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Near-surface absorption compensation technology and its application in the Daqing Oilfields*

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Abstract: High-frequency seismic data components can be seriously attenuated during seismic wave propagation in unconsolidated (low-velocity) layers, resulting in reduced seismic resolution and signal-to-noise (S/N) ratio. In this paper, first, based on Wiener filter theory, inverse filter calculations for near-surface absorption attenuation compensation were accomplished by analysis of the direct wave spectral components from different distances near the surface. The direct waves were generated by detonators in uphole shots and were acquired by receivers on the surface. The spatially varying inverse filters were designed to compensate for the frequency attenuation of 3D pre-stack CRG (common receiver-gather) data. After applying the filter to CRG data, the high frequency components were compensated with the low frequencies maintained. The seismic resolution and S/N ratio are enhanced and match better with synthetic seismograms and better meet the needs of geological interpretation.
Keywords: 3D pre-stack seismic, uphole shooting, near-surface absorption, inverse filter, space-varying compensation

Introduction

When seismic waves propagate through unconsolidated layers, their high-frequency components can be seriously attenuated and greatly decrease the seismic resolution (Li, 2008) which affects the final lithology interpretation and reservoir description. Wang (2002, 2003) and Guo and Wang (2004) estimated Q values using VSP and used high-accuracy inverse Q filters for post-stack seismic data to improve the resolution of seismic section. Chopra et al. (2003) estimated inverse filters using VSP data and processed post-stack seismic data by inverse filter to improve the resolution. The frequency components lost during the two-way propagation were partially restored. However, seismic wave attenuation caused by unconsolidated layer absorption wasn't considered in these methods.

Uphole shooting direct arrivals are commonly used for investigating of near-surface low-velocity zone structure to obtain the velocity and thickness of the low-velocity layers which provides the parameters for static corrections (Li et al., 2002). We use the direct wave information to determine inverse filters for the near-surface layers to compensate for layer absorption in the post-stack seismic data and eliminate the influence of low-velocity layers on seismic wave attenuation to a certain degree (Shi and Tian, 2007; Tian et al., 2005). However, in order to maintain the lateral consistency of post-stack seismic data, only one filter can be used for absorption compensation processing of post-stack seismic data. That is to say, spatially varying inverse filters can not be applied to

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absorption compensation of post-stack seismic data. In fact, the attenuation of seismic data caused by absorption in the low-velocity layers changes with lateral changes of the low-velocity layers. It is necessary to use many inverse filters from uphole shot data to compensate for the corresponding absorption of the low-velocity layers. In this paper, we present a method for realizing pre-stack spatially-varying compensation processing using direct wave data. Application results show that pre-stack spatially-varying absorption compensation is feasible and effective.

Theory of attenuation compensation

For uphole shot data, the shot depths can be described using borehole depths z_1, z_2, z_3, … z_n. If the shot point depths increase from point z_i to z_j along the well and assuming source excitation and detector reception to have good consistency, an operator q_j can be used to describe the influence of the low velocity layer from z_i to z_j on the seismic arrival wave. The seismic wavelet amplitude becomes $x_j(t)$ from $x_i(t)$ and the low-velocity layer can be regarded as a system. We have (Shi et. al., 2004):

$$x_j(t) = q_j(t) * x_i(t). \quad (1)$$

The inverse operator $P_j = q_j^{-1} = \{p_j(t)\}$ can be used to compensate for the attenuation of the frequency and amplitude caused by the low velocity layers from z_i to z_j. The inverse filter expression is:

$$x_i(t) = p_j(t) * x_j(t). \quad (2)$$

Equation (2) can be solved by the least-squares method to get the Wiener equation:

$$AP = b, \quad (3)$$

where A is the autocorrelation matrix for $x_j(t)$, $P=(p(t_1),p(t_2)\ldots,p(t_n))$ is the inverse operator, and $b=(b_1,b_2\ldots,b_n)$ is the cross-correlation function for $x_j(t)$ and $x_i(t)$.

