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An Improved Time-Frequency Analysis Method for Hydrocarbon Detection Based on EWT and SET

Hui Chen [1], Jiaxing Kang [1], Yuanchun Chen [1], Dan Xu [1] and Ying Hu [1,2,*]

[1] Geomathematics Key Laboratory of Sichuan Province, Chengdu University of Technology, Chengdu 610059, China; huichencdut@cdut.edu.cn (H.C.); kangjx_star@163.com (J.K.); chenyc0121@foxmail.com (Y.C.); danxu_621@163.com (D.X.)

[2] Postdoctoral Station of Geophysics, Chengdu University of Technology, Chengdu 610059, China

* Correspondence: huying15@cdut.edu.cn; Tel.: +86-28-8407-3610

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Abstract: Oil and gas reservoirs can cause increased attenuation of seismic waves, which can be revealed by time-frequency analysis for direct detection of hydrocarbons. In this paper, a new method applying the empirical wavelet transform (EWT) in association with the synchroextracting transform (SET), named EWT-SET, is proposed as an improved time-frequency analysis method for hydrocarbon detection. The SET is a novel time-frequency analysis method which can be considered as a post-processing procedure of short-time Fourier transform and can improve the energy concentration of the time-frequency representation by retaining only the time-frequency information most related to the signal time-varying features. Given the potential limitations of SET for broadband nonstationary seismic signals, using the EWT-SET method which applies SET to the signal after EWT decomposition, not only effectively extracts time-varying features of seismic signals but also improves the performance of SET in concentrating instantaneous energy. The preliminary model tests demonstrate that EWT-SET can effectively depict the location and extent of attenuation anomalies related to hydrocarbons with changing thicknesses of the gas-bearing layer. Application to field data further confirms the capacity for hydrocarbon detection of the presented method. Thus, the EWT-SET method shows significant application prospects and promotion value for hydrocarbon detection.

Keywords: hydrocarbon detection; time-frequency analysis; synchroextracting transform (SET); empirical wavelet transform (EWT)

1. Introduction

Due to the long-term exploitation of conventional oil and gas reservoirs, there is a small space to promote for the development of conventional oil and gas. However, global unconventional oil and gas resources are almost four times conventional oil and gas resources and the exploration of unconventional oil and gas is still stay in the developing stage [1]. Besides, unconventional reservoirs have complex geological structure and usually show poor petrophysical properties, such as strong heterogeneities, low porosity and permeability, which makes seismic signals more complex [2–5]. Therefore, it is necessary to find reliable methods, which can use seismic data directly for hydrocarbon detections in unconventional reservoirs. Time-frequency analysis can reveal the distribution of signal energy or strength in both time and frequency domains, which has played a significant role in seismic data processing and interpretation, such as reservoir characterization [6–9] and hydrocarbon detection [10–12].

Widely used time-frequency analysis methods, including short-time Fourier transform (STFT), wavelet transform (WT), S transform, Wigner–Ville distribution (WVD), and matching pursuit (MP) have been successfully applied for seismic time-frequency analysis [9,13–16]. However, restricted by cthe Heisenberg uncertainty principle, unexpected cross-terms, or increased computational costs [17], these methods show some limitations for practical purposes. More recently, some methods have been proposed to improve time-frequency resolution. These methods can be mainly classified as: (1) methods based on signal decomposition techniques, such as empirical mode decomposition (EMD) in combination with instantaneous frequency [18–21]; or (2) methods based on the combination of time-frequency methods followed by a reassignment step, such as synchrosqueezed wavelet transforms (SST) [22–24].

In 2017, inspired by the recently proposed SST and the theory that the signal energy of ideal time-frequency analysis should only appear in the instantaneous frequency trajectory, Yu et al. [25] proposed a novel time-frequency analysis method called synchroextracting transform (SET). Differing from the main idea of SST, which squeezes all time-frequency coefficients into the instantaneous frequency trajectory, SET removes the most-smeared time-frequency energy and only retains the time-frequency information from the STFT results most related to the time-varying features of the target signal, thus greatly enhancing the energy concentration [25].

SET is appropriate for exploring the trend in and instantaneous attributes of non-linear and nonstationary signals while different components of the target signal are separated by sufficient distance. Since seismic signals are nonstationary and non-linear and show the characteristics of broadband and multifrequency, the SET method alone is not effective when applied to seismic signals. Thus, it is necessary to decompose the target seismic data into monocomponent Amplitude Modulation-Frequency Modulation (AM-FM) signals before performing time-frequency analysis using SET.

Empirical wavelet transform (EWT), proposed by Gilles [26] in 2013, is a fully adaptive signal decomposition technique based on the frequency domain, which can decompose a multicomponent signal into a finite number of gradual AM-FM components also known as intrinsic mode functions (IMFs). Each IMF obtained by the EWT has a compact support Fourier spectrum and contains information on the local characteristics of the original signal. EWT differs from EMD and its variations in that it not only has stronger decomposition ability of signals, but also reduces the problems of mode-mixing and redundant mode [26,27].

