A Multi-Step Approach for Efficient Reverse-Time Migration

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Summary

Reverse-time migration (RTM) provides superior images in areas where there are steep salt flanks or other complex geologic structures. However, the high cost of running RTM with regard to memory requirement and computation time makes it difficult to use RTM for routine large volume production. By dividing the subsurface into two or three regions in depth according to the structures of the velocity model and applying RTM from top to bottom sequentially in each region, we are able to make RTM very cost effective for production usage.

Further more, Kirchhoff migration or one-way wave equation migration may be used to replace RTM in a region where the velocity model is relatively simple and RTM may not help to generate a better image. This hybrid approach may further improve the computation efficiency and the quality of migration images.

Introduction

Reverse-time migration (RTM), being based on the two-way wave equation, can accurately account for wave propagation in both up and down directions (Baysal et. al., 1983 and McMechan, 1983). 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 (Farmer et. al., 2006). In addition, based on its ability to image turning or prism waves, RTM can be used for refining a velocity model. Biondi and Shan (2002) showed how to generate common image gathers for velocity update, and Farmer et al. (2006) demonstrated the use of RTM for refining a velocity model where prism waves help to enhance steep and overturned salt flanks.

Despite considerable advances in computer technology, however, the cost of running RTM is still very high. The amount of computation far exceeds that of conventional one-way WEM. In addition, it requires a large amount of core memory for computation. Thus, it is critical to speed up the computation and reduce the amount of memory for production usage of RTM.

Different methods can be used to fit a massive RTM problem within limited computer memory. Domain decomposition reduces the memory requirement by splitting the computation model among multiple computer nodes (Karazincer and Gerrad, 2006). Etgen (2007) suggested an out-of-core method, in which the whole wave field and velocity model are stored on disk and only the part currently involved in the computation resides in the core memory. Variable grids may also be adopted in the finite difference computation to reduce the memory requirement (Hayashi, 1999). A couple of ways have also been suggested to speed up an RTM application. Vigh et al. (2006) used plane-wave RTM to reduce the overall computation time. Zhang et al. (2007) reported the use of harmonic sources to implement RTM in the delay shot domain to achieve efficiency.

In this paper, we present a multi-step approach to reduce the memory requirement of RTM, which is much simpler to implement and makes the computation much faster as well.

This multi-step approach can be further improved by combining different migration algorithms together. The advantages of Kirchhoff migration are its low cost and less sensitive to errors of the velocity model, but it has an issue of multipathing in complex media. Regular one-way wave equation migration (WEM) has limitation 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. Furthermore, one-way WEM generates less migration noise caused by inter-bed multiples and back scatterings (Liu, 2007), and many one-way propagators are numerically less dispersive than the finite difference solution of the wave equation (Wu et. al., 1997). So according to the complexity of the velocity model in each region, we may choose a different migration algorithm and apply RTM only when it is necessary. In this way, the computation time can be further reduced, while the benefits of RTM are retained. In addition, it may help to produce images of higher qualities as well.

Description of the Method

According to the complexity of geology, a velocity model can be divided into two or three regions in depth. Figure 1 shows a velocity model for migration which is divided into three regions. The base of region I is defined by surface A and the base of region II is defined by surface B. 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 complexly-shaped salt bodies. We assume that region III contains relatively simple structures with mild velocity variations below the complex structures with strong velocity contrasts.

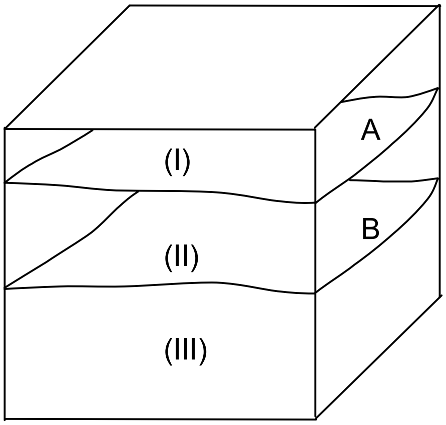

Figure 1 A velocity cube that is divided into three regions

Our method proceeds as follows. Pre-stack RTM generates an image by marching the source wave field forward in time, marching the receiver wave field backward in time and cross-correlating the two wave fields. We first apply RTM, generate an image for region I and save the source and receiver wave fields on surface A at each time step. A point source at the acquisition surface will become an area source after this step. Then we apply RTM for region II using these recorded source and receiver wave fields as input data. If the surfaces bounding region II are not flat, the computation cube for region II should be extended to the highest point of surface A and the lowest point of surface B. Similarly, if there is a region III we save both the source and receiver wave fields on surface B and apply RTM for this region.

