3D ILLUMINATION COMPENSATION AND RESIDUAL MOVEOUT METHOD IN THE ANGLE DOMAIN

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ABSTRACT

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A 3D illumination compensation and residual moveout method in the angle domain is developed to improve the quality of imaging for the data acquired by an irregular acquisition system. The approach uses the Kirchhoff integration migration to provide fast illumination analysis and amplitude compensation. A residual moveout function is presented and be used to flatten the events in the angle gather. In addition to the simple procedure and computational efficiency, the method can also avoid the singularity problem usually linked to the conventional ray tracing method. It provides a practical tool for 3D full-volume illumination analysis and extract high quality common-imaging gathers and migration sections for complicated geological structures. To demonstrate the potential application of this method, a 3D marine field-data is used to evaluate the effectiveness of our method.

KEY WORDS: angle domain, illumination analysis, residual moveout, signal-to-noise ratio.

INTRODUCTION

For a long time, the multi-coverage technique is one of the most widely used schemes in seismic exploration. Because of irregular acquisition system and complex geologic structures, the seismic illumination analysis becomes a consequent useful tool that gives high quality migration sections and potential detecting power for an imaging target. In addition, because we can only obtain the subsurface velocity model approximately in practice, some slight bent events

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are often found in pre-stack common-imaging gathers. At this time, a convenience and effective method, such as residual moveout, becomes necessary to flatten the events and improve signal-to-noise ratio of the final stacked sections. Since angle-domain common-image gathers are effective tool for studies of velocity analysis and amplitude variation (Biondi, 2006), we present an illumination compensation and residual moveout method in angle domain.

Illumination analysis in the target area is a powerful tool to study the influences of acquisition system and imaging aperture. Traditionally, illumination analysis is based on the ray tracing technique (Schneider and Winbowm, 1999; Bear et al., 2000; Muerdter et al., 2001). The high frequency asymptotic approximation and the singularity problem in complex regions theory may severely limit its accuracy in complex regions (Hoffmann, 2001). Full-wave finite difference method is widely used for wave propagation simulation and can provide illumination information of the wave propagation. In another approach (Wu et al., 2000; Wu and Chen, 2002), directional illumination and acquisition-aperture efficacy analysis based on beamlet wavefield decomposition and propagation are proposed. But the application of those methods to practical use is obviously limited by their high computation cost. In addition, those methods are both limited by accurate velocity, since we can only obtain the subsurface velocity model approximately in practice.

How to get a complex though correct velocity model is still an open issue and is beyond our scope. For this reason the Kirchhoff migration is one of the most widely applied imaging methods in industry. This is because it has the well-known capability of imaging complex structures and can also handle velocity models with various types of anisotropy. Meanwhile, Kirchhoff migration offers better handling of irregular acquisition, better amplitude control, and better understanding of all illumination and regularization issues. This understanding is needed because the regularization of illumination is the key to a reduction of classic migration artifacts and an improvement of the image quality.

In addition to the characteristic of above, the Kirchhoff integration pre-stack time migration also retains the advantage of using stacking velocity, compared to interval velocity for pre-stack depth migration (Yilmaz and Claerbout, 1980). Meanwhile, we can overcome the singularity problem of the conventional ray theory by stacking velocity. For our method, the only problem is a new procedure of illumination analysis and residual moveout function available for time domain angle gathers, because the conventional illumination analysis is often implemented in depth and residual moveout is implemented in offset domain.

Based on the above advantages, we present a illumination compensation and residual moveout method based on time domain angle gathers. In the method, we firstly present a new residual moveout function for time domain angle gather and a statistically illumination analysis method according to the Kirchhoff integration pre-stack time migration method. The residual moveout and muting in angle gathers can improve the signal-to-noise ratio of final stacked sections. At last, we compensate for illumination heterogeneity in angle gathers by statistically analyzed illumination intensity. Our method is an effective complement to conventional pre-stack time migration workflow, especially for the data acquired by irregular acquisition system. Finally, we use 3D marine field data example to demonstrate the feasibility of our method.

