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ABSORPTION COMPENSATION BASED ON CURVELET TRANSFORM

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ABSTRACT

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Stratal absorption of seismic waves caused time-varying of source wavelet and lowered the resolution of data, especially for deep signals. After the stratal absorption attenuation of the longer propagation path, high-frequency signals are absorbed so strong that it cannot reflect the real situation of the strata, which make the processing and interpretation encounter many problems. We assume that there is no strata absorption, the energy distribution relations of the time between seismic records of the different frequency bands have similarity. The energy of all frequency bands of deep reflection should be the same as that of shallow reflection of the same frequency band energy ratio, but the absolute energy of the different bands have different sizes. Because of the low-frequency energy loss less, when the high-frequency record is multiplied by time-varying factor, the energy ratio of deep layer would be the same to that of low frequency, playing the role of the compensation. In this paper we use the curvelet transform to divide the frequency of seismic data, then use the directional characteristics of curvelet transform to select the signal of each frequency band selected angle, extract the weighting factor of each time location and reciprocal weighting to make sure that the ratio of deep and shallow energy of relative angle signal for each frequency band was the same, and then reconstruct the weighted data. In practice ,we can see with this method the strata absorption is well compensated by the strata absorption. Using curvelet transform can directly compensate for the seismic data and basically does not enhance the noise, and effectively improve the signal to noise ratio of seismic data. Here we provide a new method for high precision seismic data processing. The method does not need to know the Q value in advance and can adapt to the constant Q and variable Q.

KEY WORDS: curvelet transform, strata absorption, compensation, directional compensation

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INTRODUCTION

The energy attenuation and velocity dispersion of high-frequency components of the seismic signal are two main characteristics of seismic wave propagation in the subsurface. Attenuation result in seismic wave amplitude decreases with the increase of the propagation travel time, and velocity dispersion lead to that high frequency components can travel faster than low frequency components. With the increase of propagation travel time, the waveform and phase of the seismic waves changes (Zhong and Zhang, 2008). Seismic wave frequency attenuation and velocity dispersion will result in a lower resolution of seismic data. With the high-resolution seismic data processing requirements increase, the problem of the low vertical resolution damage to the seismic wave caused by the strata absorption are is taken more and more attention. To improve the resolution of seismic data, it is necessary to eliminate the effects of earth filtering, and compensate for the attenuation induced by strata absorption. The seismic absorption property of a medium is usually described by a quality factor designated by Q. Many algorithms to estimate Q values have been published (Zhang, 2008). Among them, the most popular is the spectral ratio method (Spencer et al., 1982; Tonn, 1991). Methods are suggested by Quan and Harris (1997), Zhang and Ulrych (2002), Taner and Treitel (2003), Singleton et al. (2006). However, this method needs to know the Q value of strata, and it is very hard to obtain the accurate Q value of strata, and the application is greatly limited by the level of processing and experience of the person. In addition, most of the existing wavelet estimation and deconvolution assume that wavelet time is time invariant, which will cause a great impact on wavelet estimation and deconvolution (Zhang, 2008). let transform. Bai and Li (1999) proposed an absorption compensation method based on the short time Fourier transform (Bai and li, 1999) and wavelet packet decomposition (Li et al., 2000). Liu et al. (2006) have developed a compensation method based on the generalized S transform. The compensation method based on time-frequency analysis does not need to know the Q value in advance and can adapt to the constant Q and variable Q. In this paper we have also quantitatively studied the attenuation law of seismic waves based on the predecessor's work (Liu et al. 2011), constructed a theory model of strata absorption, and used curvelet transform to compensate it.

Curvelet transform is first proposed by Candès and Donoho (1999) ,it is a new multi-scale geometric analysis methods, and belongs to the scope of sparse function representation theory (Tong et al., 2008). It can sparsest express the high dimensional signal, be able to handle signal line singular feature. The support interval of curvelet in the frequency domain obeys the anisotropy scaling relation width $\approx$ length^2 (Candès and Donoho, 2004). This "long strip" support interval is a reflection of the "direction" feature. This "anisotropy" based on curvelet transform can represent the edges of the image more sparse (Zhang and Guo, 2006; Huang, 2007), and have efficient, stable and near-optimal representation for the smooth singularity curve of objective function. Curvelet transform is a multiresolution, band pass, and directional function analysis method, which directly use the edge as the basic representation element (Tong et al., 2008), can nearly approximate optimal representation of the seismic signals with multi-directional linear variation.

