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Q Estimation Using an Improved Frequency Shift Method

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SUMMARY

This paper proposes an improved frequency shift method to estimate the quality factor Q for hydrocarbon detection. As a powerfully diagnostic tool for structural interpretation, reservoir characterization and hydrocarbon detection, quality factor Q provides useful information in seismic processing and interpretation. The popular methods, like spectral ratio (SR) method, central frequency shift (CFS) method, peak frequency shift (PFS) method, have their respective limitations in field seismic data application. In this paper, we derive an approximate equation and propose an improved central frequency shift (ICFS) method by combining the quality factor Q, the travel time, dominant and central frequencies of two successive seismic signals, along the wave propagating direction. Tests on synthetic data and statistical experiments show the proposed method can achieve higher accuracy and robustness compared with existing methods. Application of field data also shows its potential and effectiveness to estimate seismic attenuation.

Introduction

Seismic attenuation is a fundamental mechanism of elastic waves propagating through the earth. The quantified attenuation attribute can provide important information about the subsurface to facilitate seismic interpretation (Parra and Hackert, 2002).

Quality (Q) factor is usually used to measured seismic attenuation. Ricker (1953) pioneered a wavelet broadening technique to determine attenuation. Nowadays, frequency-based methods are common in exploration geophysics because of their reliability and ease of use, which include the spectral ratio (SR) (White, 1992), central frequency shift (CFS) (Quan and Harris, 1997), peak frequency shift (PFS) (Zhang and Ulrych, 2002), improved peak frequency shift (IPFS) (Hu et al., 2013), and Gabor-Morlet joint time frequency analysis (JTFA) (Singleton et al., 2006) methods. The most classic approach is SR method, which measures the log of the ratio between two amplitude spectra computed as function of frequency. But, SR method would be easily affected by noise. While as opposed to SR method, the frequency-shift methods, such as CFS and PFS methods, just use the variations of the spectra rather than the entire amplitude spectrum, which improves the accuracy of the estimation.

In this paper, combining CFS approach and practical Ricker spectrum precondition, we derive an improved method to estimate Q. The hypothesis of the proposed method satisfies the basic characteristics of seismic signal, which provides the basis of reasonable accuracy and robustness. Finally, we calibrate the proposed method for both synthetic and field seismic data.

Central Frequency Shift Method

For frequency independent intrinsic Q in the bandwidth of interest, a seismic signal will have its spectral amplitude $\mathrm{A}_0(f)$ modified to $\mathrm{A}_1(f)$ after traveling time t at frequency f:

$$\mathrm{A}_1(f) = \mathrm{A}_0(f) e^{-\frac{\pi f t}{Q}}, \tag{1}$$

where the amplitude decay or increase caused by frequency-independent effects is ignored.

CFS method correlates Q with the changes in the central frequency of the seismic signal. For the reference seismic signal A_0 and the target seismic signal A_1, their central frequencies denoted by f_{c_0} and f_{c_1}, assuming that $|A(f)|$ is of Gaussian shape, Q can be quantified by,

$$Q = \frac{\pi t \sigma_{A_0}^2}{f_{c_0} - f_{c_1}}, \quad \sigma_{A_0}^2 = \frac{\int_0^\infty (f - f_{c_0})^2 |A_0(f)| df}{\int_0^\infty |A_0(f)| df} \tag{2}$$

where $\sigma_{A_0}^2$ is the spectrum variance of A_0.

We notice that the preconditions of CFS method are the Gaussian shape of the seismic spectrum and the unchanged spectrum variance. However, the seismic spectrum is usually a non-Gaussian distribution and the attenuation would certainly change the spectrum variance.

Improved Central Frequency Shift Method

In order to better satisfy field situations, we evaluate the amplitude spectrum variance by CFS approach modeled as a Ricker wavelet traveling. Combining Equation (1) and Ricker wavelet definition, we can get the amplitude spectrum of the received signal as

$$A(f,t) = \frac{2}{\sqrt{\pi}} \frac{f^2}{f_m^3} e^{-\frac{f^2}{f_m^2}} e^{-\frac{\pi f t}{Q}}, \tag{3}$$

where f_m denotes the dominant frequency of the source wavelet.