In the time domain, Levin's algorithm can be used for solving equation (3) and in the frequency domain equation (2) can also be solved by Fourier transform:

$$X_i(f) = P_j(f) X_j(f), \quad (4)$$

where $X_i(f)$ is the Fourier transform of $x_i(t)$. From equation (4), $P_j(f)$ can be rewritten as

$$P_j(f) = X_i(f) / X_j(f) = \frac{X_i(f)\overline{X_j(f)}}{\left|X_j(f)\right|^2 + \alpha^2}, \quad (5)$$

where α is the noise level. The inverse transform of $P_j(f)$ yields the inverse operator p_j which is the absorption compensation inverse filter (ACIF) or near-surface absorption compensation factor (NACF).

After getting the inverse filters, we can compensate for the absorption attenuation in the time or frequency domain. If in the time domain, the equation is

$$y_k(t) = p_k(t) * x_k(t), \quad (6)$$

where $x_k(t)$ is the kth seismic trace, $p_k(t)$ is the compensation filter of the near-surface absorption for the kth trace, and $y_k(t)$ is the compensated seismic data. When using the method of convolution in the time domain, seismic events can be shifted in time, which is disadvantageous to seismic data interpretation. To avoid this, we can adopt a similar zero-phase deconvolution method in the frequency domain compensate the amplitude spectrum while not modifying the phase spectrum, i.e., the high-frequency compensation can performed in the frequency domain.

Fast Fourier transform the inverse filter, $p_k(t)$, to get the frequency spectrum:

$$P_k(f) = U_{pk}(f) + iV_{pk}(f). \quad (7)$$

The amplitude spectrum of $p_k(t)$ is

$$A_{pk}(f) = \left|P_k(f)\right| = \sqrt{U_{pk}^2(f) + V_{pk}^2(f)}. \quad (8)$$

and the phase spectrum of $p_k(t)$ is

$$\phi_{pk}(f) = arctg\frac{V_{pk}(f)}{U_{pk}(f)}. \quad (9)$$

The frequency spectrum of $p_k(t)$ can also be written

$$P_k(f) = A_{pk}(f)e^{j\phi_{pk}(f)}. \quad (10)$$

When applying the inverse filters, we can let phase spectra be equal to zero. Then,

$$P_k(f) = A_{pk}(f). \quad (11)$$

Suppose the frequency spectrum of $x_k(t)$ is

$$X_k(f) = U_{xk}(f) + iV_{xk}(f), \quad (12)$$

and the frequency spectrum of the compensated seismic data is

$$Y_k(f) = A_{pk}(f) \cdot X_k(f). \quad (13)$$

Finally, by inverse fast Fourier transform of $Y_k(f)$, we have the seismic data in the time domain following the absorption compensation.

It should be noted that seismic wavelets from the two kinds of sources are inconsistent because the uphole shot data is collected using a detonator as the seismic source and surface seismic data is collected using an explosive source. However, here we suppose that the signals are consistent with the system response of the near-surface layers in the range of both frequency bands. So the NACF estimated using the uphole shot data can be used to compensate for the high-frequency attenuation of surface seismic data caused by the near-surface layer absorption.

The high frequency compensation processing flow

First, the uphole shot data are processed to obtain arrivals corresponding to each shot depth. Second, near-surface absorption compensation filters are estimated for the corresponding observation points using the arrival data based on the Wiener filtering principle and the filter database is established. Third, common receiver gathers are sorted from the raw shot gathers and the inverse filters are applied to the common receiver gathers, since all the seismic data at the same receiving position has the same inverse filter, to obtain the absorption compensated traces. Finally, the shot gathers are resorted from the CRGs and the compensated seismic data are stacked and migrated to get the final data processed by spatially-varying absorption compensation. The pre-stack spatially variant absorption compensation processing flow is shown in Figure 1.

