Multistep reverse time migration

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Reverse time migration (RTM), being based on the two-way wave equation, can accurately account for wave propagation in both up and down directions. As a result, RTM can generate much improved subsurface images in areas where strong vertical velocity gradients generate turning waves or where rugose interfaces with strong velocity contrasts generate prism waves. In addition, because of its ability to image reflection events that cannot be imaged by other techniques, RTM can be used for refining a velocity model.

Despite considerable advances in computer technology, however, the cost of running RTM is still very high. The necessary computation far exceeds that of conventional one-way wave-equation migration (WEM) and requires a large amount of core memory. Because of these requirements, RTM is considered too expensive for routine production projects with large volumes. However, by dividing the subsurface into 2–3 depth regions and applying RTM from top to bottom sequentially in each region, it becomes cost effective for production usage.

Furthermore, in a region where the velocity model is relatively simple such that RTM may not generate a better image, Kirchhoff migration or one-way WEM may be used. This hybrid approach may further improve the computational efficiency and the quality of migration images.

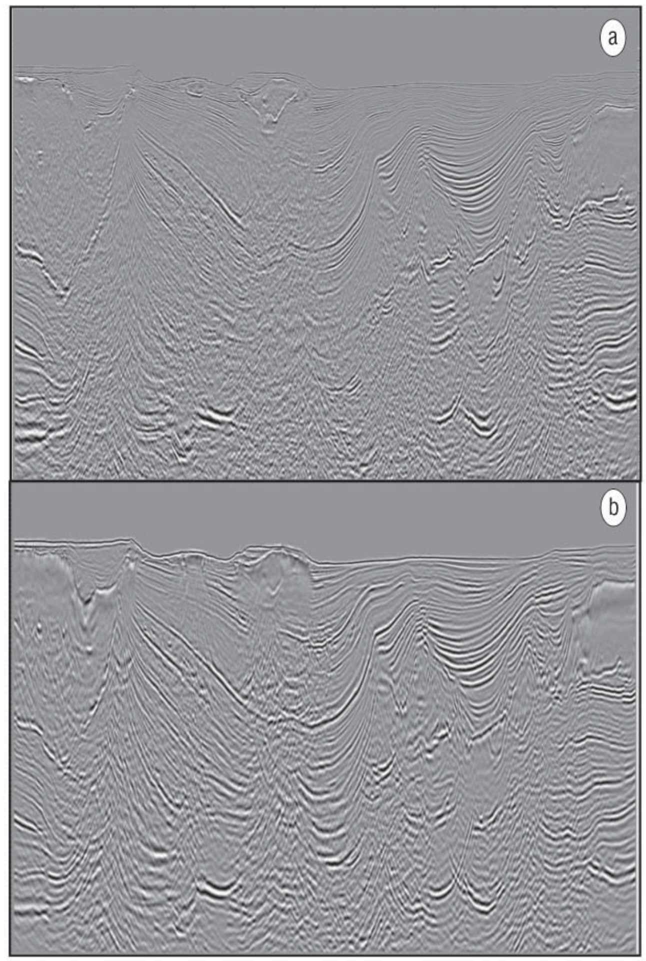

Figure 1. *Seismic depth images in the deepwater Gulf of Mexico by (a) Kirchhoff and (b) RTM.*

RTM versus other migration methods

We have run RTM on data from an area covering 386 OCS blocks in the deepwater Gulf of Mexico. Most of the subsurface is covered by complexly shaped bodies of salt, and conventional depth-imaging techniques failed to produce adequate images below the salt. Figure 1a is an image obtained by using the Kirchhoff method and Figure 1b by RTM. Because of multiple arrivals, Kirchhoff migration failed to properly focus and image many reflections below the salt, making interpretation difficult. On the other hand, by correctly accounting for the effect of complex wave propagation, RTM generated a superior image on which it was much easier to interpret subsalt reflections. Note that the continuity of reflections below the salt is significantly improved and that SNR is much higher than the Kirchhoff image.

RTM has also been applied to a data set from an area in the Gulf of Mexico where the degree of anisotropy is relatively high. Figure 2a shows a depth section obtained by anisotropic one-way WEM, and Figure 2b by anisotropic RTM.

