Back to the future

New advances in reverse time migration provide sub-salt imaging solutions.

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In their search for large oil and gas accumulations operators face what are arguably the toughest seismic imaging problems ever encountered. This is especially true in the Gulf of Mexico (GOM) subsalt, where the trapping mechanism is associated with large salt structures.

Many of the largest GOM discoveries of the past 15 years, including **Mahogany**, **Thunder Horse** and **Mad Dog**, have been associated with such formations. Salt structures, however, are inherently difficult to image effectively.

Increasingly, operators are turning to new seismic imaging technologies that can consistently extract useful information from the extremely distorted seismic reflections common to such environments. These technologies are collectively called wave equation migration (WEM). Technically, the most uncompromising form of WEM is Reverse Time Migration (RTM).

RTM is not new. But advanced RTM, developed by matching highly sophisticated algorithms with newly available computational power, is providing a much-improved solution for imaging complex subsalt prospects. The success of the technology also holds promise for other difficult imaging areas. In several recent GOM applications, advanced RTM has produced a dramatically clearer subsalt image.

The subsalt imaging challenge

The challenges of subsalt imaging are daunting. Salt structures are formed when salt sheets intrude into the higher-density sediments deposited above them. The resulting domes, walls, pillows, ridges and fountains are complex and often unique. They can be free-floating or remain attached to the base salt layer as irregular mushroom-shaped bodies called diapirs.

Many of the large discoveries in the first half of the 20th century exploited the anticlinal structures created above salt domes, which are straightforward to locate. The current area of interest is in deep water, where complex salt bodies provide geoscientists with significant imaging challenges.

These steeply dipping traps can be extremely prolific, capable of being drained with relatively few high-rate wells — ideal prospects for high-cost deepwater environments. But this also means that they have a small areal footprint, perhaps just a few hundred acres, and are thus hard to delineate.

Imaging reservoirs beneath salt bodies or along their steep flanks poses two serious problems for conventional seismic imaging technologies. First, the seismic waves reflected by the steep flanks of subsurface features are nearly horizontal. Specialized techniques are required to recognize and image these waves. Second, the top of salt structures is often highly irregular (rugose), which scatters seismic waves into multiple paths. This is because seismic waves generally have a much higher velocity when traveling through low-density salt than through surrounding sediments. Unless the imaging process is able to reconstruct this scattered energy, information from any wave that passes through the top of the salt mass is effectively lost.

These factors, if not taken into consideration, can yield misleading information about the location and geometry of prospective formations and seldom provide sufficient information to properly locate an exploration well. When the data are processed to "migrate" the seismic waves recorded at the surface back to their correct locations in the subsurface, the picture can change radically. Images of potential traps can emerge or disap-

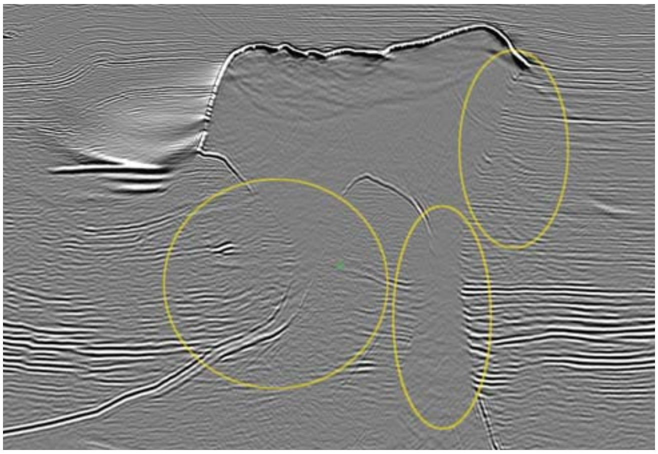

Figure 1. A subsalt image generated with conventional technology shows poor imaging of salt flanks and subsalt structures. (All graphics courtesy of GX Technology)

