Imaging dips beyond 90 degrees by a modified prestack Kirchhoff time migration

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Introduction

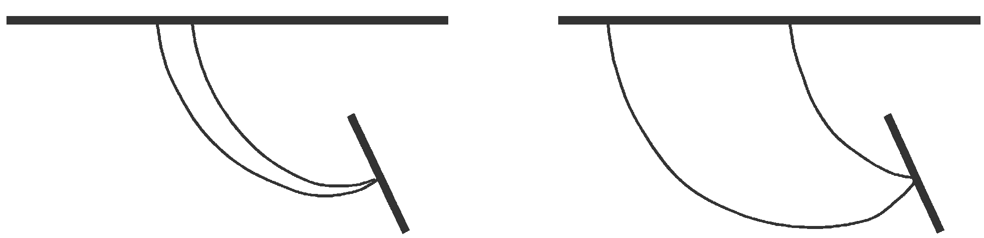
It is well-known that we can image dips beyond 90 degrees by using turning wave energy (e. g. Ratcliff *et al*. 1991 and Hale *et al*. 1992). For this purpose, the migration must have the ability to handle turning waves. It is obvious that reverse-time migration, which is based on the two-way wave equation, can do this job well. Kirchhoff migration, on the other hand, requires explicit modifications so that the turning waves are considered in traveltime calculations. There is no doubt that prestack depth migration with an accurate velocity model can deliver the best image. However, an accurate velocity model is not always attainable, and 3-D prestack depth migration usually is too expensive. If cost is a concern, one alternative option is poststack depth migration and another is prestack Kirchhoff time migration. The stack+poststack migration procedure usually is much faster compared to prestack migration, especially prestack depth migration; however this procedure is inaccurate for steeply dipping events, even when the lateral velocity change is small. The prestack time migration, on the other hand, is accurate for steep dips so long as the lateral velocity change is relatively small. Although it is true that lateral velocity change is large for salt domes, away from the domes themselves, the lateral velocity change may be relatively small, and prestack time migration could still work well. I will discuss a modified Kirchhoff prestack time migration with traveltime calculations based on an eikonal equation solver, and show a synthetic data example.

The advantage of using prestake migration to image dips beyond 90 degrees

For steeply dipping events the stake+poststack migration procedure is accurate only for near-offset traces (e. g. Hale *et.al.* 1992 and Wu, 2001). However for imaging dips beyond 90 degrees, far-offset traces can contribute significantly to the image. One interesting property of the rays associated with "beyond-90-degree" reflectors at far offsets is the fact that only one of the incident and reflected rays (but not both) are turning rays, in contrast to the near offset case where both incident and reflected rays are turning rays (Fig. 1). There is a simple relation:

$$\theta = \frac{1}{2}(\alpha_I + \alpha_R),$$

where θ is the dipping angle of reflector, and α_I and α_R are the dipping angles of wavefronts just before and after reflection respectively. It is easy to see from this equation that for θ larger than 90 degrees, it is not necessary that both α_I and α_R are larger than 90 degrees, but at least one of them must be larger than 90 degrees.



(a) (b)

Fig. 1. Imaging dips beyond 90 degrees by seismic turning waves: (a) near offset case where both incident and reflected waves are turning waves; (b) far offset case where only one (but not both) of the incident and reflected waves is a turning wave.

As I mentioned above, the prestack depth migration is the most accurate choice, but it is too expensive especially for 3-D data sets. Because the accuracy of time migration compared to depth migration is dependent on the magnitude of lateral velocity changes rather than the steepness of dips, it follows that even for steeply dipping data sets the prestack time migration works well so long as the lateral velocity changes are relatively small. Even in the case of a data set containing salt domes, prestack time migration may work well. This is because the rays which pass through the salt (i. e., those rays which bend significantly, and therefore are best handled using prestack depth migration), often are not important for imaging the exploration target. For such areas, a better option may be to simply "remove" the salt dome from the velocity model and run the modified prestack Kirchhoff time migration with the ability to image dips beyond 90 degrees reported in this paper. It is much faster than prestack depth migration and more accurate than poststack migration.

