Frequency-dependent seismic attributes and their application for hydrocarbon detection

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Summary

This paper utilizes a time-frequency analysis tapproach based on the wavelet transform and the observation that the presence of oil and/or gas results in an increase in the high frequency attenuation gradient and an increase in low frequency energy. Application of these methods in a prospective reservoir suggests that the combined use of both the high and low frequency information may be a more robust method for locating hydrocarbons than the use of either alone.

Introduction

The study of scattering theory indicates that rocks containing oil or gas will attenuate the seismic signal, with higher frequencies more attenuated than lower frequencies low-frequency energy information can be utilized to make oil and gas prediction. When a reservoir contains fluid or gas, the seismic wave propagation will appear with effect of low frequency resonance scattering, leading to the seismic energy of low-frequency abnormally amplified, that is low-frequency energy grow relatively stronger, therefore the seismic of low-frequency information can indicate hydrocarbon information.

In many studies of the time-frequency analysis technique, attention has focused on the use of high-frequency information, at the expense of the low-frequency data for detecting oil and gas. With improvements in seismic data acquisition, we can get more reliable low-frequency information. In this study we describe how using both high frequency attenuation and summed low frequency energy may lead to more reliable hydrocarbon detection.

Base on oil gas testing data of well Ma2, we choose the gas layer and non-gas layer of well Ma2 to analyze the spectrum response. As shown in its result (Fig.1), the gas layer shows relative high-frequency energy attenuatioin and low-frequency energy enhancement. So we can use this spectrum characteristic to predict the hydrocatrbon layer.

Theoretical basis

Time-frequency analysis is a commonly used signal processing method that combines time and frequency domain information Cara (1982). This well known method uses the Fast Fourier Transform to convert time-domain seismic data into the frequency domain, and can provide Time-frequency analysis methods mainly experience a short-time Fourier transform, wavelet transform, etc.

Gabor (1946) proposed the concept of short time Fourier transform. The actual signal analysis requires low-frequency signal to obtain a higher frequency resolution, and high-frequency signal to obtain a higher time resolution, which needs window function to adjust its width and bandwidth according to the signal frequency changes. Apparently, Fourier transform can not meet the need of high-precision time-frequency analysis in a short time.

Morlet (1984) discovered an obvious feature of signals in his analysis of synthetic seismic, the low-frequency end of the signal requires a very high frequency resolution, while the frequency resolution of high-frequency end can be lower. Based on Heisenberg's uncertainty principle, It is that kind of the high-frequency signals has high time resolution, and the time resolution in low-frequency can be lower. According to this characteristic of seismic signals, Morlet proposed wavelet transform.

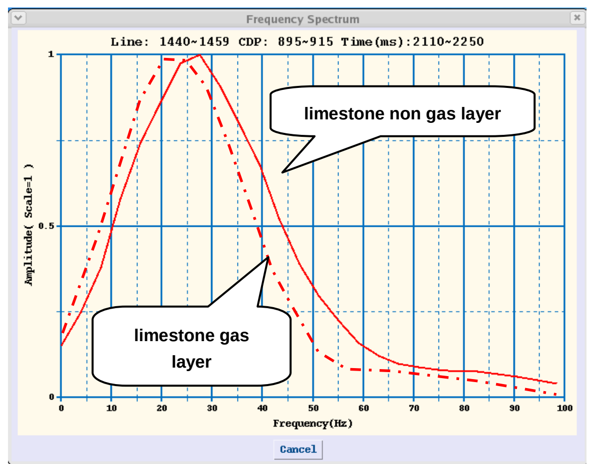

Figure 1: Spectra of gas and non gas layers in Sichuan Basin.This is an example shows the presence of gas results in an increase attenuation in the high frequency and an increasing in low frequency energy.

Instantaneous spectral analysis (ISA) based on the wavelet transform has solved the problem that length of time window will affect the results, and has greatly improved the stability and resolution.

