3-D prestack migration deconvolution

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Abstract
An undersampled acquisition geometry and a limited recording aperture often produces migration noise (i.e., acquisition footprint) that blurs the subsurface reflectivity image. Here, we develop a prestack migration deconvolution (MD) filter that deblurs the migration image. The MD filter is applied to 3-D prestack SEG/EAGE salt data as well as 3-D marine data from Alaska. Results show that MD can provide noticeably better illumination and resolution than standard migration images.

Introduction
Over the years, 3-D prestack migration has become the key tool for seismic imaging of complex structure (Gray et al., 2001; Etgen, 2002). Unfortunately, due to coarse source-receiver sampling, limited aperture width and strong velocity contrasts, the subsurface will be unevenly illuminated. Consequently, the migration section will be a blurred approximation to the actual reflectivity distribution. Mathematically, the blurred migration section can be considered as the actual reflectivity distribution modulated by the migration Green’s function or point spread function (PSF) (Schuster and Hu, 2000; Yu, 2002a).

To alleviate the blurring problems, Hu and Schuster (1998; 1999) designed a deblurring or migration deconvolution operator to suppress migration artifacts in post-stack migration data (Hu et al., 2001). To extend post-stack MD to complex structures, we now develop a stable 3-D prestack migration deconvolution operator for suppressing migration artifacts and enhancing migration illumination in prestack migration image. The key to stability is to use regularization and make sure the ration of MD operator width and height varies with depth. Examples from both synthetic and field data demonstrate its capability in suppressing migration noise and improving spatial resolution of the migration image.

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Seismic forward modeling is based on the acoustic wave equation and can be approximated as a weighted summation of Green’s function. For example, the diffraction stack modeling equation (Stolt and Benson, 1986) under the Born approximation is given by

\[ d(x_s, x_g, t) = \int w(t) * G(x_g, t|x, 0) * G(x, t|x_s, 0)r(x)dV \]  

where \( w(t) \) denotes the second-time derivative of the source wavelet, \( r(x) \) denotes the velocity perturbation (also denoted as the approximate reflectivity distribution) from the background model; and \( (x_g, x, t) \) denotes the data space coordinates. The Green’s function that satisfies the acoustic wave equation is denoted by \( G \).

The seismic data forward modeling operator \( L \) relates the actual reflectivity model \( m \) to scattered seismic data \( d \). Thus, equation (1) can be given in matrix-vector form as

\[ d = Lr, \]

where \( d \) is the observed data vector; \( r \) denotes the true reflectivity vector; and \( L \) is the forward modeling matrix associated with a specific acquisition geometry and velocity model.

We can estimate the migration image \( m \) by applying the adjoint \( L^T \) of the forward modeling operator to the data,

\[ m = L^T d, \]

where the transpose of \( L \) represents the migration operator.

After inserting equation (2) into equation (3), we obtain

\[ m = L^T L r, \]

which says that migration result \( m \) is the blurred image of the actual subsurface reflectivity distribution \( r \). To find the unblurred reflectivity distribution \( r \), we apply \((L^T L)^{-1}\) to the both sides of equation (4),

\[ r = (L^T L)^{-1} m, \]

where \((L^T L)^{-1}\) represents the deblurring or MD operator.

The deblurring operator \((L^T L)^{-1}\) used in prestack migration deconvolution can be obtained by calculating the Green’s function associated with the specified acquisition geometry and velocity model. The detailed description of the MD implementation is presented in Hu et al. (1998; 2001).
Examples

3-D Stream Channel Model. In this example, a synthetic data set is generated for a meandering stream model. In the test, a coarse acquisition geometry is used, in which there is a 3X3 array of sources with a shot interval of 1.5 km in both inline and crossline directions, respectively. For each shot gather, an 11X11 array of receivers is activated with a receiver inline and crossline spacing of 0.3 km. The meandering stream is buried at the depth of 3.6 km as shown in the top panel of Figure 1. The 3-D prestack migration result is shown in the middle panel of Figure 1. Obviously, the migration amplitude of the meandering stream is blurred by the migration noise background and it is difficult to delineate the accurate features of the target. The corresponding prestack migration deconvolution image is shown in the bottom panel of Figure 1. The Green’s function is generated by prestack data with a coarse acquisition geometry described above. Comparing these results, it is clear that prestack migration deconvolution produces high resolution images that accurately resemble the true model.