The modified prestack Kirchhoff time migration with the ability to image dips beyond 90 degrees

An accurate and efficient eikonal equation solver is used to calculate the traveltime in depth, which is then mapped to the time domain and applied to Kirchhoff time migration. Since the traveltime calculated by the eikonal equation is the first arrival, it is accurate for turning wave energy. If the program were sufficiently optimized, the run time for the modified prestack Kirchhoff time migration would be very close to that for the conventional one. It is important to note that imaging dips beyond 90 degrees is not always possible, because the turning waves don't necessarily illuminate all the events, depending on the velocity distribution with depth. The contour map of the traveltime calculated with eikonal equation can be used to assess the possibility that turning rays do indeed impinge on the event of interest.

The synthetic data example

I adopt the wave-equation method, rather than Kirchhoff modeling, to create synthetic data in order to avoid using the same method in forward modeling and migration. For both 2-D and 3-D Kirchhoff time migration only 1-D velocity is considered for each trace migrated. The difference in methodology between 2-D and 3-D Kirchhoff time migrations is not very important, however it is time-consuming to create a 3-D synthetic data set by the wave-equation method for prestack migration. Thus I chose to use a 2-D simple model for illustrative purpose (Fig. 2). The lateral extent of the line is 8000m and the depth is 3000m. The imaging target is located at the lower right hand corner below 800m. It has a flat top and its left side has a dip angle of 100 degrees. The CDP interval is 10m and the shot interval is 100m. The 79 shots are evenly distributed on the line starting at CDP 10. The minimum and maximum of the offset between shot and receiver are 40m and 2000m, respectively. The line has a 1-D velocity structure shown in Fig. 3 and the acoustic impedance of the target is assumed to be infinite. A Ricker wavelet with central frequency 25 *HZ* is used as the source at all shot points and the two-way acoustic wave equation is solved by the fourth-order finite difference method (e. g. Wu *et al*. 1996) to create the synthetic data. The modified prestack Kirchhoff time migration is applied to the data set. The migrated image in time is shown in Fig. 4, and the depth-converted section is shown in Fig.5. The top and the upper portion of the dipping edge of the target are imaged almost perfectly as expected. Note however that lower part of the dipping edge is "lost". It is easy to understand why: imaging dips beyond 90 degrees below 2 km is not possible, since the velocity does not increase below 2 km (see Fig. 3). The contour map of the traveltimes (Fig. 6) clearly shows the absence of turning seismic waves below 2 km (Fig. 6).

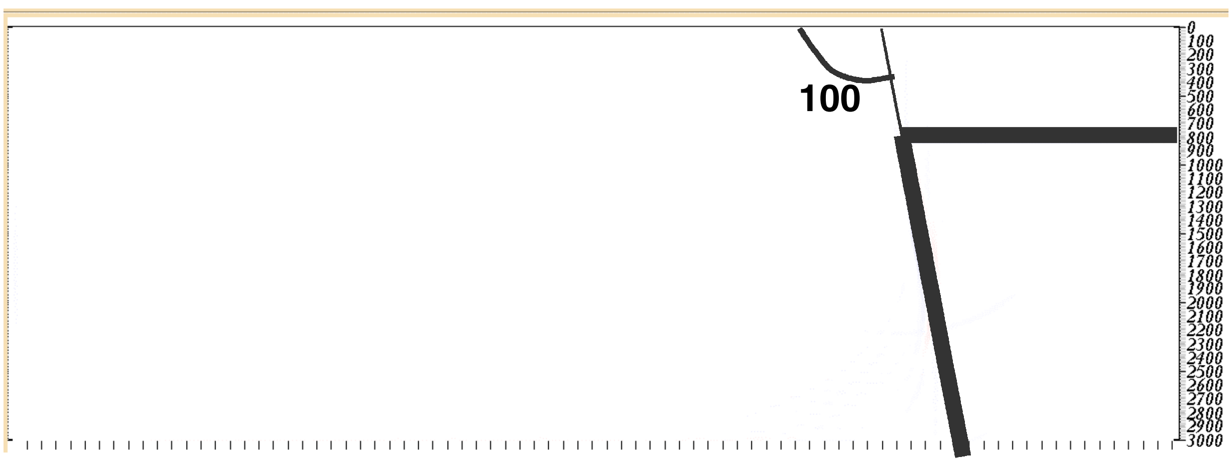


Fig. 2. A 2-D model.

