Quality factors estimation using wavelet’s envelope peak instantaneous frequency

Jinghua Gao*, Senlin Yang, Inst. Wave & Information, Xi’an Jiaotong University, Xi’an, China
Daxing Wang, Research Inst. of E & D, Chang-Qing Oil-Field Company of CNPC, Xi’an, China
Rushan Wu, Modeling and Imaging Laboratory, IGPP, University of California, Santa Cruz, California, USA

Summary

We derive an approximate equation combining the quality factor $Q$, the traveltime of a wave, and the variation of the instantaneous frequency (IF) at the envelope peaks of two successive seismic wavelets, along the wave propagating direction, based on the theory of one-way wave propagation in a 1D viscoelastic medium. We then propose a method (called the WEPIF method) to estimate $Q$ by measuring the variations of the wavelet envelope peak IF (WEPIF) with the traveltime of seismic wavelet. A test on synthetic VSP data shows that the WEPIF method is less sensitive to interference from the reflector than the logarithm spectral ratio and the centroid frequency shift methods. Applied to post-stack seismic data, the WEPIF method gives a $Q$-curve with nearly the same distribution as the results from a known well. Applied to poststack seismic data, it produces a $Q$-profile that indicates an intense absorption zone corresponding to the excellent gas-bearing reservoir. This allows us to predict a potential high-productivity gas well. Drilling confirmed this prediction. The WEPIF method can be applied to poststack seismic data and zero-offset VSP data.

Introduction

Seismic waves propagating through the earth suffer attenuation and dispersion due to the viscosity of the media (Ricker, 1953; Futterman, 1962). $Q$ is a diagnostic tool for reservoir characterization and hydrocarbon detection (Toksöz et al., 1979). Moreover, $Q$ is very important when interpreting the effects of AVO, improving the resolution of seismic imaging, and advancing the study of material properties.

In general, amplitude variations of seismic signals are used to estimate $Q$ values (Tonn, 1991). Time-domain methods involve pulse amplitude decay (Brzostowski and McMechan, 1992), pulse rising time (Gladwin and Stacey, 1974; Kjartansson, 1979), and pulse broadening (Wright and Hoy, 1981), which all use pulse amplitude information. Nevertheless, amplitude information of seismic pulses is often influenced by scattering, geometric spreading, and other factors. In the Fourier-frequency domain, approaches for estimating $Q$ include the logarithm spectral ratio (LSR) (Hauge, 1981; Stainsby and Worthington, 1985), centroid frequency shift (CFS) (Quan and Harris, 1997), and peak frequency shift (Zhang and Ulrych, 2002; Gao and Yang, 2007) methods, all of which require Fourier transforms to calculate the frequency spectra of seismic records sampled within a time window. In practice, it is difficult to properly select the window function and window length. Li et al. (2006) suggested using peak scale variations in the wavelet domain to estimate $Q$ by assuming an idealized pulse as the seismic source wavelet. Its application is, however, restricted due to the fact that the difference between the real source wavelet and an idealized pulse may be substantial.

$Q$ can also be estimated by the variation of the instantaneous frequency (IF) of a seismic signal. Tonn (1991), Barnes (1991), and Engelhard (1996) obtained the relationship between the measured instantaneous spectra and seismic attenuation. Assuming that the source wavelet is an idealized band-pass wavelet, Barnes (1991) derived the relation between $Q$ and IF variations of seismic waves, establishing a new approach for $Q$ estimation.

In this work, we develop Barnes’s work (Barnes, 1991), and propose a method for estimating $Q$. We derive an approximate equation combining $Q$, the traveltime of the wave, and the variation of the IF at the envelope peaks of two successive seismic wavelets, along the wave propagating direction, based on the theory of one-way wave propagation in a 1D viscoelastic medium. We then propose a method (called the WEPIF method) to estimate $Q$ by measuring the variations of the wavelet envelope peak IF (EPIF) with its traveltime. We finally test our method using both synthetic and field seismic data.

Theories of four $Q$ estimation methods

Considering a one-way plane wave propagating in a horizontally layered anelastic medium with a frequency-independent $Q$, we can determine the wavefield of a source wavelet traveling through a distance $z$ by (Aki and Richards, 1980; Stainsby and Worthington, 1985)

$$U(z, \omega) = \hat{U}(0, \omega) \exp \left[ -i\omega z \left( \frac{c(\omega)}{c(\omega)} - \frac{\omega z}{2 c(\omega) Q} \right) \right],$$

where $i = \sqrt{-1}$, $\omega$ is the angular frequency, $z$ and $c(\omega)$ denote the travel-distance and phase velocity, respectively, $Q$ is the quality factor of the medium, and $\hat{U}(0, \omega)$ is the wavefield of the source signature. For VSP and reflection seismograms, we assume that the source wavelet can be approximated by
Quality factors estimation using wavelet’s envelope peak instantaneous frequency