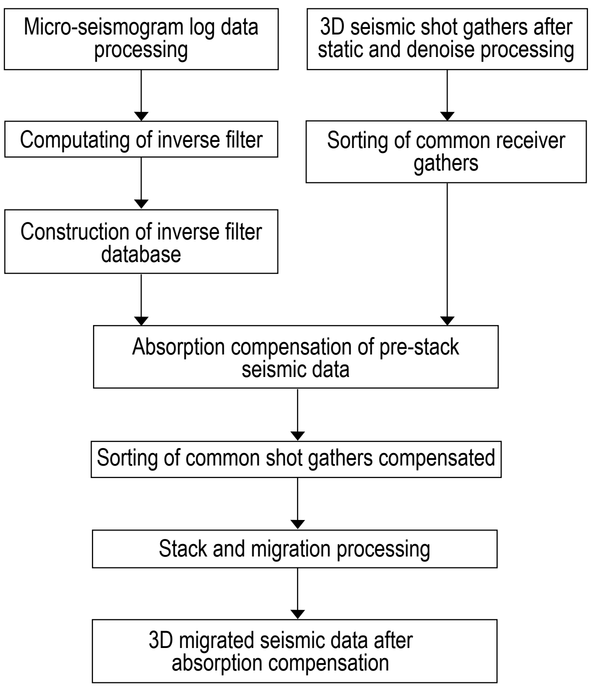

Fig. 1 Spatially variant absorption compensation processing workflow.

Application example

Work area setting

The pilot area is located in northeast China's Daqing oilfields with continental sedimentary reservoirs. The sandy loess surface is covered by grass. The low-velocity layer mainly consists of yellow sandy and gray pelinites which are unconsolidated relative to the deeper dense rock. The water table depth is about 1-12 m. The low velocity layer thickness ranges from 4 to 17 m and the P-wave velocity is 300-1400 m/s. The low-velocity layer seriously attenuates the high frequency seismic component and lowers the seismic resolution and S/N ratio.

Data acquisition and processing

In this area, we collected seismic data using uphole shooting with detonators in boreholes and receivers on the surface. There are 24 geophone channels in the acquisition geometry with six channels in each fan-shaped receiver array. Distances from borehole to receiver are 1, 2, 3, and 4 m, The data acquisition geometry is shown in Figure 2.

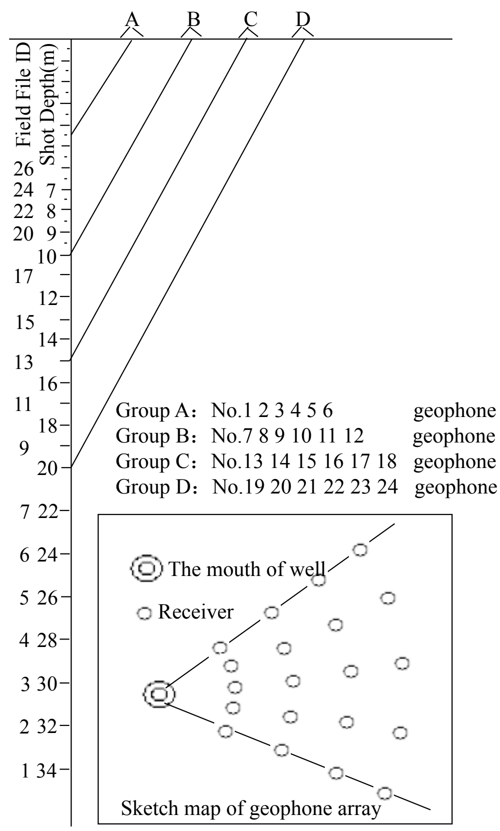

Fig. 2 The acquisition geometry for uphole shooting.

The borehole depths range from 34 to 40 m. There are 37 shot points in each borehole with gradually increasing distance in depth between shot points. For example, the first shot depth is 0.5 m, from the first shot to the 20th shot point, the interval between shot points is 0.5 m. From the 20th to 31st shot points, the spacing is 1 m. From the 31st to 37th points, the depth spacing is 2 m. Such dense shots are to ensure each layer has enough control points.

First, we resort the seismic gathers. In order to receive approximately vertical incident waves from the shots and keep the incidence angle size of the direct waves from the corresponding different excitation depths as far as possible to eliminate the influence of different incidence angles, we sort only one-trace seismic data from every shot depth. Taking the geometry shown in Figure 2 as an example, for shots 1 to 10 (FFIDs), a one-trace seismic record is sorted from the geophones of D group. For shots 11 to 15, a one-trace seismic record is sorted from C group geophones. For Shots 16-23, a one-trace seismic record is sorted from the geophones of B group. For shots 24-37, a one-trace seismic record is sorted from the geophones of A group.