The yellow curves outline the boundaries of the salt in the anisotropic velocity model. Note that the steeper part of the salt is better retained by RTM, and the continuity of reflectors below the salt is also better.

Multistep RTM

We present a multistep approach to reduce the memory requirement of RTM. It is much simpler to implement and makes the computation faster as well. According to the complexity of the geology, a velocity model can be divided into two or three depth regions (Figure 3). Suppose that region I consists of a water layer and shallow sediments with low velocities, and that region II consists of structures with steep dips and salt bodies with complex shapes. We assume that region III contains relatively simple structures with mild velocity variations.

Reverse time migration generates an image by marching the source wavefield forward in time, marching the receiver wave field backward in time, and cross-correlating the two wavefields. We first apply RTM, generate an image for region I, and save the source and receiver wavefields on the base of region I at each time step. A point source at the acquisition surface will become an area source after this step. We then apply RTM in region II, using these saved source and receiver wavefields as input data. If the surfaces bounding region II are not flat, the computation cube for region II should be

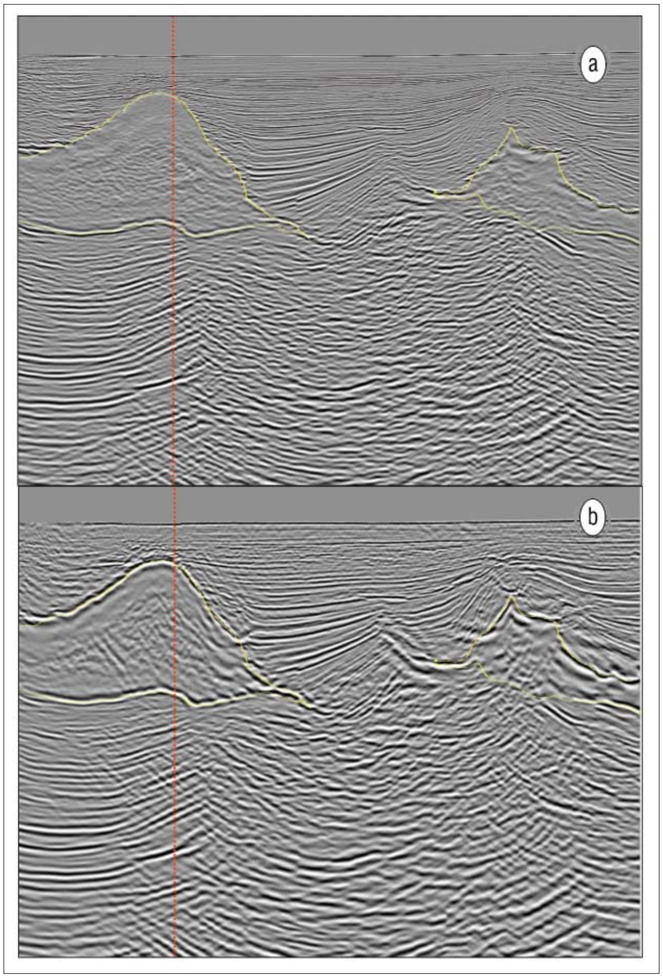

Figure 2. Seismic depth images generated by anisotropic (a) one-way WEM and (b) RTM. The yellow curves show the outline of the salt model.

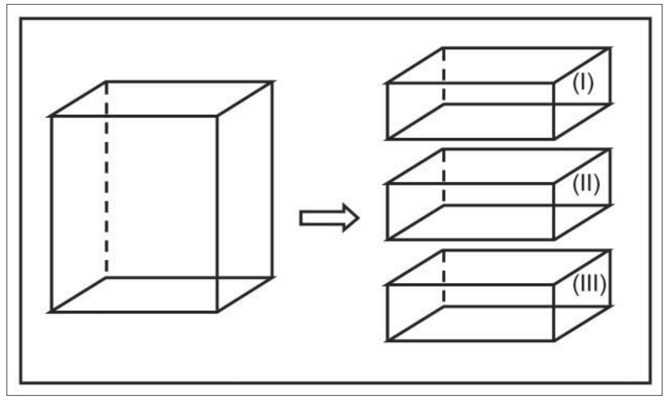

Figure 3. A velocity cube divided into three regions.