In this paper we analyze the mathematical principles of the second generation of curvelets, and briefly introduce the curvelet transform's scale and angle characteristics, then use curvelets' angle characteristics to enhance signal and attenuate noise, which is simple and useful. We have construct a theoretical model of the absorption compensation, with curvelets' angle characteristics of multi-scale directional, we compensate the post stack seismic data. From the results we can draw a conclusion that the method can not only strength the high-frequency of middle and deep stratum, broadening frequency band, but also compensate for the specific direction of the seismic signal without enhancing the interference signal and random noise corresponding, greatly improves the resolution and signal to noise ratio of seismic data.

CURVELET TRANSFORM

The first generation of curvelet transform theory is evolved from the basis of Ridgelet Transform, we can see the first generation curvelet transform as a multi-scale Ridgelet transform (Liu, 2008). Due to the first generation curvelet have more complex discrete realization and higher redundancy, Candès constructs a new tight frames of curvelets (Candès et al., 2005), directly giving curvelets' representation in the frequency domain, then give the rapid realization of the discrete algorithm (Candès et al., 2005), the second generation curvelet transform.

In the two-dimensional space R^2, assume the spatial location variable is x, frequency domain variables is ω, the polar coordinates in the frequency domain is r, θ, W(r) and V(t) represent the radius of the window and the angle of the window, respectively, W is support in $r \in (1/2,2)$, V is support in $t \in (-1,1)$, and satisfies admissibility conditions:

$$\sum_{-\infty}^{\infty} W^2(2^j r) = 1 \ , \qquad r \in (3/4,\ 3/2) \tag{1}$$

$$\sum_{-\infty}^{\infty} V^2(t - l) = 1 \ . \qquad t \in (-1/2,\ 1/2) \tag{2}$$

For each $j \geq j_0$, use the Fourier transform to define frequency window function

$$U_j(r,\alpha) = 2^{-3j/4} W(2^{-j} r) V(2 \lfloor j/2 \rfloor \theta/2\pi) \ . \tag{3}$$

Here, $\lfloor j/2 \rfloor$ is the integer part of j/2. The wedge-shaped region which is limited by W and V's support interval is the support interval of U_j. The wedge-shaped region is associated with the anisotropic scaling properties, and from the corresponding relationship between curvelet transform's frequency domain and space domain grid we can see that the larger the scale, the smaller the grid area of the space domain Cartesian, the higher the frequency resolution. Define

$$\hat{\varphi}_j(x) = U_j(\omega) \ . \tag{4}$$

Curvelets with other scales can all be represented by the "mother" function by rotational and translational. Define the angle of rotation sequence as $\theta_1 = 2\pi \cdot 2^{-\lfloor j/2 \rfloor} \cdot l, l = 0,1......0 < \theta_l < 2\pi$; translation parameters $(k_1,k_2) \in Z^2$, then we define the curvelet in 2^{-j} scale, θ_l angle, (k_1,k_2) translation parameters as:

$$\varphi_{j,l,k}(x) = \varphi_j[R_{\theta_l}(x - x_k^{j,l})] \ . \tag{5}$$

$x_k^{j,l} = R_{\theta_l}^{-1}(k_1 \cdot 2^{-j}, k_2 \cdot 2^{-j})$, $R_\theta = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$ represents the rotation of θ, R_θ^{-1} is the mathematics of the inverse of R_θ, and $R_\theta^{-1} = R_\theta^T = R_{-\theta}$. So the curvelet can be expressed as the inner product of f(x) and $\varphi_{j,l,k}$

$$C(j,l,k) = \langle f, \varphi_{j,l,k} \rangle = \int_{R^2} f(x) \overline{\varphi_{j,l,k}(x)} dx \ . \tag{6}$$

It can be seen that curvelet transform is very sensitive to direction, there are in total $A \cdot 2^{\lfloor j/2 \rfloor}$ angles at scale j (A is the amount of angle splits, multiple of 4) (Zhang and Liu, 2010). If the target signal is on angle l, scale j, the coefficient after curvelet transform is relatively large, so curvelet transform can describe the characteristics of information in different directions very well.