Second, the muting process. A file including the 37 seismic traces consists of the all resorted seismic traces. Then mute processing is carried out to only keep the direct arrival. The processed direct wave records are shown in Figure 3 and the frequency spectra of some of the record traces are shown in Figure 4.

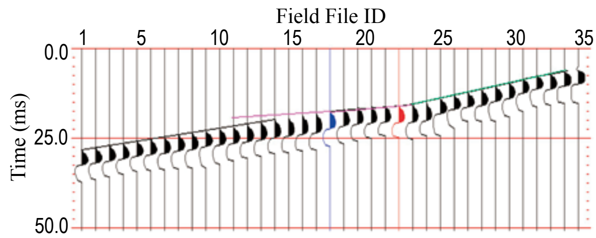

Fig. 3 Seismic direct wave records after mute processing.

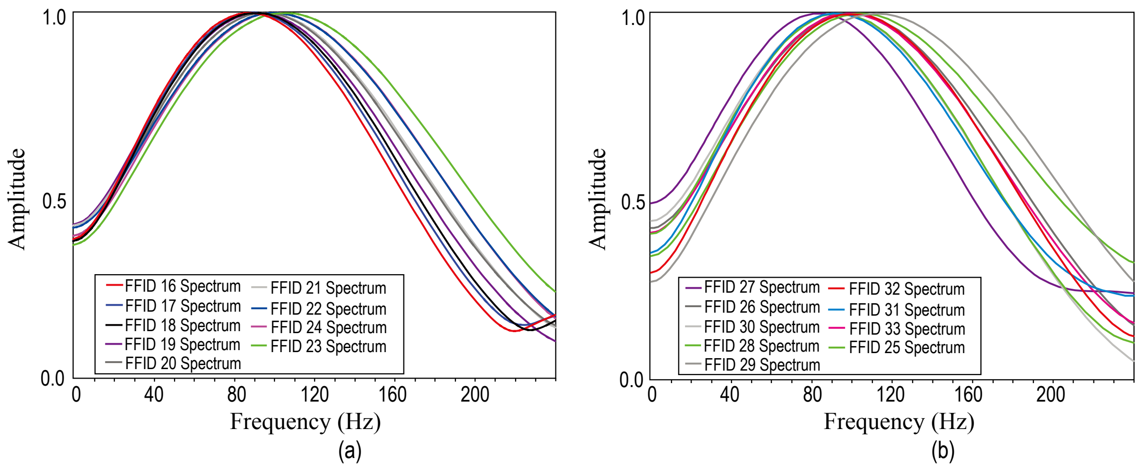

Fig. 4 Amplitude spectra of direct waves: The left panel is the intermediate velocity-down layer (a) and the right panel is the surface low-velocity layer (b).

Computation of inverse filters and construction of the inverse filter database

The propagation distance of the direct waves is the arithmetic square root of the shot depth and the distance between the borehole and receiver point. If we ignore the borehole to receiver distance, for the same layer velocity, the propagation distance of the direct wave with its arrival time is a linear relationship. In this paper, the borehole to receiver distance can be ignored for computing the propagation distance of the direct wave because the distance between borehole and receiver point is too small relative to the shot depths below 2 m. The direct wave arrivals are on a line with a constant slope and the near-surface layer velocity has an approximately linear relationship, as shown in Figure 3. So the slope of the arrival line can be used to divide the near-surface layer based on the velocity.

First, we analyze the velocity variation of the near-surface unconsolidated layers at measuring points using the direct wave data. The unconsolidated layers are divided into three velocity layers in depth: the surface low velocity layer, the intermediate lower-velocity layer, and high velocity layer as shown by the different colored lines in Figure 3. For each layer, the shot coupling in the layer is almost the same for the direct waves, so the difference of the direct waves can cancel the effects of shot coupling. Second, the area where the geophone is buried on the surface is small, so the receiver coupling effect on the direct waves are almost same and the difference of the direct waves in each layer is due to layer absorption. We select the direct wave from a deeper depth as input and select the direct wave from a shallow shot as the output and estimate the inverse filter for each layer. We then combine the inverse filters from the different velocity layers into a single filter to get the compensation factor for near-surface absorption at the test point.

The direct waves from the 2 m depth range are distorted due to the dynamic range of seismic instrument, so we didn't estimate inverse filters for this layer interval. Finally, we complete the computation of the inverse filters, output them as SEGY files, and establish the inverse filter databank.