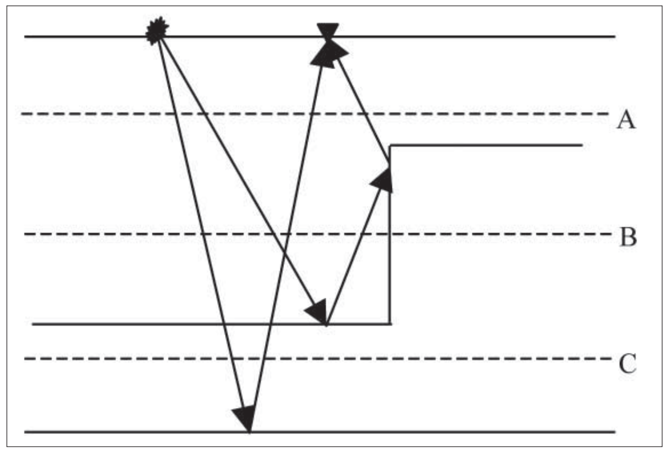

Figure 4. A or C is an acceptable region boundary, but B is unacceptable because it will divide the region where the source wave travels in both directions before reflecting from the steep reflector.

extended to the highest point of the interface between region I and II and the lowest point of the interface between region II and III. Similarly, if there is a region III, we save both the source and receiver wavefields on the interface between region II and III and apply RTM in region III.

This multistep approach reduces the memory requirement and speeds up the computation for the following reasons.

Firstly, we handle a smaller model at each step.

Secondly, given a maximum frequency, the computation cell size for RTM are mainly determined by the minimum velocity in the region. Since velocities typically increase with depth, the minimum velocity in regions II and III should be higher than that in region I, allowing for a larger cell size when running RTM in these regions. A larger cell size reduces the number of grids in the computation model for RTM, requiring less memory, less computation, and less disk space to store the temporary source wavefields. The memory and disk space required for 3D RTM is inversely proportional to the third power of the cell size, and the computation time is inversely proportional to the fourth power of the cell size. Therefore, much less memory and disk space are needed, and the computation time can be significantly reduced by the multistep approach. For example, suppose that the minimum velocity of a migration velocity model is the water velocity, which is about 1500 m/s, for region I and that the minimum velocity of region II is 2000 m/s. Then, the computation time for a 3D problem may be reduced by a factor of 3.2, and the memory and the disk space may be reduced by a factor of 2.4.

Thirdly, the time of the computation may be reduced accordingly in the lower regions, because only the period when the waves travel in that region and below is useful for imaging.

This multistep approach can be made more efficient by employing different migration algorithms for each region according to the complexity of the velocity structure. The advantages of Kirchhoff migration are its ability to image steep or overturned reflections and computational efficiency, but it has difficulty when handling multipathing in complex media. Regular one-way WEM has limitations in dealing with steep dips and is unable to correctly image overturning waves or prism waves, but it has been a main tool for imaging structures under complex overburdens that generate multiple wave paths and is much faster than RTM. Thus, according to the complexity of the velocity model in each region, we may choose a different migration algorithm and use RTM only for regions where it is necessary.

Care must be taken when dividing the velocity model to

Figure 5. The 2004 BP velocity benchmark model.

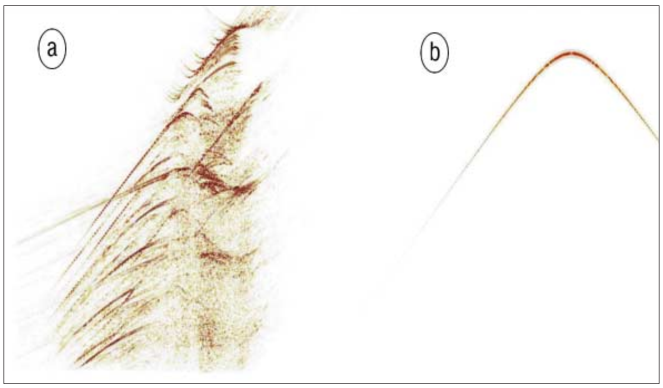

Figure 6. Receiver (a) and source (b) wavefields extrapolated to a datum at a depth of 2100 m.