METHODOLOGY

Residual moveout in time domain angle gathers

Firstly, we derive the expression for residual moveout function to be applied to the time domain angle gathers. We assume that S and R are the source and receiver positions at the surface, Z_0 is the depth of a imaging point I under the stacking velocity V, the dip angle and incident angle are α and γ, as shown in Fig. 1. The total travel time through source, imaging point and geophone is given by Sava and Fomel (2003)

$$t = 2(Z_0/V)[\cos\alpha\cos\gamma/(\cos^2\alpha - \sin^2\gamma)] \quad . \tag{1}$$

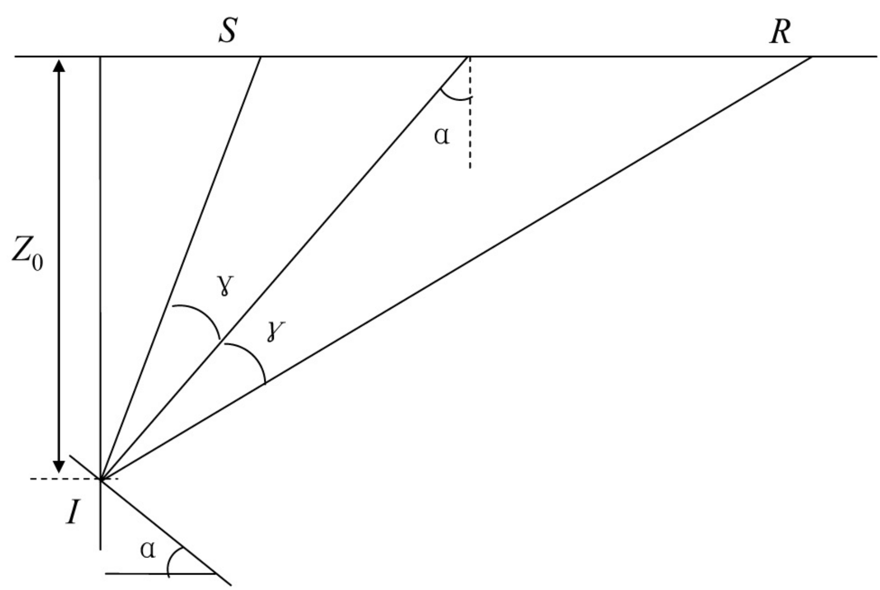

Fig. 1. Illustration of reflection geometry. S and R are the source and receiver positions at the surface, Z_0 is the depth of an imaging point I under the stacking velocity V, the dip angle and incident angle are α and γ.

We assume that the dip angle, the incident angle and the path of wave propagation remain unchanged under slight velocity error. Supposing $\rho = V'/V$, where V' is the migration velocity, the travel time can be expressed as

$$t_\rho = 2(Z_0/V')[\cos\alpha\cos\gamma/(\cos^2\alpha - \sin^2\gamma)] \quad . \tag{2}$$

Supposing the travel time error caused by velocity error, that is , we obtain the normal shift by Fermat's principle and trigonometry (Etgen, 1990; Stork, 1992)

$$\Delta\mathbf{n}_{tot} = (V\Delta t/2\cos\gamma)\mathbf{n} = [(\rho - 1)/\rho][Z_0\cos\alpha/(\cos^2\alpha - \sin^2\gamma)]\mathbf{n} \quad , \tag{3}$$

where $\mathbf{n}$ is the normal vector of the reflector. Now the residual moveout shift can be expressed by the difference of imaging depth with incident angle γ to $\gamma = 0$ in the angle gather, that is

$$\Delta\mathbf{n}_{RMO} = \Delta\mathbf{n}_{tot}(\gamma) - \Delta\mathbf{n}_{tot}(\gamma = 0)$$

$$= [(\rho - 1)/\cos\alpha][Z\sin^2\gamma/(\cos^2\alpha - \sin^2\gamma]\mathbf{n} \quad , \tag{3}$$

where Z is the imaging depth, and can be approximately expressed as $Z = \rho Z_0$. Supposing $T = Z/V'$ is the one-way travel time in time migration and $\alpha = 0$ in the simplified case which is suitable to 3D time migration, the time domain residual moveout normal shift can be expressed in the angle domain as

$$\Delta T_{RMO} = T(\rho - 1)\tan^2\gamma \quad . \tag{4}$$

We present a velocity error parameter ρ field estimation method by scanning scheme. That is, we stack the angle gathers by residual moveout function using a group of changing parameters ρ, then pick the parameters corresponding to the best stacked events.

