Sains Malaysiana 46(11)(2017): 2169-2177
http://dx.doi.org/10.17576/jsm-2017-4611-18

The Synthesis and Decomposition of Signals and its Application in Subei Basin Exploration

(Sintesis dan Penguraian Isyarat serta Aplikasinya dalam Penerokaan Lembangan Subei)

XIANGSHENG BAO, QUANWEN LIU & HAIYAN ZHOU*

ABSTRACT

Subei basin is the most promising onshore oil and gas bearing basin in South China. With the deepening of exploration, subtle hydrocarbon reservoirs have gradually become the major target of exploration. Seismic record often shows low signal to noise ratio (SNR), resulting that conventional seismic records have three shortcomings in the identification of subtle reservoirs: difficult to identify small faults; difficult to show the distribution law of sand body; and difficult to find traps. In order to solve this problem, we conducted the research on signal synthesis and decomposition. The research results showed that seismic record of different frequency bands can be restored from original seismic record and both of them contain real stratigraphic information. Based on this, when a certain band or several bands in the original seismic record is affected by noise and result in the reduction of SNR of seismic record, seismic information seriously affected by noise can be abandoned, leaving only less affected seismic information to obtain seismic record with higher SNR. In the collection of actual seismic record, the low and high band seismic information is seriously affected by noise, while medium-band seismic information is less affected. Therefore, based on this, the medium-band seismic information can be restored from the original seismic record to be new record, which is called predominant frequency band seismic record. In this paper, based on the research result, the predominant frequency band seismic record was applied to the two areas of Subei basin and the result showed the research result can be used as a good instruction on well placement and the improvement of drilling success rate.

Keywords: Low SNR; predominant frequency band seismic record; signal synthesis and decomposition; Subei basin; subtle reservoirs

ABSTRAK

Lembangan Subei merupakan daratan lembangan bearing minyak dan gas yang paling berpotensi di Selatan China. Dengan pendalaman penerokaan, takungan hidrokarbon tidak ketara secara beransur-ansur telah menjadi sasaran utama penerokaan. Rekod seismik sering menunjukkan isyarat rendah kepada nisbah hingar (SNR), menyebabkan rekod seismik konvensional mempunyai tiga kelemahan dalam pengenalpastian takungan tidak ketara: sukar untuk mengenal pasti kesilapan kecil; sukar untuk menunjukkan pembangunan hukum jasad pasir; sukar untuk mengenal pasti perangkap. Dalam usaha untuk menyelesaikan masalah ini, kami menjalankan uji kaji ke atas isyarat sintesis dan penguraian. Keputusan penyelidikan menunjukkan rekod seismik daripada jalur frekuensi berbeza boleh dipulihkan daripada rekod seismik asal dan kedua-duanya mengandungi maklumat stratigrafi asal. Berdasarkan maklumat ini apabila sesetengah jalur atau beberapa jalur dalam rekod seismik asal dipengaruhi oleh bunyi hingar dan mengakibatkan pengurangan SNR dalam rekod seismik, maklumat seismik teruk terjejas oleh hingar boleh ditinggalkan, meninggalkan hanya maklumat seismik yang kurang terjejas untuk mendapatkan rekod seismik dengan SNR lebih tinggi. Dalam pengumpulan rekod seismik yang sebenar, maklumat seismik jalur rendah dan tinggi teruk terjejas oleh bunyi hingar, manakala maklumat jalur sederhana seismik kurang terjejas. Oleh yang demikian, maklumat jalur sederhana seismik boleh dipulihkan daripada rekod seismik asal menjadi rekod baru yang dipanggil rekod seismik jalur frekuensi pradominan. Dalam kertas ini, berdasarkan keputusan kajian, rekod seismik jalur frekuensi pradominan digunakan untuk dua kawasan di lembangan Subei dan keputusan kajian menunjukkan ia boleh digunakan sebagai satu arahan yang baik untuk penempatan telaga serta pembaikan kadar kejayaan penggerudian.

Kata kunci: Isyarat sintesis dan penguraian; lembangan Subei; rekod seismik jalur frekuensi pradominan; SNR rendah; takungan halus