In this paper, in combining the characteristics of SET and EWT, a new high-precision time-frequency analysis method named EWT-SET is proposed to process seismic signals for the purpose of hydrocarbon detection. The rest of this paper is organized as follows: Section 2 details the theory of EWT, SET, and the steps of realizing EWT-SET for hydrocarbon detection; in Section 3, a synthetic signal is used to demonstrate the high time-frequency resolution of EWT-SET compared to the methods combining EWT with Hilbert transform (EWT-HT) or only using SET; Section 4 applies three designed models of different thickness and the field data respectively to explore the capacity of EWT-SET for hydrocarbon detection in tight sandstone reservoirs; and lastly, conclusions are drawn in Section 5.

2. Theory

2.1. Empirical Wavelet Transform (EWT)

EWT, proposed by Gilles [26], is a novel and adaptive signal decomposition technique. The algorithm segments the Fourier spectrum based on the detected local maxima of the spectrum signal, and defines an appropriate wavelet filter bank on each segment, so as to extract the different modes, namely AM-FM signals.

Assume the Fourier spectrum is divided into N continuous segments and each segment is defined as $\Lambda_n = [\omega_{n-1}, \omega_n]$, where $\omega_n(\omega_0 = 0, \omega_N = \pi)$ denotes the boundaries of each segment. Then define the empirical wavelets band-pass filters on each Λ_n and center on each ω_n a transition phase of width $2\tau_n$ is defined. Several options are possible for τ_n, i.e., $\tau_n = \gamma\omega_n(0 < \gamma < 1)$ is simplest; thus, the expressions for the Fourier transform of scaling function $\hat{\phi}_n(\omega)$ and the empirical wavelets $\hat{\psi}_n(\omega)$ are given as:

$$\hat{\phi}_n(\omega) = \begin{cases} 1 & if\ |\omega| \le (1-\gamma)\omega_n \\ \cos[\frac{\pi}{2}\beta(\frac{1}{2\gamma\omega_n}(|\omega| - (1-\gamma)\omega_n))] & if\ (1-\gamma)\omega_n \le |\omega| \le (1+\gamma)\omega_n \\ 0 & otherwise \end{cases} \quad (1)$$

$$\hat{\psi}_n(\omega) = \begin{cases} 1 & if\ (1+\gamma)\omega_n \le |\omega| \le (1-\gamma)\omega_{n+1} \\ \cos[\frac{\pi}{2}\beta(\frac{1}{2\gamma\omega_{n+1}}(|\omega| - (1-\gamma)\omega_{n+1}))] & if\ (1-\gamma)\omega_{n+1} \le |\omega| \le (1+\gamma)\omega_{n+1} \\ \sin[\frac{\pi}{2}\beta(\frac{1}{2\gamma\omega_n}(|\omega| - (1-\gamma)\omega_n))] & if\ (1-\gamma)\omega_n \le |\omega| \le (1+\gamma)\omega_n \\ 0 & otherwise \end{cases} \quad (2)$$

where the function $\beta(x)$ is most used as:

$$\beta(x) = x^4(35 - 84x + 70x^2 - 20x^3) \quad (3)$$

Hence, the main steps of EWT are shown as:

(1) Apply the FFT to the analyzed signal $f(t)$ to obtain the frequency spectrum $F(\omega)$.
(2) Estimate the relative optimal number N of modes, identify the largest $N-1$ maxima in $|F(\omega)|$, and sort them in decreasing order. Calculate the center between two consecutive maxima as the boundaries ω_n, thus obtain $N-1$ extra boundaries except 0 and π.
(3) According to the same method for the classic wavelet transform, the detail coefficients $W_f^\varepsilon(n,t)$ is defined by the inner products with the empirical wavelets. The approximation coefficient is denoted by the convention $W_f^\varepsilon(0,t)$, which is given by the inner products with scaling function. The reconstruction can be given by:

$$f(t) = W_f^\varepsilon(0,t) * \phi_1(t) + \sum_{n=1}^{N} W_f^\varepsilon(n,t) * \psi_n(t) = (\widehat{W}_f^\varepsilon(0,\omega) + \sum_{n=1}^{N} \widehat{W}_f^\varepsilon(n,\omega)\widehat{\psi}_n(\omega))^\vee \quad (4)$$

where $*$ represents the convolution operation.
(4) According to the above formalism, the empirical mode f_k can be expressed as:

$$\begin{aligned} f_0(t) &= W_f^\varepsilon(0,t) * \phi_1(t) \\ f_k(t) &= W_f^\varepsilon(k,t) * \psi_k(t) \end{aligned} \quad (5)$$

2.2. Synchroextracting Transform (SET)

SET is a new time-frequency analysis method proposed by Yu in 2017 [25], which can be regarded as a post-processing procedure of STFT. The greatest advantage of SET is that this algorithm can obtain a more energy-concentrated time-frequency representation compared with classical time-frequency analysis methods through only obtaining the time-frequency information of STFT results most related to time-varying features of the target signal.