Illumination analysis and compensation

Based on time migration, our method obtains the illumination intensity of the incident angle by analyzing the positions of source, geophone and imaging point, then stack the statistical illumination intensity of valid incident angle to accomplish the illumination analysis for the acquisition system. For a imaging trace with the source and geophone location at $(x_s,y_s,0)$ and $(x_g,y_g,0)$, we calculate the incident angle by

$$\gamma = \tfrac{1}{2}\arccos[(t_{SI}^2V^2 + t_{GI}^2V^2 + off^2)/2t_{GI}t_{SI}V^2] \quad , \tag{5}$$

for a imaging point location at (x_I, y_I, T), where

$$t_{SI} = \sqrt{\{(x_s - x_I)^2/V^2 + (y_s - y_I)^2/V^2 + T^2\}} \quad , \tag{6}$$

and

$$t_{GI} = \sqrt{\{(x_g - x_I)^2/V^2 + (y_g - y_I)^2/V^2 + T^2\}} \quad , \tag{7}$$

are the traveltimes from the source position and the geophone position to the imaging position, respectively,

$$\mathrm{off} = \sqrt{\{(x_s - x_g)^2 + (y_s - y_g)^2} \quad , \tag{8}$$

is the length of the source position to the geophone position (offset), V is the stacking velocity of this imaging point. If the imaging point is in the range of the imaging aperture (Zhang and Zhang, 2012) of this trace, the statistical illumination intensity of the imaging point $R_{\overline{(x_I,y_I,T,\gamma)}}$ will be increased by 1. Strictly speaking, it is not accurate illumination intensity of imaging point, rather than pseudo illumination intensity matching the Kirchhoff integration migration. But that also make our method more efficient, since we can accomplished this procedure in the process of migration. Then, the illumination intensity of acquisition system can be obtained by $R_{\overline{(x_I,y_I,T)}} = \Sigma_\gamma R_{\overline{(x_I,y_I,T,\gamma)}}$. At last, we can compensate the amplitude by illumination intensity to extract reliability amplitude pre-stack angle gather and high resolution stacked sections.

NUMERICAL IMPLEMENTATIONS

To show the effectiveness of our method, we apply it to a 3-D marine field-data. Fig. 2 is a sketch showing the geometry of the acquisition system by

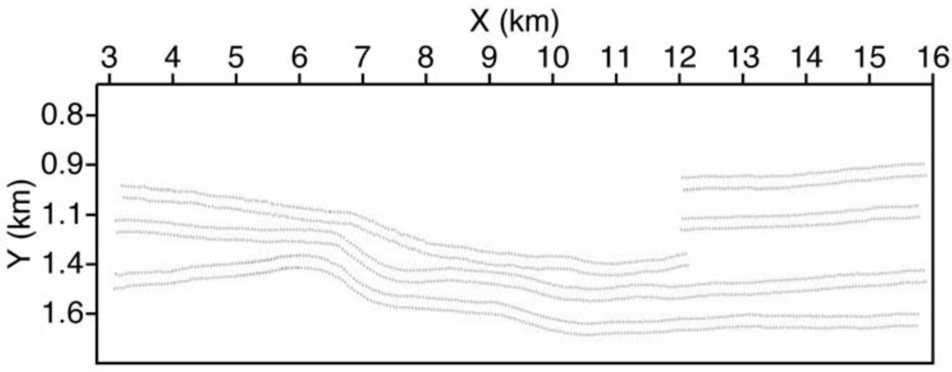

Fig. 2. Illustration of the acquisition system by shot positions. The illumination intensity of the imaging target in the middle of the figure is heterogeneous.

