates the need for adequate aperture both in acquisition and in setting the migration imaging parameters.

Wave Path Tomography

In regions of structural complexity such as in the Repsol model and below rugose salt bodies in general, ray tracing-based tomographic velocity model updating suffers from similar problems as Kirchhoff migration–it may not be possible to trace rays through certain parts of the model, and multipathing is not easy to take into account. Wave field continuation imaging methods, such as shot profile migration and RTM, overcome these shortcomings naturally. It is, therefore, desirable to base the velocity model building on the same methods. Wave path tomography replaces back projection of velocity errors along rays with back projection along wave paths that are generated with the same propagation operator as the seismic image.

To streamline the velocity model updating process, we have implemented an automatic method of signal detection that eliminates the need for manual reflector picking by scanning the seismic data volume with prediction-error filters, and automatically selecting back projection points based on dip coherency and semblance strength. This approach can save months of human time on a typical 3-D seismic imaging project, shortening seismic imaging project turnaround time while exploiting the full redundancy of the recorded data. The automation also reduces human bias and manual picking error, while retaining the option to control quality and steer the solution. This approach is used with both standard tomographic ray trace updating and the wave path method.

Selecting back projection points independent of manually-picked horizons involves calculating the best single dip in a window and the coherency of the dip by iteratively applying plane-wave destructor filters. Points that satisfy specified levels of dip coherence, amplitude, semblance strength and distance from other points and the edges of the image

FIGURE 5

Sigsbee Synthetic Model

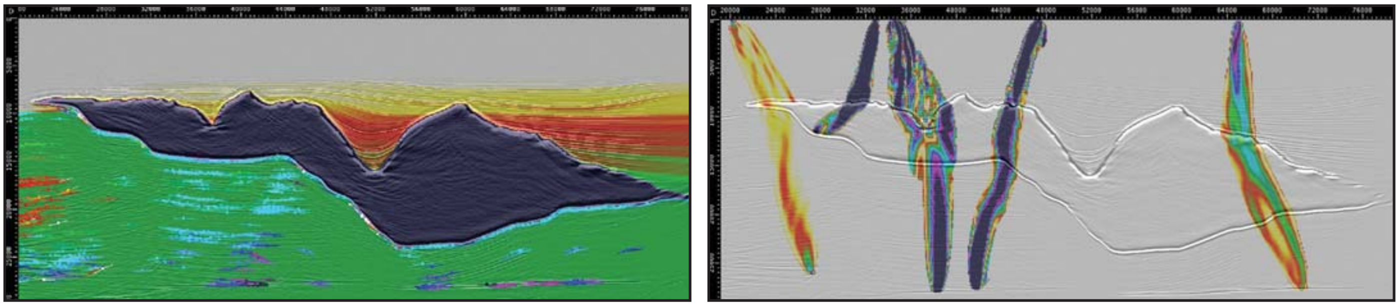
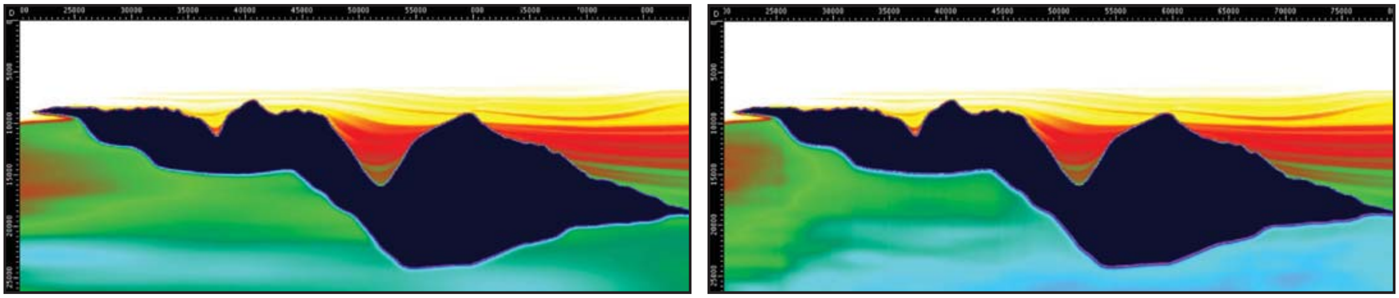


FIGURE 6

Two Iterations of Wave Path Tomography (Sigsbee Starting Velocity Model)



are selected as back projection points. This method allows for an even distribution of back projection points in the absence of strong geologic boundaries (reflectors) that define the velocity model.

