remote sensing

Technical Note

Q-Compensated Gaussian Beam Migration under the Condition of Irregular Surface

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Abstract: The viscosity of actual underground media can cause amplitude attenuation and phase distortion of seismic waves. When seismic images are processed assuming elastic media, the imaging accuracy for the deep reflective layer is often reduced. If this attenuation effect is compensated, the imaging quality of the seismic data can be significantly improved. Q-compensated Gaussian beam migration (Q-GBM) is an effective seismic imaging method for viscous media, and it has the advantages of both wave equation and ray-based Q-compensated imaging methods. This study develops a Q-GBM method in visco-acoustic media with an irregular surface. Initially, the basic principles of Gaussian beam in visco-acoustic media are introduced. Then, by correcting the complex-value time of the Gaussian beam in visco-acoustic media, energy compensation and phase correction are carried out for the forward continuation wavefield at the seismic source of the irregular surface and the reverse continuation wavefield at the beam center, which effectively compensates the absorption and attenuation effects of visco-acoustic media on the seismic wavefield. Further, a Q-GBM method under the irregular surface is proposed using cross-correlation imaging conditions. Through migration tests for three numerical models of visco-acoustic media with irregular surfaces, it is verified that our method is an effective depth domain imaging technique for seismic data in visco-acoustic media under the condition of irregular surfaces.

Keywords: irregular surface; visco-acoustic media; Q-compensated; Gaussian beam migration; seismic imaging

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1. Introduction

Traditional theories of seismic wave propagation generally assume that the underground medium is isotropic and completely elastic. However, it is widely accepted that the real internal medium of the Earth has nonnegligible viscosity [1]. When seismic waves propagate in viscous media, amplitude attenuation and phase distortion will inevitably occur. In addition, the viscosity of underground media can lead to a decrease in frequency bandwidth and resolution reduction. With the gradual shift in exploration targets from shallow-stratum reservoirs to middle- and deep-stratum complex oil and gas reservoirs, the influences of the viscosity of underground medium on seismic exploration become increasingly important. When seismic imaging in these areas is processed based on the elastic medium hypothesis, the imaging accuracy for the deep reflective layer is often reduced, which is not conducive to the seismic interpretation of deep-stratum data. It is observed that compensating for such attenuation effects can improve the imaging quality of seismic data.

Early absorption compensation methods tried directly performing inverse Q filtering on seismic traces [2]. However, these methods usually compensate seismic records trace by trace using one-dimensional models without considering the propagation paths of seismic waves and cannot accurately correct the complex underground structures. In practice, absorption and attenuation are closely related to their propagation paths. Consequently, ideal compensation methods should be based on the propagation paths of seismic waves, and the corresponding compensation must be performed during the migration process. At present, migration methods for viscous media are primarily divided into two categories based on their difference in imaging operators, i.e., Q-compensated migration methods utilizing the ray theory [3–6] and based on the wave equation theory [7–12]. Attenuation compensation via wave equation migration has high imaging accuracy for complex structures but low computational efficiency. In contrast, traditional Q-compensated migration methods using ray theories (such as the Kirchhoff migration) are simple, efficient, and have good flexibility, but they suffer from multi-value traveltime, which causes blind spots in the imaging process of complex structures.

The Gaussian beam migration (GBM) method is an excellent imaging algorithm developed recently. It has imaging accuracy close to wave equation migration and preserves the flexible and highly efficient advantages of the Kirchhoff migration method, which can effectively address the issue of multi-value traveltime [13]. Since Hill [14,15] proposed the GBM method, researchers have conducted massive studies on the complex-surface, anisotropy, and multi-component GBM [16–22]. In addition, Wu et al. [23] created a visco-acoustic Gaussian beam prestack depth migration (GB-PSDM) method by correcting the complex-value traveltime of the Gaussian beam and then proposed a Q-compensated multi-component GBM method based on wavefield separation. Shi et al. [24] proposed a vector viscoelastic GBM method for attenuation compensation, which provides an efficient method for accurately imaging seismic wavefields in viscous media.

In addition to the viscosity of underground media, the complexity of near-surface conditions is also a tricky problem. The imaging processing of seismic wavefields under complex surface conditions in the piedmont zone is always a significant challenge in seismic exploration. Static correction and wave equation datuming schemes are conventional methods used to eliminate the influences of complex surfaces on a seismic wavefield. The conventional static correction method only applies to areas with relatively gentle terrain and low near-surface velocity, whereas the wave equation datuming method is greatly affected by the near-surface velocity [25,26]. In contrast, the migration method with complex earth surface can effectively address traveltime problems and imaging errors caused by the changes in surface elevation and velocity and thus accurately image complex geological structures under complex surface conditions [27–30].

In this study, the Q-compensated GBM (Q-GBM) method is applied to seismic wavefield imaging in visco-acoustic media with complex surfaces, and a Q-compensated GB-PSDM (QGB-PSDM) method is proposed under irregular surface conditions. Initially, the fundamental principles of Gaussian beam in visco-acoustic media are introduced, and the expression of Gaussian beam in a visco-acoustic medium is provided. Then, the absorption-attenuation effect of visco-acoustic media on the seismic wavefield is compensated by correcting the complex-value traveltime of the Gaussian beam in visco-acoustic media, and the forward continuation wavefield of the seismic source and the reverse wavefield at the beam center are, respectively, compensated. Thus, a QGB-PSDM method is presented for the irregular surface. Finally, three numerical models of visco-acoustic media under irregular surface conditions are developed to test and verify the proposed migration method's accuracy and effectiveness.