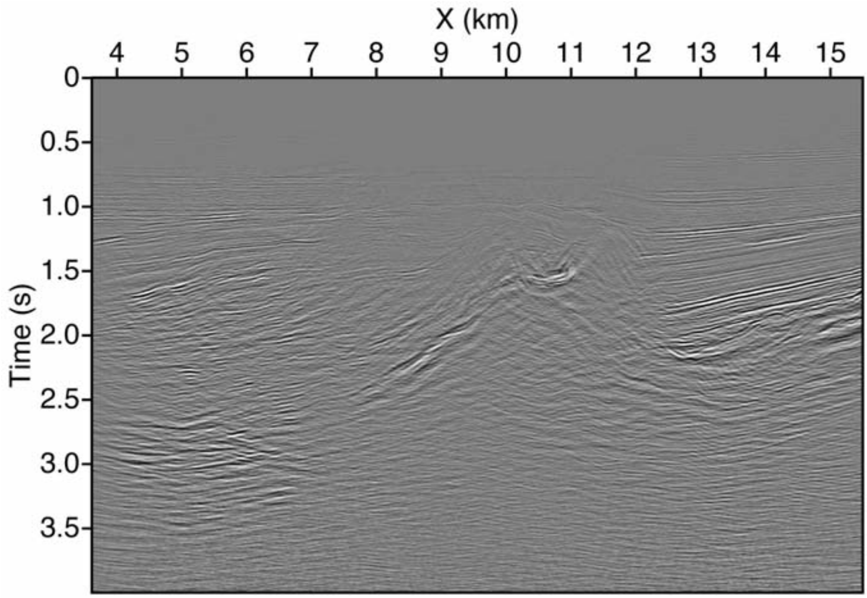

Fig. 3. A migration section positioned at Y = 1.1 km by time migration. Insufficient illumination was found between X = 7 km and X = 12 km.

shot positions. Obviously, the illumination intensity of imaging target in the middle of the figure is heterogeneous. A migration section positioned at Y = 1.1 km by time migration is shown in Fig. 3, through which obvious insufficient illumination was found between X = 7 km and X = 12 km.

Fig. 4a is an angle gather positioned at Y = 1.1 km and X = 6.2 km. Fig. 4b is the residual moveout parameter scanning gather stacked by eq. (4) using a group of changing parameters ρ. The solid line denotes the picked parameters which can extract the best stacked events. Fig. 5a is the same gather shown in Fig. 4a after residual moveout, and Fig. 5b is the gather having been muted the large incident-angle noisy to improve the signal-to-noise ratio of the final stacked section, as shown in Fig. 6.

Fig. 7a is the statistical illumination intensity in the angle domain of the angle gather as shown in Fig. 4a. The angle gather compensated by illumination is shown in Fig. 7b. It is obvious that the amplitudes from deep and shallow part shown in Fig. 7b seem much more balance than those shown in Fig. 5b. The illumination intensity of the acquisition system is shown in Fig. 8, by which the migration section compensated was shown in Fig. 9. Comparing with Fig. 3 and Fig. 6, the homogeneity of illumination intensity and signal-to-noise ratio are improved obviously in Fig. 9, which demonstrate the potential application of this method.