A DIRECTIONAL COMPENSATION METHOD BASED ON CURVELET TRANSFORM

Formula (6) shows that the target signal in the curvelet domain achieves greater value in the specific direction of the coefficient matrix in each scale, this direction coefficient is determined by the angle of the target signal. Therefore, after curvelet transform, lineup area's data in which energy is more concentrated, will obtain the maximum in specific scale and specific angle of the curvelet coefficient.

Similarly, for the data which have little difference with the angle of lineups in different time points, its perpendicular to the lineup angle's corresponding coefficient matrix in the curvelet domain, can be considered as noise figure, by multiplying this matrix with a small factor, denoising effect can be achieved. We can multiply a compensation factor by the lineup angle's coefficient matrix in the curvelet domain to increase its value; multiplying a compensation factor by the perpendicular to lineups angle's coefficient matrix decreases its value, the rest of the direction of the coefficient matrix is multiplied by the appropriate compensation factor: the closer the coefficient matrix with the lineups, the greater the compensation factor, the more away from the coefficient matrix with the lineups, the smaller the compensation factor, will be able to achieve the purpose of enhance the effective signal and denoising.

As is shown in Fig. 1, (a) is the data before compensation, we can see that the data noise is relatively strong. Fig. 1 (b) is the original data in certain scale of curvelet domain (in this case is the highest scale), after that the coefficient matrix of the corresponding angles is multiplied by the corresponding compensation factor, and then we do a reverse curvelet transform back to the physical domain. It can be seen that the method described above can effectively enhance the effective signal and suppress the noise.

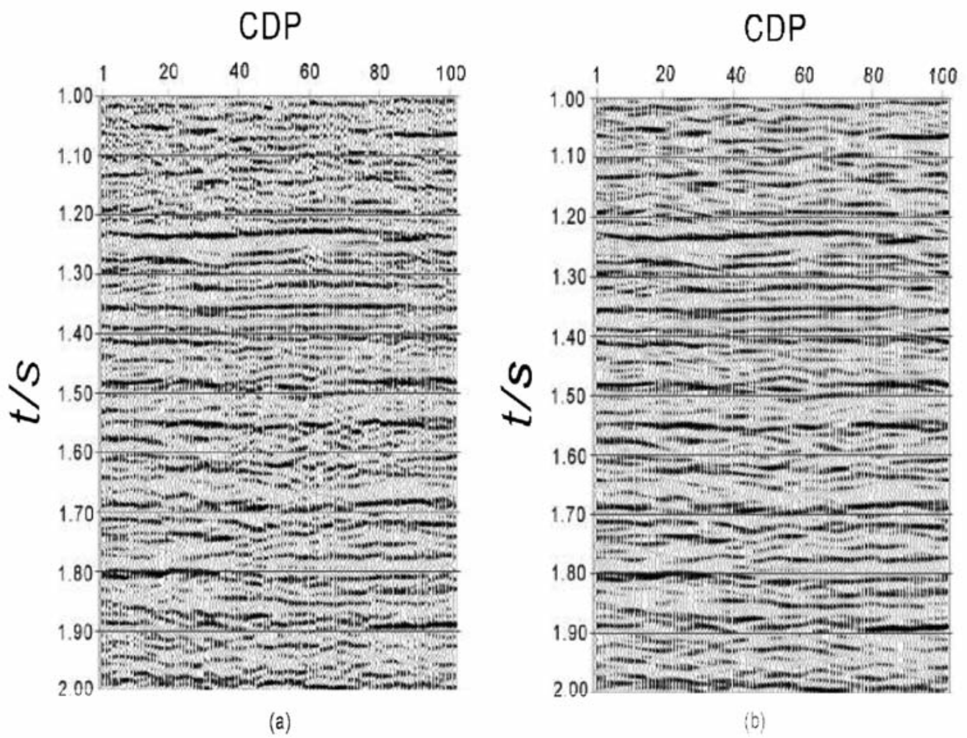


Fig. 1. The data before and after compensation.