The inverse filter operator is related to the unconsolidated layers' thickness and velocity. In the work area, because the layers' thickness and velocity change only over a range of about 1 to 2 km and the observation point distribution density is 1 point per km^2, so a certain number of measuring points are needed to measure the unconsolidated layer variations. If the thicknesses or velocities of the unconsolidated layers vary rapidly, the observation points need to be increased to determine the unconsolidated layers' thickness and velocity variations. Typical inverse filter waveforms and amplitude spectra are shown in Figure 5. We can see that in the 0-125 Hz range, amplitude increases with frequency, indicating the compensation of high-frequency components. Moreover, the characteristics of different inverse filters are different to a certain degree, which shows that there are differences in near-surface layer absorption on seismic waves at different locations.

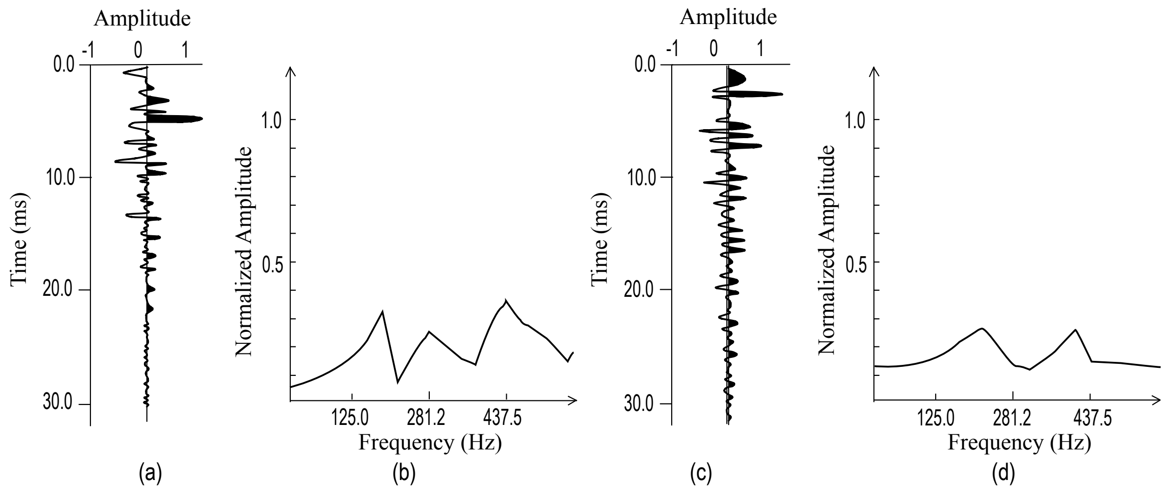

Fig. 5 Typical layer filters and their frequency spectra

(a) and (c) are inverse filter waveforms and (b) and (d) are their corresponding amplitude spectra.

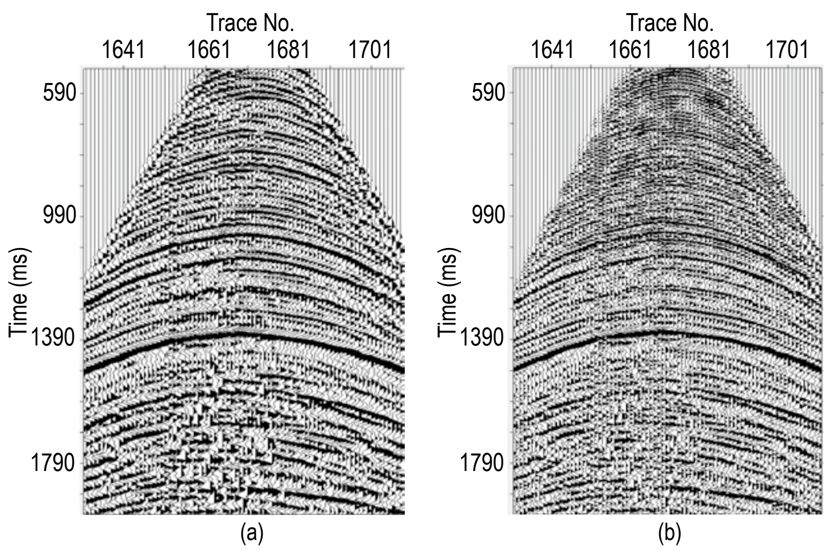

Fig. 6 Shot gathers (a) before and (b) after absorption compensation.