SET assumes that the multicomponent signal under investigation $s(t)$ is the sum of n nonstationary modes,

$$s(t) = \sum_{k=1}^{n} s_k(t) = \sum_{k=1}^{n} A_k(t) \cdot e^{i\varphi_k(t)} \quad (6)$$

and the different modes are well separated by sufficient distance, i.e.,

$$\varphi'_{k+1}(t) - \varphi'_k(t) > 2\Delta \quad (7)$$

where s_k, A_k and φ_k are the $k-th$ modes, their corresponding instantaneous amplitude (IA) and instantaneous phase, respectively. φ_k' , as a one-order derivative of φ^k , denotes the instantaneous frequency (IF). Δ represents the frequency support of the window function. The STFT representation $G_e(t,\omega)$ of signal $s(t)$ is given in the following first-order approximation form:

$$G_e(t,\omega) \approx \sum_{k=1}^{n} A_k(t) \cdot \hat{g}\left(\omega - \varphi_k'(t)\right) \cdot e^{i\varphi_k(t)} \tag{8}$$

Instantaneous frequencies (IF) are then calculated by:

$$\varphi'(t,\omega) = \sum_{k=1}^{n} \varphi_k'(t,\omega) = -i \cdot \frac{\partial_t G_e(t,\omega)}{G_e(t,\omega)} \tag{9}$$

where $\hat{g}(\cdot)$ denotes the Fourier transform of the window function $g \in L^2(R)$.

In order to enhance the energy concentration of the time-frequency representation, Yu et al. proposed to only retain the time-frequency information of the STFT results most related to time-varying features of the target signal and remove most of the smeared time-frequency energy, thus the SET expression should be written as:

$$Te(t,\omega) = G_e(t,\omega) \cdot \delta\left(\omega - \varphi'(t,\omega)\right) \tag{10}$$

where $\delta(\omega - \varphi'(t,\omega)) = \begin{cases} 1, & \omega = \varphi'(t,\omega) \\ 0, & else \end{cases}$, which is called the synchroextracting operator (SEO).

Combining Equation (8) with Equation (10), the following expression can be deduced:

$$Te(t,\omega)\Big|_{\omega - \sum_{k=1}^{n} \varphi_k'(t) = 0} = G_e(t,\omega)\Big|_{\omega - \sum_{k=1}^{n} \varphi_k'(t) = 0} \approx \sum_{k=1}^{n} A_k(t) \cdot \hat{g}(0) \cdot e^{i\varphi_k(t)} \tag{11}$$

2.3. EWT-SET as a Hydrocarbon Detection Tool

Seismic attenuation is usually separated into attenuation connected to various physical processes, such as scattering effects, and attenuation corresponding to the conversion of seismic energy into heat or fluid flow [18–30]. When seismic signals propagate through hydrocarbon reservoirs, waves induced by fluid flow are the main causation of attenuation of energy and frequency. The characteristics of the loss of high-frequency energy and the conservation of strong low-frequency energy resulting from the above mention that attenuation can be found in different frequency data, which have been successfully applied for reservoir characterization and hydrocarbon detection by many scholars [31–34]. Time-frequency analysis is an important tool for revealing the variation of signals in both the time and frequency domains. Thus, hydrocarbon detection can be realized from the energy distribution of the different common frequency sections with time-frequency analysis methods.

To ensure adequate separation of each mode from the time-frequency representation, SET presupposes that different modes of the target signal are separated by sufficient distance, namely that there is the least possible aliasing of instantaneous frequency of different modes. It means that SET may not perform well when the instantaneous frequency of different modes is close. To take full advantage of SET, the seismic signals under investigation, which are usually considered as broadband nonlinear and nonstationary signals, are recommended to be decomposed into a group of AM-FM signals using signal decomposition technologies before applying SET. However, EWT can adaptively decompose a complicated seismic signal into a series of gradual AM-FM signals, which can better meet the conditions of SET compared to the original signal.

Therefore, the newly presented method in this paper combining EWT with SET shows potential for improved time-frequency resolution and it is theoretically possible to use EWT-SET as an effective time-frequency analysis tool for hydrocarbon detection.

The method using EWT-SET for hydrocarbon detection can be summarized as follows:

(1) Decompose the target seismic signal into a series of IMFs using EWT, which can be expressed as gradual AM-FM signals.
(2) Apply the SET to the IMFs to remove the most-smeared time-frequency energy and to obtain the energy-concentrated time-frequency spectrum.
(3) Choose characteristic frequencies based on the attenuation comparison of several seismic traces.
(4) Extract common frequency data based on the time-frequency spectrum obtained from EWT-SET, which can be employed to reveal the abnormal attenuation associated with hydrocarbons.

