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Combined Adaptive Multiple Subtraction Based on Optimized Event Tracing and Extended Wiener Filtering

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Abstract The surface-related multiple elimination (SRME) method is based on feedback formulation and has become one of the most preferred multiple suppression methods used. However, some differences are apparent between the predicted multiples and those in the source seismic records, which may result in conventional adaptive multiple subtraction methods being barely able to effectively suppress multiples in actual production. This paper introduces a combined adaptive multiple attenuation method based on the optimized event tracing technique and extended Wiener filtering. The method firstly uses multiple records predicted by SRME to generate a multiple velocity spectrum, then separates the original record to an approximate primary record and an approximate multiple record by applying the optimized event tracing method and short-time window FK filtering method. After applying the extended Wiener filtering method, residual multiples in the approximate primary record can then be eliminated and the damaged primary can be restored from the approximate multiple record. This method combines the advantages of multiple elimination based on the optimized event tracing method and the extended Wiener filtering technique. It is an ideal method for suppressing typical hyperbolic and other types of multiples, with the advantage of minimizing damage of the primary. Synthetic and field data tests show that this method produces better multiple elimination results than the traditional multi-channel Wiener filter method and is more suitable for multiple elimination in complicated geological areas.

Key words multiple adaptive attenuation; surface-related multiple prediction; Wiener filtering; short-time window FK filtering; event tracing technique

1 Introduction

In marine seismic exploration, both the sea surface and the seabed are usually strong acoustic impedance interfaces. Therefore, a large number of multiples exist in marine seismic records, which may seriously impair the authenticity and reliability of the seismic imaging, and even mislead subsequent seismic-geologic interpretation; it is thus necessary to eliminate multiples during marine seismic data processing.

In recent years, many multiple elimination methods have been developed based on wave theory, such as the wavefield extrapolation method (Wiggins, 1988), inverse scattering series method (Weglein *et al.*, 1997), surface-related multiple elimination (SRME) method (Verschuur *et al.*, 1992; Berkhout and Verschuur, 1997; Verschuur and Berkhout, 1997) and the extended SRME (ESRME) method (Jakubowicz, 1998; Verschuur and Berkhout, 2005; Ye *et al.*, 2014; Liu *et al.*, 2014). Of these, the SRME method has become the mainstream technique used in multiple suppression in current industrial production. Multiple elimination methods based on wave theory include two steps: multiple prediction and attenuation. Multiples in a seismic record are firstly predicted under the guidance of wave theory and various multiple adaptive attenuation methods (which use predicted multiple records) are then used to eliminate multiples in the original seismic record.

Multiple adaptive attenuation in a multiple record is crucial for the effects of multiple elimination when employing wave equations methods in complicated geological areas. Two major multiple adaptive attenuation methods are currently applied in contemporary wave equation multiple elimination; these are presented as follows. The first type is the multi-channel Wiener filter method, and in this respect, Verschuur *et al.* (1992) successfully eliminated predicted surface-related multiples according to the least-square criterion, which enabled SRME to be used in ac-

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tual production. In addition, Monk (1991) determined that compared to original multiple records, predicted multiple signals have problems such as amplitude differences, phase (constant phase reversal) differences, and time delay. As a result, original seismic traces (with only multiple information included) can be expanded as the sum of multiple record traces, the Hilbert Transform (HT) of multiple record traces, and the time derivative of these. Based on this theory, Wang (2003b) proposed the pseudo-multichannel matching filter method and extended the multichannel matching filter method, which significantly promoted the Wiener filter multiple suppression capacity. In addition, Li *et al.* (2007) proposed the forward equipoise pseudo-multichannel matching filter method, which improves the adaptive attenuation effects under non-orthogonal primary and multiples, and Li *et al.* (2011) subsequently developed an extended pseudo-multichannel matching filter method with a better amplitude preservation. Furthermore, Li *et al.* (2010) proposed the equipoise multichannel multiple adaptive attenuation method with a L1-norm constraint.

The second type of multiple adaptive attenuation method is based on different mathematics transformation domains. Zhou and Greenhalgh (1996) proposed an adaptive attenuation method applied in a parabolic Radon domain, where the method firstly makes a parabolic Radon transformation of an original seismic record and a multiple record and then eliminates multiple elements in the original record through mask filter. Following this, taking Radon domain data as the model of filter, Wang *et al.* (2003a) achieved matching subtraction in the time domain, and Herrmann *et al.* (2008) proposed methods for primary and multiple separation in the curvelet domain, which laid the foundation for multiple adaptive attenuation based on complex curvelet transform (Dong *et al.*, 2015). Subsequently, Li *et al.* (2014) used the projection of predicted multiple in the Radon domain to design parameters for matching subtraction.

In addition to the two major types mentioned here, other adaptive attenuation methods have been developed using other constraint conditions. For example: a model-based matching subtraction technique (Spitz, 1999), adaptive attenuation based on principal component analysis (Lu and Liu, 2009; Liu and Lu, 2015), a matching subtraction technique based on the multi-dimensional predicted error filter (Guitton, 2005), a non-stationary regression matching subtraction technique (Fomel, 2008), elimination of predicted multiples in the inverse wavelet domain (Jin *et al.*, 2008), use of multiple matching subtraction based on multi-channel convolutional signal blind separation (Li *et al.*, 2012), and adaptive subtraction using plane-wave prediction (Yan and Liu, 2014).

Although in most cases the multi-channel Wiener filter method can effectively suppress various multiples, information relating to primaries can be easily damaged when an event intersection occurs between primaries and multiples. Multiples in adaptive attenuation methods within mathematics transformation domains are better eliminated when an event intersection occurs. However, it is presumed that the multiple event occurs in accordance with hyperbolic principles, and thus non-hyperbolic multiples crossing in complicated geological areas are less effectively eliminated and the primary is more easily damaged when primaries and multiples have small apparent velocity differences (these normally exist near an offset).

This paper introduces a combined adaptive multiple attenuation method using multiple elimination based on an optimized event tracing technique and the extended Wiener filtering method (hereafter referred to as the 'combined adaptive multiple attenuation method'). Firstly, based on predicted multiple information, the original record is separated into an approximate primary record and an approximate multiple record using the optimized event tracing method and the short-time window FK filtering method. Residual multiples in the approximate primary record can then be eliminated using the extended Wiener filtering method. In addition, damaged primaries can be restored from the approximate multiples record. Both model and field experiments show that this method can dramatically improve multiple suppression effects and effectively avoid damage to primaries. It thus has good applicability in complicated geological areas.