Best matching wavelet theory

Gao Jinghuai(2001) provides a new analysis wavelet with three adjustable parameters, so that it can match the best seismic wavelet, named as the best matching wavelet：

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$$\psi(t;A,\sigma,\tau,\beta)=A\exp\left[-\tau(t-\beta)^2\right]\exp(i\sigma t)+R(A,\sigma,\tau,\beta,t) \quad (1)$$

where, τ is the energy attenuation factor, β is the energy delay factor, σ is seismic wavelet modulation frequency.We use the vector $\Gamma=(A,\sigma,\tau,\beta)$ to stands for parameter; a series of value of A,σ,τ,β can be demonstrated in formula (2) as：

$$\psi(t,\Gamma)=A\exp\left[-\tau(t-\beta)^2\right]\exp(i\sigma t)+R(t;\Gamma) \quad (2)$$

The correction item is：

$$R(t;\Gamma)=-A\sqrt{2}\exp\left[-\sigma^2/(8\tau)\right]\exp\left[-2\tau(t-\beta)^2\right]\exp(i\sigma t) \quad (3)$$

When the best match wavelet contains only slow-varying wavelet for frequency and amplitude components of the signal, then apply large values $\sigma^2/(8\tau)$, in which equation (2) of the second type (i.e., correction term) can be omitted. However, if the type of wavelet is used to analyze the signals with rapid frequency and amplitude variation, in order to get the best time resolution, and also be able to get the signal components of various frequencies separately, it requires that σ is a comparatively small value. In this case, the correction term $R(t;\Gamma)$ can not be ignored.

Three parameters wavelet theory

Although the best matching wavelet still meets the permit conditions in a small value, but its time localized nature is unsatisfactory, that is, changes from a single peak to a multi peaks. To make wavelet transform with application of the multi-peak analysis of wavelet signal will lead to localization of the signals on a number of different locations which will produce a false impression in the measurement of instantaneous frequency and amplitude. Professor Gao (2007) starts from formula (4)-has generated a new category of analysis wavelet, that is, the three-parameter wavelet.

The formula for the three-parameter wavelet is:

$$\psi(t;\sigma,\tau,\beta)=e^{-\tau(t-\beta)^2}\{\{p(\sigma,\tau,\beta)*\left[\cos(\sigma t-k(\sigma,\tau,\beta)\right]+iq(\sigma,\tau,\beta)\sin(\sigma t)\} \quad (4)$$

we use $\Lambda=(\sigma,\tau,\beta)$ as the assemble of all factors.

The expression for factor $p(\Lambda),q(\Lambda),k(\Lambda)$ is listed below：

$$k(\Lambda)=e^{-\frac{\sigma^2}{4\tau}}\left[\cos(\beta\sigma)+\frac{iq(\Lambda)}{p(\Lambda)}\sin(\beta\sigma)\right] \quad (5)$$

$$p(\Lambda)=\left(\frac{2\tau}{\pi}\right)^{\frac{1}{4}}\left[4\left(e^{-\frac{\sigma^2}{2\tau}}-e^{-\frac{3\sigma^2}{8\tau}}\right)*\cos^2(\beta\sigma)+1-e^{-\frac{\sigma^2}{2\tau}}\right]^{-\frac{1}{2}} \quad (6)$$

$$q(\Lambda)=\left(\frac{2\tau}{\pi}\right)^{\frac{1}{4}}\left[4\left(e^{-\frac{\sigma^2}{2\tau}}-e^{-\frac{3\sigma^2}{8\tau}}\right)*\sin^2(\beta\sigma)+1-e^{-\frac{\sigma^2}{2\tau}}\right]^{-\frac{1}{2}} \quad (7)$$