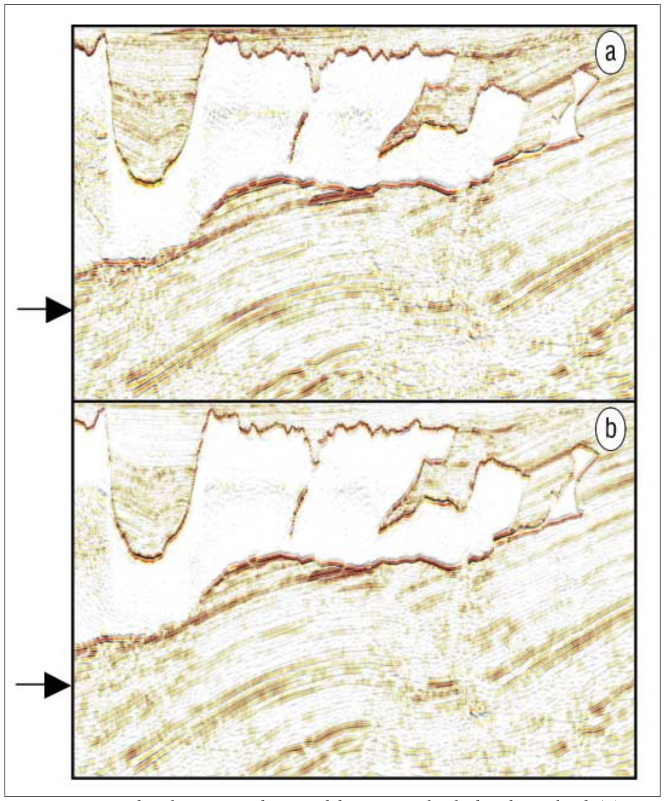

Figure 7. A depth image obtained by using the hybrid method (a) and RTM (b). The arrows indicate the depth of 7700 m.

avoid losing information which may help to image turning waves or prism waves. When either the source or receiver wavefield propagates in both upward and downward directions, a region should fully include the part of the model where the waves propagate in both directions. Figure 4 illustrates how the velocity model can be properly divided into a few regions. Either the source or receiver wavefield propagates only in one direction above boundary A or below C. The waves propagate in both upward and downward directions in the region bounded by A and C. If we divide this region by another boundary indicated by B, the saved source wavefield at B cannot account for the wave reflected from the steep reflector. Thus, if there is a deep-rooted salt body with steep or overturned interfaces, it is not recommended to split it into two regions. In such a case, we may divide the velocity model into only two regions, one for shallow water and simpler structures and one for the deep-rooted salt body.

Examples of multistep RTM

Figure 5 shows part of the 2004 BP benchmark velocity model where the salt canopy causes a complex pattern of wave propagation. The model was divided into three regions with a boundary at a depth of 2100 m and another at a depth of 7700 m. Since the velocity structure above 2100 m and below 7700 m is relatively simple, we used one-way WEM to generate an image for these two regions. Figure 6 shows receiver and source wavefields extrapolated to the depth of 2100 m using one-way WEM.

The saved source and receiver wavefields at a depth of 2100 m were used to generate an image in the middle region using RTM. While running RTM in the middle region, we saved the wavefield at a depth of 7700 m for generating an image for the bottom region using one-way WEM. We called this combination of one-way WEM (or other migration algorithm) and RTM a hybrid method.

Figure 7a shows a depth image obtained by using the hybrid method. RTM was used only for the middle region bounded by the depth of 2100 m and 7700 m. The top and bottom regions were imaged by one-way WEM. Since the structures in the middle region are complicated with many near-vertical interfaces, we should use RTM to image complex wavefronts into their correct locations.

Figure 7b shows a depth image obtained by running RTM for the entire depth range. There are no significant differences between the two images. The steep salt-sediment interfaces are clearly focused in both images and the reflectors underneath the complex salt canopies are well imaged. By running RTM only for the region where we have to use RTM and using one-way WEM or Kirchhoff methods for other regions, we considerably reduce computational cost.

