High resolution analysis based on deconvolution and matching pursuit

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Abstract. The complexity of seismic exploration targets makes the exploration process more difficult and requires higher resolution of seismic data. Singular Methodology (inverse Q filtering, spectrum shaping, etc.) is limited in improving the resolution of seismic data and cannot meet the requirements of data interpretation. In this regard, combining time-varying frequency division deconvolution and matching pursuit (MP) methods, first perform time varying frequency division deconvolution processing on the original signal, and then use matching pursuit to remove the strong reflection seismic event and reconstruct the signal. Which can reflect the characteristics of reservoirs. By testing analog signals, deconvolution and matching pursuit methods improve the signal resolution. In the actual seismic data analysis, the comprehensive use of several methods can better identify the distribution characteristics of the effective tight carbonate reservoirs, and correspond well with the actual geological structure and drilling data. Which also provides a reference basis for further capacity analysis.

1. Introduction  
With the continuous deepening of seismic exploration and development, the exploration targets are gradually shifting to tight layers and thin reservoirs. The difficulty of oil and gas exploration is increasing, which requires higher resolution seismic data.

When seismic waves propagate underground, the high-frequency part is more attenuated than the low-frequency part due to the absorption and attenuation of the underground medium. Therefore, the resolution of seismic data can be improved by compressing seismic wavelets. In addition, actual drilling data, logging data and related geological data can also guide and test the seismic data analysis process. conventional high-resolution processing method of seismic data, such as deconvolution⁴, spectrum shaping⁵, inverse Q filtering⁶, impedance inversion under logging constraints⁷. These methods have good application effects on sandstone reservoirs. However, for effective reservoirs (high permeability zones) in tight carbonate rocks, a single method cannot meet the actual needs, and further research is needed.

As an adaptive signal analysis method, matching pursuit has a good sparse representation of seismic data⁸. Through the sparse representation of the signal, the signal is decomposed into a series of linear combinations of time-frequency atoms, which is not limited by the frequency band and window function and has a higher resolution. At the same time, the reconstructed signal based on different time-frequency atoms can also show the hidden information of the original signal.

The Majiagou Formation in the Ordos Basin is a tight carbonate reservoir. Due to the control of lithology and fracture zones, effective reservoir sections are developed, and the spatial distribution is complex. It is basically located within 100m from the top of the Majiagou Formation. The effective
reservoir section is relatively thin. At the same time, because the overburden is mud and coal seams, the strong wave impedance difference results in a strong reflection event on the top of the Majiagou Formation, and the effective reservoir is completely submerged in strong reflections. It is difficult to identify effective reservoirs with conventional seismic profiles. In order to solve this problem, high-resolution analysis is required.

2. Materials and Method

In order to study the seismic reflection characteristics of thin carbonate reservoirs, the time varying frequency deconvolution and orthogonal matching tracing methods are used to analyze and process the seismic reflection characteristics. Firstly, the characteristics of the simulation signal are analyzed, and then the seismic data of the actual gas bearing thin reservoir is processed. Finally, the prediction of the gas bearing thin reservoir is realized through the verification of logging and geological structure.

2.1. Deconvolution

The seismic record $x(t)$ can be expressed as the convolution of $w(t)$ (the seismic wavelet) and $r(t)$ (the reflection coefficient of the formation) when the noise is ignored, the expression is:

$$x(t) = w(t) * r(t)$$  

Where * represents the convolution operation. According to the Fourier transform, the frequency domain expression of formula (1) is obtained:

$$X(\omega) = W(\omega) \cdot R(\omega)$$  

Among them, $X(\omega), W(\omega)$ and $R(\omega)$ respectively represent the Fourier spectrum of seismic records, seismic wavelets and formation reflection coefficient, $(\omega = 2\pi f, f$ represent frequency (Hz)). It can be seen from formula (2) that the formation reflection coefficient spectrum is fixed, so change the input seismic wavelet Frequency components can cause different response characteristics in seismic sections. High dominant frequency wavelets can improve the accuracy of describing thin reservoirs, and low dominant frequency wavelets are beneficial for describing thicker formations. Based on the thin layer reflection coefficient inversion proposed by Portniaguine and Castagm [9], time-varying frequency division deconvolution obtains local frequency spectrum information through frequency division method, accurately extracts time-varying wavelets, and reduces the influence of wavelets on the processing results. This method is more accurate in removing time-varying elements in the time domain. Wave, recover the low-frequency and high-frequency information of the reflection coefficient suppressed by the wavelet, so as to obtain the full-band reflection coefficient sequence and high-resolution seismic profile.