Spatially-varying high-frequency compensation processing and results analysis

First, seismic shot gather data is processed by pre-stack denoising and static corrections, then common receiver gather (CRG) data is sorted, the absorption compensation filters are applied to the corresponding CRGs, and shot gathers are resorted. In Figure 6, we compare shot gathers before and after using the inverse filtering. After absorption compensation, more seismic events have appeared in the single shot record and the reflection information is obviously increased. Figure 7 shows the amplitude spectrum of a single shot record before and after application of inverse filtering. From Figure 7, we can see that the frequency bandwidth has an increase of nearly 20 Hz. The effective frequency band is 8 to 80 Hz before compensation and 8 to 100 Hz after compensation, significantly improving the seismic resolution.

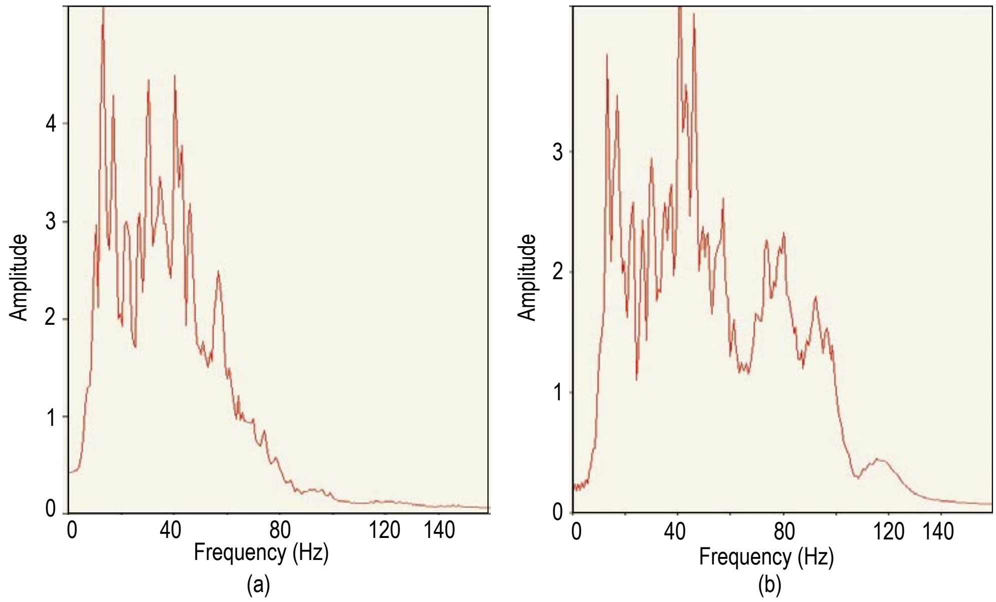

Fig. 7 Shot gather spectra before absorption compensation (a) and after absorption compensation (b).

The shot gather records after inverse filtering are input to conventional high-resolution processing to 3D stacked data. From the stacked section after the absorption compensation (Figure 8 right), we see that seismic events become "thinner" which indicates that seismic resolution is increased. From Figure 8 we can see that some geology structure imaging has become worse after compensation (at 0.7- 0.8 s in Figure 8) possibly due to reducing the S/N ratio after compensation. However, this has only a small influence on the geologic interpretation. The spectra in Figure 9 show that frequency bandwidth has been enhanced from 8 to 70 Hz to 8 to 90 Hz and the low frequency components are maintained.