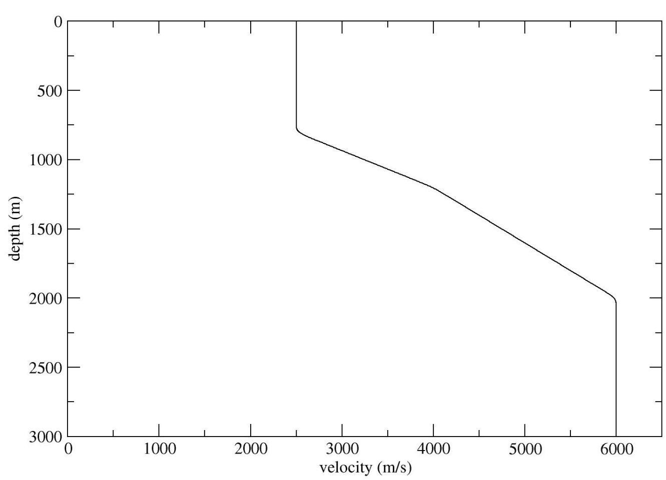


Fig. 3. Velocity in depth.

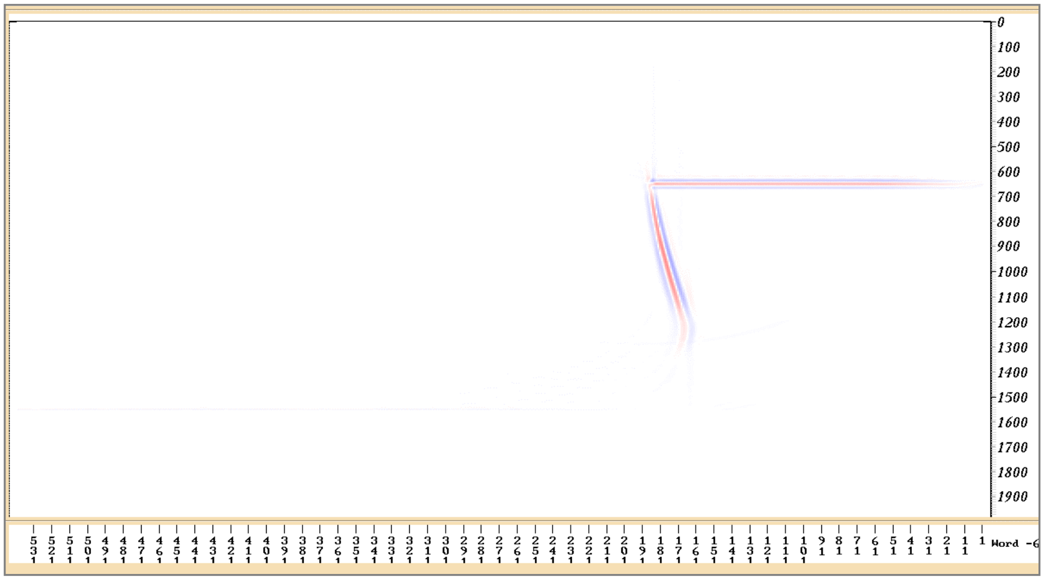


Fig. 4. Prestack migrated image in time.