INTRODUCTION

Subei basin is a large Cretaceous-Tertiary fault basin east of the Yangtze paraplatform, with an area of 35,000 km^2. It developed on the basis of a complete set of paleozoic - early generation fold and is the most promising onshore oil and gas bearing basin in South China (Qiu et al. 2006). Literature (Liang 2007) shows that structural traps have been explored in Subei basin for a long time; on the one hand, with the deepening of the oil and gas exploration, the structural traps is more and more highly proven and it is more and more difficult to find a large favorable structural trap; on the other hand, a lot of geological research has shown that Subei basin has rich subtle reservoirs, which amount to at least 90,000,000 tons. Subei basin mainly has composite reservoir of fault and lithology, lithological updip pinchout reservoir and stratigraphic onlap reservoir (Liao et al. 2014; Liang 2007; Mao et al. 2013). Relative to structural reservoir, however, it is very difficult to find subtle reservoirs mainly because conventional seismic technology has three shortcomings in the identification of subtle reservoirs due to low SNR of seismic record: Difficult to identify small faults (Partyka et al. 1999); Difficult to show the distribution law of sand body (Partyka et al. 1999); Difficult to find traps (Wang et al. 2015; Zhang et al. 2011). In view of such shortcomings, the signal synthesis and decomposition is researched to search some technology which obtained a kind of high-SNR seismic record restored from origin seismic record and then we can use the high-SNR seismic record to identify the subtle reservoirs better.

METHODS

THE COMPOSITION OF SEISMIC SIGNALS

Seismic records from field seismic acquisition include effective wave and disturbing wave (Partyka et al. 1999) and they have their respective predominant frequency band, therefore, the full-band seismic records, including seismic signals of different band ranges, have different SNRs. Generally, seismic signals in lower band tend to show low SNR due to the interference of surface wave; seismic signals in higher band also show low SNR due to the interference of high-frequency noise. High-SNR seismic signals are often in the medium frequency band (10-60 Hz in general). Sometimes seismic signals with higher SNR are only in a narrow band due to intense noise disturbance.

After a series of seismic processing including outlier removal, surface wave attenuation, high-frequency random noise suppression and multiple wave suppression, the quality of full-band seismic records from field seismic acquisition is improved, but the SNR of low-band and high-band seismic signals is still lower than 1 (Li 1993). Therefore, the existence of low-SNR seismic signals in this frequency band will affect the identification of geological feature with full-band seismic records. As the full-band seismic records include low-band, mid-band and high-band seismic signals, it is generally believed in existing interpretation that only full-band seismic records can truly reflect the underground geological information (Li 1993). If research could prove that seismic information of different bands without noise disturbance can truly reflect underground geological information, underground geological information can be better interpreted by making new seismic records with mid-band high-SNR seismic signals. In this paper, We first point out the research feasibility from the composition and decompostion of periodic signal and then forward modeling method is used to illustrate that seismic signals of different bands can reflect the underground geological information.

THE SYNTHESIS AND DECOMPOSITION OF PERIODIC SIGNALS

Famous German mathematician Dirichlet pointed out that periodic signals that meet Dirchlet conditions can be expanded to be sine or cosine signals of different amplitudes, different frequency and different phases in [-T/2,T/2].

If it is expressed in sine signals, f(t) can be expressed by (1).

$$f(t) = \sum_{n=0}^{\infty} A_n sin(n\omega_0 t - \varphi_n). \quad (1)$$

If it is expressed in cosine signals, f(t) can be expressed in (2).

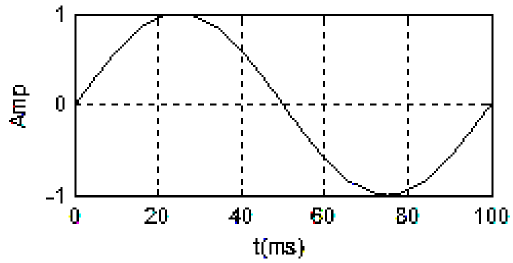
$$f(t) = \sum_{n=0}^{\infty} A_n cos(n\omega_0 t - \varphi'_n). \quad (2)$$

In (1) and (2), $f(t)$ is periodic signal with T as the cycle; n=1, 2,...; An is a constant; ω_0 is fundamental frequency, in Hz; t is time, in seconds; φ_n and φ'_n are phases; $\varphi'_n = \varphi_n - \frac{\pi}{2}$.

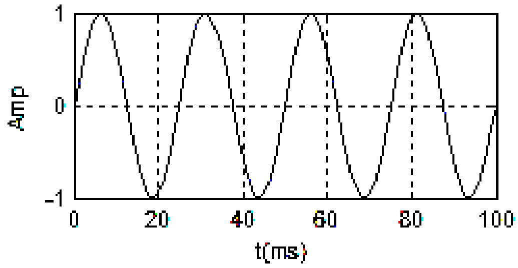
It can be seen that the seismic records obtained by seismic processing is formed by convolution of zero phase Ricker wavelet and reflection coefficient (Li 1993). Ricker wavelet meets Dirichlet conditions and can be seen as a periodic vibration signal (Zhang 1996) synthesized by a certain number of sine or cosine signals of different amplitudes, different frequency and different phases.