3. Comparative Analysis Between SET, EWT-SET, and EWT-HT

In this section, in order to illustrate the advantages of EWT-SET in terms of capturing valuable information of the different frequency components of a seismic signal, we designed a synthetic signal to compare the performance of EWT-SET, SET, and EWT-HT. The synthetic signal (Figure 1b) is a superposition of five distinct subsignals (Figure 1a) as follows:

$$sig1 = 2t^2$$
$$sig2 = 0.4\sin(34\pi t)$$
$$sig3 = \begin{cases} 0.5\cos(56\pi t) & t \in [0, 0.5] \\ 0, & t \in (0.5, 1] \end{cases}$$
$$sig4 = \begin{cases} 0, & t \in [0, 0.5] \\ 0.5\cos(74\pi t), & t \in (0.5, 1] \end{cases}$$

$sig5$ is a seismic record simulated by an attenuated Ricker wavelet. The dominant frequency of the wavelet is 80 Hz and the attenuation factor (Q) is 70.

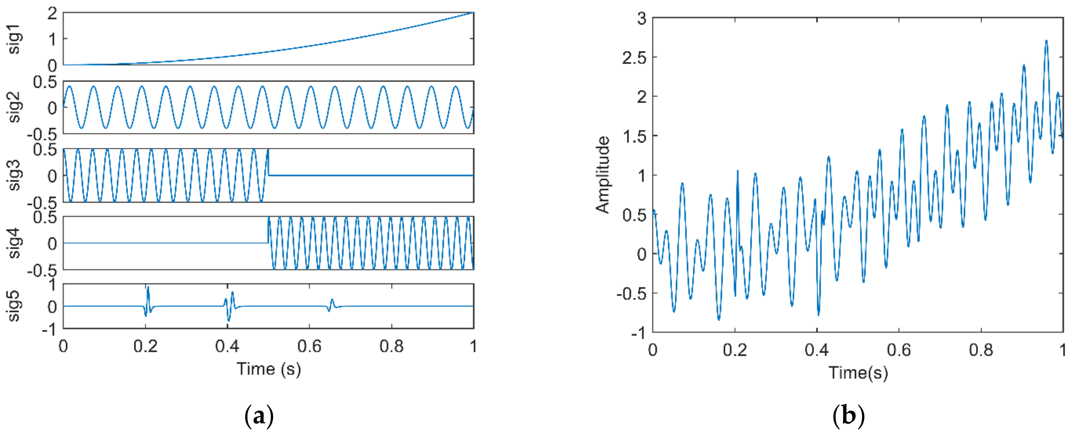

Figure 1. (**a**) Subsignals; and (**b**) synthetic signal.

We utilize the SET, EWT-SET, and EWT-HT methods to obtain time-frequency spectra of the synthetic signal, which are presented in Figure 2. Figure 2a shows the SET result. It can be seen that it is difficult to accurately identify the frequency of 17 Hz and 28 Hz cosine wave. However, the EWT-SET method not only clearly identifies all individual components of the synthetic signal, but also can precisely depict frequency of the signal (Figure 2b), which demonstrates that it is necessary to adopt EWT for the decomposition of multicomponent signals before the SET is applied. Although the EWT-HT result shown in Figure 2c is similar to EWT-SET at first glance, the EWT-SET method (Figure 2b) can obtain a higher frequency resolution compared to EWT-HT (Figure 2c).

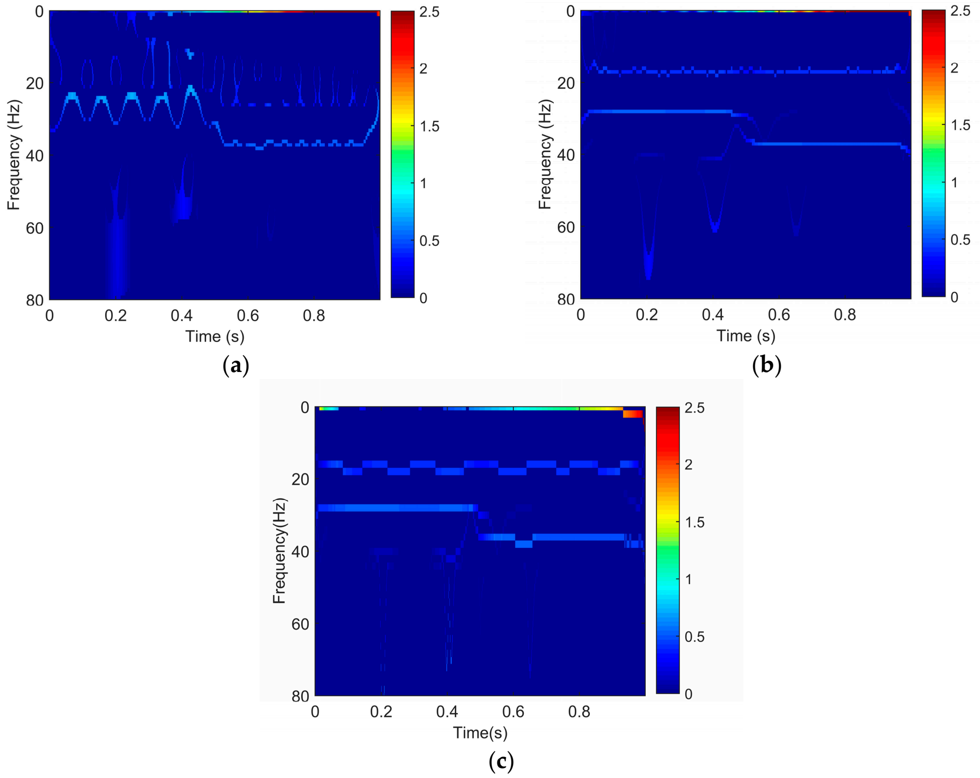

Figure 2. Time-frequency spectra of the synthesized signal based on (**a**) synchroextracting transform (SET); (**b**) empirical wavelet transform (EWT) combined with SET (EWT-SET); and (**c**) EWT combined with Hilbert transform (HT) (EWT-HT).