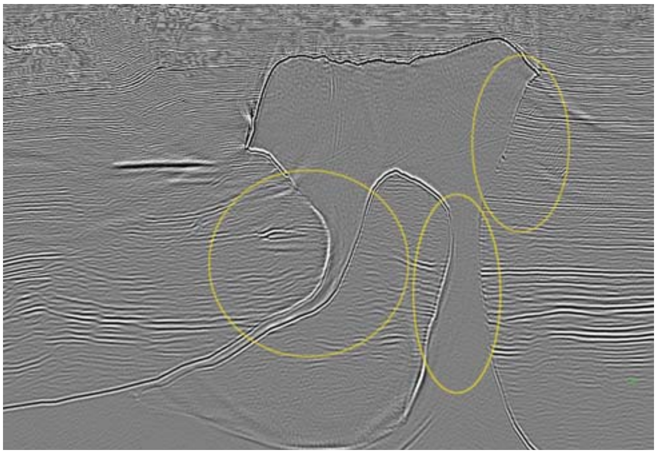

Figure 2. A subsalt image generated with RTM technology shows significant improvement in imaging salt flanks, even beneath the salt.

pear, or their location can move enough to change their economic potential, depending on which technology is used.

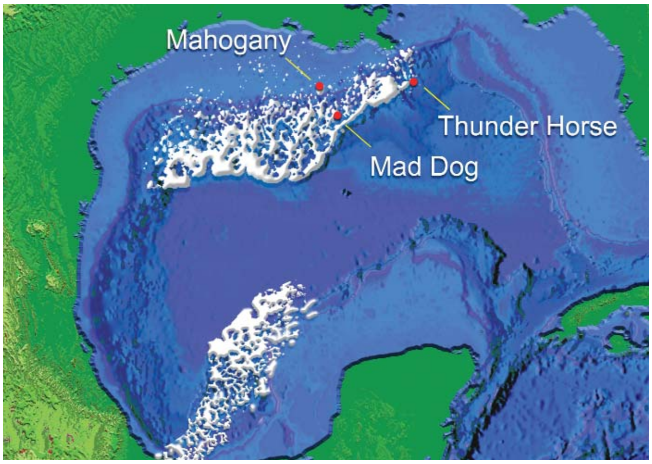

Figure 3. Salt sheets in the Gulf of Mexico underlie many of the most prospective areas, both in the United States and Mexico.

Partial solutions

Partial solutions to these problems using wave-based depth migration technology have been available for more than a decade. The focus has been on producing usable images of two key regions that are the most prospective — the regions masked by the salt bodies above them and the formations trapped against near-vertical salt walls.

Currently this requires the use of two imaging techniques. For imaging through the salt, one-way wave migration is used. To image reflections from steeply dipping features, the Kirchhoff imaging method is applied. Kirchhoff imaging is a high-frequency approximate wave equation method. It is capable of imaging steep dips, but it is not capable of imaging energy that passes through complex geologic conditions such as rugose salt-sediment interfaces.

Because wave migration techniques require computation of a vast number of wave paths, they use considerable computing resources. To help reduce this computational effort, approximations are used in wave migration. These approximations can create imaging problems.

One-way wave migration takes wave fields from the source and the receivers for each shot and extrapolates them into the earth. The two-wave fields at each depth level are then combined to generate a partial image with cross-correlation. This extrapolation is made through a user-estimated model that defines seismic wave velocities at all points in the subsurface. Partial images from all the shots in a survey are then summed together to form the final image. To get the proper amplitude, the image is adjusted to account for the amount of seismic energy lost in the subsurface.

This wave equation method is effective at imaging through the top of the salt and thus is capable of resolving features in the “shadow” below salt overhangs. However, one of the assumptions is that the wave field travels along the direction of extrapolation only in one direction, down for the source and up for the receiver or scattered wave field. In reality, each of these wave fields will generally travel both up and down in the presence of complex velocity variations like those found around salt structures. The method fails when faced with waves that propagate close to horizontal. This imposes limits on the dips that can be imaged with wave-equation techniques, typically less than 80°.