FORWARD MODELING

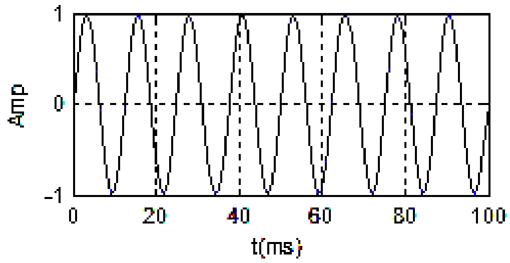
Through the analysis of the synthesis and decomposition of periodic signal, we only show that our research has a certain theoretical basis, but it cannot well explain our ability to use the part band seismic data restored from full band seismic data to reflect the underground geological information. Forward modeling has been regarded as one of the most important tools to improve the level of cognition, therefore, we use it to solve our problems (Khan et al. 2017). Forward modeling is performed on the basis of this theory, therefore as to make clear through seismic signal synthesis and decomposition whether the information restored from narrow band can reliably reflect the underground geological information.



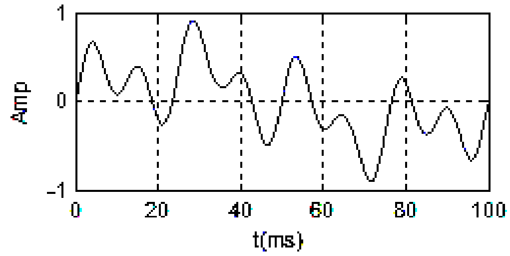
a. 20Hz



b. 40Hz



c. 80Hz



d. Mixed-frequency signals

FIGURE 1. Signals of Different Frequencies

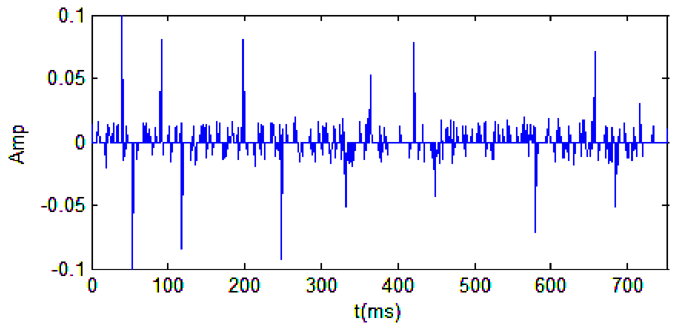
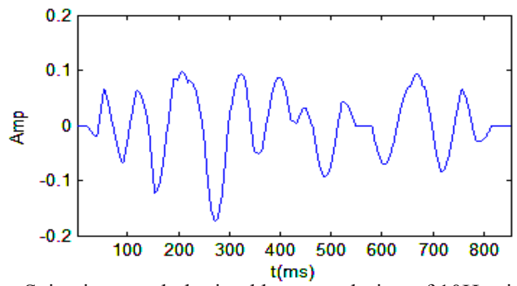
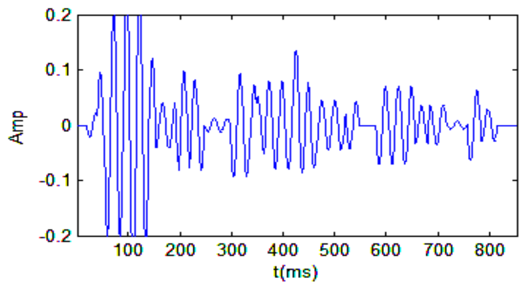


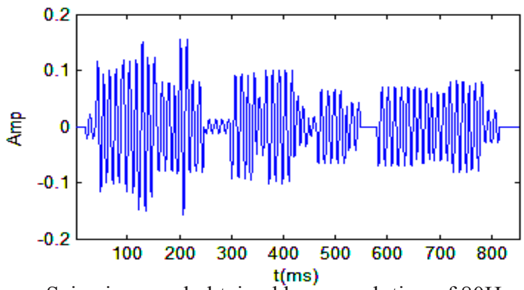
FIGURE 2. Reflection coefficient



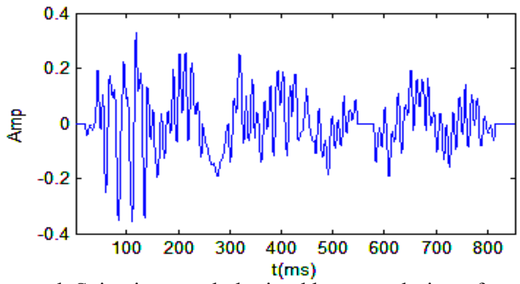
a. Seismic record obtained by convolution of 10Hz sine wavelet and reflection coefficient



b. Seismic record obtained by convolution of 40Hz sine wavelet and reflection coefficient



c. Seismic record obtained by convolution of 80Hz sine wavelet and reflection coefficient