2. Theory

2.1. Basic Principles of Gaussian Beam in Visco-Acoustic Media

The quality factor Q representing the value of viscosity can be regarded as independent of frequency in seismic exploration. In this case, the seismic wave in visco-acoustic media can be regarded as the wavefield propagation in the acoustic media with a certain complex velocity that is represented by the acoustic velocity v_r and quality factor Q. Its imaginary part represents the attenuation effect of the visco-acoustic medium. The complex velocity can be expressed as follows [31]:

$$v_c(\mathbf{x}) = v_r(\mathbf{x})\left[1 + \frac{1}{\pi Q(\mathbf{x})}\ln(\omega/\omega_r) + \frac{i}{2Q(\mathbf{x})}\right] \tag{1}$$

where $\mathbf{x}$ represents the underground position and ω_r is the reference frequency. Equation (1) indicates the inherent dispersion relation in visco-acoustic media. The imaginary part of complex velocity implies exponential attenuation of seismic waves, while its real part contains a dispersion term, which guarantees the accuracy of the solution of the wave equation.

For the first-order term, the attenuation effect does not affect the path of ray propagation, and the viscosity affects the waveform by changing the complex-value traveltime. The complex-value traveltime can be described as follows:

$$T_a(\mathbf{x}) = T_0(\mathbf{x}) - \frac{1}{\pi}T_c(\mathbf{x})\ln(\omega/\omega_r) - \frac{i}{2}T_c(\mathbf{x}) \tag{2}$$

where $T_a(\mathbf{x})$ and $T_0(\mathbf{x})$ are the traveltime of a ray in visco-acoustic and acoustic media, respectively; $T_c(\mathbf{x})$ is the change of traveltime caused by viscosity, which is defined as

$$T_c(\mathbf{x}) = \int_{s_0}^{s} \frac{1}{v_r(\mathbf{x})Q(\mathbf{x})}ds \tag{3}$$

where ds is the spatial step length along the ray path, and the integral expression represents the integral along the ray path.

The Gaussian beam is expressed by the complex-value amplitude and complex-value traveltime. By substituting the complex-value traveltime shown in Equation (2), the Gaussian beam in the visco-acoustic media can be determined as follows:

$$U_a = A\exp(i\omega T) \tag{4}$$

$$T = \tau(\mathbf{x}) - \frac{1}{\pi}T_c(\mathbf{x})\ln(\omega/\omega_r) + \frac{n^2}{2}\frac{\xi(\mathbf{x})}{\eta(\mathbf{x})} - \frac{i}{2}T_c(\mathbf{x}) \tag{5}$$

where U_a represents a Gaussian beam in visco-acoustic media; A and T are the complex-value amplitude and complex-value time of the Gaussian beam in visco-acoustic media, respectively; n is the vertical distance from a point near the ray to the central ray; $\xi(\mathbf{x})$ and $\eta(\mathbf{x})$ are the dynamic parameters calculated by the dynamic ray tracing [32], which contain the dynamic characteristics of wavefield propagation along the ray and determine the energy distribution of the Gaussian beam.

2.2. Q-GBM under the Condition of Irregular Surfaces

Q-GBM can compensate for the absorption attenuation effect of visco-acoustic media by correcting the complex-value traveltime of the Gaussian beam in visco-acoustic media. For GBM in visco-acoustic media, the visco-acoustic absorption attenuation compensation can be realized by inverting the last two terms in Equation (5). After compensating the forward continuation and reverse wavefields, respectively, and under cross-correlation imaging conditions, the compensated imaging results can be obtained. By combining the GBM method from the irregular surface proposed by Han et al. [33], the formula for QGB-PSDM under the condition of an irregular surface can be described as

$$\begin{aligned} I_Q = C\int dx_s \sum_L \int d\omega \int dp_{sx} \int dp_{Lx} D(\mathbf{L}, \mathbf{p}_L, \omega) \\ \times U_Q^*(\mathbf{x}, \mathbf{x}_s, \mathbf{p}_s, \omega) U_Q^*(\mathbf{x}, \mathbf{L}, \mathbf{p}_L, \omega) \end{aligned} \tag{6}$$

where I_Q is the imaging value after compensating the seismic wavefield in visco-acoustic media with irregular surfaces; C is the corresponding constant; $U_Q^*(\mathbf{x}, \mathbf{x}_s, \mathbf{p}_s, \omega)$ is the compensated Gaussian beam along the ray parameter vector $\mathbf{p}_s = (p_{sx}, p_{sz})$ emitted from the source $\mathbf{x}_s$ on the irregular surface; $U_Q^*(\mathbf{x}, \mathbf{L}, \mathbf{p}_L, \omega)$ is the compensated Gaussian beam along the ray parameter vector $\mathbf{p}_L = (p_{Lx}, p_{Lz})$ emitted from the beam center $\mathbf{L}$ on the irregular surface; $D(\mathbf{L}, \mathbf{p}_L, \omega)$ is the local slant stack formula of the seismic record under irregular surface condition, which can be calculated by

$$\begin{aligned} D(\mathbf{L}, \mathbf{p}_L, \omega) &= \left|\frac{\omega}{\omega_r}\right|^{1/2} \int dx_r \cos(\varphi_L - \sigma_r) u(\mathbf{x}_s, \mathbf{x}_r, \omega) \\ &\times \exp\left[-\left|\frac{\omega}{\omega_r}\right| \frac{(x_r - L_x)^2}{2L_0^2}\right] \exp\{-i\omega[p_{Lx}(x_r - L_x) + p_{Lz}h]\} \end{aligned} \tag{7}$$

where φ_L is the exit angle of the Gaussian beam at the beam center on the irregular surface, σ_r is the dip angle at the receiving point $\mathbf{x}_r$ on an irregular surface, $u(\mathbf{x}_s, \mathbf{x}_r, \omega)$ is the seismic record in visco-acoustic media under the condition of the irregular surface, and h is the height difference from receiving points to the beam center.