Thus, the EWT-SET method is beneficial for extracting valuable information from different frequency components and becomes a valuable tool for high-resolution time-frequency analysis of seismic signals.

4. Hydrocarbon Detection Using EWT-SET

Tight sandstone reservoirs show strong heterogeneities and have the geological characteristics of low porosity and low permeability [2,35], thus making it important to find a high-resolution time-frequency analysis method for the identification of hydrocarbon reservoirs. In this section, we attempt to apply the EWT-SET method to the field data, which is typical of tight sandstone reservoirs from the Zhongjiang gas field located in Western Sichuan, China. Three models and the field data are adopted to preliminarily demonstrate and confirm the effectiveness and reliability of the EWT-SET method for hydrocarbon detection in the tight sandstone reservoir.

4.1. Model Test

Inspired by the method that simulated the seismic response based on the diffusive viscous wave equation [36,37] and considering that the different locations within the reservoir have different thicknesses in field data, we designed three geological modes with different thicknesses of gas-bearing layers to obtain a reliable result of EWT-SET for hydrocarbon detection.

There are six layers in the models. The layer marked ④ is a gas-bearing reservoir. The parameters of each layer shown in Table 1 are set as the equivalent parameters of the seismic data and logging data from the Zhongjiang gas field located in the Western Sichuan Basin, China. The gas-bearing layers of three models are 15 m, 20 m, and 30 m, respectively. Considering that the dominant frequency of the field data is around 30 Hz, the frequency of the wavelet of these three models was set to 30 Hz.

Sampling frequency was 1000 Hz. The geological models and their corresponding seismic responses are, respectively, shown in Figures 3–5.

Table 1. Main parameters for the geological models. The diffusion coefficient, viscous coefficient, and *Q* represent the dispersion degree of the strata, degree of viscous of fluid, and quality factor, respectively. One of the most distinct features of the gas-bearing reservoir is very low quality factor *Q* (5~30). The energy attenuation of the seismic signal will be more obvious when the *Q* value becomes lower [36].

Layer	Velocity ($m \cdot s^{-1}$)	Diffusion Coefficient (Hz)	Viscous Coefficient ($m^2 \cdot s^{-1}$)	Density ($g \cdot cm^{-3}$)	*Q*
①	4200	1.0	1.0	2.4	800
②	4400	1.0	1.0	2.45	800
③	4500	1.0	1.0	2.5	800
④	4100	30.0	200	1.96	15
⑤	4600	1.0	1.0	2.5	800
⑥	4700	1.0	1.0	2.5	800

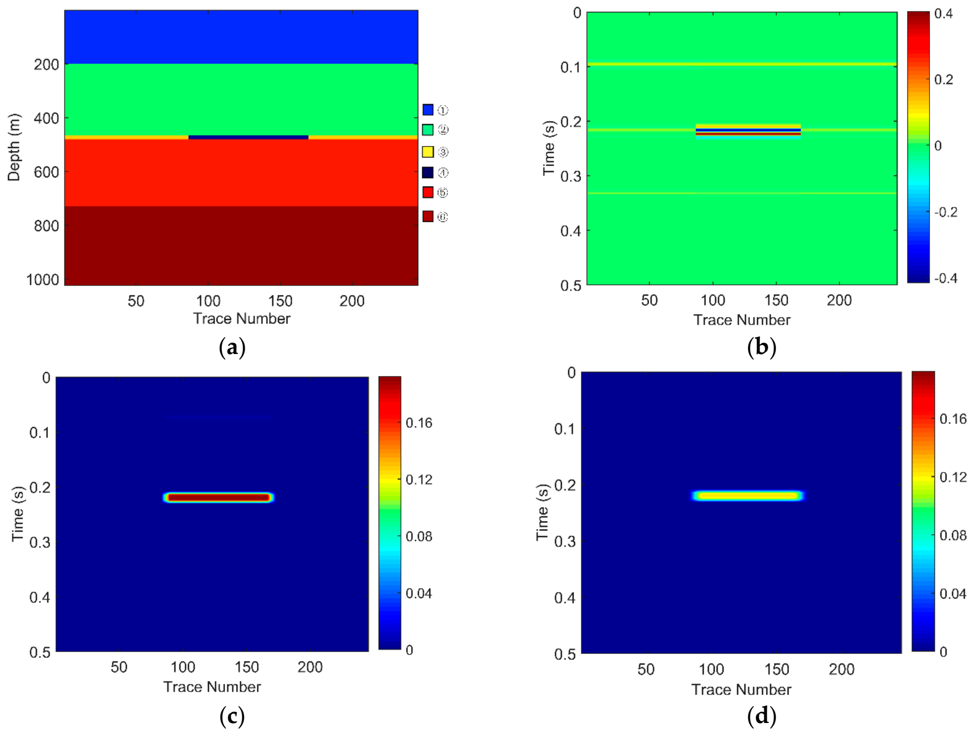

Figure 3. For Geological Model 1: (**a**) the gas-bearing layer is 15 m; (**b**) the seismic response; (**c**) the low frequency section; and (**d**) the high frequency section.