By contrast, Kirchhoff migration is able to image steep structures because it accommodates the near-horizontal wave paths they produce. The simplifying assumption made in Kirchhoff migration is that energy propagates along at most a few paths between any two points. Effectively, this prevents imaging below the rugose top of the salt that creates multiple wave paths.

One approach is to use both methods, but this creates two image volumes that must be reconciled by intervention from geoscientists. The industry is not finding this manpower-intensive procedure a technically acceptable solution; even in combination, these two techniques still neglect waves that experience both near-horizontal propagation and significant multipathing.

The choice: Reversing time

The emerging choice is reverse time migration. The RTM method is often described as the ultimate imaging solution because it allows waves to propagate in all directions, thus handling the full array of imaging information. Its great advantage in subsalt applications is the ability to image both the steep sides of salt bodies and underneath them, regardless of the dip and rugosity at the top.

As shown in the Figure 1 data example, the impact can be very significant. Vertical contacts between sediment layers and the salt wall can be resolved even when the slope is more than 90°. Features start to emerge that were previously obscured in the salt shadow, including the vertical subsalt interfaces that can be prime exploration targets.

RTM properly propagates the wave field through velocity structures of arbitrary complexity. It can accommodate anisotropic velocity fields for which wave velocity varies with angle of propagation, measured from vertical. RTM also has the ability to image multiple internal reflections, allowing the method to resolve images from data that would otherwise be ignored as noise. This effect can illuminate some previously hidden reflectors impossible to image with simple primary reflections.

The concept has been understood for many years but, until recently, it has not been able to deliver images in a time frame acceptable to operators.

Significant progress has been made with the development of more efficient code and the availability of well-managed dedicated computing resources. These advances are making the practical application of RTM a reality.

The RTM process

RTM is not a standalone process. The key to its effective, economic use is a process with three robust key phases.

First, the data has to be conditioned properly. Key conditioning steps include noise removal and the attenuation of unwanted multiple reflections, phase corrections and deconvolution. Good conditioning improves both the quality and speed of the next phase, velocity modeling estimation.

All depth migration methods require a velocity model — essentially the field that transforms seismic travel-time into distance. Model building is often the most difficult part of the depth imaging process, particularly when building the velocity field below the top of the salt where signal strength is low.

Velocity model building is an iterative process that typically uses redundant structural information from within the conditioned dataset to derive the model. Imaging the shape of the high-velocity salt body is a key to velocity modeling, and RTM can be "tuned" to make this process more efficient. Using currently available tools that effectively combine visualization with computational rigor, velocity models are derived that are sufficiently accurate to commence the final migration phase. These tools ensure model quality.

During the final migration phase, RTM is computationally intensive, but the tuned algorithms and increased computing power are eliminating this barrier. Significant reductions in processing time can be achieved by ensuring that the computing resources work together like a well-tuned machine. Active management of the computing infrastructure, such as checking interim results while the image builds, is key to success.

Unlocking new reserves

Advanced RTM methods have successfully been applied on GOM and West African projects. A growing understanding and real-world experience with the technology indicates that it is a significant advance in subsalt imaging.

The timing is right. In the United States, the federal government's Minerals Management Service (MMS), noting a serious challenge in meeting US energy demand, recognized the importance of subsalt reserves as one of the two primary areas in the GOM with the potential for significant new discoveries. The MMS specifically addresses the difficulty in subsurface imaging by allowing operators to extend leases by 2 years to identify appropriate targets.

Conclusion

Massive dedicated computer power is making the long-standing promise of RTM a reality. Historically, the industry has been slow to adopt new technologies. However, there is a new urgency abroad, driven by the need to find new reserves quickly. Some operators, faced with tough decisions about whether to relinquish blocks with unexplored subsalt potential or which new deepwater blocks to pursue, are moving away from a decade of cost-driven management and are aggressively seeking stronger collaboration with technology providers. Increasingly, RTM is becoming part of the explorationist's upgraded arsenal for making these right decisions. E&P