By substituting the corresponding compensated Gaussian beam expressions into Equation (6), the QGB-PSDM formula with an irregular surface can be rewritten as follows:

$$\begin{aligned} I_Q = C \int dx_s \sum_L \int d\omega \int dp_{sx} \int dp_{Lx} D(\mathbf{L}, \mathbf{p}_L, \omega) A_{\mathbf{x}_s}(\mathbf{x}, \mathbf{p}_s) \\ \times A_{\mathbf{L}}(\mathbf{x}, \mathbf{p}_L) \exp\left\{-i\omega\left[T_{\mathbf{x}_s}^Q(\mathbf{x}, \mathbf{p}_s) + T_{\mathbf{L}}^Q(\mathbf{x}, \mathbf{p}_L)\right]\right\} \end{aligned} \tag{8}$$

where $T_{\mathbf{x}_s}^Q(\mathbf{x}, \mathbf{p}_s)$ and $T_{\mathbf{L}}^Q(\mathbf{x}, \mathbf{p}_L)$ are the complex-value time of the compensated Gaussian beam emitted from the source on the irregular surface and the beam center, respectively.

3. Numerical Tests

Three numerical models of visco-acoustic media under the condition of an irregular surface were established for migration testing. First, a single-shot migration test was conducted using a single interface model of the visco-acoustic medium under an irregular surface. Then, a sag model of a visco-acoustic medium under the condition of an irregular surface was designed to verify the efficacy of the method. Finally, a complex fault model of a visco-acoustic medium under the condition of an irregular surface was built to verify the accuracy of imaging complex structure models. In these models, the seismic datasets are generated using a 2nd-order in time and 14th-order in space staggered-grid finite-difference scheme of an irregular surface for acoustic and visco-acoustic media.

3.1. Single-Interface Model of the Visco-Acoustic Medium under the Condition of Irregular Surface

We first designed a single interface model of a visco-acoustic medium under an irregular surface. The model velocity and Q value are presented in Figure 1. Figure 2 depicts the visco-acoustic single-shot seismic records under the condition of the irregular surface. The shot is located at the Earth's surface position corresponding to the horizontal middle position. The seismic recording time is 2.4 s, and the trace interval is 10 m. Due to the irregular surface's influences, the seismic record's reflection event appears to be non-hyperbolic. Figure 3a,b exhibit the single-shot imaging results of visco-acoustic seismic records under an irregular surface via conventional GBM and Q-GBM, respectively. As can be seen, the Q-GBM under the condition of the irregular surface takes into the absorption of the stratum and compensates for the attenuation energy of visco-acoustic seismic records in the migration process; the profile energy after compensation (Figure 3b) is significantly higher than that without compensation (Figure 3a). The results verify that our method can effectively compensate for the absorption effect of underground media on seismic waves.

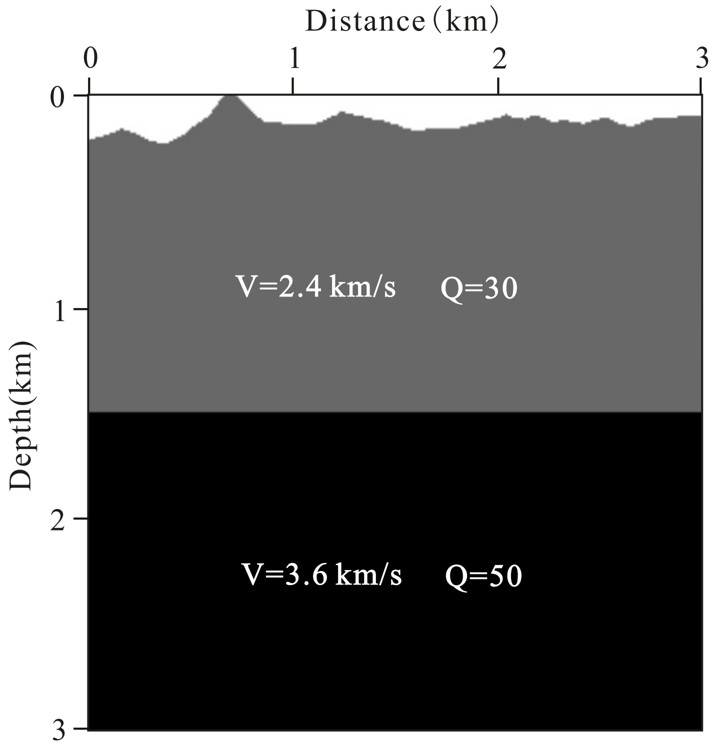


Figure 1. Single-interface model of the visco-acoustic medium under the condition of irregular surface. The upper and lower Q values are 30 and 50, respectively.

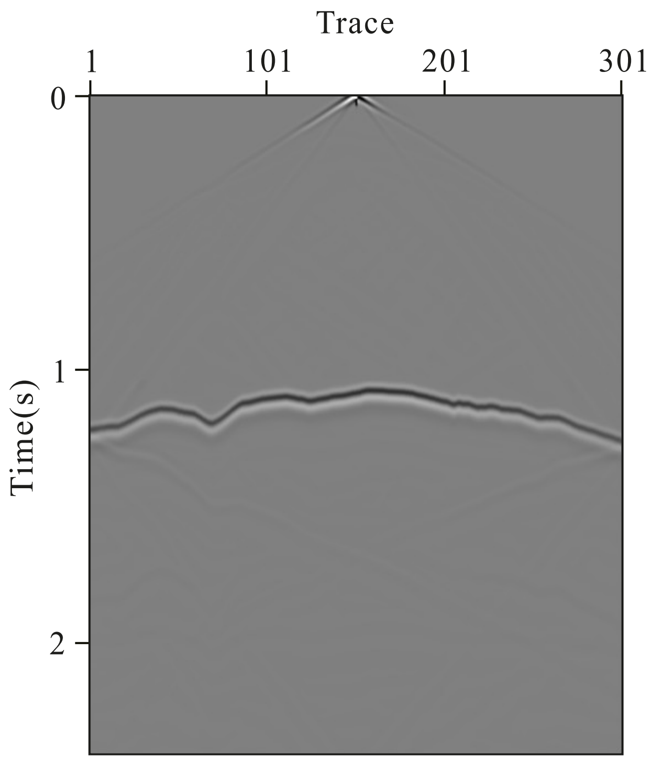


Figure 2. Visco-acoustic single-shot seismic records.