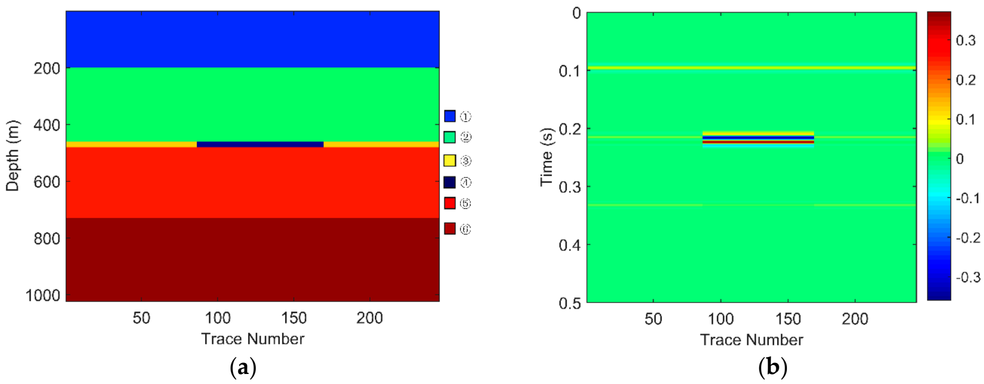

Figure 4. *Cont.*

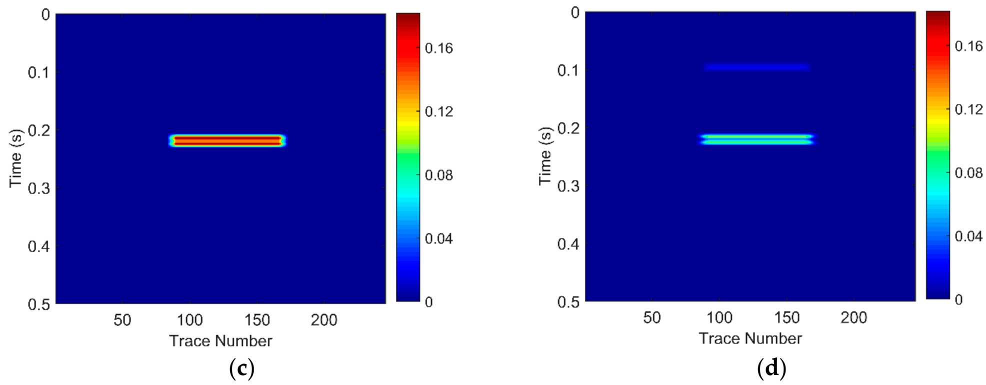

Figure 4. For Geological Model 2: (**a**) the gas-bearing layer is 20 m; (**b**) the seismic response; (**c**) the low frequency section; and (**d**) the high frequency section.