There are, however, situations where the velocity structures are so complex that RTM is required for every region. Since the velocity usually increases as the depth increases, however, the computation cells can be made larger for deeper regions, thereby reducing computation time. Although we use a larger

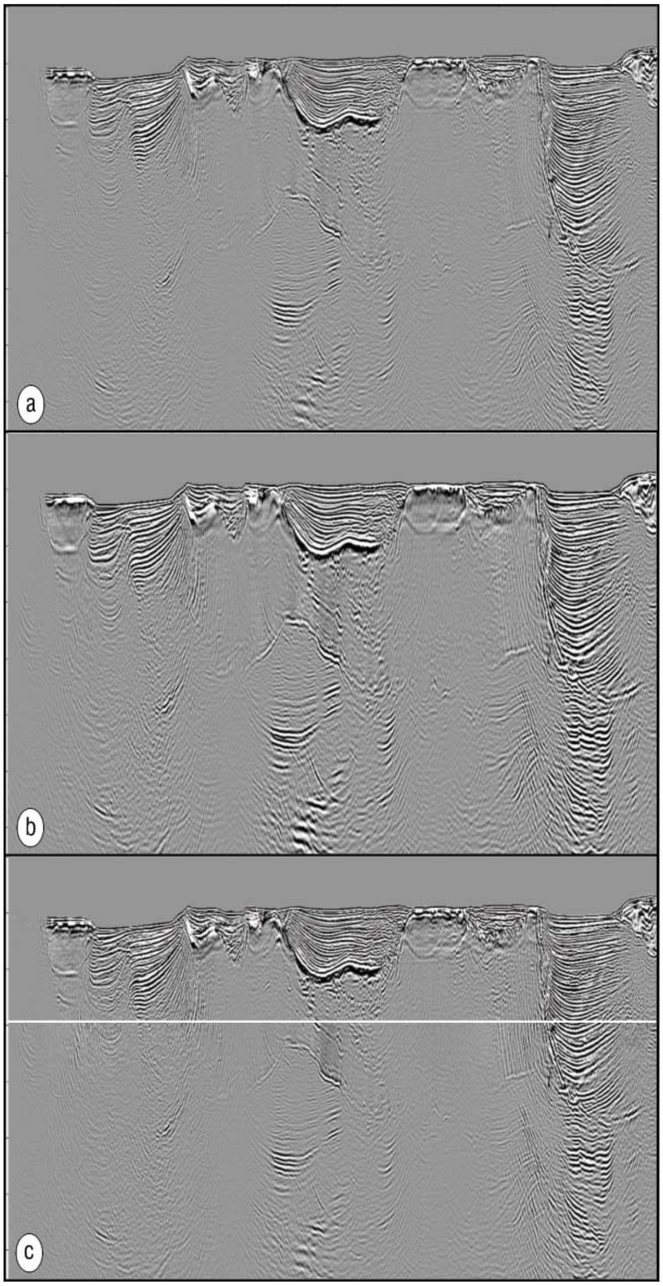

Figure 8. A depth image obtained by using (a) one-step RTM with a 20-m grid (b), one-step RTM with a 30-m grid, and (c) two-step RTM with a 20-m grid for the top and 30-m grid for the bottom region, respectively.

grid size for deeper regions, we may still maintain the same maximum frequency as that of the top region because of the increased minimum velocity.

Figure 8 shows a line in a 3D depth cube generated by one-step RTM with a 20-m grid, one-step RTM with a 30-m grid, and two-step RTM with a 20-m grid for the top and a 30-m grid for the bottom. The white line indicates the surface dividing the velocity model into the two regions. The maximum frequency for the 20-m grid was 30 Hz and that for the 30-m grid was 20 Hz. Increasing the grid size will reduce the core memory requirement, but might require using a lower maximum frequency to propagate the wavefields accurately