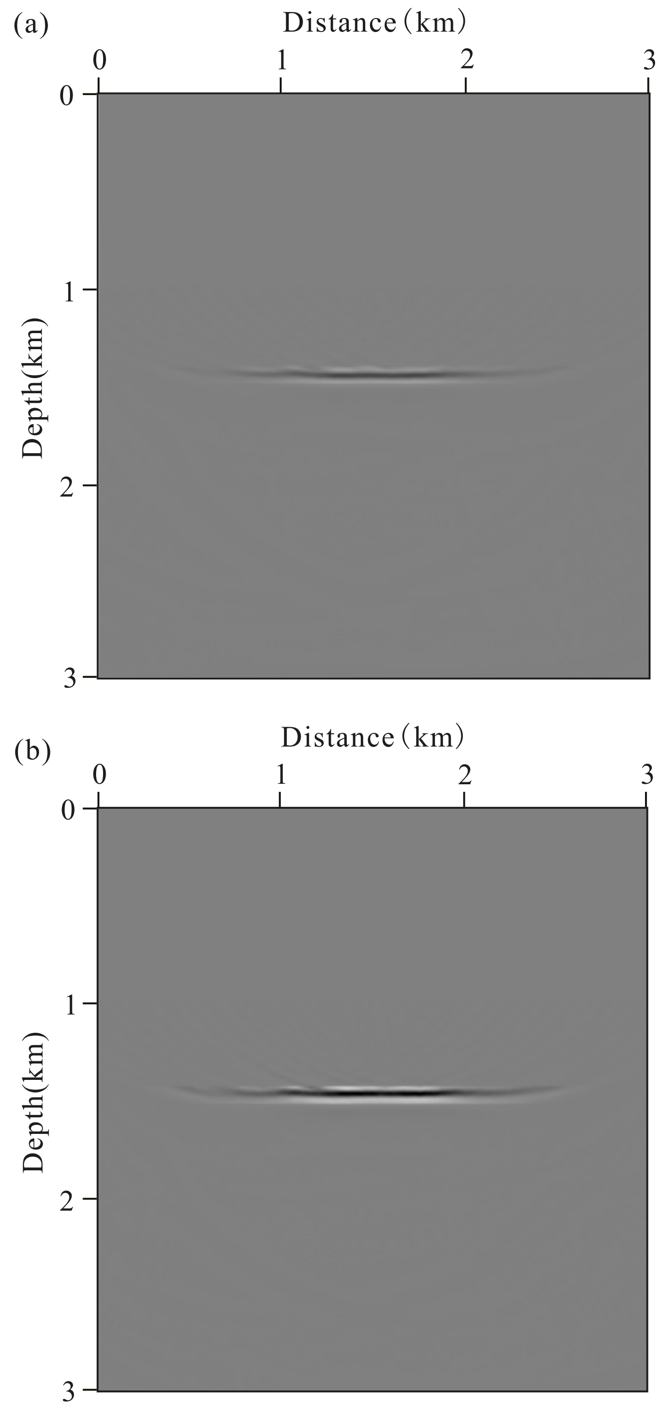


Figure 3. Single-shot imaging results of the single-interface model with irregular surface: (**a**) conventional GBM for visco-acoustic seismic records; (**b**) Q-GBM for visco-acoustic seismic records.

3.2. Sag Model of the Visco-Acoustic Medium under the Condition of Irregular Surfaces

A sag model of a visco-acoustic medium under the condition of an irregular surface was designed for the migration test. The velocity model and Q model are shown in Figure 4. A total of 79 shots of seismic records were simulated with the finite-difference method of an irregular surface, the distance between two shots was 50 m, and 401 receivers recorded every shot. Conventional GBM and Q-GBM were, respectively, performed on the visco-acoustic seismic records under the condition of the irregular surface, and the imaging results are depicted in Figure 5, where the profile energy after compensation (Figure 5b) is higher than that without compensation (Figure 5a). The vertical profiles from the above imaging results and theoretical optimal image (Figure 6) are plotted to clearly display the imaging improvements. Figure 7 is the vertical profile drawn from x = 2 km, where the Q-GBM method under an irregular surface can effectively compensate for the attenuation of the visco-acoustic seismic records and correct the phase distortion. By comparing the imaging results of the sag model, it is further verified that the method is accurate and effective for seismic wavefield imaging in visco-acoustic media under an irregular surface. In addition, we added random noise to the visco-acoustic seismic records for migration testing. Figure 8 shows the 40th visco-acoustic single-shot seismic record with random noise under the condition of the irregular surface, where it has high noise. Figure 9 shows the imaging result of the noised visco-acoustic seismic data using our Q-GBM method, where the noise has little effect on imaging, and an accurate imaging result is also obtained. It is proved that the proposed Q-GBM method has good noise resistance.