It should be argued that the above method is just to use the curvelet transform's angle characteristics to initially enhance the effective signal and denoising the data, which have little change in the angle of efficiency signal in the time domain, rather than corresponding compensate the attenuated signal due to strata absorption. This method only enhances the effective signal's energy without compensating for its phase attenuation, and the compensation factor is generous, so do not have practical significance. In the following section we have described how to use the curvelet transform to get the stratum absorption factor to compensate strata absorption. But we can see from Fig. 1 that through strengthening the effective signal and noise attenuation, seismic data's events lineups becomes clear, random noise is greatly attenuated and signal-to-noise ratio have greatly improved. Location of the effective signal did not change after processing, indicating that changing the curvelet coefficient of effective signals does not influence the surrounding data, which can fine-process seismic data. Curvelet transform's angle characteristics and directional processing capability and other time frequency transforms, like the wavelet transform and the generalized S-transform can't be achieved. Therefore, curvelet transform will play a more important role in high-precision seismic data processing.

ABSORPTION COMPENSATION BASED ON CURVELET TRANSFORM

Assume that there is no absorption, then different frequency bands of seismic records have similarity for the energy distribution relationship of time, that is the ratio of deep reflection energy and shallow reflection energy at the same frequency band should be the same for each frequency bands. However, the absolute energy of the different bands have different sizes. Due to less energy loss of the low frequency, the high-frequency record is multiplied by a variable factor, so that the ratio of deep reflection energy and shallow reflection energy was the same for the ratio of deep reflection energy and shallow reflection energy for low-frequency records, playing the role of compensation.

The theoretical model of strata absorption and compensation

Due to the propagation of seismic waves in the stratum has energy loss, so there is bound to decay, the greater the depth of the reflecting surface, the more high-frequency attenuation. It is similar to a low-pass filter which experienced a time-varying from the ground records. This filter is called the Q-filter, it gives a lower resolution, and the greater the reflecting surface depth, the lower the resolution (Zhang and Liu, 2010).

Set the reflection coefficient sequence r_k ($k = 0,1,\ldots\ldots K$), each reflection coefficient is subject to a different Q-filtering, we set T_k as the reflection time of a reflection coefficient r_k, so that the amplitude response of the Q-filter is

(Saatcilar and Coruth, 1995):

$$A_k(\omega,T_k) = A_0(\omega,0)e^{-\omega T_k/Q_{eq}(T_k)} \quad , \tag{7}$$

$$Q_{eq}(T_k) = Tk \, / \int_0^{T_k} [\tau/Q(\tau)]d\tau \quad . \tag{8}$$

$Q_{eq}(T_k)$ is the equivalent Q value at reflection time T_k, $A_0(\omega,0)$ is the equivalent amplitude attenuation at initial time. If we only consider the amplitude attenuation, then reflected wave records can be expressed as

$$\hat{\chi}(\omega) = \sum_0^K r_k A_k(\omega,T_k)e^{-j\omega T_k} \, \hat{\omega}(\omega) \quad . \tag{9}$$

If the strata is thick enough, reflected waves of adjacent reflecting surface do not overlap each other on the seismic records, so

$$a(\omega,T_k) = |x(\omega,T_k)|/|x(\omega,0)|$$

$$= |r_k A_0(\omega,0)A_k(\omega,T_k)\hat{\omega}(\omega)|/|A_0(\omega,0)\hat{\omega}(\omega)| = |r_k A_k(\omega,T_k)| \quad . \tag{10}$$

Here: $A_k(\omega,T_k) = e^{-\omega T_k/Q_{eq}^{-1}(T_k)}$.