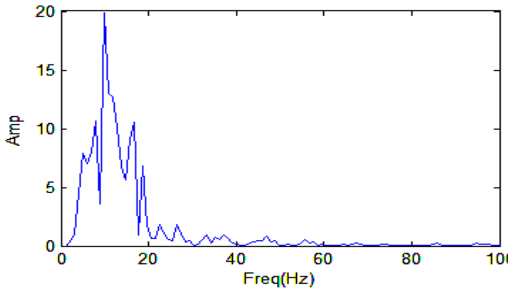
d. Seismic record obtained by convolution of mixed-frequency wavelets and reflection coefficient

FIGURE 3. Seismic records of different frequencies

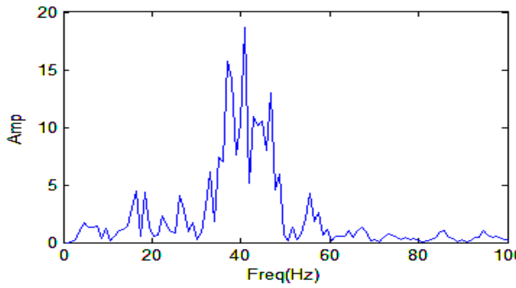
The results of forward modeling

Figure 1 shows the single- and mixed-frequency wavelets for forward modeling. Figure 1(a), 1(b) and 1(c) are 10, 40 and 80 Hz sine signal wavelets, respectively; Figure 1(d) is the wavelets composited by the three single-frequency sine signals. Figure 2 is the analog reflection coefficient series that reflects formation characteristics. Convolution of wavelets of different frequencies in Figure 1 and reflection coefficient in Figure 2 is performed to obtain the analog seismic record, as shown in Figure 3. Fourier transform is applied to the four seismic records in Figure 3 to obtain the amplitude spectrum of signals expressed in frequency domain (Figure 4). Figure 4(a), 4(b) and 4(c) shows that different single-frequency seismic records have their own major bands. The major bands of 10, 40 and 80 Hz single-frequency seismic records are roughly 0-20, 30-50 and 70-90 Hz, respectively. Figure 4(d) shows amplitude spectrum obtained on the basis of mixed-frequency seismic records and it can be seen that the major bands are 0-20, 30-50 and 70-90 Hz. In other words, the major band of the mixed-frequency seismic records is the composite of the major bands of the three single-frequency seismic records (Anees et al. 2017).

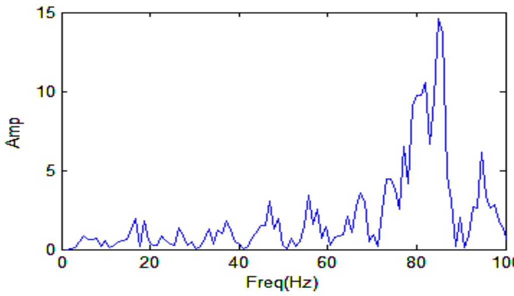
In the forward modeling above, whether the seismic records are of single frequency or mixed frequencies, they carry complete underground geological information. In the seismic data of field acquisition, seismic records can be expressed by the convolution of countless different single-frequency sine signals and reflection coefficient that reflects underground geological information. Therefore, if almost real seismic records from the convolution of wavelets of single frequency or some frequency ranges and reflection coefficient can be restored from mixed-frequency seismic record in forward modeling, the high-SNR seismic information in local part can be used to make new seismic records in reality, which can better reflect underground geological characteristics.



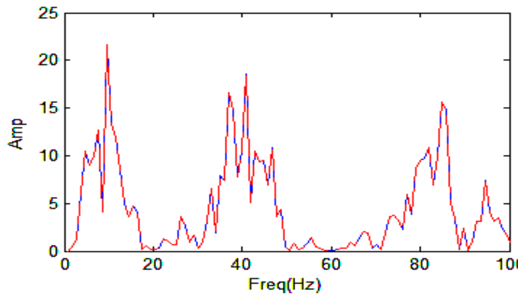
a. Amplitude spectrum of 10Hz synthetic seismic record



b. Amplitude spectrum of 40Hz synthetic seismic record



c. Amplitude spectrum of 80Hz synthetic seismic record

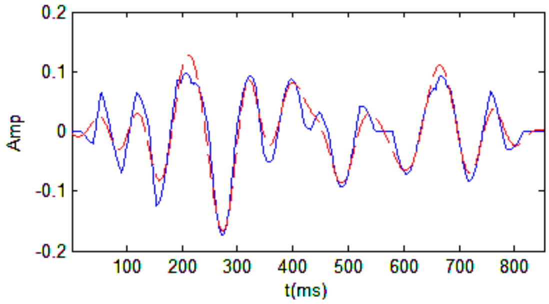


d. Contrast between the amplitude spectrum obtained from mixed frequencies(blue) and the superposition of a, b and c(red)