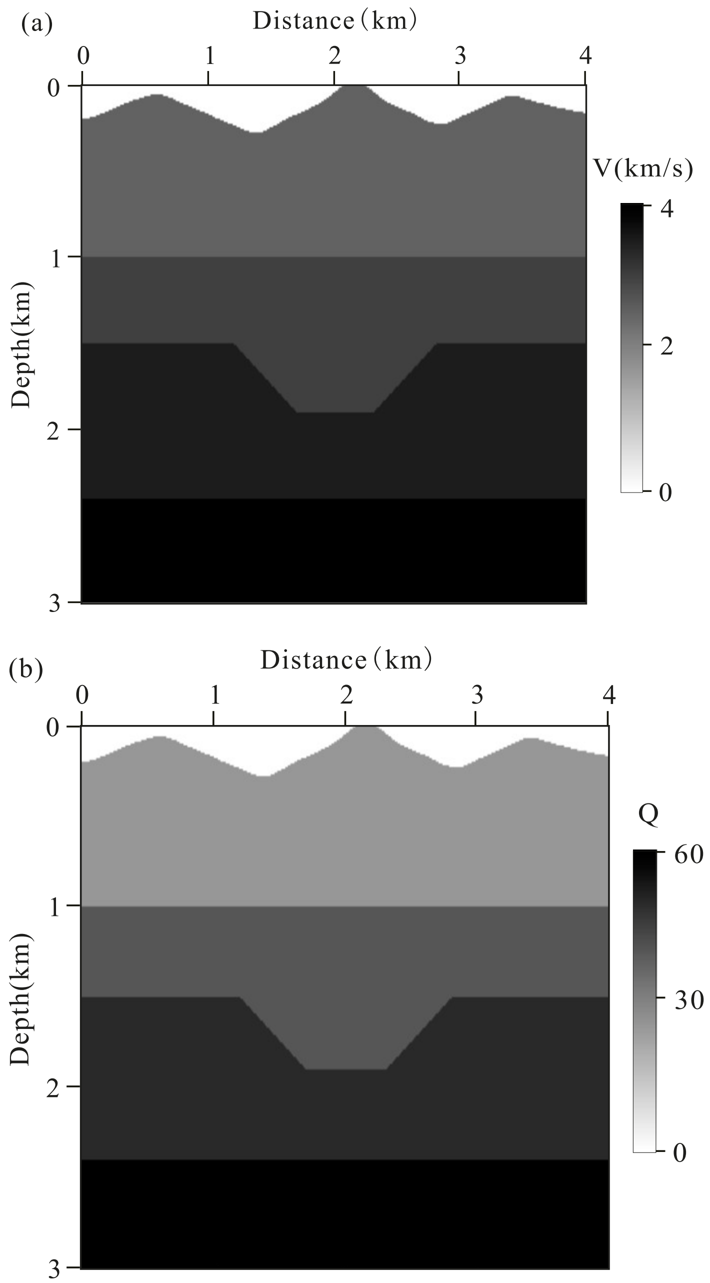


Figure 4. Sag model of the visco-acoustic medium under the condition of an irregular surface: (**a**) velocity model; (**b**) Q model.

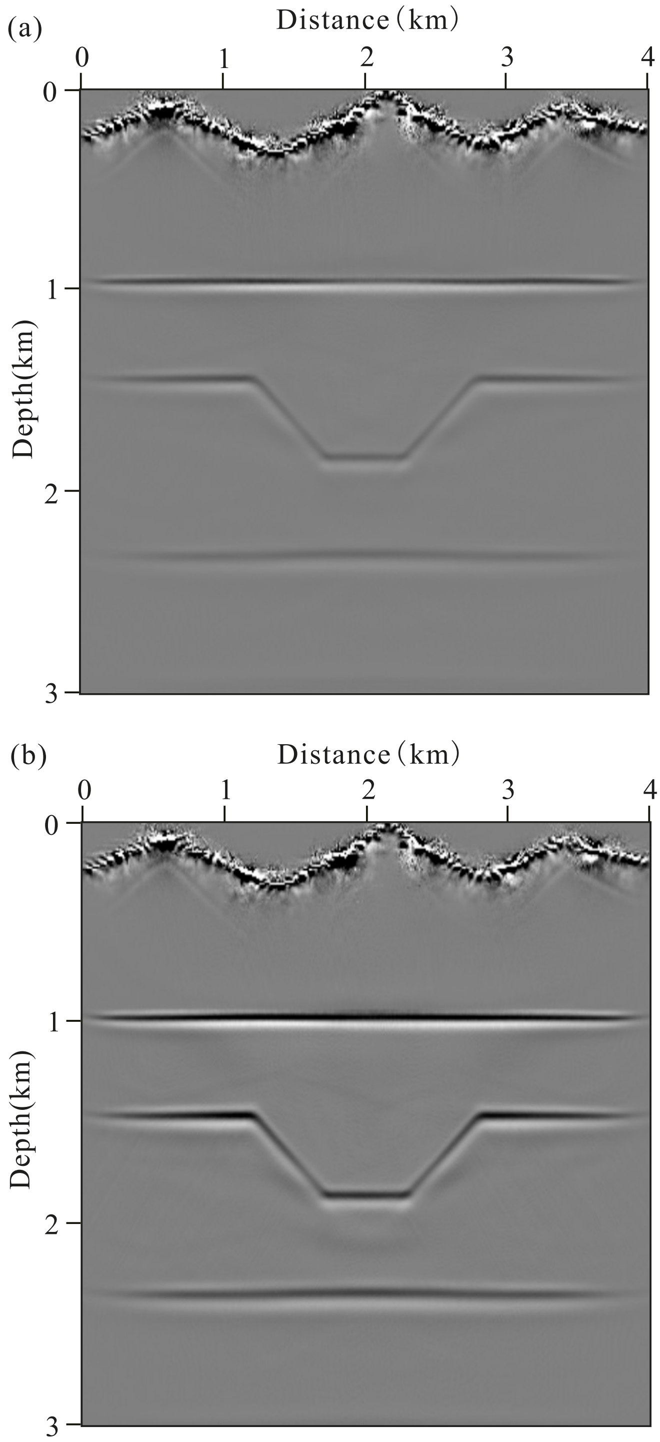


Figure 5. Imaging results of the sag model under the condition of an irregular surface: (**a**) conventional GBM for visco-acoustic seismic records; (**b**) Q-GBM for visco-acoustic seismic records.