$x(\omega,T_k)$ is the amplitude spectrum of reflection waves at reflection time T_k in the seismic records. In order to eliminate the influence of the reflection coefficient, we divide $a(\omega,T_k)$ by $a(\omega_0,T_k)$, hence

$$D(\omega,T_k) = a(\omega,T_k)/a(\omega_0,T_k) = e^{-\omega T_k/Q_{eq}^{-1}(T_k)}/e^{-\omega_0 T_k/Q_{eq}^{-1}(T_k)} \quad . \tag{11}$$

The above equation shows that for a given frequency, the attenuation ratio is only time-related, so that use of the reciprocal of the attenuation ratio to weigh the corresponding frequency band's seismic records, can eliminate the dependence of stratal absorption to frequency, and make them only related with the absorption of a specific frequency, it has nothing to do with the other frequencies. In other words, if the ω_0 is given, the stratal absorption is only a function of the propagation travel time, performance in the seismic record is that seismic wave in different time has the same waveform, but the amplitude difference of a scaling factor, can be eliminate through the balancing of the time domain.

We establish the absorption theory model under the assumption that the strata is thick enough, and the reflected waves of different reflecting surfaces do not overlap each other, because we are unable to decompose the seismic records into a single reflected wave. Fortunately, with the change of ω and T_k, $A_k(w,T_k)$ is essentially the same. So the treatment is better in the adjacent reflective layers which have a certain distance. Processing can reduce the effects of reflected waves overlapping by adding a smoothing window.

The methods and steps of absorption compensation

We derive formula (17) under the assumption that the reflected waves of different reflecting surfaces do not overlap each other. We come to the conclusion that the attenuation ratio is only time-related, so we use curvelet transform to split the seismic records into the superposition of different narrow bandwidth signals $x_{j,l}(\omega,t)$. Among them, j and l represent the curvelet transform's scale and angle parameter, respectively. In order to reduce the effects of reflected wave overlapping, we can obtain $X_{j,l}(\omega,T_k)$ by adding a smoothing window. We use $X_{j,l}(\omega,T_k)$ instead of $x_{j,l}(\omega,t)$ to pointwise recursive seek the attenuation ratio $D_{j,l}(\omega,T_k)$, then use $D_{j,l}(\omega,T_k)$ reciprocal weight $x_{j,l}(\omega,t)$ to eliminate the impact of strata absorption. Then the anti-Curvelet transform of the weighted data can obtain the seismic records after strata absorption compensation by curvelet transform.

As the data which is needed to be compensated is usually the stacked seismic records, the seismic reflection events are usually horizontal or have small inclined angles, so it can use the advantage of curvelet transform's angle characteristics to compensate for the specific direction of data. Only compensating for horizontal or nearly horizontal angle's data can enhance the effective signal without enhancing the noise or random disturbance. Generally, for the data of which the reflection events are horizontal or nearly horizontal, the compensation angle is usually around 45°.

The Steps of Curvelet Transform Absorption Compensation are:

(a) use Curvelet transform to split the seismic records into different narrow bandwidth signal $x_{j,l}(\omega,t)$.

(b) use Gaussian window to smooth the decomposition signal, obtain $X_{j,l}(\omega_j,T_k)$.

(c) point by point recursive seeking $a_{j,ll}(\omega_j,T_k) = X_{j,ll}(\omega_j,T_k)/X_{j,ll}(\omega_j,0)$ for the particular angles of each band, in which ll is the curvelet angle coefficient of the angles around 45° in the spatial domain.

(d) demand for the compensation coefficient of every frequency band $D_{j,ll}(\omega_j,T_k) = a_{j,ll}(\omega_j,T_k)/a_{jj,lll}(\omega_{jj},T_k)$, in which jj is the scale value of the base frequency band, lll is the corresponding angle parameter value of the reference frequency band, corresponds to the high-frequency specific angle ll.

(e) use the multiplicative inverse of $D_{j,ll}(\omega_j,T_k)$ weighing the signal of the corresponding angle corresponding frequency band.

(f) do anti-curvelet transform of the weighted signal to obtain the new records of compensation.

RESULTS

We use this method to do absorption compensation processing for two-dimensional stacked seismic data, the sampling interval of data is 1 ms, the fold number is 101, the length of time is 5 s. Use the inverse Q-filtering to compensate for the prestack data, the results are not very good. There we decompose the data by curvelet transform and smooth the sub-frequency signal by Gaussian window. Fig. 2 shows the comparison results of the superficial data before and after processing, shallow reflection waves will not change much, contrast to the results of treatment, the energy of the shallow data after compensation is little strengthened, and random noise is significantly attenuated.