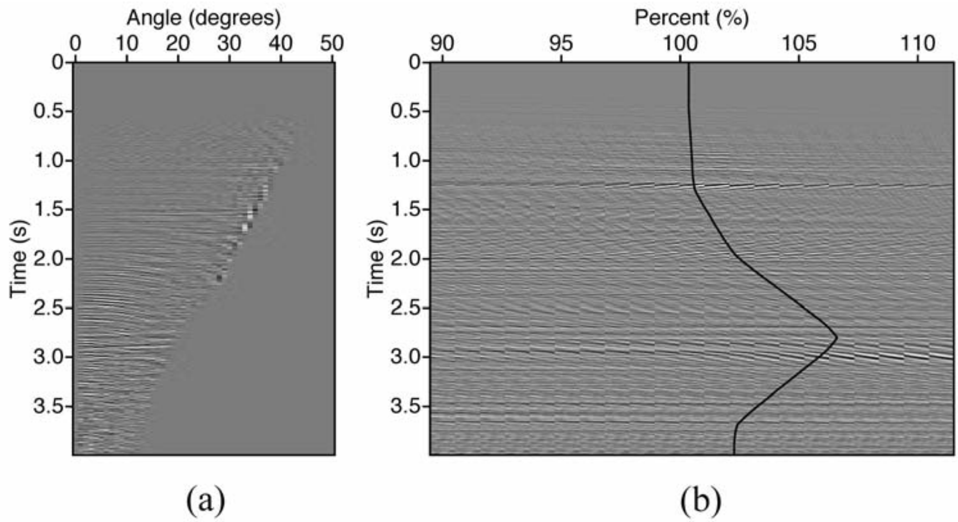

Fig. 4. An angle gather positioned at Y = 1.1 km and X = 6.2 km (a) and the corresponding residual moveout parameter scanning gather (b) stacked by eq. (4) using a group of changing parameters ρ. The solid line denotes the picked parameters which can extract the best stacked events.

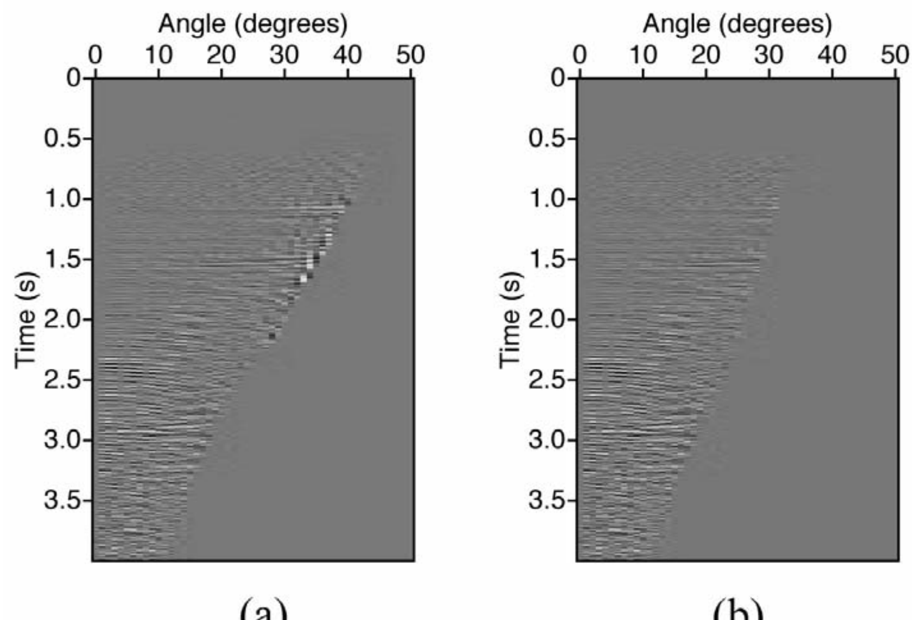

Fig. 5. The same apparent angle gather shown in Fig. 4a after residual moveout (a) and a further step of muting the large angle noisy to improve the signal-to-noise ratio of the final stacked section.