2.2. Matching Pursuit

The Matching Pursuit (MP) algorithm is a kind of iterative greedy algorithm, which realizes the decomposition and reconstruction of the signal by constructing an over-complete time-frequency atom library (dictionary) [10]. Each iteration of the algorithm selects the most relevant atom (the largest inner product with the current residual) from the built dictionary, and then subtracts the inner product from the inner product to obtain a new residual. The basic expression is:

$$f = <f, g_n > g_n + R^if$$  

Where $f$ denotes any signal in Hilbert space, $<f, g_n >$ represents the inner product of the first iteration with the currently selected atom, and the differential residual value $R^if$. After passing the $m$ next iteration, we can get:

$$f = \sum_{n=0}^{m-1} <R^nf, g_n > g_n + R^mf$$  

$R^mf$ represents the residual error remaining in $m$ iterations. When the residual error meets the iteration threshold or reaches the preset number of iterations, it can be ignored. The original signal can
be written as a linear superposition of multiple signals.

\[ f = \sum_{n=0}^{m-1} \langle R^n f, g_{\gamma_n} \rangle g_{\gamma_n} \]  \hspace{1cm} (5)

The original signal is reconstructed by selecting different time-frequency atoms to reflect the different characteristics of the original signal.

3. Results & Discussion

In this chapter, the analog signal and actual seismic data are processed, the characteristics of deconvolution and matching tracking methods are analyzed, and the two methods are combined to achieve a higher resolution than conventional spectral shaping. It shows certain advantages.

3.1. Deconvolution of analog signals

Figure 1(a) and Figure 1(b) show the reflection coefficient and synthetic seismic records respectively. The zero-phase rick wavelet is used as the wavelet. Figure 1(c) shows the theoretical deconvolution results of synthetic seismic records. From the part circled in red in the figure, it can be seen that the resolution of the synthetic seismic record is worse than that of the formation reflection coefficient, and the thin layer cannot be distinguished well. Comparing Figure 1(c) and Figure 1(a), it is found that the deconvolution result of the analog signal corresponds well to the reflection coefficient of the simulated formation, and the spectrogram has a higher resolution. However, in actual situations, when seismic records are deconvolved, the extraction and compression of wavelets cannot achieve ideal results and cannot be completely compressed. The result of the deconvolution is shown in Figure 1(d). The resolution has been improved.

3.2. Decomposition and reconstruction of signal

Use matching pursuit algorithm to decompose and reconstruct the analog single channel signal. First, from the pre-defined time-frequency atom dictionary, continuously extract the atoms that best match the residual signal in this iteration, find the corresponding amplitude coefficient, and decompose the original seismic signal into one linear superposition of series of sub-signals. As shown in Figure 2, it is an analog single-channel signal and its decomposition diagram.

Figure 2(a) is a signal to be decomposed composed of 5 rick wavelets with different frequencies and amplitudes. The frequency and amplitude are (40Hz,0.5), (50Hz,0.8), (20Hz,1), (80Hz,0.8), (60Hz, 0.6).
Figures 2(b), 2(c), 2(d), 2(e), 2(f), and 2(g) are the sub-signals and residual residuals after the original signal is decomposed in sequence 1 to 5 times. It can be seen that after 5 decompositions, the residual value is very small, and the original signal can be approximately expressed as the superposition of the decomposed 5 signals. The analog signal is reconstructed after decomposition, and the result shown in Figure 3 is obtained.

![Figure 3. Comparison of signals after reconstruction with different decomposition times.](image1)

![Figure 4. Comparison of reconstruction results of different sub-signals.](image2)

Figure 3(a) is a comparison of the reconstructed signal after 5 decompositions and the original signal, and Figure 3(b) is a comparison of the reconstructed signal after 10 decompositions and the original signal. Judging from the reconstruction results, the more the signal is decomposed, the closer the reconstructed signal is to the original signal, and the smaller the error from the original signal.

On the basis of analog signal decomposition, the single-channel signal of seismic profile is extracted for analysis. The actual seismic signal to be analyzed is decomposed into the remaining residual and K sub-signals are superimposed.

\[ x(t) = r + \sum_{n=1}^{k} w_n \]  

Choose different \( w_n (n = 1, 2, \ldots, k) \) to reconstruct the original signal to get the result, which shown in Figure 4. Figures 4(a), 4(b), and 4(c) respectively \( (w_{1}, w_{2}, \ldots, w_{r}; r) \), \( (w_{1}, w_{2}, \ldots, w_{r}; r) \), and \( (w_{k}, w_{r}, \ldots, w_{1}; r) \) the comparison of the reconstructed signal with the original signal. Figure 4 show that removing different sub-signals is equivalent to removing the energy at different positions of the original seismic signal. The discarded ones correspond to the strong amplitude in Figure 4(a), and the results of this processing are shown on the seismic section to remove the strong seismic event. After removing the strong energy, comparing the reconstructed signal with the original seismic record, it is found that the removed part reflects the stratum information that was not reflected in the original signal.