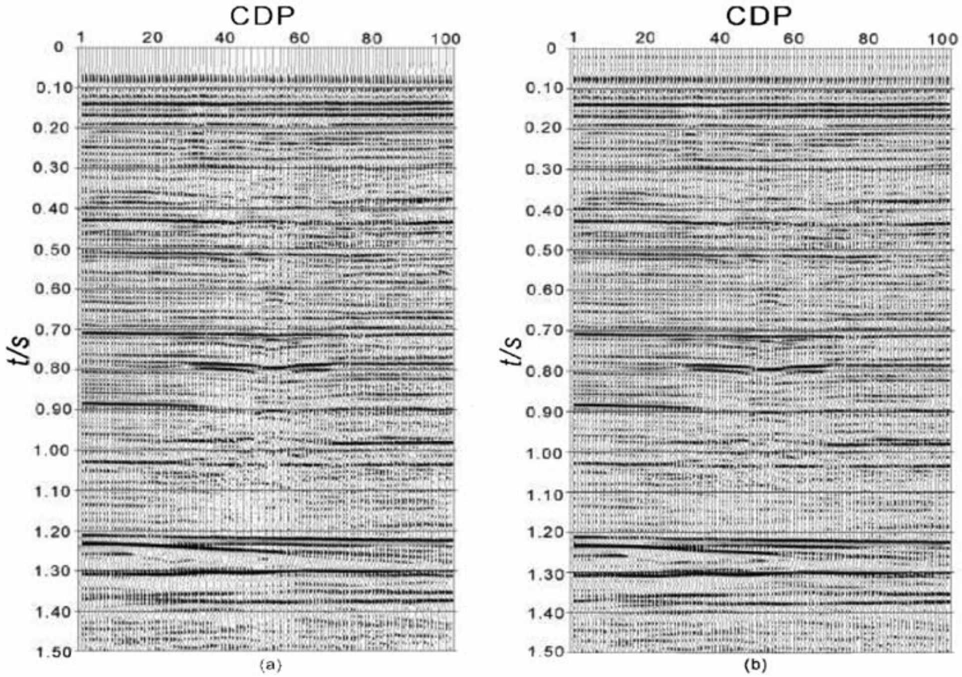
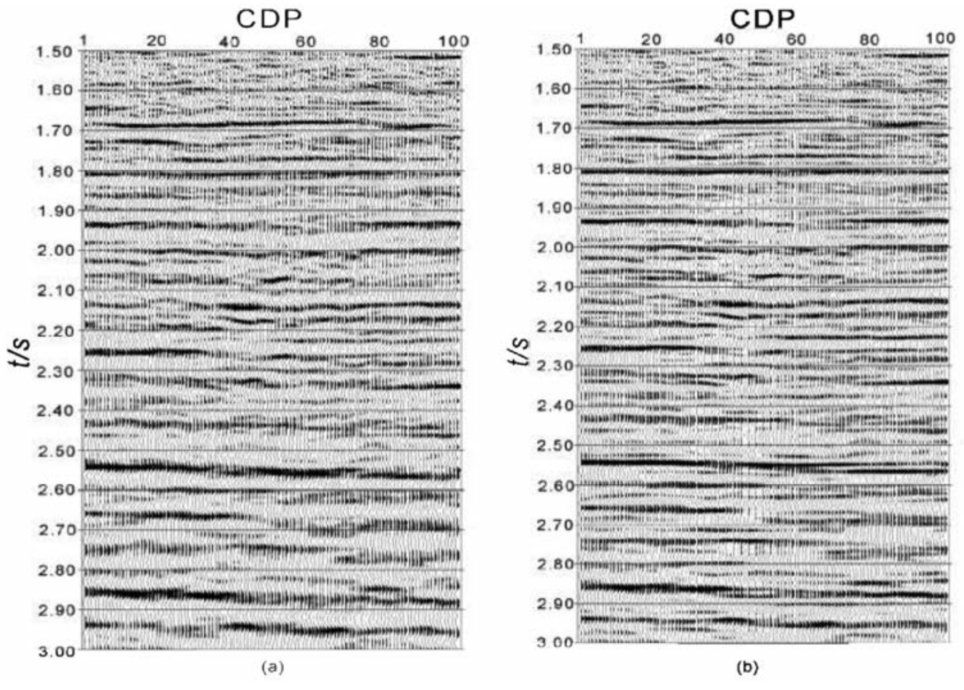


Fig. 2. The comparison results of the shallow data. (a) The data before compensation. (b) The data after compensation.