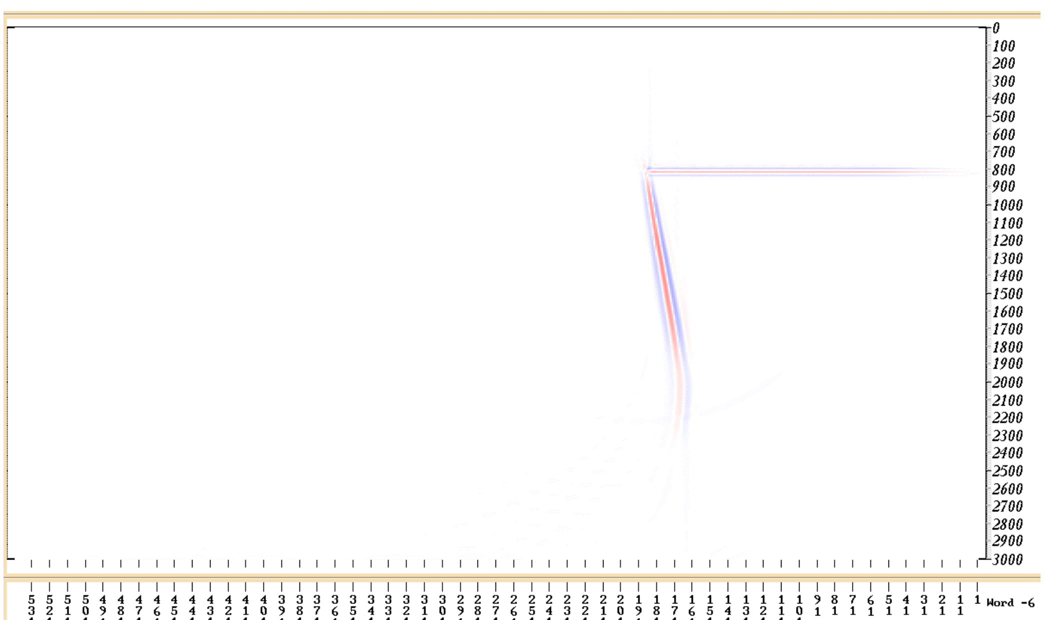


Fig. 5. Prestake migrated image in depth (converted from that in time).

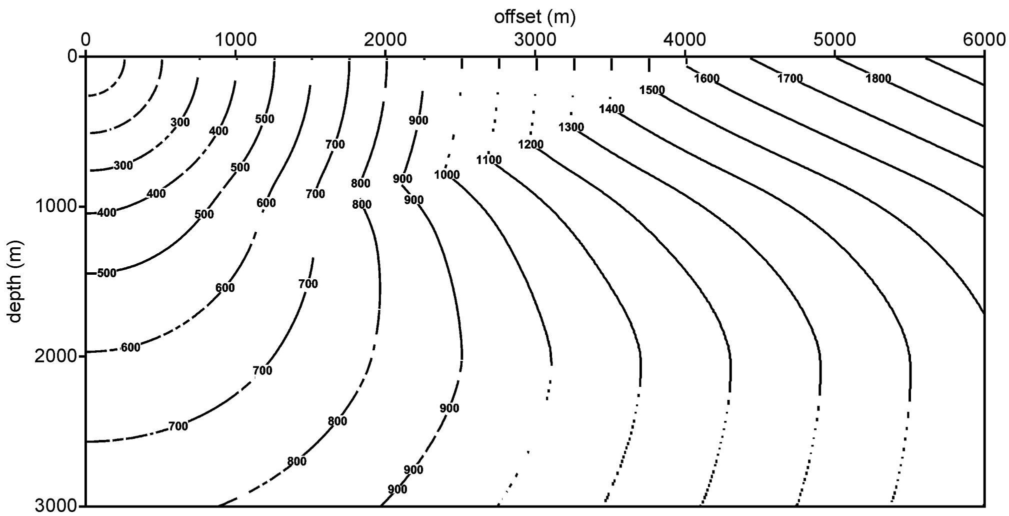


Fig. 6. The contour map of the traveltimes.

Conclusions

(1) It is possible to image dips beyond 90 degrees if velocity increases with depth. The contour map of traveltimes calculated by the eikonal equation can be used to check for the existence of turning waves.

(2) The modified prestack Kirchhoff time migration with first arrival traveltimes calculated using the eikonal equation, as discussed in this paper, has the ability to image dips beyond 90 degrees. Generally speaking, it is much faster than prestack depth migration especially for 3-D data sets, and it is more accurate than stack+poststack migration procedure for large dips.

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