With wave path tomography, instead of tracing rays to back project residual velocities, a "wave path" is constructed using the actual wave field continuation operator to represent the wave propagation between surface source/receiver pairs and subsurface reflection points. In this way, multipathing, sharp velocity contrasts and the band-limited nature of seismic wave propagation can be modeled more naturally than with geometric rays.

As an example, consider a tomographic update of the subsalt region in the Sigsbee velocity model (Figure 5). The starting migration velocity is correct down to the base of salt and constant below. A fairly small number of back projection points is selected (at left in Figure 5) based on reflection and semblance strengths, and reflector coherency (color indicates velocity residual). Examples of normal incidence wave paths are shown on the right side of Figure 5 (offset wave paths, where source and receiver surface location are separate, are not shown for this example). In contrast to infinitely narrow ray paths, the width of the wave paths provides a natural regularization of the inversion.

The updated velocity model (Figure 6, at left) is smoothed to compensate for the considerable gaps in back projection point coverage. The result is comparable with what can be achieved with ray tomography using the same residual data, but with 20 times the number of rays (normal and oblique incidence).

A further iteration (Figure 6, at right) brings the subsalt velocity model into agreement with the actual background model so that the flat subsalt reflector is positioned correctly and major subsalt faults and point diffractors are well resolved (Figure 7).

Detecting Subsalt Hazards

As a test case that combines these techniques, we chose a widely used 2-D synthetic data set provided by BP. Figure 8 shows the results of ray tomography and wave path tomography for detecting subsalt low-velocity zones. Wave path tomography based on actual subsalt residual move-out measured from the angle gathers is able to accurately detect and delineate potential drilling hazards.

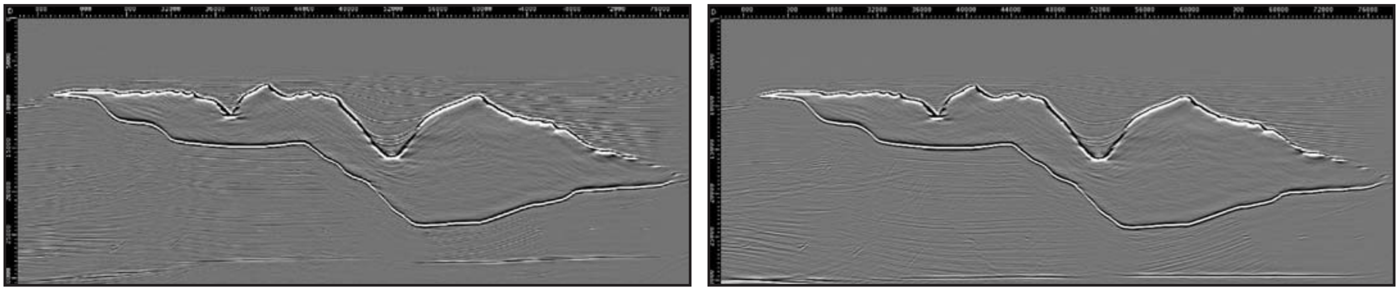
In this example, the target is the narrow, low-velocity anomaly below the left salt body. For the starting model, it is assumed that the velocity above salt and the salt bodies are known exactly, whereas the velocity below salt is a simple gradient extended laterally from the center of the section. The synthetic data are migrated with a downward continuation operator, and the reflector continuity in the zone of interest is very poor, which is also reflected in the low semblance strength of the common image gathers (CIGs) below salt.