2 Separation of Approximate Primary and Multiple Based on Optimized Event Tracing Technique

2.1 Multiple Event Tracing and Extraction in CMP Domain

Multiple records from SRMP generally show great changes in the amplitude and waveform of multiple signals (Monk, 1991) even though the event directivity remains the same as that in the original records; therefore, the stack velocity remains the same. Tan and Wang (2012) observed that a hyperbolic event in the CMP domain corresponds with suborbicular energy in the stack velocity spectrum; this implies that suborbicular energy can be detected using the isoline tracing method and that traveltime information pertaining to the hyperbolic event can be acquired in the CMP domain. This process is known as event tracing. In this way, based on predicted records a velocity spectrum can be created that contains only multiple stack energy. In addition, traveltime information relating to the multiple event can be extracted using event tracing technique, and multiples can be suppressed using short-time window FK fan filtering.

After acquiring multiple records from SRMP, the NMO and stacking of a series of constant stack velocities with CMP gather $m(x, t)$ can provide velocity domain records with the stack velocity, v, as the x-coordinate and the zero-offset, τ, as the y-coordinate (Thorson and Claerbout, 1985). The absolute value representing the multiple velocity domain spectrum, is shown in the formula

$$E_m(v,\tau)=\left|\sum_{n=1}^{N} m\left(x_n, t=\sqrt{\tau^2+x_n^2/v^2}\right)\right|, \quad (1)$$

in which n ($1 \le n \le N$) is the number of the trace and x_n is the offset of trace n.

Due to time-space truncation artifacts, the event stack energy in the velocity spectrum, E_m, appears as a 'scissor' shape (with two horizontal and tilted tails) instead of a suborbicular shape (Wang, 2003a). This distortion not only decreases the resolution of the velocity spectrum, but also affects the accuracy when following event tracing. Therefore, to suppress truncation artifacts in velocity stacking, homophase weighting is introduced into the preliminary multiple stack velocity spectrum, and the weighting formula is shown as follows (Stoffa *et al.*, 1981),

$$b(v,\tau)=\frac{\sum_L\left[\sum_{n=1}^{N} m\left(x_n, t=\sqrt{\tau^2+x_n^2/v^2}\right)\right]^\lambda}{\sum_L\sum_{n=1}^{N}\left|m^\lambda\left(x_n, t=\sqrt{\tau^2+x_n^2/v^2}\right)\right|+C}, \tag{2}$$

where λ ($\lambda\geq 2$) represents the order (when the value of λ is larger, the resolution is higher); L determines the time window length; and C is a constant (to ensure the denominator is not zero and is always 0.01–0.001 times the average amplitude).

If homophase weighting is introduced into calculation of the multiple velocity spectrum, formula (1) can be expressed as

$$E_m(v,\tau)=\left|b(v,\tau)\sum_{n=1}^{N} m\left(x_n, t=\sqrt{\tau^2+x_n^2/v^2}\right)\right|. \tag{3}$$

With omission of time-space truncation artifacts, the hyperbolic event of stack velocity, v_0, and zero-offset, τ_0, in $m(x, t)$ will generate suborbicular structural energy with a central extreme value (v_0, τ_0) in $E_m(v, \tau)$ after moderate smoothing. The isoline tracing method (Tan and Wang, 2012) is able to calculate the distribution of suborbicular energy and locate the extreme point. According to the coordinate of the extreme point (v_0, τ_0), the event in a time-space domain can be projected out and reflects traveltime, t_n, as

$$t_n=\sqrt{\tau_0^2+x_n^2/v_0^2}\ . \tag{4}$$

Once the stack velocity of multiple events in the original record $d(x, t)$ meets the multiple record $m(x, t)$, the traveltime, t_n, of every event passing the seismic traces in the original record $d(x, t)$ can be directly achieved based on formula (4).

Multiple events obtained from traveltime information in the CMP record can be extracted by FK fan filtering using the following steps:

1) The t_n-centered record segment $e(x_n, t)$ for given time window length in the seismic traces is cut out, as shown in the formula

$$e(x_n, t)=d\left(x_n, t+t_n-\frac{l}{2}\right), \tag{5}$$

in which $e(x_n, t)$ represents the multi-trace event record and t ($0\leq t\leq l$) is the travel time. As $e(x_n, t)$ contains a t_n-centered record segment, this implies that the traces aligned at a starting point and that the targeted event was corrected at a horizontal level.

2) With intercepted multiple records as the input, the corrected horizontal multiple events are extracted using the FK fan filtering method. Firstly, the 2-D fast Fourier transform (2-D FFT) is needed for $e(x_n, t)$, as shown below,

$$G(k,\omega)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} e^{-i(kx+\omega t)}\,dx dt\ , \tag{6}$$

where $G(k, \omega)$ is FK domain data, and k and ω respectively denote wave number and frequency. Multiple energy is fasten on the region near k=0 of $G(k, \omega)$, therefore multiple data $G'(k, \omega)$ can be extracted by cutting off the outside region of the fan shape. Finally, the 2-D inverse fast Fourier transform (2-D IFFT) is applied to $G'(k, \omega)$

$$e'(x_n, t)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} G'(k,\omega)e^{i(kx+\omega t)}\,dk d\omega\,, \tag{7}$$

where $e'(x_n, t)$ is a multi-trace event record containing only multiple FK domain data.

3) The extracted event is added to the original time window position in the new record $d'(x, t)$. The record thus includes only extracted multiple events, which marks the separation of primary and multiple signals in the original records. The process is shown as follows,

$$d'\left(x_n, t+t_n-\frac{l}{2}\right)=d'\left(x_n, t+t_n-\frac{l}{2}\right)+e'(x_n, t)\,. \tag{8}$$

2.2 Optimized Tracing of Multiple Events

When processing seismic data, predicted multiples may have traveltime errors (these are particularly obvious in medium and far offsets) in relation to the existence of complicated geological structures. This is the main cause for the failure of traditional multiple adaptive attenuation. It is thus necessary to accurately perform multiple event tracing to eliminate traveltime error. The difference between parameters v_0 and τ_0 in the stack velocity spectrum shows that the traveltime errors of multiple events can be corrected according to the real parameters in the original record.