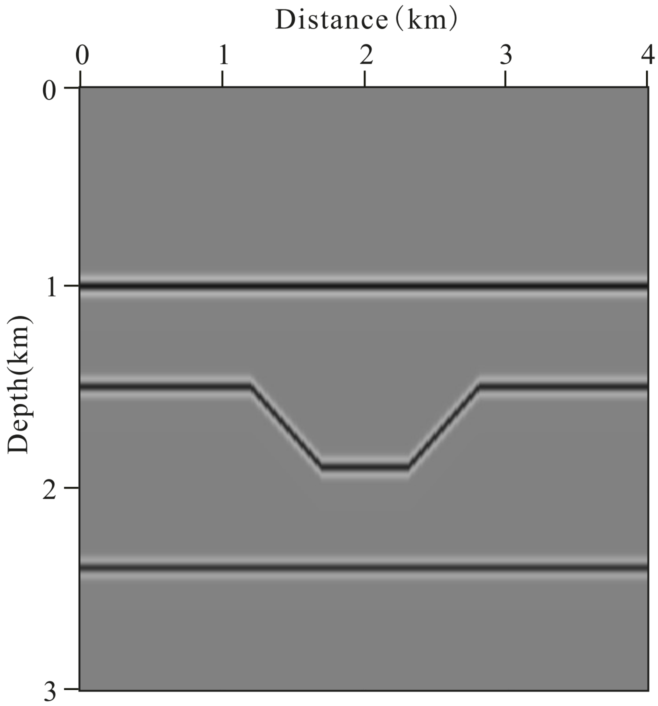


Figure 6. Theoretical optimal image of sag model without considering the rugged topography.

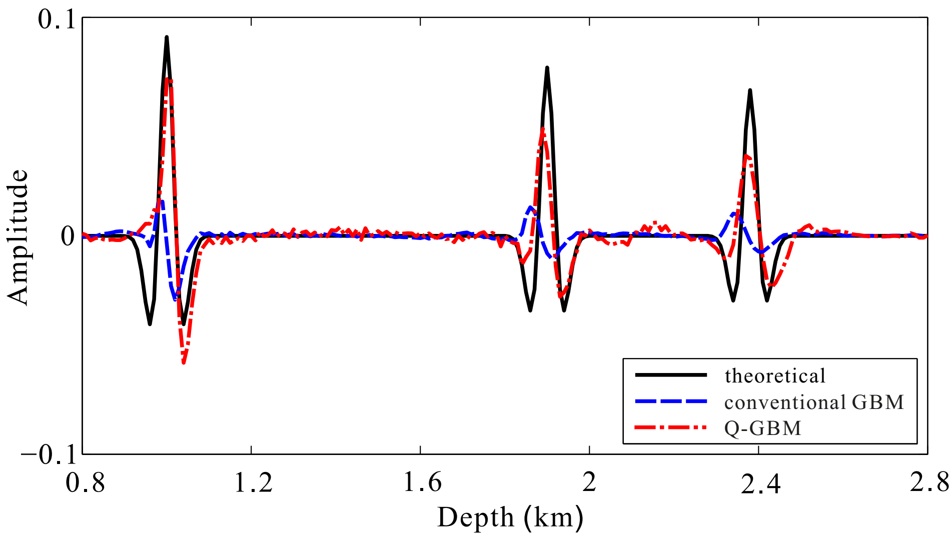


Figure 7. The vertical profile drawn from x = 2 km. The theoretical optimal imaging is plotted with the black line. The imaging with the conventional GBM and the Q-GBM method is indicated by the blue and red lines, respectively.

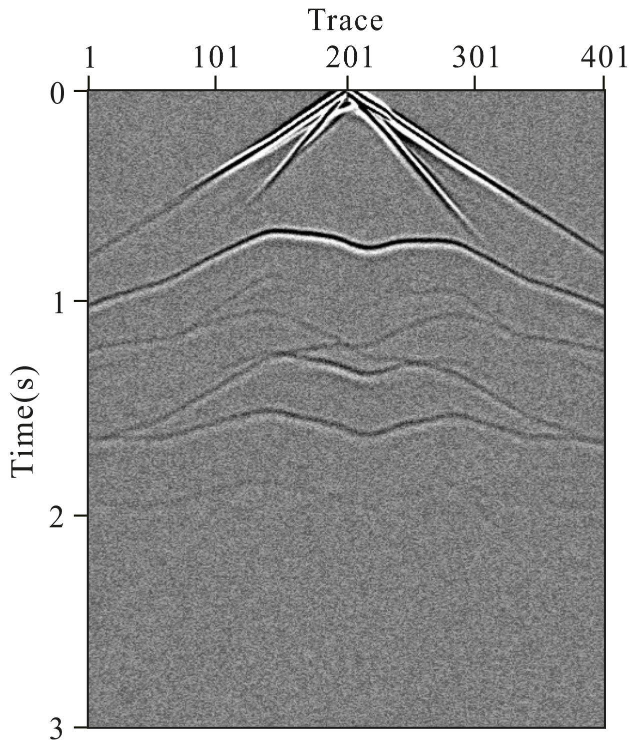


Figure 8. The 40th visco-acoustic single-shot seismic record with random noise.