Starting from the dip fields of stack and CIGs, we generate automatic picks of back projection points, reflector normal directions and residual move-out. The back projection data are fed both into ray-based and the wave path-based tomographic workflows. The inversion contains about 22,000 back projection points and the back projection paths cover an offset range of 15 kilometers. The velocity model and wave fields are sampled at 12.5 meters vertically and 25 meters horizontally. Both methods pick up lowered velocities below the base of salt, but only the wave path inversion comes close to resolving the magnitude near the salt base, and the fact that there is a low-velocity zone extending to greater depth. The location of the subsalt low-velocity zone, indicative of overpressure, is well resolved (upper right image of Figure 8).

In areas of complex velocity that are challenging for ray tracing-based velocity inversion methods, wave path tomography offers a naturally regularized alternative that is consistent with the wave field continuation migration method used to produce the seismic image. The expense of computing a single wave path kernel is partially offset, in com-

FIGURE 7

Sigsbee Seismic Image with Starting Velocity Model (Left) and Post-Velocity Updates (Right)



parison to ray tomography, by the smaller number of back projections necessary to sample the velocity model adequately.

RTM has been widely recognized as the next chapter in seismic exploration. It can overcome the limitations of current migration methods in imaging complex geologic structures that exist in the Gulf of Mexico. The chief impediment to the large-scale, routine deployment of RTM has been a lack of sufficient computer power. To be commercially viable and widely usable, RTM needs orders of magnitude more computing power than what is used in exploration today. Therefore, advancing seismic imaging to the next level of precision poses a multidisciplinary challenge. This challenge is being met by advanced algorithms and hardware innovations, such as those developed through the Kaleidoscope project.

In areas of complex velocity that are challenging for ray tracing-based velocity inversion methods, wave path tomography offers a naturally regularized alternative that is consistent with the wave field continuation migration method used to produce the seismic image. Even if the velocity field is very smooth and simple, as is the case with the Sigsbee example, wave path tomography adds robustness to the inversion because it does not have a problem with erratic ray paths resulting from multiple internal or "underside" reflections generated by the high-velocity contrast between the sediments and the salt body, or strong deflections of the ray path caused by a rugose salt boundary.❒

Editor's Note: The co-authors acknowledge the SMAART JV and BP for providing the synthetic data sets used in this article.

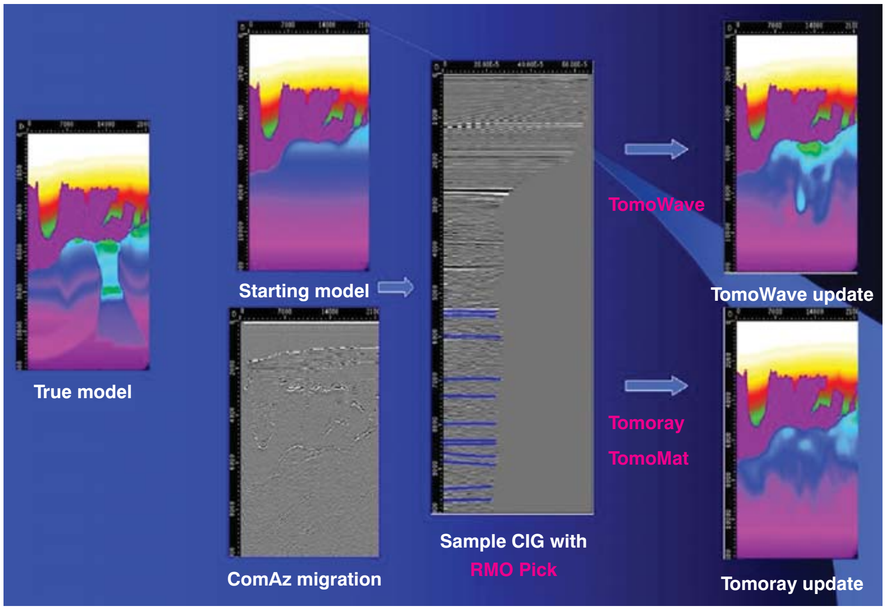


FIGURE 8
Ray/Wave Path Tomography for Detecting Subsalt Low-Velocity Zones

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