The relationships of scale factor and dominant frequency of three parameter wavelet are:

$$\alpha=\frac{\omega^*}{2\pi f} \quad (8)$$

$$\omega^*=\frac{\sqrt{\pi}\sigma p(\Lambda)q(\Lambda)\left(1-e^{-\frac{3\sigma^2}{8\tau}}\right)}{\sqrt{2\tau}} \quad (9)$$

$$a=\frac{\sigma\left[1-e^{-\frac{3\sigma^2}{8\tau}}\right]}{\left[3e^{-\frac{\sigma^2}{2\tau}}-4e^{-\frac{3\sigma^2}{8\tau}}+1\right]^{\frac{1}{2}}\left[1-e^{-\frac{\sigma^2}{2\tau}}\right]^{\frac{1}{2}}} \quad (10)$$

High and low frequency attribute calculation

High frequency attenuation attribute calculation

Based on the fact that energy of high frequencies of seismic waves attenuate in reservoirs, Mitchell et al.(1996) presented a method to calculate energy attenuation of seismic signals. The core of this technology lies in the calculation of high frequency exponential attenuation factor from the spectrum of the signal. The relevant exponential function has the form of exp(a,w), where a is the attenuation factor. The calculations are carried on a series of time windows (for example, the time windows with Gaussian distribution), where the scales of the windows are determined to be slightly larger than the seismic period. After moving the windows continuously on the traces and carrying on the calculation, we get the output attenuation factor which is the function of time. The corresponding procedure is shown in Figure 2.

Based on the previous analysis, wavelet-based time-frequency decomposition method can be employed in the real data processing to analyze seismic signal with a specific time window and calculate the attenuation factor a. Finally, the data volume of frequency attenuation gradient can be obtain

ed by the repeated calculations on a series of windows whose middle points move continuously on the seismic trace.

Low frequency energy attribute calculation

According to BIOT theory and experimental data, Sa Liming and others (2002) proposed that when fluid flow in low velocity relative to solid particles, that is, fluid is "locked" in the skeleton, attenuation is at a minimum level and amplitude is at its highest. the phenomenon is the so-called "resonance". The low frequency energy resonance scattering will occur during the seismic wave propagate the reservoir with fluid or gas, which resulting in relatively stronger low frequency compared to high frequency energy.

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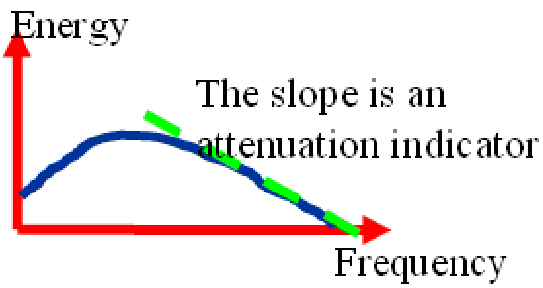
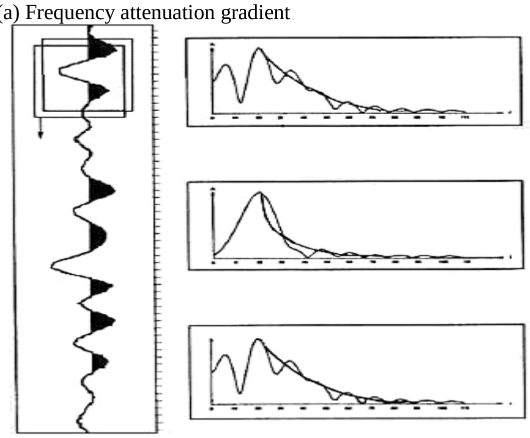
Based on the above analysis, we have adopted previous spectral decomposition based on FFT to analyze the signal in single time window, and calculate the sum of low-frequency energy as well as the ratio of it to total energy along a moving time window to produce a low-frequency energy cube.



(a) Frequency attenuation gradient



(b) Operating flowchart.

Figure 2: Principle of FAA technology and its operating

Using the method of instantaneous spectral analysis based on the wavelet transform, we can generate a series of energy and phase cubes for single frequencies, from which we extract the characteristics of the low-frequency components.