This multi-step approach reduces the memory requirement and speeds up the computation for the following reasons. Firstly, we handle a much smaller model at each step. Secondly, the computation cell size for RTM is determined by the minimum velocity in the region. Since velocities typically increase with depth, the minimum velocity in region II and III should be higher than that in region I, allowing for a larger cell size for RTM. A larger cell size makes the number of grids of the computation model for RTM smaller, requiring less memory, a less amount of computation and less disk space to store the temporary source wave field. The memory and disk space required for 3-D 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 multi-step approach. For example, usually the minimum velocity of a migration velocity model is the water velocity, which is about 1500 m/s, while the minimum velocity of region II below surface A may be 2000 m/s. In this case, for a 3-D problem the computation time 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 length of the computation time 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.

The efficiency of this multi-step RTM can be further improved by employing a different migration method for each region. If the migration velocity model is properly divided, one-way WEM should be adequate to generate an accurate image for region I and III, where dips and lateral velocity contrasts are relatively mild and geological structures are so simple that turning waves and prism waves do not exist. Another option is to apply Kirchhoff migration in region I, which may further reduce the computation time. RTM is then used only in region II where steep dips, turning waves, or prism waves may exist.

Care must be taken when dividing the velocity model to avoid losing information which may help to image steep dips, turning waves or prism waves. Because up-going waves do not travel through regions, all possible wave modes which may help to image the complicated structures in region II have to be included in this region. For example, if there is a deep rooted salt body with steep or overturned interfaces, it is not recommended to split it between 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.

Results

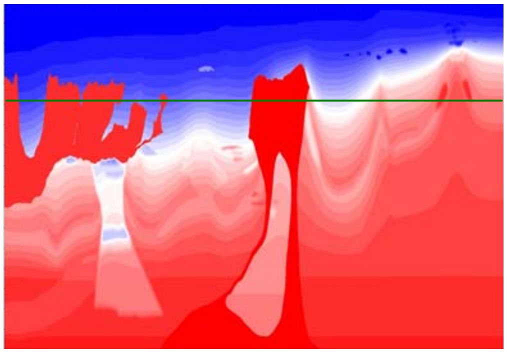

Figure 2 The 2004 BP velocity benchmark model. The green curve defines the base of region I.

A 2-D example is used to illustrate the points. Figure 2 shows the 2004 BP benchmark velocity model (Billette and Brandsberg-Dahl, 2005). The model is separated into two regions as indicated by the green line. Figure 3a shows an image by RTM in one step and Figure 3b shows an image by two-step RTM. The dominant frequency of the data set is 27Hz, and a grid size of 12.5m is used in both cases. The two images are similar.

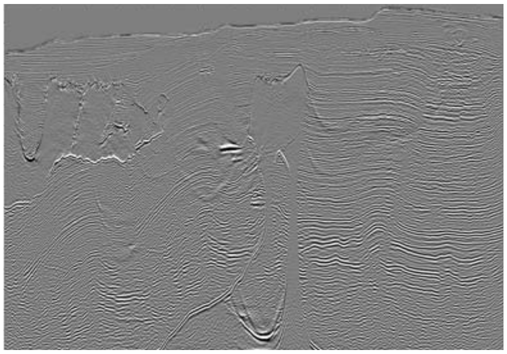

Figure 3a One-step RTM result

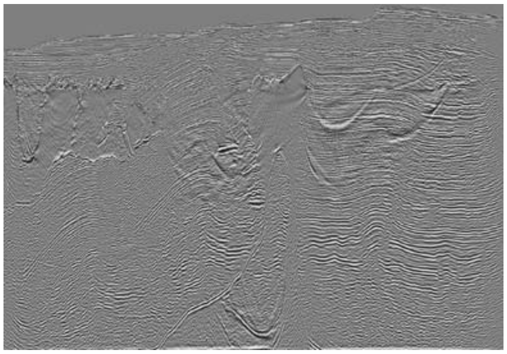

Figure 3b Two-step RTM result

Figure 4 shows the same velocity model that is differently divided into three regions to illustrate the result of using a one-way WEM and RTM hybrid method. Because the geology is very simple in the top region, we can image the top region using one-way WEM. On the other hand, since the structures are complicated with many near vertical interfaces in the middle region, RTM should be used to image such complex structures.