To eliminate interference of the primary to optimize tracing, after generating the stack velocity spectrum $E_d(v, \tau)$ of the original record $d(x, t)$ based on formulas (2) and (3), it is necessary to obtain the multiple velocity spectrum $E_{dm}(v, \tau)$ from the original records using the mask filter method (Zhou and Greenhalgh, 1996). Here the velocity spectra $E_d(v, \tau)$ and $E_m(v, \tau)$ are overlapped, and the latter spectrum is used (similar to color separation) as a 'mask' to shield the corresponding signals in the former one. The eliminated primary filter factor is

$$f(v,\tau)=1-\frac{1}{\sqrt{1+\left[\frac{B(v,\tau)}{\varepsilon A(v,\tau)}\right]^\eta}}\ , \tag{9}$$

where ε is the equipoise coefficient between $E_m(v, \tau)$ and $E_d(v, \tau)$; η is the smoothing coefficient for the mask filter;

$A(v, \tau)$ and $B(v, \tau)$ indicate the sum of $E_d(v, \tau)$ and $E_m(v, \tau)$ within a certain region of velocity and time, respectively, as shown below

$$\begin{cases} A(v,\tau)=\sum_{i=v-\Delta v}^{v+\Delta v}\sum_{j=\tau-\Delta t}^{\tau+\Delta t} E_d(i,j) \\ B(v,\tau)=\sum_{i=v-\Delta v}^{v+\Delta v}\sum_{j=\tau-\Delta t}^{\tau+\Delta t} E_m(i,j) \end{cases}, \quad (10)$$

where Δv and Δt represent the statistical window length for velocity and time respectively.

The following formula shows how to obtain the multiple velocity spectrum $E_{dm}(v, \tau)$ of the original record using the filter factor from formula (5),

$$E_{dm}(v,\tau)=E_d(v,\tau)f(v,\tau). \quad (11)$$

The process used to eliminate multiple event traveltime errors through local tracing of the velocity spectrum $E_{dm}(v, \tau)$ can be described as follows: center the original parameter (v_0, τ_0) in the velocity spectrum $E_{dm}(v, \tau)$, seek the extrema of the preliminary traced multiple event (according to a certain region of velocity and time), and determine the accurate parameters τ_0' and v_0' based on the coordinates of the extrema position.

2.3 Iterative Separation of Approximate Primary and Multiple

Repeated iterative event tracing and extraction is required for all multiple events in the original record $d(x, t)$ as follows (the specific processing flow is shown in Fig.1):

1) Parameters (including N_m and E_0) are essential to enable stable event tracing. N_m is the average multiple event number per unit time window length (which is designed for the number of events obtained per iteration); and E_0 defines the stack energy threshold of the events being traced. The value of these is decided by seismic records and stack velocity spectrum analysis.

2) During the iterative optimized event tracing and extraction process, a stack velocity spectrum $E_m^n(v,\tau)$ is created with a residual multiple record $m^{n-1}(x,t)$ in the n ($n\geq 1$) time iteration. If the maximum amplitude, $E_{\max}$, is not less than E_0, then strong multiple events remain in the seismic record and further tracing is required. In this way, an event number of N ($N=N_m \cdot t_{\max}$, $t_{\max}$ is the maximum record length) is obtained. Multiple event extraction based on formulas (5)–(8) is used for each event that has a stack amplitude that is not less than E_0. Event tracing and extraction per iteration is shown below as,

$$\begin{cases} d^{n-1}(x,t) \xrightarrow{\text{Optimized event tracing and extraction}} d_m^n(x,t)+d^n(x,t) \\ m^{n-1}(x,t) \xrightarrow{\text{Optimized event tracing and extraction}} m_h^n(x,t)+m^n(x,t) \end{cases}, \quad (12)$$

where $d_m^n(x,t)$ and $m_h^n(x,t)$ are the extracted records of the n time iterative algorithm, $d^n(x,t)$ and $m^n(x,t)$ are residual records after n times extraction, and $d^0(x, t)$ and $m^0(x, t)$ represent the original record $d(x, t)$ and multiple record $m(x, t)$ in the first iterative algorithm, respectively.

3) Optimized event tracing and extraction are repeated for multiples (namely step 2) until the extremum $E_{\max}$ in the residual velocity spectrum is smaller than the threshold, E_0.

When the iterative records are summed, $d(x, t)$ and $m(x, t)$ can be separated into four records as follows,

$$\begin{cases} d_m(x,t)=\sum_{n=1}^{N} d_m^n(x,t),\ d_p(x,t)=d^n(x,t) \\ m_h(x,t)=\sum_{n=1}^{N} m_h^n(x,t),\ m_l(x,t)=m^n(x,t) \end{cases}, \quad (13)$$

where $d_p(x, t)$ and $d_m(x, t)$ are the approximate primary record and approximate multiple record, respectively, and $m_h(x, t)$ and $m_l(x, t)$ are the hyperbolic multiple record and residual multiple record, respectively. Formula (13) shows that $d_m(x, t)$ includes most of the multiple events; however, there is a small quantity of damaged primary information in positions where a small time difference exists between the primary and multiple event (such as near offset traces) because of the use of a short-time window and the FK apparent velocity filtering method. As $d_p(x, t)$ represents the residual record after multiple subtraction, it thus consists mainly of primary and only a small amount of complex multiples, the events of which do not fit a hyperbolic form. Hyperbolic events are included in $m_h(x, t)$ and these are extracted from $m(x, t)$. In addition, residual complex multiple information is included in $m_l(x, t)$, which has a very weak amplitude that even approaches zero when the events of the CMP record belong to (or are similar to) hyperbola.

According to the above analysis, the multiple elimination method based on optimized event tracing can avoid analysis of stack velocity and thus decrease the amount of time involved in computing compared to performing traditional Radon transformation and FK filtering. In addition, compared with the Wiener filter methods, it is capable of getting rid of multiple waveform distortion and better-eliminating multiple crossing with the primary event. However, the method has some limitations, which are as follows. Firstly, it is difficult to remove non-hyperbolic complex multiples, and residual complex multiple interference is sometimes caused in the approximate primary record. Secondly, short-time window FK apparent velocity filtering may damage primary signals and leave an amount of primary information in the approximate multiple record $d_m(x, t)$ if differences between the primary and multiple are small when separating them through the optimized event tracing method. Therefore, this paper introduces an additional adaptive subtraction of the approximate primary record and the approximate multiple record using the extended Wiener filtering method, with the aim of further eliminating complex multiples in the approximate primary record and restoring damaged primary information from the approximate multiple record.