3-D SEG/EAGE Salt Model. The 3-D SEG/EAGE salt data have become a benchmark for testing 3-D prestack depth migration methods. The data set used in this example consists of 5 shot lines, each shot line consisting of 9 shot gathers with inline and crossline shot spacings of 960 m. For each shot gather, there is a 201X201 array of geophones with geophone intervals of 20 m in both the inline and crossline directions. This coarse geometry gives rise to a migration image with both noise and poor energy focusing at the salt boundary. The top panel in Figure 2 shows a migration slice at depth 1.2 km generated by a wave-equation migration method (Yu, 2002b). The result after applying 3-D prestack MD produces significant improvements in migration quality, as shown in Figure 2, with less noise and better boundary focusing.

Marine Converted Wave Data. Figure 3 shows the application of prestack MD to PS wave marine data acquired from the Gulf of Mexico. The data recording length consists of 1501 sample points with a sampling interval of 8 ms in this test. The PS migration velocity model provided by an oil company is used for migration deconvolution. The top panel in Figure 3 shows the PS prestack time migration (PSTM) image, in which above 4.0 s there is some unwanted coherent noise in the migration image. The PS wave migration deconvolution result is shown in the bottom panel of Figure 3 where MD noticeably improves the migration quality, both reducing migration noise and increasing illumination of reflectors and fault positions.

3-D field data. Figure 4 shows the application of 3-D prestack MD to 3-D field data acquired from Alaska. The data recording length consists of 2001 sample points with a sampling interval of 2 ms. The migration velocity model used for migration deconvolution is courtesy of Unocal company.

Figure 4 compares the zone of interest for the prestack time migration along the crossline direction before (left panel) and after (right panel) prestack MD processing. MD noticeably improves the migration quality with increasing spatial resolution. The small fault which is invisible in the migration image (left panel) is clearly identified in the MD image (right panel) indicated by a dashed line. Figure 5 shows the comparison of the prestack migration time slice at 2.0 s before (left) and after (right) applying MD. It is seen that the MD image produces the image with better spatial resolution. Similar results are also obtained at different depth levels that provides more detailed information about the complex structure characterization than standard migration images.

Conclusions

A 3-D prestack migration deconvolution method is presented and applied to both synthetic and field data. As expected, the results show an improved migration response with fewer artifacts and higher spatial resolution. Tests on synthetic data and 3-D SEG/EAGE salt data show significant improvements in enhancement of image resolution and illumination for subsalt imaging. The application of migration deconvolution to field data demonstrates that prestack MD is capable of improving the spatial resolution and suppressing migration artifacts for complex subsurface formations.

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References


Yu, J., 2002b, 3-D SEG/EAGE salt model imaging using sparse frequency wavefield extrapolation, UTAM Annual Report, 233-245.

Figure 1: Comparison of 3-D prestack migration image and migration deconvolution image of 3-D meandering stream model. (Top panel) Meandering stream model at depth of 3.6 km; (middle) 3-D prestack migration result; (bottom) Same as middle panel except application of 3-D prestack migration deconvolution. Note that MD yields significant improvements in migration quality.

Figure 2: (Top) 3-D prestack migration slice at depth of 1.2 km generated by 3-D prestack depth migration method; Coarse acquisition geometry in this data set generates an unsatisfactory image in the complex part. (Bottom) 3-D prestack migration deconvolution result which has less noise and better energy focusing.
Figure 3: (Top) PS wave prestack migration image courtesy of Unocal company; (bottom) prestack migration deconvolution image. Prestack MD reduces noise and produces better migration quality with more detailed information about the faults.

Figure 4: (a) Cross section of 3-D prestack time migration cube in cross-line direction (courtesy of Unocal); (b) same as (a) except prestack MD has been applied (color figure). Note that MD image provides a clear fault track as indicated by the dashed line.

Figure 5: (a) A time slice of 3-D prestack time migration cube (courtesy of Unocal); (b) same as (a) except the application of 3-D prestack MD (color figure). Note that MD produces better migration quality with more detailed information about the faults.