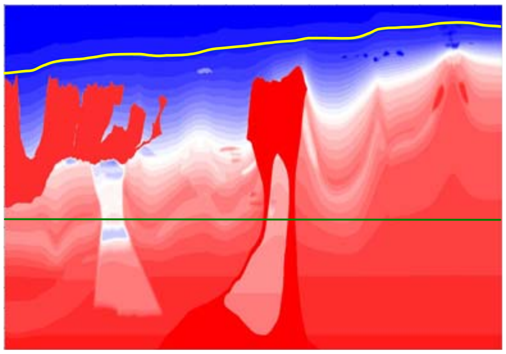

Figure 4 The 2004 BP velocity benchmark model. The yellow curve defines the base of the top region and the green curve defines the base of the middle region

Figure 5a shows an RTM image in the left side of the BP model, and 5b shows a composite image obtained by using one-way WEM for the top and bottom regions and RTM for the middle region. A step size of 12.5m was used for one-way WEM, which is the same as the grid size of RTM. 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. Figure 6 shows a similar comparison in an area with the deep-rooted salt body. The most part of the images are virtually identical to each other. However the hybrid method did a better job in imaging very steep events as indicated by the yellow arrows. Compared with the result of RTM, the steep dips in figure 6b are more continuous and the amplitude is more balanced. This may be because that the low velocity zone of the water layer and shallow sediments is migrated by one-way WEM. Specifically we used an implicit finite-difference algorithm plus Li's correction (Zhou, et. al., 2001; Li, 1991), which has less numerical dispersion error as compared with the full-wave finite difference method. So the back-propagated traces of the hybrid approach have higher frequency content, and the image is sharper and the amplitude is more accurate.

Conclusions

Although RTM is a more rigorous approach to generate an accurate subsurface image, particularly in areas with complex geologic structures where steep dips, turning waves and prism waves must be properly imaged to produce a better image, its computation time and memory requirement make the cost of using RTM high. To make RTM cost effective, we have developed a multi-step approach. By dividing the subsurface in depth into two or three regions and apply RTM sequentially in each region, we are able to substantially reduce the computation time and the memory requirement. It can be further improved by applying a different migration algorithm in each step. By combining the strength of different migration methods, this multi-step approach may be more efficient and generate images of higher qualities. A 2-D example of the 2004 BP model demonstrates the feasibility of this approach.

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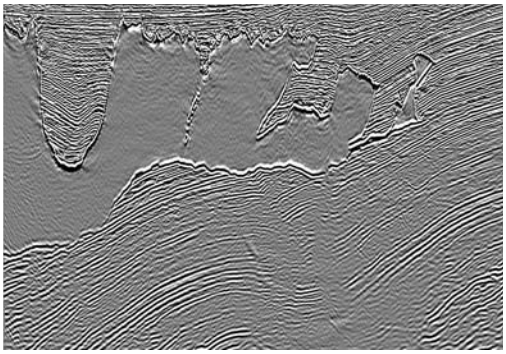

Figure 5a. An image produced by RTM

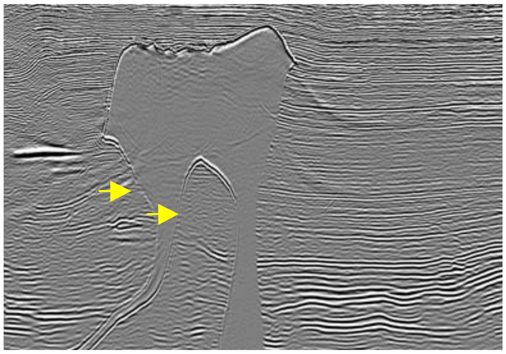

Figure 6a An image produced by RTM

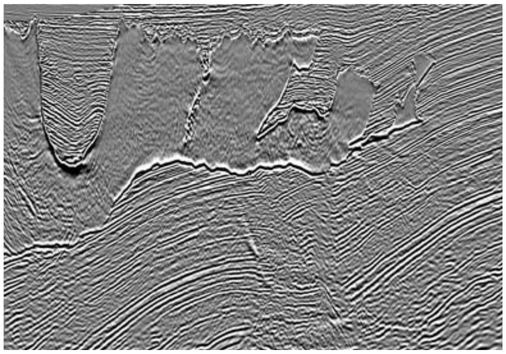

Figure 5b An image produced by the hybrid method

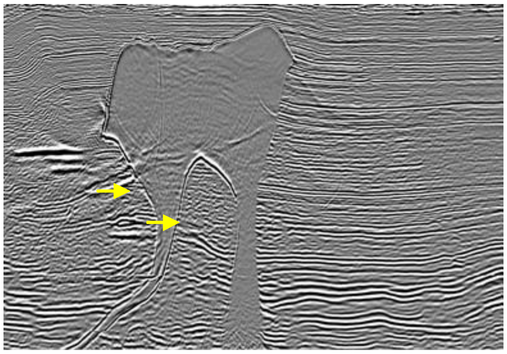

Figure 6b An image produced by the hybrid method

EDITED REFERENCES

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