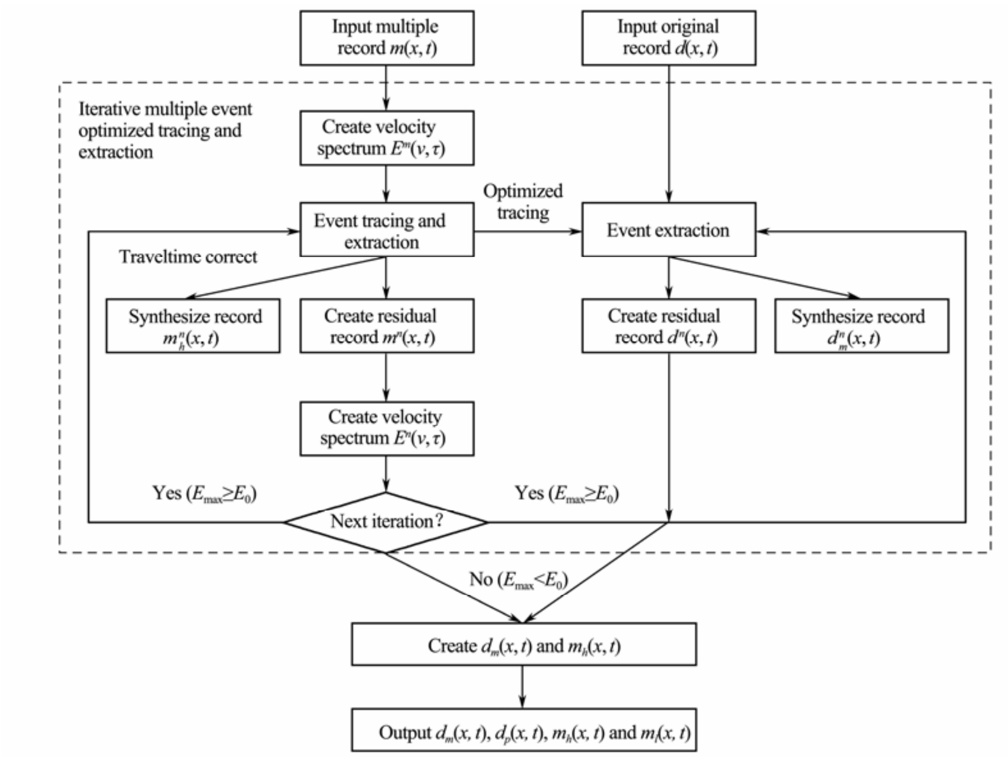

Fig.1 Processing flow chart for separating approximate primary record and approximate multiple record using iterative algorithm.

3 Multiple Adaptive Attenuation Based on Extended Wiener Filtering

To enable better separation of primary and multiple information from the approximate primary record and approximate multiple record, as an alternative to using multi-channel Wiener filtering (Treitel, 1970; Wang, 2003b), which regards multi-channel data as the input, this paper extends traditional single-trace Wiener filtering to the extended Wiener filter method (based on the method of Monk (1991)). Without the limitations produced by the hyperbolic traveltime equation, this method can be applied in residual multiple suppression within the approximate primary record $d_p(x, t)$ and in primary and multiple separation from the approximate multiple record, thereby restoring some of the damaged primary information to a certain extent.

3.1 Basic Principle of Extended Wiener Filtering

Compared with the original seismic record, multiple signals in the multiple record have problems such as amplitude variation, constant phase rotation, and a slight time delay. Monk (1991) supposed that multiple signals in the original seismic record signify the sum of the predicted multiple signals, the Hilbert transform of the predicted multiple signals, and the time derivative of these. Transform signal filtering can be further explained as

$$d(t)=f_1(t)*m(t)+f_2(t)*m_H(t)+f_3(t)*m'(t)+f_4(t)*m'_H(t), \tag{14}$$

where $d(t)$ is the multiple signal in the original seismic record; $m(t)$ is the predicted multiple signal; $m_H(t)$ is the HT of $m(t)$; $m'(t)$ is the time derivative of $m(t)$; $m'_H(t)$ is the time derivative of $m_H(t)$; $f_i(t)$ is the filter factor; and '*' marks the convolution operator.

When the filtering effect is guaranteed, $m(t)$, $m_H(t)$, $m'(t)$, and $m'_H(t)$ are marked as $m_1(t)$, $m_2(t)$, $m_3(t)$, and $m_4(t)$, respectively, to efficiently acquire the filter factor. Formula (14) can thus be revised as iterative Wiener filtering, namely,

$$\begin{cases} d^{(n)}(t)=d^{(n-1)}(t)-f_n(t)*m_n(t) \\ d^{(0)}(t)=d(t) \end{cases}, \tag{15}$$

where $d^{(n)}(t)$ is the result of the original seismic signal after n times iterative attenuation, and n ($1\le n\le 4$) stands for the iteration time.

In every iterative algorithm, the filter factor $f_n(t)$ is decided by the minimum error sum of squares, e,

$$e=\sum\left[d^{(n)}(t)-f_n(t)*m_n(t)\right]^2 . \tag{16}$$

During the process of multiple adaptive attenuation under formula (16), top-bottom sliding window filtering is applied to every seismic trace based on the given time window length. Generally, the predicted outcomes of multiples in a near offset are more accurate than in medium and far offsets, and this therefore leads to a space-variant of the iterative algorithm time, n. In other words, the value of the iterative algorithm time, n, is less in near offsets than in medium and far offsets. However, the adaptive attenuation ability of multiples has been strengthened during the iterative attenuation and there is an increased risk of damage to the primary signal; therefore, use of the optimized iterative algorithm time, n, depends on practical conditions during field record processing.

3.2 Primary Restoration and Residual Multiple Attenuation Based on Extended Wiener Filtering

To filter out primary information in an approximate multiple record, $d_m(x, t)$, and to further eliminate the residual multiple in an approximate primary record, $d_p(x, t)$, adaptive attenuation is again applied to the approximate multiple record, $d_m(x, t)$, and the approximate primary record, $d_p(x, t)$, using the extended Wiener filter method. The relevant processes involved are as follows,

$$\begin{cases} p_1(x,t)=ELSF\left[d_m(x,t), m_h(x,t)\right] \\ p_2(x,t)=ELSF\left[d_p(x,t), m_l(x,t)\right] \end{cases}, \quad (17)$$

where $ELSF$ represents the extended Wiener filter operator, $p_1(x, t)$ includes the filtered primary information in the record $d_m(x, t)$, and $p_2(x, t)$ is the outcome of record $d_m(x, t)$ after complex multiple elimination.

Primary information in the approximate multiple record, $d_m(x, t)$, mainly exists in the near offset where the multiple and primary differ slightly in traveltime. Therefore, filtering focuses on seismic traces in the near offset, and the residual traces of record $p_1(x, t)$ are set as zero. The final record of multiple subtraction is the sum of the filtering results shown in formula (17) and is shown as follows,

$$p(x,t)=p_1(x,t)+p_2(x,t), \quad (18)$$

where $p(x, t)$ is the final result of combined adaptive attenuation.