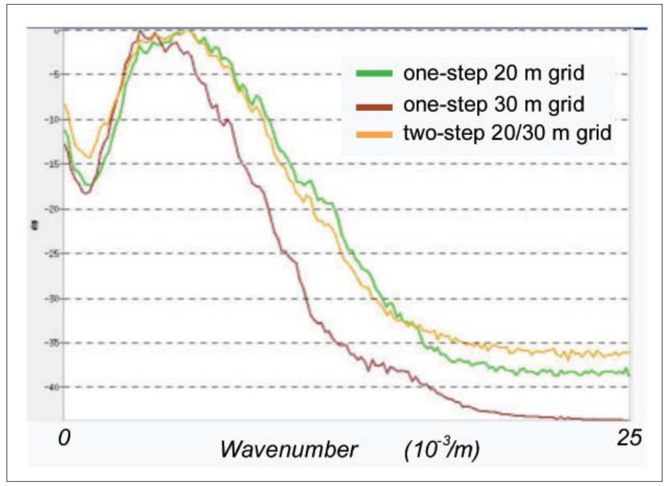

***Figure 9.** Vertical wavenumber spectra of the images in Figure 8.*

and generate a high quality image. On the other hand, a two-step approach allows the same maximum frequency for the top region and, by using a larger grid size, for the bottom region because the minimum velocity of the bottom region is usually higher than that of the top region.

Note that the one-step RTM image with a 20-m grid (Figure 8a) shows higher resolution than the one-step RTM image with a 30-m grid (Figure 8b). On the other hand, although the two-step RTM used a 30-m grid for the bottom region, its resolution looks as good as the one-step RTM image with a 20-m grid. Figure 9 shows the vertical wavenumber spectra of these three images for the bottom region. Clearly, the spectrum of the two-step image is as broad as that of the one-step image with a 20-m grid and broader than that of the one-step image with a 30-m grid.

Table 1 shows the ratio of the run time, memory, and disk space used for one-step and two-step RTM with the parameters used to generate Figure 8a and Figure 8c. Note that the amount of memory and disk space was significantly reduced for the two-step RTM. In addition, the computation time was also reduced because of the larger cell size for the second step. The higher minimum velocity for the second region allows a larger cell while retaining the same maximum frequency as for the top region.

	Run time	Memory	Disk space
One step	1	1	1
Two steps	0.66	0.38	0.34

***Table 1.** The ratios of the run time, memory, and disk space used for one-step to two-step RTM.*

Conclusion

RTM, a more rigorous imaging technique than one-way wave-equation-based imaging approaches, works particularly well in areas underneath complex geologic structures because of its ability to properly focus diving waves or prism waves. However, large computation time and memory requirements make the cost of RTM too high for routine production work.

To make RTM usable for large-scale projects, we developed a multistep approach. By dividing the subsurface into 2–3 depth regions and applying RTM sequentially to each, we substantially reduce computation time and memory requirement. Further improvements are possible by applying a different migration algorithm in each step. By combining the strengths of different migration algorithms, this multistep approach can be made more efficient and generate images of higher qualities.

One-step RTM computation can be made to fit in the available core memory, but this may require using a larger grid size which in turn requires a lower maximum frequency. However, since velocity usually increases as a function of depth, multistep RTM can use a larger grid size for deeper regions while retaining a higher maximum frequency.

In addition, redatuming data to a datum below a complex overburden can be used for analyzing the velocity structure which can be very difficult to resolve because of complicated wave propagation through the overburden. Since RTM can account for the effects of wave propagation through such complex media, it can preserve all the necessary information for velocity analysis. As RTM becomes more efficient and cost-effective, it can become a tool of choice even for velocity analysis below complex overburdens.

Suggested reading. "Reverse time migration" by Baysal et al. (Geophysics, 1983). "Migration by extrapolating time-dependent boundary values" by McMechan (*Geophysical Prospecting*, 1983). "Application of reverse time migration to complex imaging problems" by Farmer et al. (*First Break*, 2006). "Computational methods for large-scale 3D acoustic finite-difference modeling: A tutorial" by Etgen and O'Brian (Geophysics, 2006). "An efficient 3D reverse-time prestack depth migration" by Karazincer and Gerrad (EAGE 2006 *Extended Abstracts*). "Comparisons of shot-profile vs. plane-wave reverse time migration" by Vigh and Starr (SEG 2006 *Expanded Abstracts*). "A hybrid approach for efficient reverse time migration applications" by Guan et al. (EAGE 2008 *Extended Abstracts*). "Reverse-time migration: Amplitude and implementation issues" by Zhang et al. (SEG 2007 *Expanded Abstracts*). TLE

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