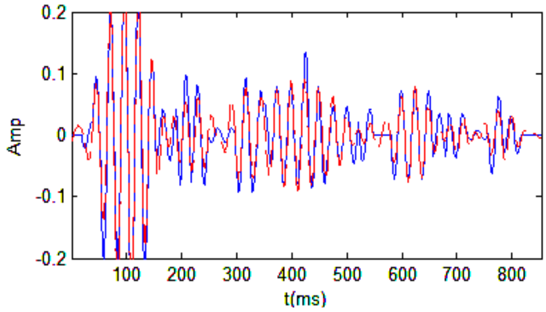
FIGURE 4. Amplitude Spectrum of Different Frequencies

As seen from the contrast between Figure 4(d) and Figure 4(a), 4(b) and 4(c), 0-20 Hz spectrum information in Figure 4(d) is basically consistent with that of major bands in Figure 4(a); 30-50 Hz spectrum information in Figure 4(d) is basically consistent with that of major bands in Figure 4(b); 70-90 Hz spectrum information in Figure 4(d) is basically consistent with that of major bands in Figure 4(c). Therefore, the seismic records obtained by inverse Fourier transform of 0-20, 30-50 and 70-90 Hz information from Figure 4(d) can be contrasted with 10, 40 and 80 Hz single-frequency seismic records; if they are roughly consistent, it indicates that the seismic record restored from the mixed-frequency records can also reflect the underground geological information and can be used for the research on underground geology (Patterson & Savas 2016).

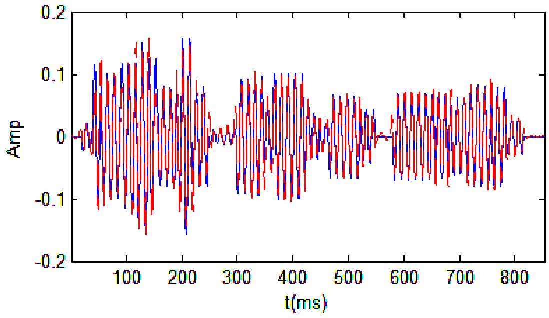
Figure 5 is the contrast between 10, 40 and 80 Hz seismic records restored from mixed-frequency seismic record and the original single-frequency seismic record, which shows good consistence. Forward modeling can come to the conclusion as follows: If the actual seismic record has reliable band information, this information can be used to better reflect underground geological information.



a. 10 Hz



b. 40 Hz

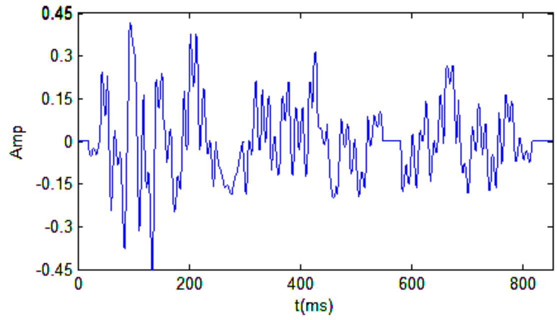


c. 80 Hz

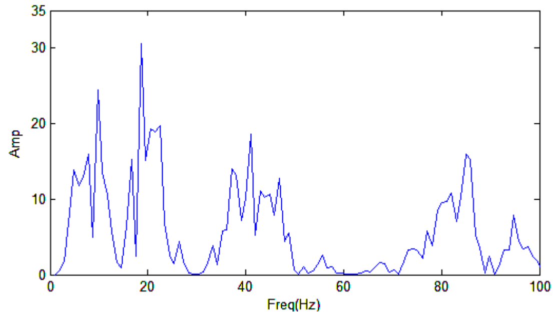
FIGURE 5. Contrast between restored single-frequency seismic record (red) and the original single-frequency seismic record (blue)

Actual seismic record is often a full-band signal. However, low-frequency signal shows low SNR due to the effect of regular interference waves such as surface wave; high-frequency signal has low energy due to the effect of spherical diffusion and stratigraphic absorption and tends to show low SNR after affected by even slight high-frequency noise. Therefore, the direct utilization of full-band seismic record in solving actual geological issues shows low precision and unreliable judgement, which is adverse to better study of reservoirs and further increase the exploration risks. The mid-band signal in seismic record has relative reliable quality and it can be understood that the seismic record obtained from mid-band signal is made by superposition of the convolution of single frequency sine waves of different mid bands and reflection coefficient.

To further illustrate that mid-band seismic signal can be restored from seismic data, suppose seismic record is obtained by convolution and superposition of 10, 20, 40 and 80 Hz sine wavelets and reflection coefficient in Figure 1 (see Figure 6(a)). Figure 6(b) shows the amplitude spectrum of the mixed signals. Suppose the signals to be restored is between 20 and 40 Hz, the contrast (Figure 7) between the effective signals restored according to the amplitude spectrum in Figure 6(b) and the actual mixed signals (seismic record obtained by convolution of 20 and 40 Hz single-frequency sine wavelets and reflection coefficient) shows a good consistency between the restored signal and the real signal.