Thus, the central frequency of the received seismic amplitude spectrum $A(f,t)$ is expressed as,

$$f_c = \frac{\int_0^\infty f |A(f,t)| df}{\int_0^\infty |A(f,t)| df} = \int_0^\infty \frac{2}{\sqrt{\pi}} \frac{f^3}{f_m^3} e^{-\frac{f^2}{f_m^2}} e^{-\frac{\pi f t}{Q}} df \Big/ \int_0^\infty \frac{2}{\sqrt{\pi}} \frac{f^2}{f_m^3} e^{-\frac{f^2}{f_m^2}} e^{-\frac{\pi f t}{Q}} df. \tag{4}$$

After simplifying, separating the factors and computing the integrals, we can get an approximate relationship as follows

$$f_c = f_m \frac{\left(\frac{\pi f_m t}{2Q}\right)^3\left(1-\sqrt{\pi}\right)+\left(\frac{\pi f_m t}{2Q}\right)^2+\left(\frac{\pi f_m t}{2Q}\right)\left(1-\frac{3}{2}\sqrt{\pi}\right)+1}{\left(\frac{\pi f_m t}{2Q}\right)^2\left(\sqrt{\pi}-1\right)-\left(\frac{\pi f_m t}{2Q}\right)+\frac{\sqrt{\pi}}{2}}. \tag{5}$$

As our goal is to estimate Q factor, we derivate equation (5) to an equation about unknown parameter Q. Because that equation is a cubic equation in one variable, we can only get an approximate solution,

$$Q \approx 2\sqrt{\pi}\frac{\left(\sqrt{\pi}-1\right)^2 f_c - 0.3\pi f_m}{f_c - \frac{2}{\sqrt{\pi}} f_m} f_m t. \tag{6}$$

The relationship between the central frequency, dominant frequency and Q factor has been established by now. Thus, we can obtain the quality factor estimation. It is an improved CFS method, as we substitute Gaussian spectrum to non-Gaussian spectrum of Ricker wavelet, which is more coincident with the actual situation as wave propagates under the survey. In addition, we get rid of the variance estimation of the reference spectrum, which makes calculation more straight forward and free from the inaccuracy from ignorance of the shape difference between reference and received spectra.