Two different procedures are targeted by the extended Wiener filter method in formula (17). The first relates to residual multiple elimination in the approximate multiple record, and the second one aims to avoid damage to the effective signals when multiples and primaries have small time differences. The two procedures are optional for use in seismic record features and analysis of first multiple attenuation during field data processing.

4 Processing of Combined Adaptive Multiple Attenuation

In summary, the combined adaptive multiple attenuation method used in this paper consists of two major steps. Firstly, based on the predicted multiple record, the optimized event tracing technique is used to trace multiple events. A short-time window FK apparent velocity filter method is then used to separate the original record into an approximate primary record and an approximate multiple record. Adaptive attenuation is then applied to those records, based on the ELSF method, to eliminate complex multiples from the approximate primary record. Damaged primary information is thus restored from the approximate multiple record. The processing flow chart for combined adaptive multiple attenuation is shown in Fig.2.

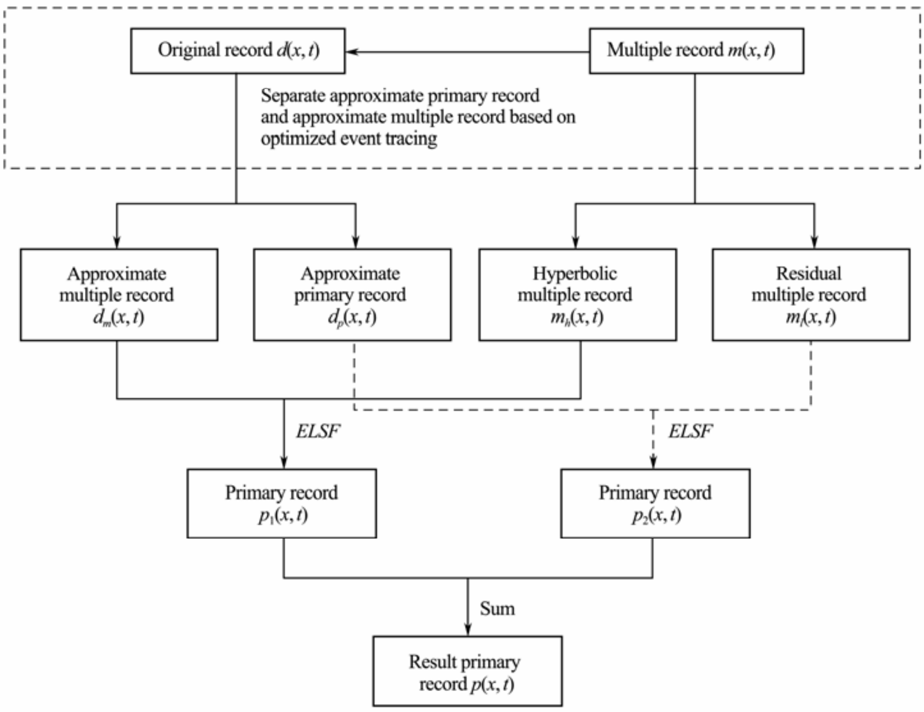

Fig.2 Processing flow chart for combined adaptive multiple attenuation.

According to the processing steps, use of the combined adaptive multiple attenuation method colligates the advantages of the multiple attenuation method based on optimized event tracing and the extended Wiener filter technique. It is theoretically able to suppress both common hyperbolic multiples and non-hyperbolic multiples in complicated geological areas and can significantly reduce primary damage.

5 Model Experiment

An experiment is conducted to eliminate multiples that either intersect or occur near a primary event, to illustrate the properties of multiple adaptive attenuation. The combined adaptive multiple attenuation technique and the multi-channel Wiener filter method (Treitel, 1970; Wang, 2003b) are adopted to suppress multiples with small traveltime differences and to test the combined adaptive multiple attenuation method. Based on the velocity model shown in Fig.3, this paper uses 35 Hz main frequency Ricker wavelet (see Fig.4) as the source and the finite difference method of the acoustic wave equation to generate a seismic record that includes multiples. There are 500 shot gathers in the seismic record and 160 traces in each shot gather; both the shot interval and trace interval are 10 m and the minimum offset is zero (the 500th CMP recorded in this shot gather is shown in Fig.5(a)).

In Fig.5(a), the arrow points to a multiple event that intersects with the primary event in the same time range. The number (ii) multiple event nearly overlaps the primary event at a near offset. According to the processing of the optimized event tracing multiple elimination method, this paper firstly acquires the multiple record (in which the 500th CMP record is shown in Fig.5(b)) using SRMP, and then creates a multiple velocity spectrum based on the multiple record (as shown in Fig.5(c)). The suborbicular energy region is then defined using the isoline tracing method, which identifies the multiple event in the original record (as shown in Fig.5(d) with colored curves (i)–(ii)).

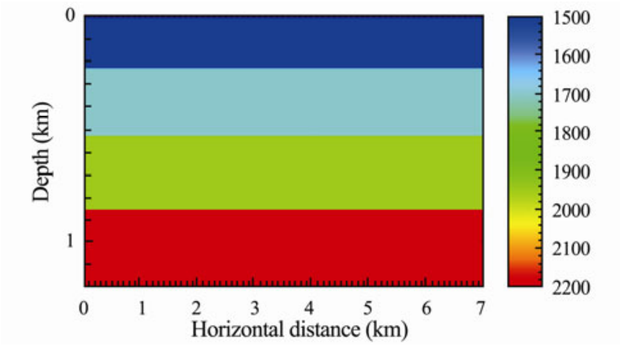

Fig.3 Horizontal layered grid velocity model.

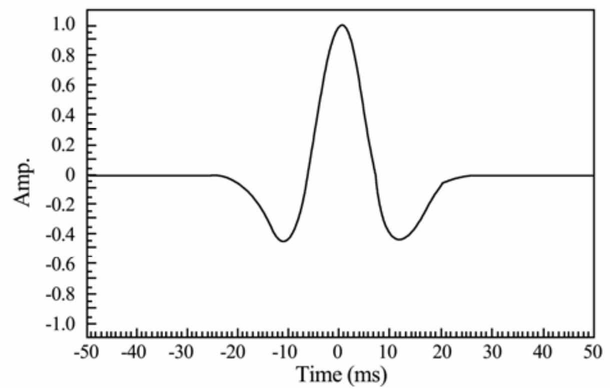

Fig.4 Waveform of 35 Hz main frequency Ricker wavelet.