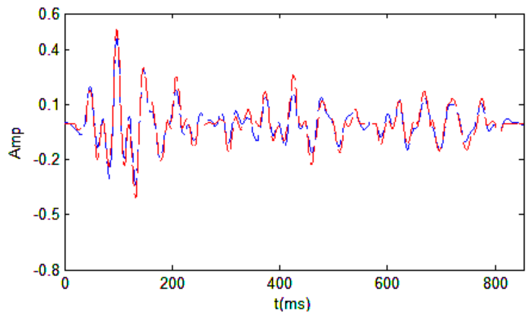


a. Mixed signal, obtained by superposition of the convolution of 10 Hz, 20 Hz, 40 Hz, 80 Hz single frequency sine wavelets with reflection coefficient in Figure 1



b. Amplitude spectrum of mixed signal

FIGURE 6. Mixed signals and its amplitude spectrum



(Signal restored from 15-50 Hz band information; the blue is the original signal and the red is the restored signal)

FIGURE 7. Contrast between the restored predominant frequency band signal and original signal

It is concluded from the research on signal synthesis and decomposition that seismic information of some bands can be restored from the original seismic record and similar to the original seismic record, this information also carries geological information that reflects real underground situation.

PREDOMINANT FREQUENCY BAND SEISMIC RECORD AND ITS APPLICATION

Through the research and analysis, high-SNR mid-band information can be restored from actual seismic record for research. For the ease of description, the seismic record restored from the high-SNR mid-band information is called predominant frequency band seismic record.

As predominant frequency band seismic record has the advantage of high SNR, it can help with the identification and exploration of subtle reservoirs and placement of wells. In order to illustrate the advantages of predominant frequency band seismic record in the identification of subtle reservoirs. The following is the application of predominant frequency band seismic record in the exploration of fault lithological reservoir in Zone S1 and lithological reservoir in Zone S2 of Subei basin.

APPLICATION OF PREDOMINANT FREQUENCY BAND SEISMIC RECORD IN ZONE S1 OF SUBEI BASIN

In Zone S1, a method base on forward and inversion is adopted. Firstly, the forward research based on the wells of Zone S1 is carried out and the research shows the predominant frequency band seismic record has obvious advantage in highlighting the distribution of sand body than the full band seismic record and then the inversion research is carried out, the RMS attribute of predominant frequency band record obtained from real full frequency seismic record solves the recognition problem of transverse distribution of sand body.

THE FORWARD RESEARCH IN ZONE S1

Based on the data of well in Zone S1, the geologic model (1,000 m in width and 300 m in height) in Figure 8 is built. The model has three strata, namely mudstone section on top (grey part), target stratum in the middle (in the box) and mudstone section at the bottom (blue). The target stratum in the middle is modeled by reference to the five sandstone/mudstone inter-bedding characteristic summarized in the well data of Zone S1 in Subei basin (yellow refers to sandstone and purple refers to mudstone). The lithological velocities are as shown in the figure and the lithological densities are obtained using the classic Gardner's Equation.

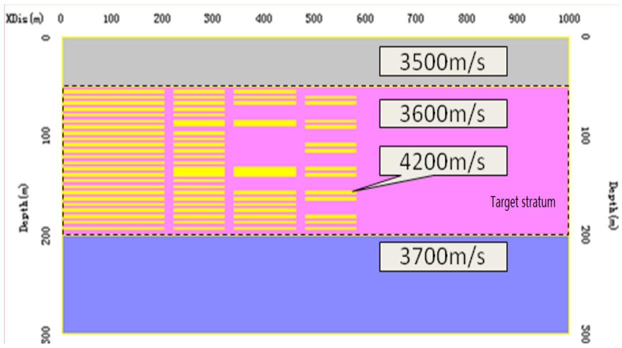


FIGURE 8. Geological Model

In view of the geological model in Figure 8, Ricker wavelet with the dominant frequency of 28 Hz was used to generate the seismic profile with noise in Figure 9. The analysis of its amplitude spectrum showed that the 10-60 Hz seismic information in mid band has higher SNR and such mid-band seismic information was used to obtain predominant frequency band seismic record (Figure 10).