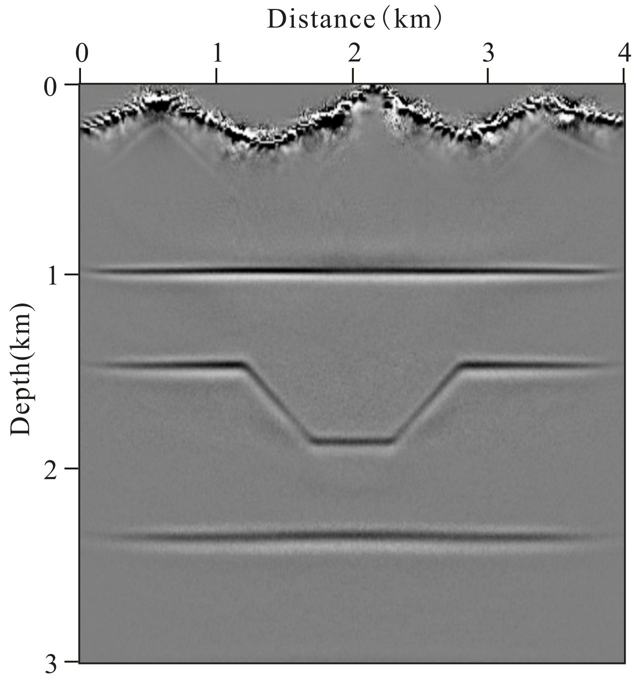


Figure 9. Imaging result of the noised visco-acoustic seismic data using our Q-GBM method.

3.3. Complex Fault Model of the Visco-Acoustic Medium under the Condition of Irregular Surfaces

In order to prove the effectiveness of our imaging technique for complex structures in visco-acoustic media under an irregular surface, a complex fault model of visco-acoustic media under the condition of an irregular surface condition was developed in this study. The velocity model and Q model are shown in Figure 10. The finite difference method was applied to simulate the 119 shots of seismic records. The distance between the two shots was 50 m, and 601 receivers recorded every shot. Figure 11a displays the GBM results of acoustic seismic records under the condition of an irregular surface, and Figure 11b,c show the imaging profiles of visco-acoustic seismic records under irregular surface conditions using conventional GBM and Q-GBM, respectively. Compared to the uncompensated imaging results of visco-acoustic seismic records under an irregular surface (Figure 11b), the compensated imaging profile (Figure 11c) presents a significantly enhanced amplitude of the deep reflective layer, and the phase distortion is also corrected. As a result, the imaging quality is significantly improved, and the breakpoints of the fault structure are clear. Overall, the imaging effect of visco-acoustic seismic records under the condition of irregular surface after Q-compensation is comparable to that of acoustic seismic records under irregular surface conditions. The above migration test of the complex fault model under an irregular surface demonstrates further that our Q-GBM method is effective for imaging complex geological structures in visco-acoustic media under the condition of an irregular surface.

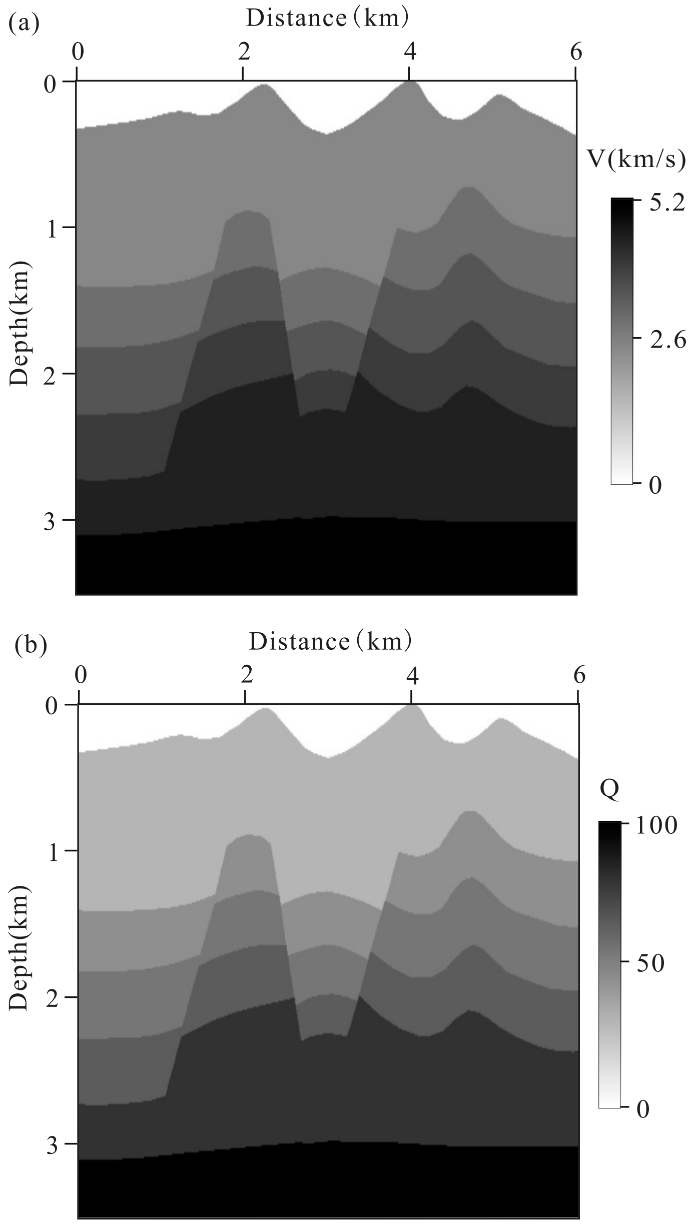
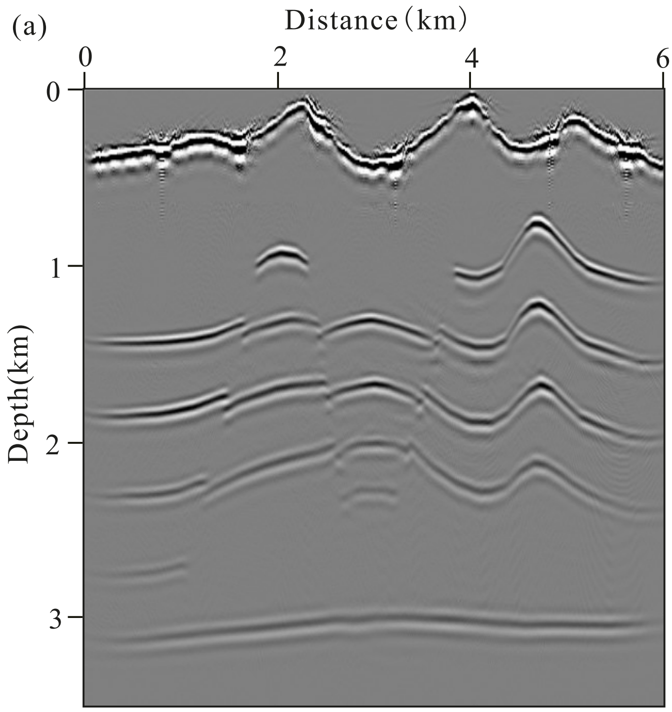