Case analysis

As an example, We applied this method to calculate the attenuation gradient and low-frequency energy attributes for an exploration area in the Sichuan Basin, China. The attenuation gradient of the higher frequencies should increase over zones containing oil and/or gas relative to similar zones without hydrocarbons.. Similarly, the low frequency energy should be high over regions containing oil and/or gas.

The area around Ma2 is expanded in both figures to indicate zones of high exploration potential (red) from the attenuation gradient (Figure 3) and the summed low frequency energy (Figure 4). Correspondence of the summed low frequency energy zones to zones of high attenuation gradient is the indicator of good hydrocarbon potential.

In the sections of both attenuation gradient and low frequency energy, we can see a high attenuation zone in the Feiyi layer, that contains strong low frequency energy. On the map views of the Feiyi Layer (Figures 5 and 6), we can also find the well developed area in northeastern area,

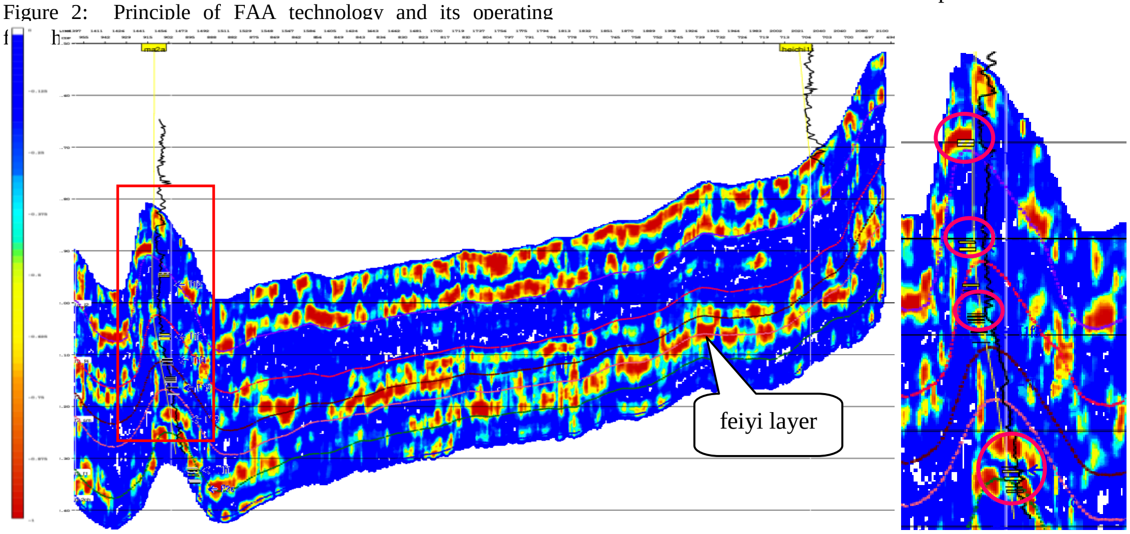


Figure 3: Attenuation gradient section across well Ma2 and well h1 in Sichuan Basin,the hot colors (red) indicate regions of higher attenuation gradient, that is our favorable area. The right picture is a amplification at well Ma2 zone, it shows that higher attenuation gradient is consistent with the testing data of well Ma2.