3.3. The actual data processing

Based on the above-mentioned foundation, a cross-well section of Majiagou Formation in the Ordos Basin (Figure 5) was processed. The reservoirs in the Majiagou Formation are thin and have strong heterogeneity, making it difficult to describe favorable reservoirs. Among them, a few meters to a dozen meters below the M5-top horizon are the main gas producing zones in this area. In Figure 5, wells A, B, C, and D have all been drilled and tested under M5-top.

Among them, Well A is a dry well in the test zone, Wells B and C are high-yield gas zones in the test zone, and the analysis result of the test zone of Well D is expressed as a low-yield gas zone. The blue curve in the figure represents the GR curve. Judging from the original data, the resolution of seismic data is low, the entire reservoir section shows strong amplitude, and the characteristics of the effective reservoir section are not obvious.
The original seismic profile was subjected to spectrum shaping and time-varying frequency division deconvolution to obtain the processing results in Figure 6 and Figure 7. It is found that the deconvolution method is more obvious in improving the resolution of the profile. In the parts I and II marked in the figure, the deconvolution profile has a higher resolution than the original seismic profile, which can better realize the thin reservoir. However, the processing results of the target interval cannot reflect the actual reflection characteristics of the reservoir.

According to the relatively stable characteristics of the strong reflection characteristics of the target interval, the matching pursuit method is used to strip the strong reflection layer to study the actual seismic geological characteristics of the reservoir. Compared with the strong reflection, the weak reflection of the reservoir has little contribution to the seismic record, and the seismic response charac-
Characteristics of the reservoir can be better identified after the strong reflection event is stripped.

Figure 9. Stripping area amplification

The seismic records after deconvolution are processed with matching pursuit, and the result is shown in Figure. 8. Comparing the results of magnification of the strong reflection peeling area (Figure. 9) with the deconvolution processing result, it is found that the energy of peeling the strong reflection area is reduced, while the resolution is improved.

4. Conclusion

The further development of seismic exploration research requires higher resolution of seismic data. It is difficult for a single high-resolution processing method to meet the actual exploration requirements, so different processing methods can be combined to study the seismic data.

Seismic deconvolution and matching pursuit are used to study analog and actual signals. The results show that time-varying frequency division deconvolution can better extract time-varying wavelets for compression, and obtain a seismic profile with higher resolution; matching pursuit sparsely represent the signal, using fewer sub-signals to reconstruct the actual Signal, and reflects the hidden information of the original signal.

In the application of actual data, the problem of strong reflection shielding the weak signal of the reservoir makes the fine prediction of the reservoir more difficult, and the single spectrum shaping and deconvolution method has limitations. The seismic data after deconvolution is used to remove the strong seismic event by matching tracking, and the result is more consistent with the drilling test.

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Reference

[1] LI J L, LI Z C, GUAN L P, et al. 2015. Seismic wave attenuation and compensation method[J]. Geophysical and Geochemical Exploration, 39(003):456-465. (In Chinese)
[2] JIANG B. 2020. Method and technology of seismic data reprocessing[J]. Geophysical Prospecting for Petroleum, 59(04):551-563. (In Chinese)
[3] LI C, GAO Y F, JING B, et al. 2015. Identification of carbonate reservoirs with weak seismic response[J]. Oil Geophysical Prospecting, 50(05):951-955+806. (In Chinese)
[4] WU D L. 2011. Analysis of processing technology and application effect of spectrum shaping to improve resolution[J]. Geophysical Prospecting for Petroleum, 50(01):33-37+18. (In Chinese)
[5] SONG G J, YU J Y, WANG C, et al. 2018. Near-surface medium Q estimation and its application in the northern Tahe oilfield[J]. Geophysical Prospecting for Petroleum, 57(03):436-442. (In Chinese)
[6] Wang, Y H. 2002. A stable and efficient approach of inverse Q filtering[J]. GEOPHYSICS, 67(2):657-663.
[7] LIANG H X. 2017. Summary of well-constrained seismic processing technology[J]. Progress in Geophysics, 32(06):2485-2492. (In Chinese)

[8] ZHANG F C, LAN N Y, LI C H, et al. 2020. Seismic matching pursuit technology and application research progress[J]. Geophysical Prospecting for Petroleum, 59(04):491-504. (In Chinese)

[9] Portniaguine O, Castagna J. 2005. Spectral inversion: lessons from modeling and Boonesville case study[J]. Seg Technical Program Expanded Abstracts, 2668.

[10] LIU L F, WANG L, LI L H. Using bidirectional matching pursuit to improve seismic resolution[J]. Oil Geophysical Prospecting, 2016,51(04):769-773+6. (In Chinese)