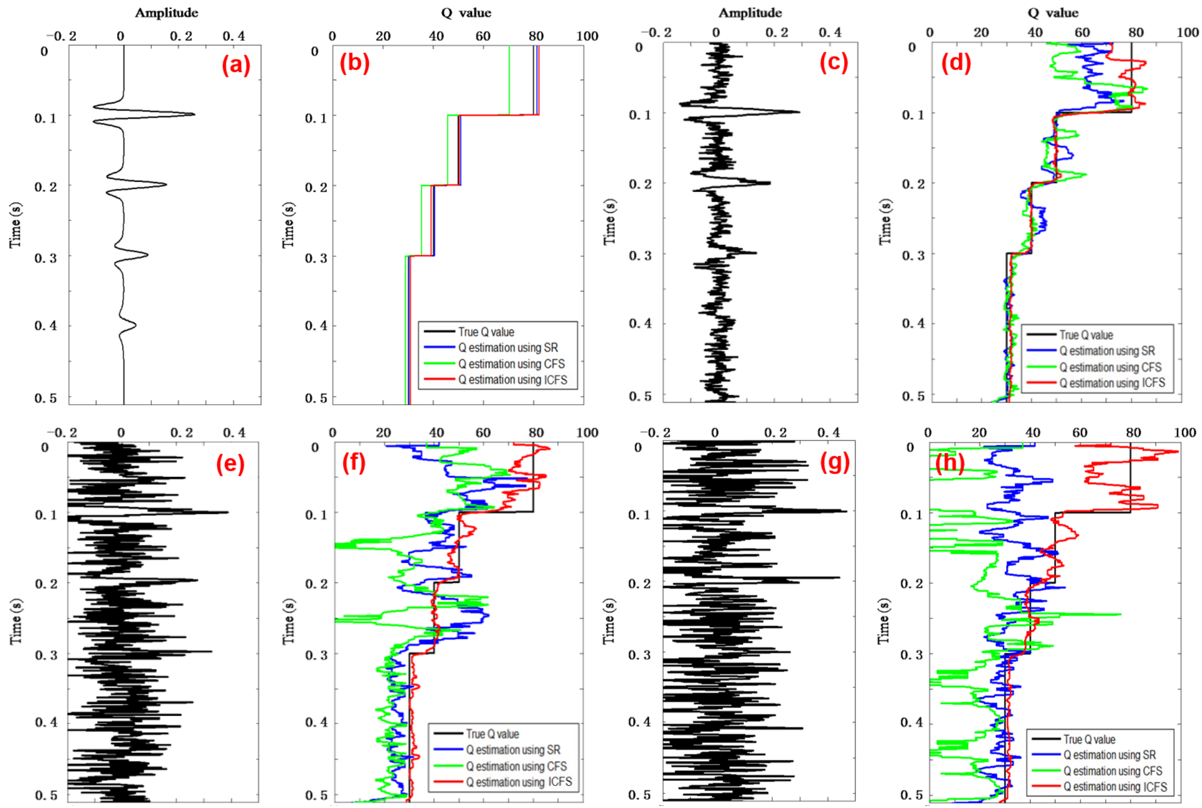

Figure 1 *Comparison between the proposed ICFS method and SR, CFS methods. (a) A noise-free synthetic generated by a 40 Hz Ricker wavelet with Q values of 80, 50, 40 and 30. (c), (e) and (g) show synthetic traces with SNR=10, 0, and -1 dB random noise, respectively. (b), (d), (f) and (h) show the corresponding the results of Q estimation using SR, CFS and ICFS methods. Note that the results applied by ICFS method are closer to the true Q values even with decreasing of SNRs.*

Synthetic Tests

In order to check the effectiveness and stability of our proposed improved CFS(ICFS) method, we estimate Q values on both noise-free and noisy synthetic data and analyze the results calculated by SR, CFS and ICFS methods. We use a Ricker wavelet with a 40 Hz dominant frequency to produce a noise-free synthetic with Q values 80, 50, 40 and 30 shown in Figure 1(a). The most difficult problem is the stability in evaluating Q factor when the data is contaminated by noise. Therefore, we also create synthetic traces added by different noise levels with SNR=10, 0, and -1 dB shown in Figure 1(c), 1(e) and 1(g). We can observe from the results that there are noticeable differences between three methods. For SR method, accuracy and stability of estimation highly depends on the SNR of original data. When SNR is below 10 dB, ICFS method performs more robustly, and the results calculated by ICFS are closer to the true Q values than those of the other two methods.

In addition, For the attenuated layer with real Q value 30, we carry out 100 independent experiments in different situation of SNR=10, 0 and -1dB. The statistical analysis shown in Table 1 demonstrates that the mean value applied by ICFS is closer to the actual value, and the standard deviations have no obviously large fluctuation even when noise level is greater than the signal (SNR=-1 dB), whereas the anomaly large values of standard deviation using SR and CFS method imply that these two methods have less robustness under the situation of low SNR compared to our proposed method.

SNR(dB)	SR		CFS		ICFS	
	Mean	SD	Mean	SD	Mean	SD
10	32.33	7.28	34.53	13.52	31.63	0.85
0	159.77	1548	28.36	86.35	32.36	3.18
-1	348.95	3853	52.17	219.28	32.53	3.75

Table 1 *Statistical data calculated by 100 experiments using SR, CFS and ICFS methods. The actual Q value is 30. SD denotes the standard deviation.*

Field Data Application

We applied ICFS method to a 3D land survey acquired in Western China, showing its value in detecting gas reservoir. Figure 2(a) shows a vertical seismic slice crossing three wells, wherein the wells A and B are productive, while the well C is nonproductive. Figure 2(b) shows the gas reservoir distribution, lithology and well logs (e.g. GR, RT, AC and DEN), in which the sandstone full of gas is painted yellow under the layer L2 at Well A and B, but there is no oil-gas response at well C location.