Fig. 3 shows the comparison of the mid-deep before and after treatment. We can see the resolution is greatly improved, the events are more pronounced and the energy is correspondingly increased. Fig. 4 shows the comparison of the deep data before and after treatment, it can be seen that the resolution is greatly improved, the blurry events are separated from each other, and the energy of events is enhanced greatly. Fig. 5 is the time-frequency distribution of the data before and after treatment. As can be seen from the graph, the data before process the frequency decline and bandwidth is narrowed as time increases. The dominant frequency and frequency bandwidth are basically the same for the mid-deep reflection wave of processed data, the mid-deep high frequency has been strengthened, the frequency band broadening. Form Figs. 2 to 5 we can draw the conclusion that the above method allows the strata absorption to get better compensation, the reflection waveform of the superficial, mid-deep and deep layer are basically the same, the resolution of mid-deep is significantly improved, high frequency is enhanced and the frequency band is broadened.



(a)

(b)

Fig. 3. The comparison results of the mid-deep data. (a) The data before compensation. (b) The data after compensation.

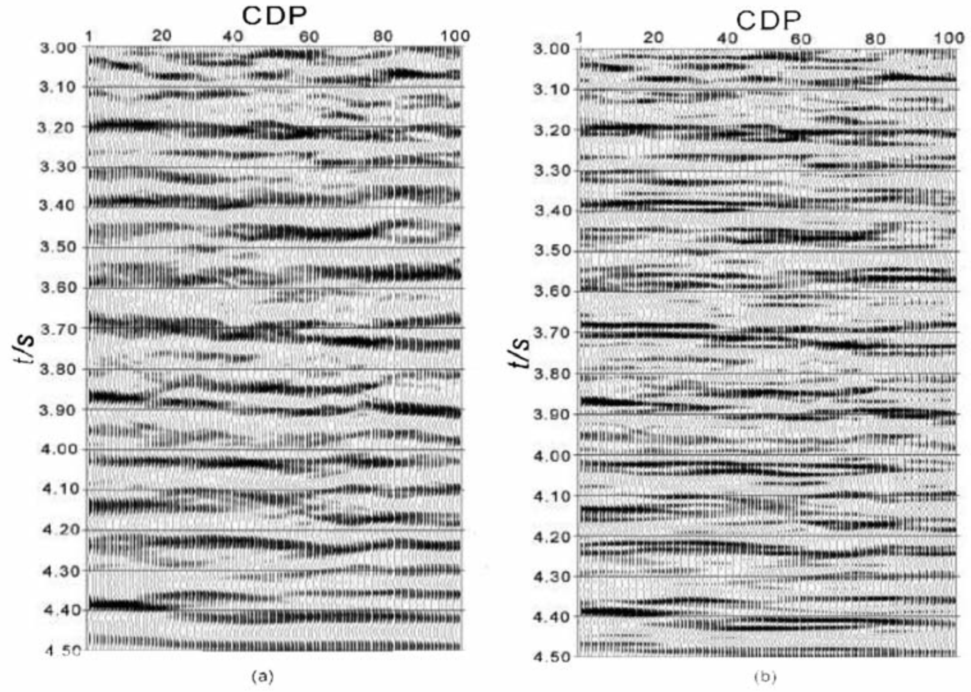


Fig. 4. The comparison results of the deep data. (a) The time-frequency distribution before compensation. (b) The time-frequency distribution after compensation.