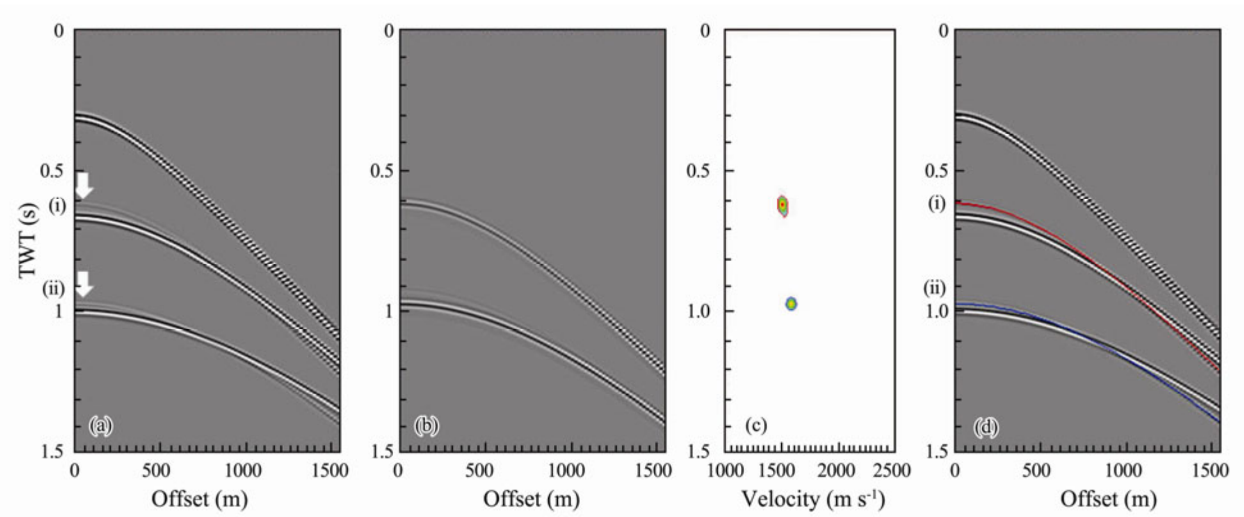

Fig.5 Example of event tracing.

After the multiple event is traced out, the optimized tracing method is used to separate the multiples and primaries. As shown in Fig.6(a), event (i) is firstly extracted, the multi-trace event record is then acquired, and the multiple event is corrected at a horizontal level. Subsequently, the multi-trace event record is transformed to the FK domain with 2-D FFT and the region near k=0 is cut off. Finally, the approximate primary record is generated by 2-D IFFT and an approximate multiple record is produced through filtered multiples. Multiple event (ii) then processed in the same way and the final approximate primary record is obtained in addition to the approximate multiple record (as shown in Fig.6(b) and Fig.5(c)). Fig.6 shows that the multiple event in the approximate primary record has been completely eliminated without residual multiple information. However, the primary information is slightly damaged because multiple event (ii) almost overlaps with the primary event (as shown in the rectangular area in

Fig.6(b)). The damaged information exists in the approximate multiple record (as shown in the rectangular area in Fig.6(c)).

Extended Wiener filtering is applied only to the approximate multiple record based on the predicted multiple record, and filtered primary information is added to the approximate primary record; the final result is combined adaptive multiple attenuation (the 500th CMP record of the combined adaptive multiple attenuation result is shown in Fig.7(a)). Fig.7(a) shows that damaged primary information is well restored after extended Wiener filtering; Fig.7(b) demonstrates the result of multiple attenuation through multi-channel Wiener filtering; and Figs.7(c) and (d) respectively illustrate that the multiple is subtracted by a combination of the adaptive multiple attenuation technique and the multi-channel Wiener filter method. In addition, a comparison of Figs.7(a), (b), (c), and (d) shows that the traditional multi-channel Wiener filter method damages the primary when the multiple event occurs close to the primary event, whereas the combined adaptive multiple attenuation technique is better at retaining the primary when suppressing the multiple.

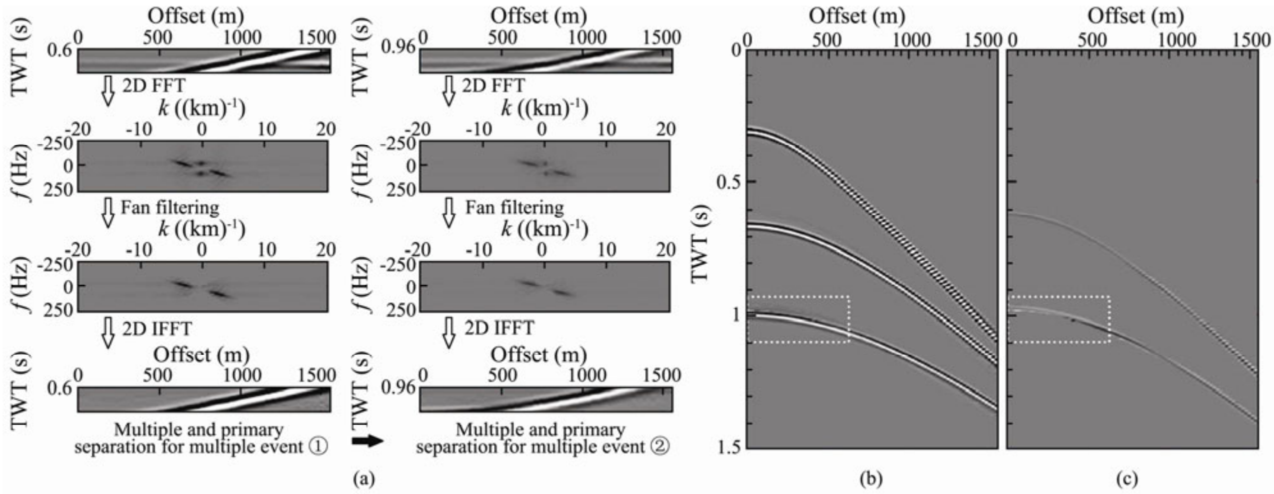

Fig.6 Process of separating primary and multiple by optimized event tracing. (a) short-time window FK apparent velocity filter; (b) example of approximate primary; (c) example of approximate multiple.