Figure 10. Complex fault model of visco-acoustic media under the condition of an irregular surface: (**a**) velocity model; (**b**) Q model.



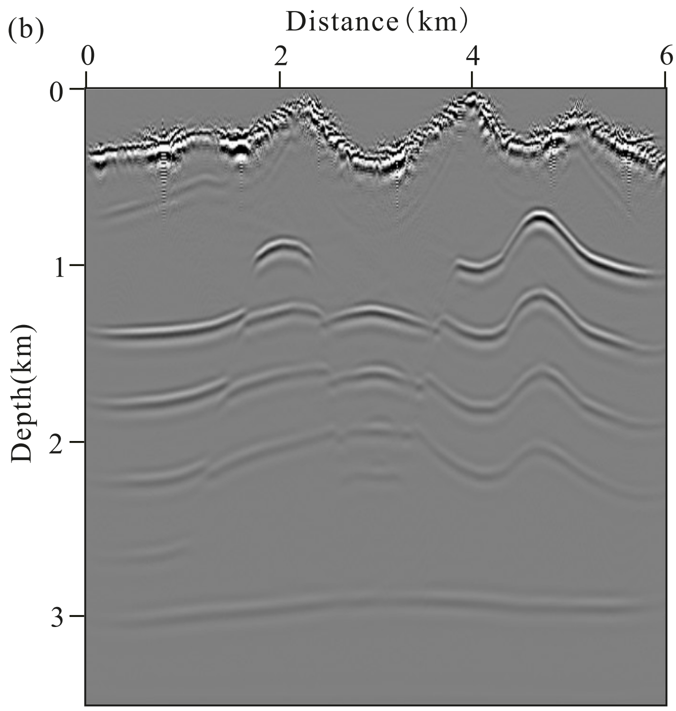


Figure 11. *Cont.*

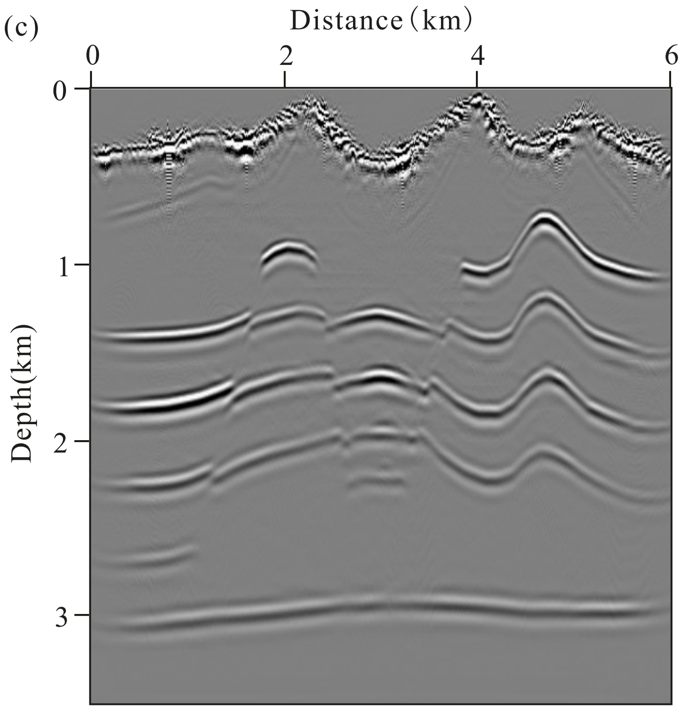


Figure 11. Imaging results of the complex fault model under the condition of an irregular surface: (**a**) GBM for acoustic seismic records; (**b**) conventional GBM for visco-acoustic seismic records; (**c**) Q-GBM for visco-acoustic seismic records.

4. Conclusions

This study develops a QGB-PSDM method for an irregular surface to effectively compensate for the attenuation effect on the imaging results of the seismic wavefield, thereby providing an effective imaging technique for seismic data in visco-acoustic media under the condition of an irregular surface. The dip angle and elevation information of the irregular surface is considered in the local slant stack, and seismic records are decomposed into local plane waves with different exit directions directly on the irregular surface to continue the wavefield. In addition, by correcting the complex-value traveltime of the Gaussian beam in visco-acoustic media, energy compensation was performed on the forward continuation wavefield at the seismic source on the irregular surface and the reverse-continuation wavefield at the beam center, thus realizing the GBM of the irregular surface after compensation. As determined through migration tests for three numerical models of visco-acoustic media under the conditions of an irregular surface, the Q-GBM method for irregular surfaces can effectively compensate for the attenuation of visco-acoustic seismic records and correct the phase distortion. The amplitude of the deep reflective layer of the compensated imaging profile was significantly enhanced compared to that of the uncompensated imaging profile, and the imaging quality was significantly improved. The migration test results proved that the proposed approach is an effective and accurate technique suitable for depth domain imaging of a seismic wavefield in visco-acoustic media under the condition of irregular surfaces.

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Conflicts of Interest: The authors declare no conflict of interest.

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