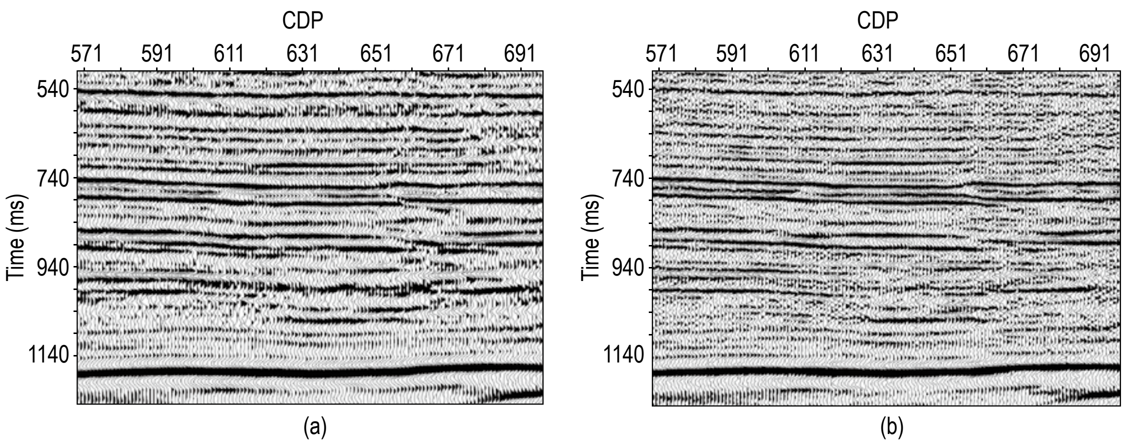

Fig. 8 Stack sections (a) before and (b) after absorption compensation.

The synthetic seismograms from sonic logs and the stacked data before and after absorption compensation are shown in Figure 10. The seismic events on the stacked section before absorption compensation agree with the synthesized trace from a 40 Hz Ricker wavelet but do not agree with the synthetic seismic events of a 50 Hz Ricker wavelet (Figure 10c). However, the stacked section after absorption compensation matches the 50 Hz Ricker wavelet synthetic and the seismic events are clear (Figure 10d). This proves that the frequency components compensated are effective and believable.

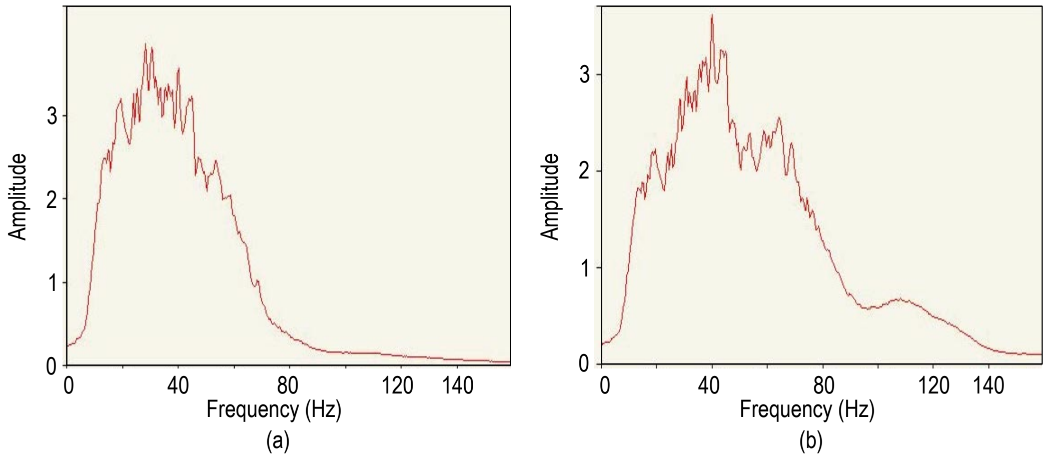

Fig. 9 Frequency spectra of the stacked seismic section before (a) and after absorption compensation (b).