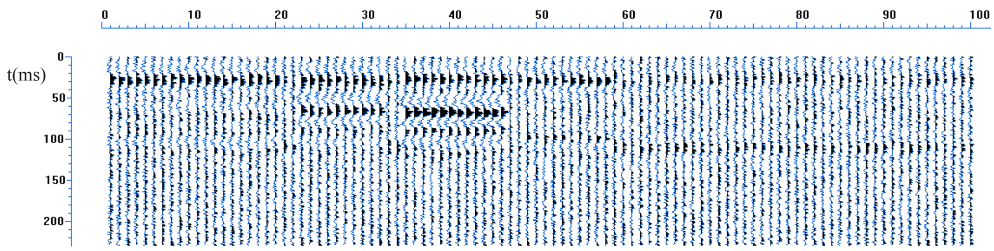


FIGURE 9. Seismic record with noise

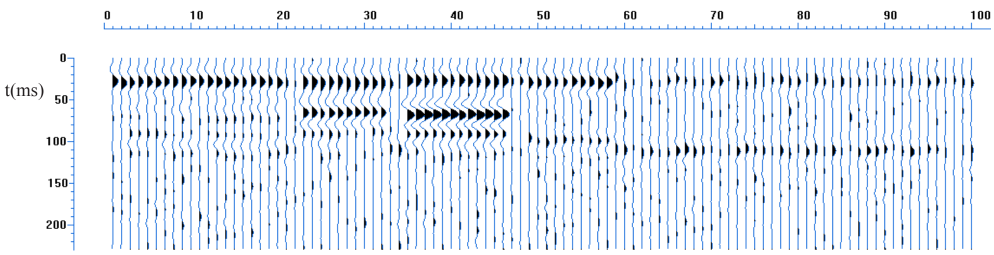
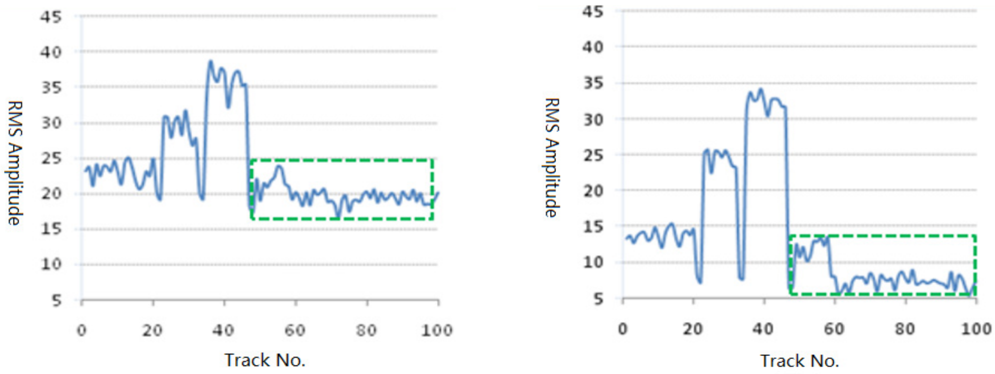


FIGURE 10. Seismic profile (record) obtained from predominant frequency band data



a. RMS attribute extracted based on full-band seismic record

b. RMS attribute extracted based on predominant frequency band seismic record

FIGURE 11. Contrast between full-band attributes and predominant frequency band attributes

Figure 11 is the contrast between the RMS attribute extracted from the original seismic record (full-band seismic record) (Figure 11a) and the RMS attribute extracted from predominant frequency band seismic record (Figure 11b). As can be seen from the figure, it is very difficult to distinguish between the 4th sand/mud interbed and the 5th sand/mud interbed (pure mudstone) according to the attribute extracted from full-band seismic record (Figure 11a), while the attributes extracted from the predominant frequency band seismic record can be used to clearly distinguish between the 4th sand/mud interbed and the 5th sand/mud interbed (pure mudstone). It means that, compared with full-band seismic record, predominant frequency band seismic record has more advantages in the identification of favorable sand body. Forward modeling shows that the sand body distribution in the target stratum in Zone S1 can be better reflected by the predominant frequency band seismic record, so as to provide some reference for well placement.

THE INVERSION RESEARCH IN ZONE S1

Figure 12 is the RMS amplitude extracted from the target stratum in Zone S1 of Subei basin, where well W38-1 and W38 (the reservoir where they are located is fault lithological reservoir) are marked. Before the drilling of well W38-1, full-band seismic record showed that the sand body between wells W_{38-1} and W_{38} has little variance in terms of development and has good connectivity. However, it was found after drilling that the two wells are not connected in the target stratum, which indicates that sand body changes rapidly between the two wells. In order to learn about the sand body development near the two wells, the RMS amplitude of the target stratum was extracted based on predominant frequency band seismic record (Figure 12). It can be seen from Figure 12 that the locations of well W_{38} and W_{38-1} are mainly yellow, which means the sand body near the wells are developed; the interwell part is mainly pale blue, which means the sand body is not developed. It indicates that the sand body from well W_{38} to W_{38-1} shows great difference, which causes disconnectivity. This result has provided a good decision-making basis for subsequent well placement.