From Q estimation results in Figure 3(a) calculated by ICFS, the low values of the target layer at the location of productive wells A and B are highlighted by red color, which implies strong absorption or attenuation in the gas-bearing sandstone, and there is no such characteristic at the nonproductive well C. In Figure 3(b), the Q estimation curves of layer L2 (denoted by the red curve in Figure 3(a)) demonstrate that the most reasonable result is from ICFS (red-dashed curve), because the proposed method curve successfully distinguishes productive Well B and dry-hole Well C, while SR (blue curve) and CFS (green curve) do not show obvious value difference between Well B and C. Therefore, the reasonable Q value curve from ICFS clearly characterizes oil/gas reservoirs by low values and nonproductive reservoirs by high values.

Conclusions

This paper proposes a novel method for Q estimation based on the assumption of the non-Gaussian amplitude spectrum of Ricker wavelet, wherein a simply effective Q approximate equation is built between dominant frequency and centroid frequency. It not only overcomes the shortage of SR method highly depending on the SNR of seismic data, but improves the robustness and accuracy compared to CFS method. Synthetic and field examples calibrate the effectiveness of the proposed method, and also confirm the results calculated by ICFS are reliable and provide useful guides in the hydrocarbon detection and reservoir characterization.

Acknowledgments

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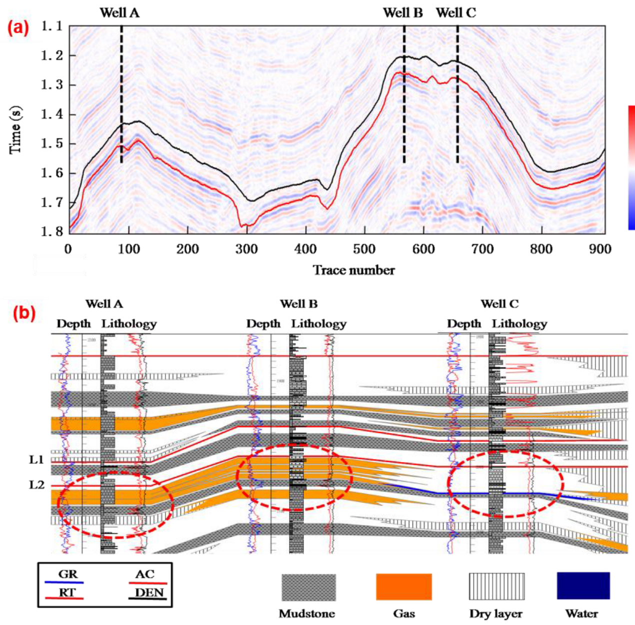

Figure 2 *(a) Vertical profile of seismic amplitude data that cross three joint wells. (b)The gas reservoir distribution, lithology and well logs (e.g. GR, RT, AC and DEN) through three joint wells. The red ovals denote the comparing zones under target layer L2.*

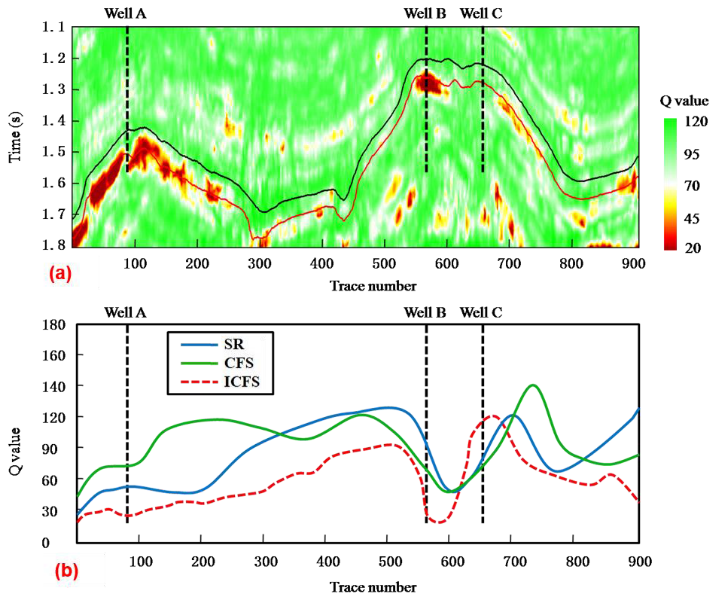

Figure 3 *(a) The Q estimation profile obtained by ICFS method. (b) Average Q value curves calculated by SR, CFS and ICFS methods for target layer L2 within 20ms downward time window.*

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