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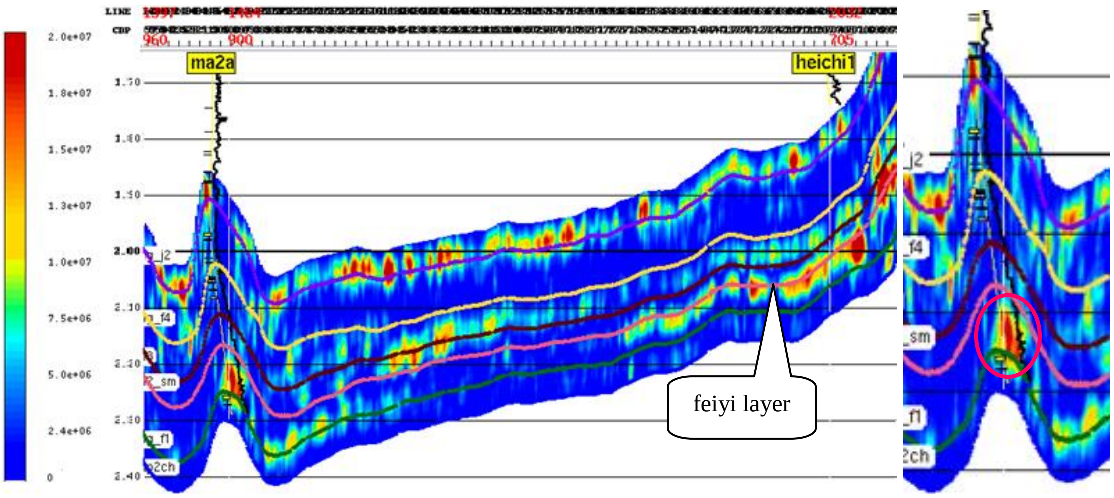

Figure 4: Low frequency energy section across well Ma2 and well h1 in Sichuan Basin,the hot colors indicate regions where the summed low frequency energy is the highest,that is our favorable area. The right picture is a amplification at well Ma2 zone, it also shows that stronger low frequency energy is consistent with the testing data of well Ma2,but the low frequency energy has slightly low vertical resolution.

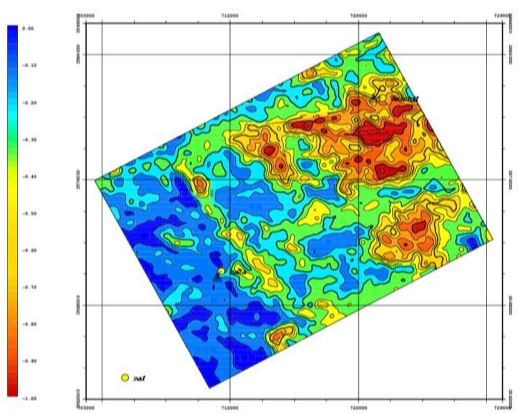

Figure 5: Map view of frequency attenuation gradient in Fei Xian Guan group. The hot colors (red) indicate regions of higher attenuation gradient.

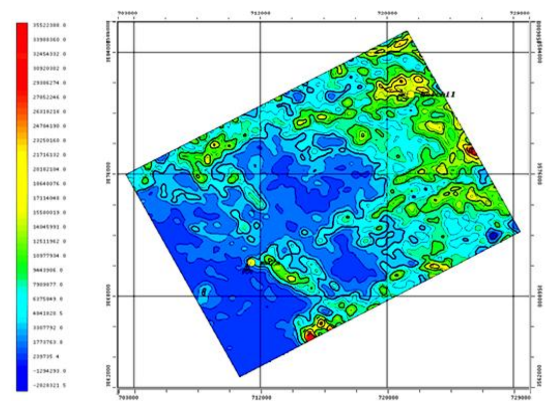

Figure 6: Map view of low frequency energy in Fei Xian Guan group. The hot colors indicate regions where the summed low frequency energy is the highest.

which proves that the two methods have good consistency with each other that helps to enhance the reliability of the prediction method.

Conclusion

Reservoir that contains oil and gas will cause high frequency energy attenuation and low frequency energy increase. The adoption of high frequency attenuation method in oil and gas prediction is widely accepted and applied, however the fact that low frequency energy increases has caught little attention. In areas with complex structure, it is not enough to simply apply the high frequency attenuation gradient because of difficulties caused bylow low signal/noise ratios.. This problem can be partially overcome by using lower frequency energy methods, because they have less difficulty with signal to noise. Combining both methods shows promise in characterizing zones of increased hydrocarbon potential.

Acknowledgements

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