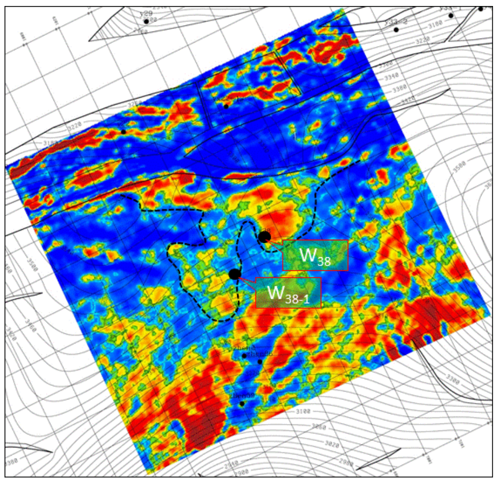
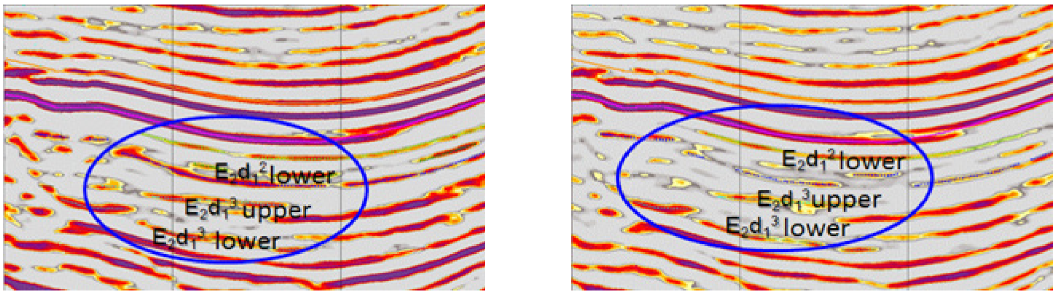


FIGURE 12. RMS amplitude of target stratum extracted from predominant frequency band (20-45 Hz) seismic record

APPLICATION OF PREDOMINANT FREQUENCY BAND SEISMIC RECORD IN ZONE S2 OF SUBEI BASIN

In Zone S2, a inversion method is adopted. The inversion method highlights the advantage of prodominant frequence band seismic record from the seismic profiles.

Through the analysis of the core, geological researchers have realized that Subei basin has a lot of sand body (Yuan et al. 2016) caused by gravity flow; and based on ancient landform condition, provenance system and the inducement mechanism, it was pointed out that there is sublacustrine fan lithological reservoir in Zone S2 of Subei basin. However, it is very difficult to depict the sublacustrine fan. Figure 13 is the contrast between full-band seismic record and predominant frequency band (20-45Hz) seismic record. In the figure, the blue circle is the place of sublacustrine fans, including three



a. Full-band seismic record. b. Predominant frequency band seismic record (20-45Hz).

FIGURE 13. Contrast between full-band seismic record and predominant frequency band seismic record

fans E_2d1^2 lower, E_2d1^3 upper and E_2d1^3 lower. In seismic record, a sublacustrine fan is often similar to a 'potato' in shape and both ends of the phase axis where it is located are disconnected from other phase axis. However, this characteristic is not clear in a full-band seismic record (Figure 13a). Especially, phase axes have good horizontal continuity near the sublacustrine fan E2d1^2 lower in the figure, with almost no 'potato' features. The extracted predominant frequency band seismic record (Figure 13b) shows that it shows good 'potato' features near E_2d1^2 lower and the distribution of sublacustrine fans in the profile is better depicted, providing good exploration data for subsequent drilling. Subsequent drilling showed reservoirs in E_2d1^2mid-lower, E_2d1^3 upper and E2d1^3 lower. It shows that predominant frequency band seismic record can better present sand body feature distribution, which can help well placement and improve the success rate of drilling.

Conclusion

In order to improve the success rate of subtle reservoir drilling, the research on signal synthesis and decomposition as well as its application has been conducted and the following points have been concluded:

Through the research on signal synthesis and decomposition, it is pointed out that seismic information of partial band restored from the original seismic record also carries the geological information that reflects real underground situation.

Forward and inversion study shows that predominant frequency band seismic record has advantages over the original seismic record in the identification of subtle reservoirs;

The application of predominant frequency band seismic record can help with correct well placement and the improvement of drilling success rate.

Acknowledgements

This research was financially supported by Guangdong 'Sail Plan' Urgently Needed Personnel Introduction Project (No. 916022), Innovation School Features Innovative Project (No.650125 and No.650471), Talent Introduction Project From Guangdong Institute of Petrochemical Technology (650125) and Science & Technology Project From Maoming City (917304). Our gratitude is given to the Organization Department of Guangdong Province, Guangdong Provincial Department of Science and Technology, Guangdong University of Petrochemical Technology and Maoming Government for their financial support. Our thanks also go to draft reviewers for their precious suggestions for amendments and also to the editor for his editing and correction.

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Received: 30 January 2017
Accepted: 27 May 2017