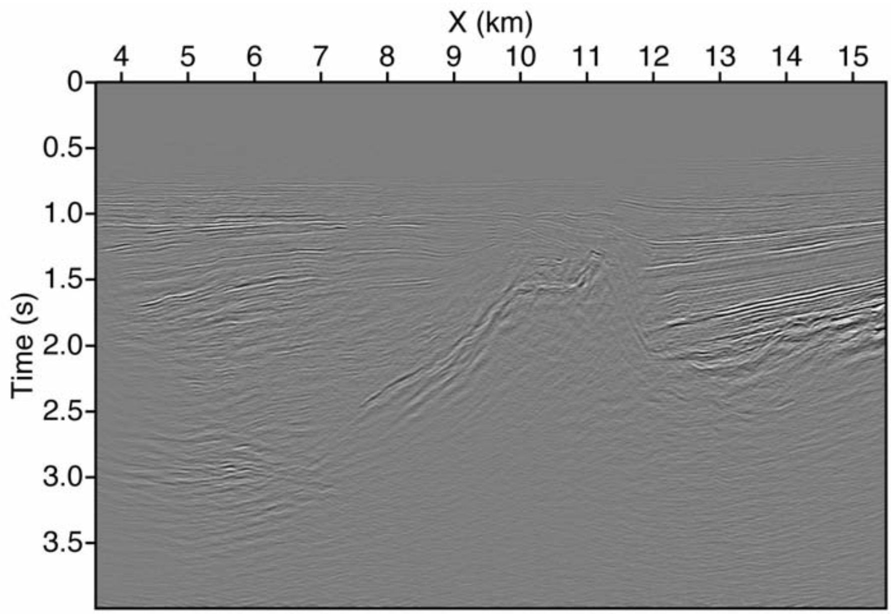

Fig. 6. The same migration section that was obtained by stacked gathers having been implemented by residual moveout and muting. The signal-to-noise ratio has clearly been increased.

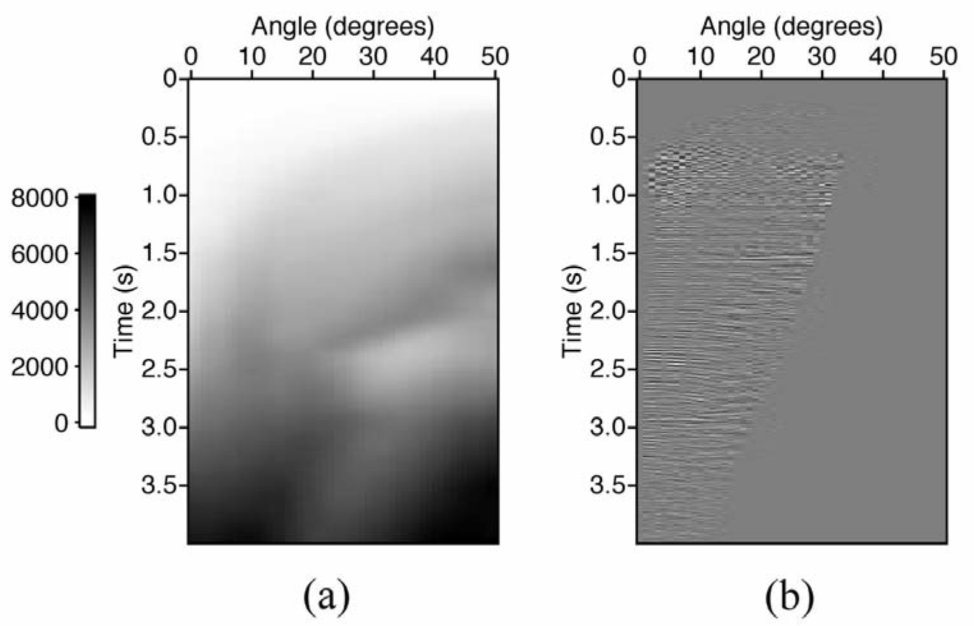

Fig. 7. The statistical illumination intensity (a) of the angle gather as shown in Fig. 4a and the angle gather (b) compensated by illumination intensity. It is obvious that the amplitudes from deep and shallow part shown in Fig. 7b seem much more balance than those shown in Fig. 5b.