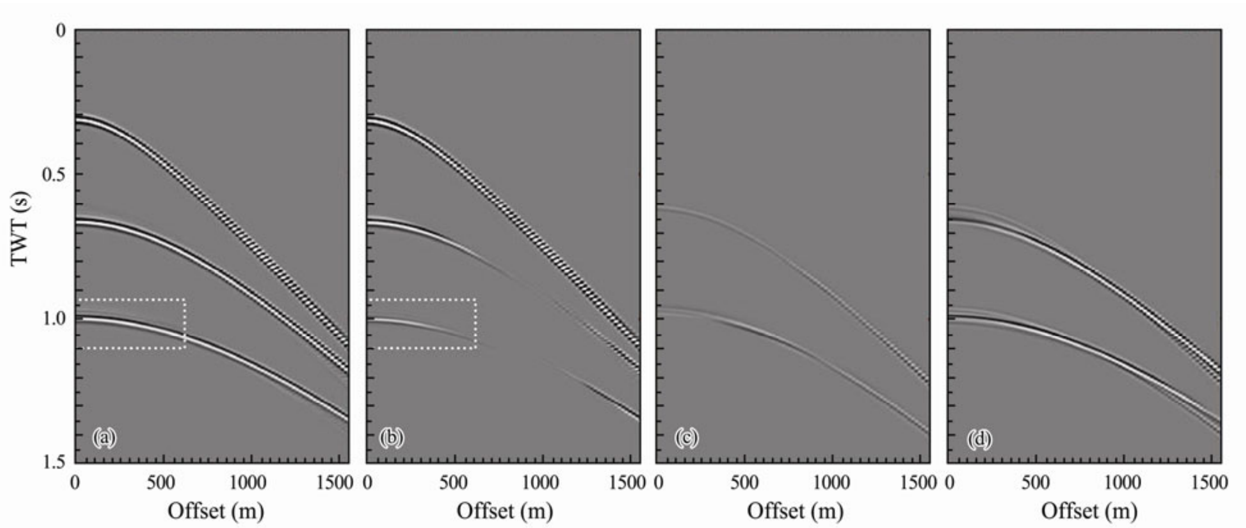

Fig.7 (a) CMP record processed using combined adaptive multiple attenuation, (b) CMP record processed using multi-channel Wiener filter, (c) multiple record subtracted using combined adaptive multiple attenuation, (d) multiple record subtracted using multi-channel Wiener filter.

6 Field Experiment

The 2D seismic line ML_A lies on a rigid seafloor area with a drastically undulating seabed where the seawater depth ranges between 1100 m–1650 m. There are strong surface-related multiples and other complex multiples in the original shot gather record. The field acquisition parameters of this line are: 2362 shots in the original record, 180 traces in each shot, a 26.6 m trace interval or shot interval, and a 218.8 m minimum offset.

The original shot gather of line ML_A needs to be preprocessed before SRMP is used, and this is achieved using the following steps: 1) the first break signals in the shot record are cut out; 2) low frequency signals under 5Hz in the original seismic record are eliminated by band-pass filtering; and 3) the spherical spreading compensation method is used to enhance reflection information in the medium-deep range of the shot gather record. Fig.8(a) shows the 600th shot record after preprocessing. The 600th multiple record is produced using SRMP (as is presented in Fig.8(b)); however, some errors exist in the rectangular area because of the drastically undulating seabed.

Figs.9(a) and (b) respectively give examples of a shot gather record after multiple elimination using the combined adaptive multiple attenuation technique and multi-channel Wiener filtering method (refer to Figs.8(a) and (b) for examples of original record and predicted multiple record). It is evident that in Fig.9(b) the strong reverberation multiple at the sea bottom and on the underlying wave impedance interface shown in Fig.9(a) has entirely been eliminated. However, strong residual multiples exist in the rectangular area of the shot gather record after multi-channel Wiener filtering (as shown in Fig.9(b)). Figs.10(a) and (b) respectively illustrate multiple subtraction using the aforementioned methods and prove that the combined adaptive multiple attenuation is superior in subtracting the multiple than the multi-channel Wiener filtering; it is evident that no obvious primary event remains. Therefore, the method introduced in this paper is shown to preserve primary information and significantly improve the multiple suppression effect, even when prediction errors exist.

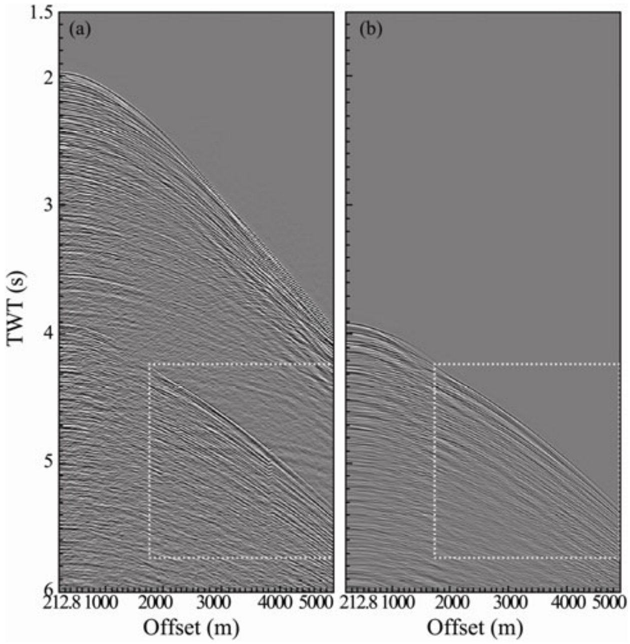

Fig.8 Example of (a) original shot gather record and (b) predicted multiple record.

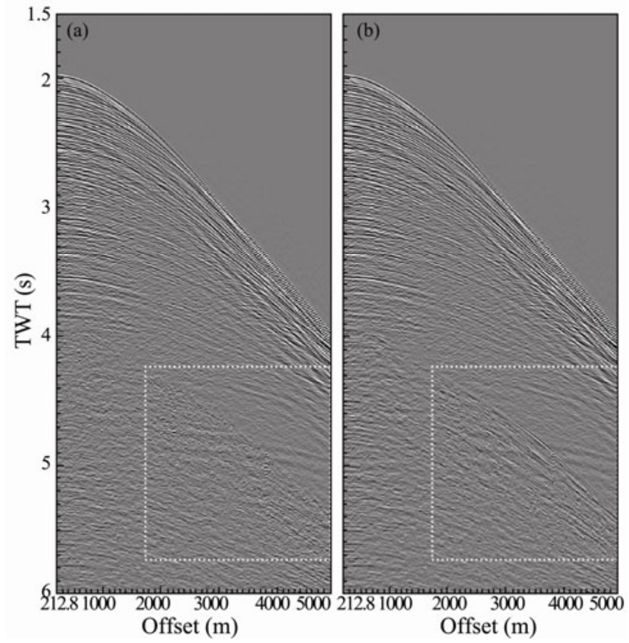

Fig.9 Examples of shot gather processed by: (a) combined adaptive multiple attenuation and (b) multi-channel Wiener filtering.