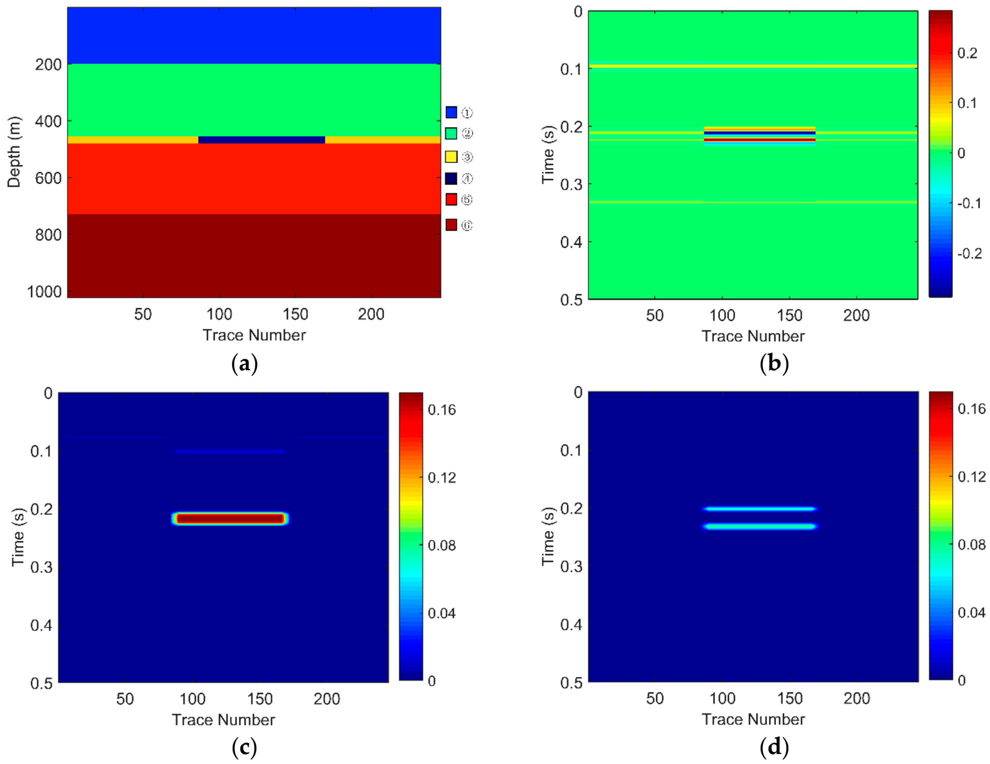

Figure 5. For Geological Model 3: (**a**) the gas-bearing layer is 25 m; (**b**) the seismic response; (**c**) the low frequency section; and (**d**) the high frequency section.

The EWT-SET method is applied to the simulated seismic sections of the models (Figures 3b, 4b and 5b). Following this, we extract the 26 Hz low-frequency sections (Figures 3c, 4c and 5c) and the 37 Hz high-frequency sections (Figures 3d, 4d and 5d) on the time-frequency spectra based on the EWT-SET method.

As can be seen from Figures 3–5, compared with other regions, the areas of the gas-bearing reservoir all appear with strong reflection. In the low frequency sections, we can easily find the strong energy in the gas reservoir but the strong energy is weakened while in the high frequency sections. This phenomenon is consistent with the attenuation characteristic of seismic waves when they propagate through hydrocarbon reservoirs, which not only demonstrates that the EWT-SET method can be adopted but also illustrates the availability of EWT-SET for hydrocarbon detection with a changing thickness in the gas-bearing layer. Furthermore, as the thickness of the gas-bearing layer is increased, the attenuation of high frequency energy becomes more obvious and the upper and lower boundaries of the reservoir are gradually depicted.

Therefore, the EWT-SET method is not only effective for hydrocarbon detection, but also shows potential ability to provide an initial estimate of the thickness of the gas-bearing reservoir.

4.2. Field Data

We adopt the two-dimensional (2-D) seismic field data from the Zhongjiang gas field located in Western Sichuan, China for further analysis, which consists of 1079 seismic traces with a time sample interval of 2 ms, as shown in Figure 6a. The zone between a black solid curve and a black dotted curve is a gas reservoir-developed area. The three red vertical lines denote three wells, which are represented symbolically by A, B, and C. Among them, well A and well C are gas wells and well B is a dry well. We extract seismic signals intersecting well B and well C, and display their waveforms in Figure 6b.

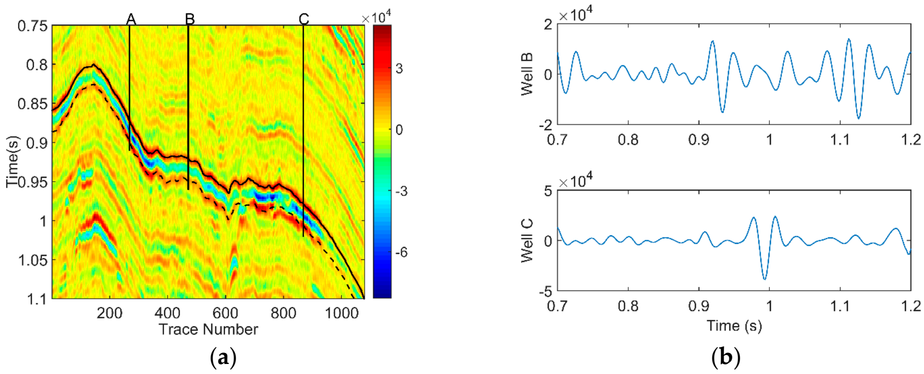

Figure 6. (**a**) Field seismic data; (**b**) waveform of well B and well C.

4.2.1. Characteristic Frequency Selection

To select appropriate characteristic frequencies for further hydrocarbon detection, we first obtained the dominant frequency range of the seismic section by the time-frequency analysis of well B and well C. As can be seen from Figure 7a, no matter whether the seismic signal travels across the reservoir or not, we find that the range of frequency with a strong amplitude is 27–45 Hz. Then, slices of the spectrogram from well B and well C at the reservoir interval were extracted for the comparison of energy attenuation. From the black rectangle in Figure 7b, it can be seen that well B decayed more rapidly than well C. According to the above analysis, we reasonably selected 30 Hz and 40 Hz as the low and high frequencies, respectively.