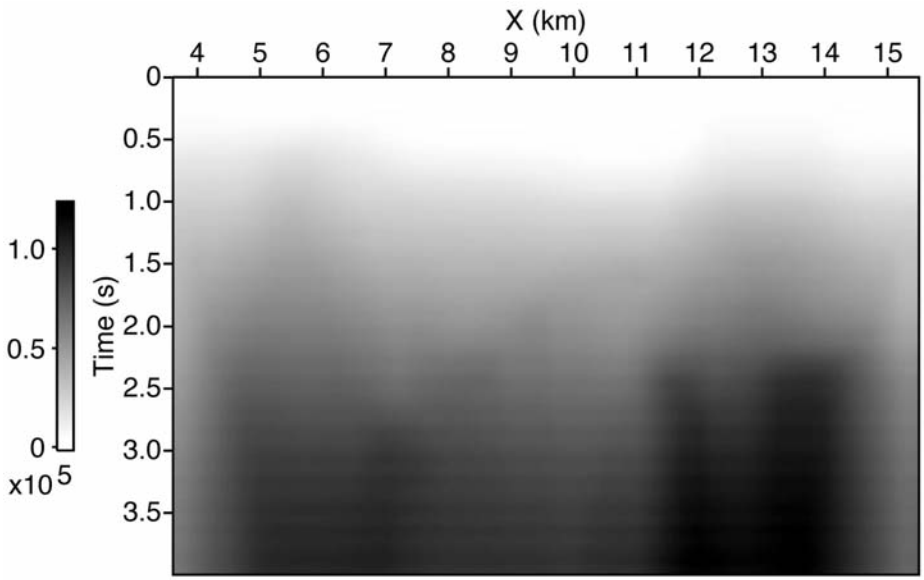

Fig. 8. The statistical illumination intensity of the acquisition system was obtained by stacking the angle domain illumination intensity.

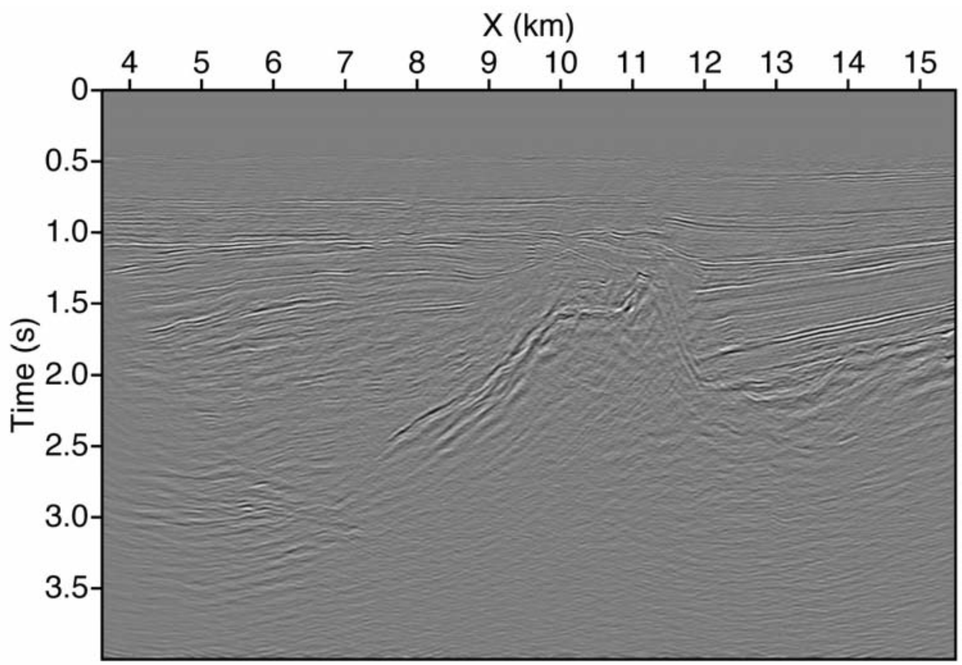

Fig. 9. The same migration section was obtained by compensating illumination. Comparing with Fig. 3 and Fig. 6, the homogeneity of illumination intensity and signal-to-noise ratio are improved obviously.

CONCLUSIONS

We demonstrate an angle domain method to implement illumination compensation and residual moveout. This algorithm can improve the signal-to-noise ratio of the migration signals and extract high fidelity seismic migration sections, in order to provide a high-resolution in detecting small-scale geological structures in seismic exploration. The result of our method is an effective complement to conventional exploration workflow, especially to the data acquired by an irregular acquisition system. A marine field data example demonstrates that our method is obviously capable of improving the signal-to-noise ratio, and extracting reliability amplitude migration sections compared to conventional migration. We believe our method should be helpful to the seismic exploration for the data acquired by irregular acquisition system.

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