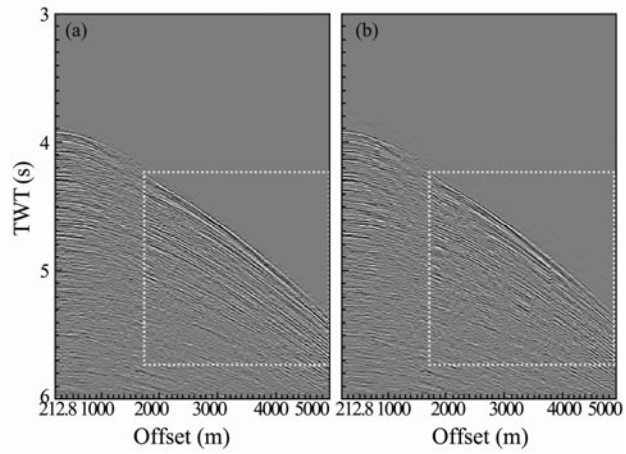

Fig.10 (a) Multiple record subtracted by combined adaptive multiple attenuation, (b) multiple record subtracted by multi-channel Wiener filter.

For the primary migration velocity field, Kirchhoff prestack time migration is applied to the original shot gather record, multiple suppression shot gather record, and the multiple subtracted by the combined adaptive multiple attenuation method (sections are shown in Figs.11–14). For the purpose of comparison and analysis, only sections of the rugged sea bottom are selected. The horizontal distance ranges from 10 to 30 km, and the traveltime is between 1.55 s. Multiple information is suppressed during the seismic imaging process using the primary migration velocity, but strong multiple events remain in places (the original section arrows points to these areas in Fig.11).

A comparison of the combined adaptive multiple attenuation method and the multi-channel Wiener filtering technique is shown in Figs.12 and 13. It is clear from these that the strong multiple events shown by the arrows in Fig.12 are eliminated completely in Fig.13, although residual multiples remain. However, the migration section of the multiple in Fig.14 has no obvious primary event, which proves that the method discussed in this paper causes no severe harm to the primary. The experiments show that even with a rugged sea bottom with complex multiple conditions, the method introduced here is capable of preserving primary information and significantly improving the multiple adaptive attenuation effect.

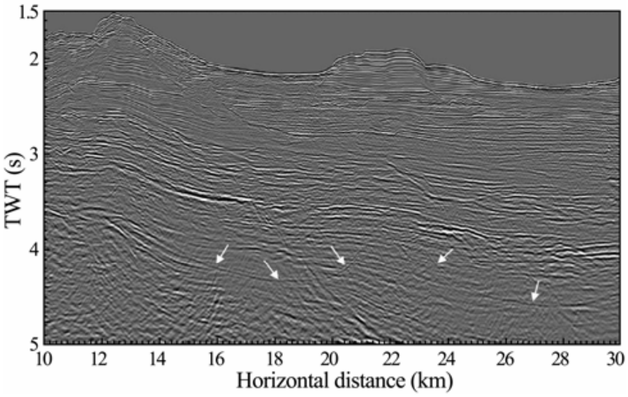

Fig.11 Migration section of original shot gather.

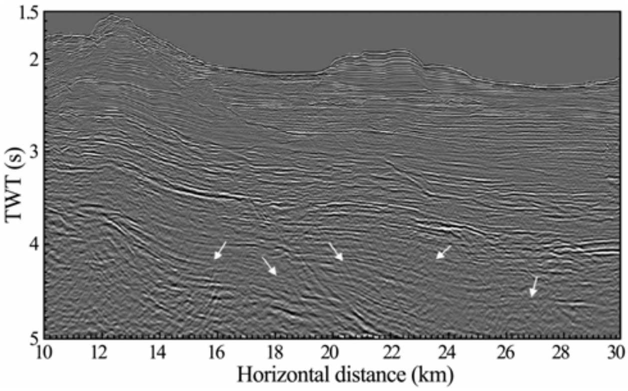

Fig.12 Migration section processed by combined adaptive multiple attenuation.

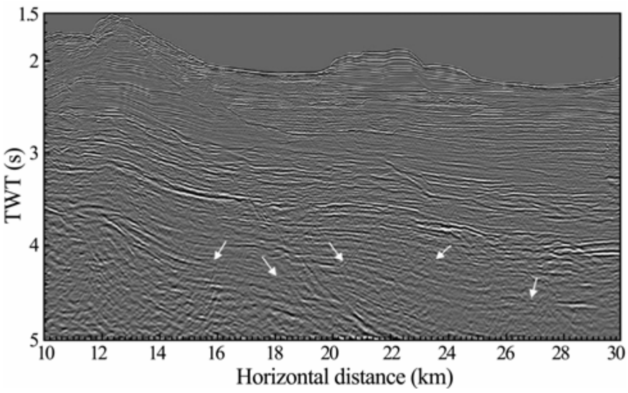

Fig.13 Migration section processed by multi-channel Wiener filter.

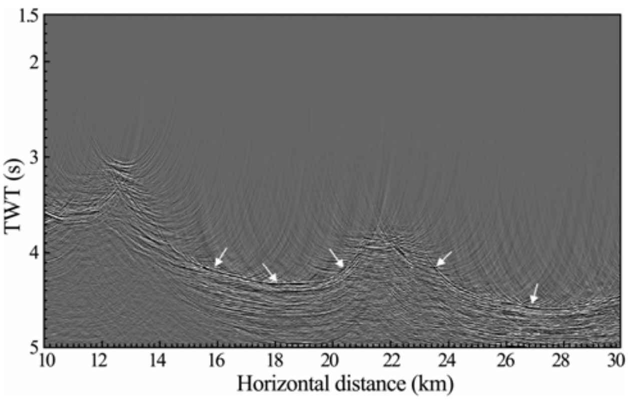

Fig.14 Migration section of multiple subtracted by combined adaptive multiple attenuation.

7 Conclusions

The paper introduces a combined adaptive attenuation method based on the optimized event tracing multiple attenuation technique and the extended Wiener filter method, which comprehensively combines the advantages of the two methods. Both common hyperbolic multiples and other multiples can be effectively suppressed using this method, and little damage is inflicted on the primary. Model and field experiments show that the method has better multiple elimination effects than the normal multi-channel Wiener filtering technique and is better applied in complicated geological areas.

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