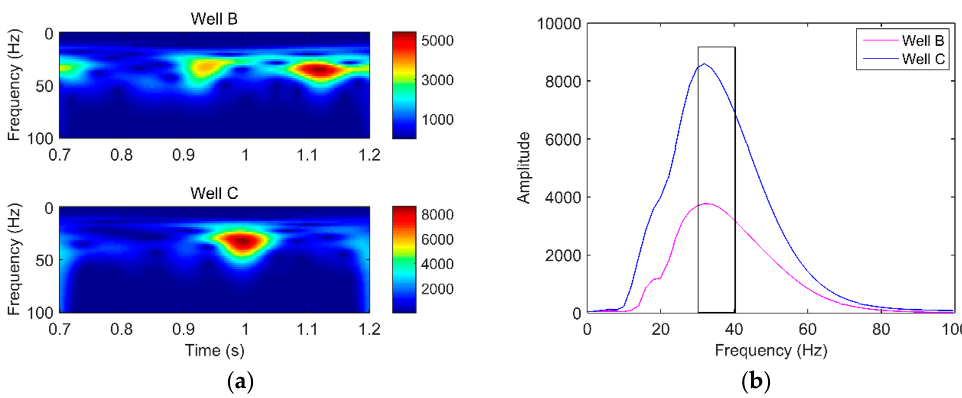

Figure 7. (**a**) Time-frequency spectra of well B and C; (**b**) the energy absorption analysis curve of well B and C at the reservoir interval.

4.2.2. Hydrocarbon Detection

In the following, we extracted common frequency sections (Figure 8) based on time-frequency spectra obtained by the EWT-SET process of every seismic trace from the 2-D seismic field data (Figure 6a).

Figure 8 displays the low-frequency section of 30 Hz (Figure 8a) and the high-frequency section of 40 Hz (Figure 8b). The gas reservoir developed area has been depicted clearly using EWT-SET. Comparing the low-frequency section (Figure 8a) with the high-frequency section (Figure 8b), we can find that in the low-frequency section, there exists a strong energy near wells A and C, but in the high-frequency section the energy has been absorbed. However, for the energy of well B, there is no obvious change whether in the high-frequency or low-frequency section. This phenomenon is consistent with the fact that wells A and C are gas wells and well B is dry. Thus, the EWT-SET method is an effective tool for hydrocarbon detection in tight sandstone gas reservoirs.

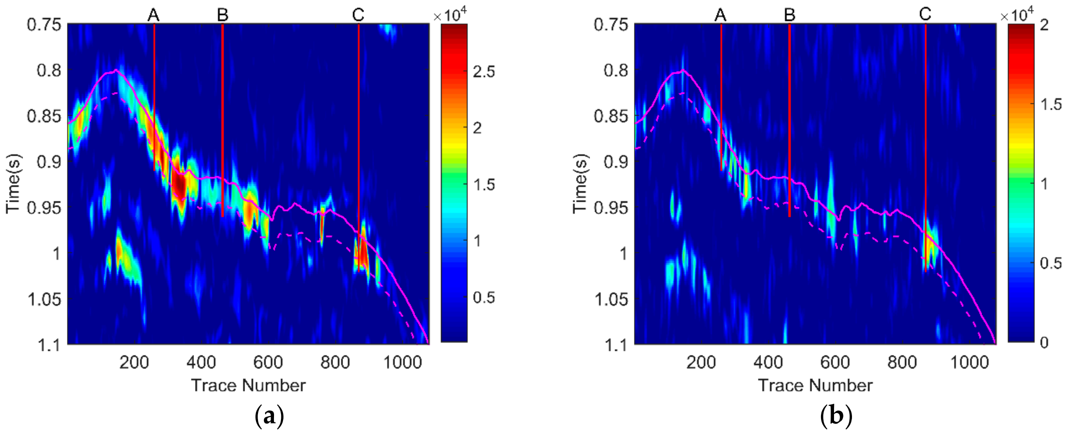

Figure 8. Common frequency sections based on EWT-SET (**a**) at 30 Hz; (**b**) at 40 Hz.

5. Conclusions

In this paper, inspired by the newly developed SET, an improved time-frequency analysis method combining EWT and SET is proposed for hydrocarbon detection, which is termed EWT-SET. The proposed method employing EWT to produce IMFs before time-frequency analysis by SET not only inherits both the merits of EWT and SET, which makes it effective for separating and identifying the frequency components of multicomponent signals, but also provides higher resolution in the synthetic signal compared to using EWT-HT or only using SET. The three models with different thicknesses of gas-bearing layer have been used to confirm the effectiveness of EWT-SET for hydrocarbon detection in the tight sandstone reservoir. The application of the presented method to the Zhongjiang gas field located in Western Sichuan, China illustrates that the proposed method can be successfully applied to the field data for the purpose of hydrocarbon detection. Thus, the EWT-SET method is suitable for seismic data analysis and is highly promising for the depiction of the increased attenuation associated with hydrocarbon.

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Author Contributions: Ying Hu and Hui Chen conceived the idea of this research. Ying Hu, Hui Chen, and Jiaxing Kang build a detail analysis framework. Jiaxing Kang, Yuanchun Chen and Dan Xu conceived, designed and performed the experiments under supervision of Ying Hu and Hui Chen. Ying Hu provide seismic data.

Yuanchun Cheng and Dan Xu analyzed the data. The paper was written by all the authors with different degree of contribution.

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

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