DISCUSSION

The theoretical analysis and actual real data processing results show that using curvelet transform to divide the frequency of seismic data, and then weighting high-frequency signals through the ratio of high-frequency coefficient of shallow depth layer to the low frequency coefficient of shallow depth layer, can effectively eliminate the absorption and time-varying of seismic records, and improving the resolution of seismic data. This method does not have much requirements for the signal-to-noise ratio of data, has wide adaptation and can directional meticulous process the real seismic data by the angle characteristics of curvelet transform.

The limitations of the method is the energy focus in particular channel (where curvelet coefficient is very large) amplitude changes dramatic in the processing, and it is easy to generate singular value when we seek the compensation factor (the processing above has alias in shallow frequency after processing), before it is processed first smoothing the curvelet data can effectively weaken this effect. There is large randomness for the angle parameter selection, we can choose according to actual needs. Horizontal or near-horizontal events are generally within the compensation coefficient of ±45°, and the compensation angle of a high-frequency signal can be larger. If the post-stack data has steep dip events, the angle parameters should also be consistent with the angles of the events in the time domain. We assume that the reflected waves of different reflecting surfaces do not overlap each other, in fact reflected waves of adjacent reflecting surfaces overlap each other in the presence of a thin-layer, it can affect the processing precision to some extent. We can reduce the effects by adding a smoothing window. From Fig. 2 to Fig. 4, we can see that the blurry events are separated from each other and the thin-layer can also be clearly distinguished after processing.

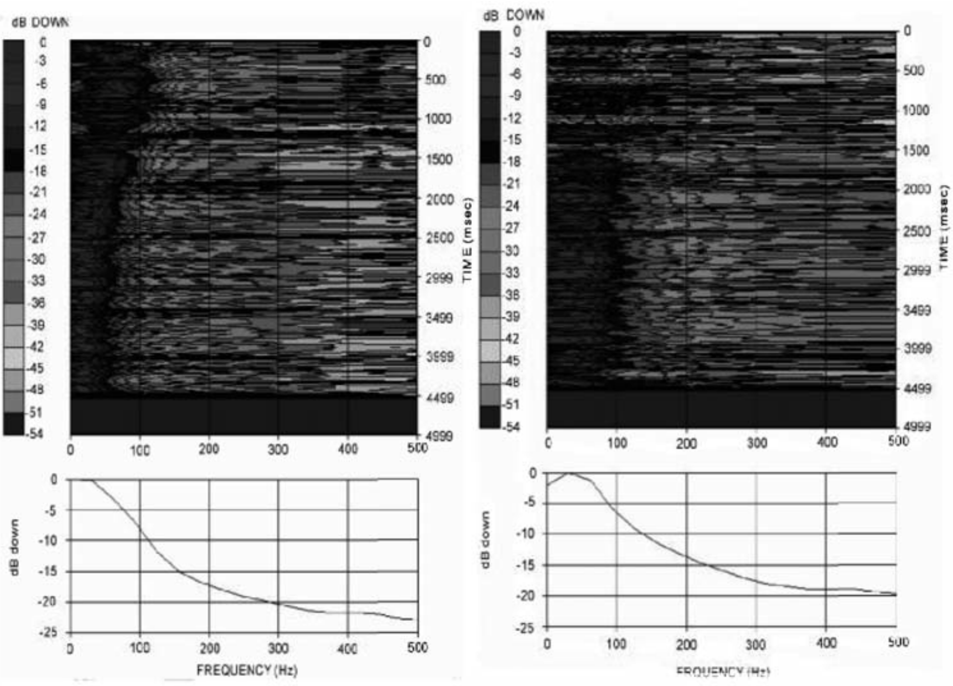


Fig. 5. The time-frequency distribution of the data before and after compensation.

Effective signal and random noise have a significant difference in the curvelet domain, we can only extract the effective signal when processing, and omit part of the small curvelet coefficients to suppress random noise and improve the signal-to-noise ratio of data. The most typical characteristics of absorption compensation based on curvelet transform are only compensate effective signals without corresponding enhance noise and random interference.

We can take advantage of curvelet transform's directional characteristics for fine processing, only for some specific angle seismic trace without affecting other ones. This directed fine handling capacity provides an efficient method of high-precision seismic processing.

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