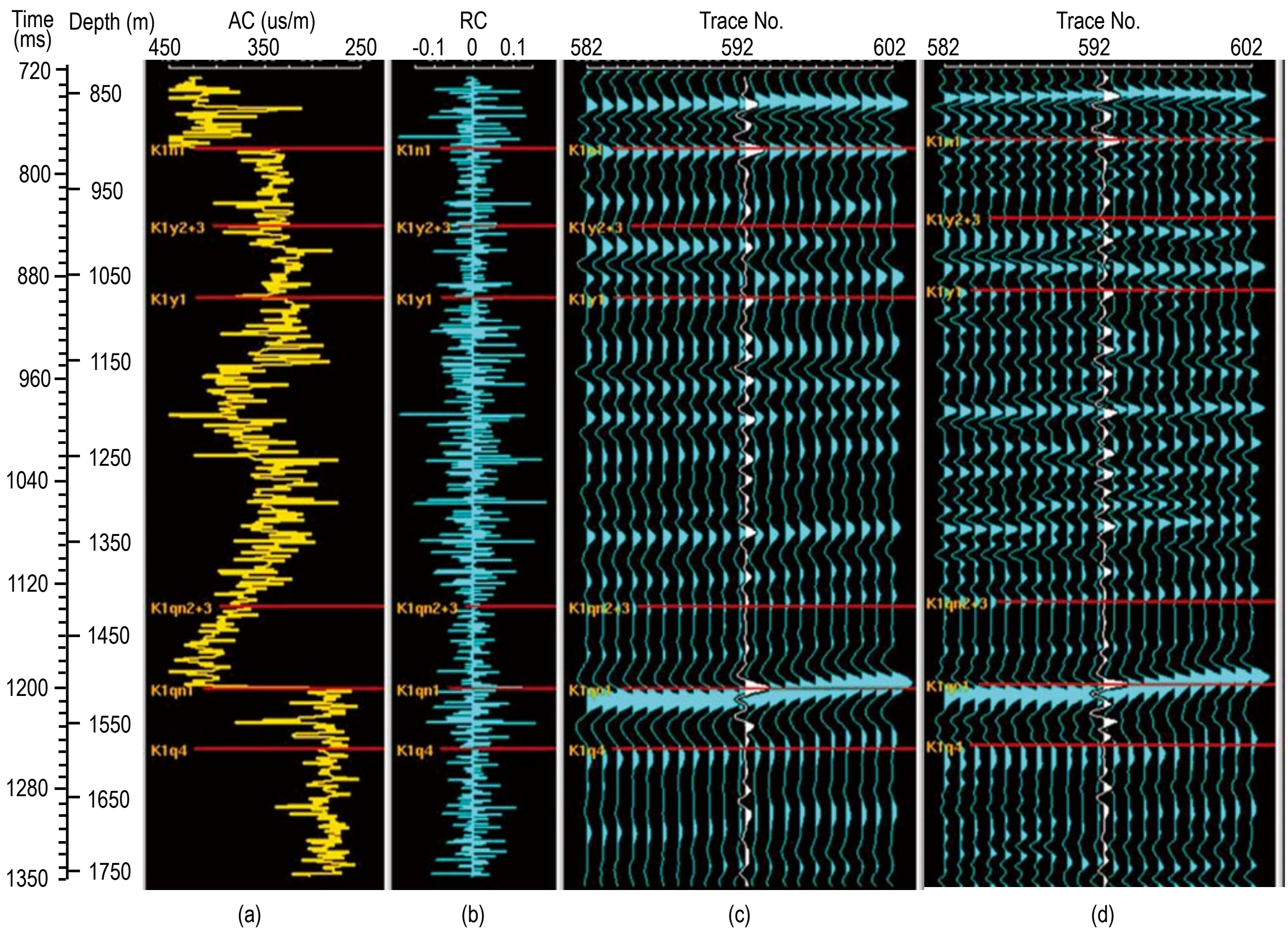

Fig. 10 Comparison of synthetic seismograms and stacked data. (a) is acoustic transit time, (b) is reflection coefficient, and (c) and (d) are the stacked data before and after pre-stack absorption compensation.

Conclusions

The application results show that spatially-varying absorption compensation of low-velocity layers can be carried out in pre-stack CRG data using inverse filters to overcome the difficulty of being unable to realize post-stack spatially-varying absorption compensation.

The frequency bandwidth is enhanced with the low frequencies maintained. 3D pre-stack spatially-varying absorption compensation processing opens a new use for uphole shooting. The distribution density of measuring points depends on the thickness and velocity change of the unconsolidated layers with the aim of understanding variations in the unconsolidated layers.

In this paper, we assume the seismic wave incidence angle is vertical in the unconsolidated layers. This is acceptable since the thickness and velocity of the unconsolidated layers change little in this area. However, if the thickness and velocity of the unconsolidated layers change abruptly, the incident ray paths of the seismic waves will need to be considered to reduce the error of high-frequency compensation.

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