\[ u(0,t) = A \left( \frac{\delta^2}{\pi} \right)^{1/4} \exp \left[ i(\sigma t + \varphi) - \frac{\delta^2 t^2}{2} \right] , \quad (2) \]

where \( \sigma \) is the modulated frequency (i.e., dominant frequency), \( A \) and \( \varphi \) are the amplitude and phase factor, respectively, and \( \delta \) is the energy decay factor of the wavelet. The wavelet, defined by equation 2, has four parameters \((A, \varphi, \sigma, \delta)\) to be determined properly so that it can match the actual source signature. Applying the Fourier transform to equation 2, the source wavefield can be expressed as

\[ \hat{U}(0,\omega) = A \left( \frac{4\pi}{\delta^2} \right)^{1/4} \exp \left[ -\frac{(\omega - \sigma)^2}{2\delta^2} + i\varphi \right] . \quad (3) \]

According to the definition of Barnes (1991), equation 3 is a constant-phase wavelet. A constant-phase wavelet, being non-causal, is not physically realistic; however, a real causal source wavelet can be converted to a constant-phase wavelet by an appropriate phase rotation (Toksoz and Johnston, 1981; Barnes, 1991). Also, wavelets derived by seismic-to-well correspondence often have a near-constant phase (Sheriff, 1984; Robertson and Nogami, 1984; Bodine, 1986; Barnes, 1991). A phase wavelet propagated for time \( \tau \) through a homogeneous anelastic medium, its EPIF is exactly equal to the average Fourier frequency weighted by its amplitude spectrum (Sheriff, 1984; Robertson and Nogami, 1984; Bodine, 1986; Barnes, 1991), i.e.,

\[ f_p(\tau) = \int_0^\infty \! A(\tau, f) df \int_0^\infty \! A(\tau, f) df , \quad (5) \]

where \( f = \omega/2\pi \) is the frequency, \( A(\tau, f) \) and \( f_p(\tau) \) are the amplitude spectrum and the EPIF of the wavelet after traveltime \( \tau \), respectively. \( \hat{A}(\tau, f) = |\hat{U}(\tau, f)| \), and \( \tau = z/c \). From equations 3 and 5, we get

\[ f_p(0) = \frac{\sigma}{2\pi} + \frac{\delta^2}{4\pi} \exp \left[ -2\pi^2 \left( \frac{\sigma}{2\pi} \right)^2 \right] \int_0^\infty \! \exp \left[ -2\pi^2 \left( \frac{f - \sigma}{2\pi} \right)^2 \right] df , \quad (6) \]

where \( f_p(0) \) is the EPIF of the source wavelet. Similarly, by inserting equation 4 into equation 5, we obtain

\[ f_p(\tau) = \frac{\sigma}{2\pi} \frac{\delta^2}{4\pi} \exp \left[ -2\pi^2 \left( \frac{\sigma}{2\pi} \right)^2 \right] \int_0^\infty \! \exp \left[ -2\pi^2 \left( f - \sigma \right)^2 \right] df . \quad (7) \]

After analyzing characteristics of the seismic wavelets which are extracted from zero-offset VSP data and poststack seismic data, using the first-order Taylor approximation for equations 6 and 7, we obtain an approximated relationship as follows (Gao et al., 2008)

\[ Q = \pi \delta^2 \kappa(\eta)/(4\pi^2 \Delta f_p) \quad (8) \]

where \( \sigma \) and \( \delta \) are the modulated angular-frequency and the standard deviation of the wavelet, \( \Delta f_p \) is the EPIF variation between the reference pulse and received pulse, \( \kappa(\eta) = 1 - \sqrt{2\pi \eta} e^{-2\pi^2 \phi^2} (2\pi \eta) \), and \( \phi(x) \) is the probability integration of standard normal distribution, i.e., \( \phi(x) = (2\pi)^{-1/2} \int_{-\infty}^x e^{-t^2/2} dt \). We call the method of Q estimation by equation (8) as the WEPIF method for short.

Estimation of Q by equation 8 requires the parameters such as EPIF, traveltime and parameters of the reference pulse to be known.

For a given depth \( z \), wavelet \( u(z,t) \) is a function of time determined by parameters \((A, \delta, \sigma, \varphi)\). Letting \( \psi(t, A, \sigma, \delta, \varphi) \) be the real part of \( u(z,t) \) and \( \psi(t) \) be the reference pulse, the wavelet parameters can be solve a optimal problem

\[ \min_{A, \delta, \sigma, \varphi} \int_{t(z),t} |u(z, t) - \psi(t)| \, dt . \quad (9) \]

For seismic data with a high signal-to-noise ratio (SNR), the IF is usually computed using the derivative of the instantaneous phase. However, field seismic data is usually contaminated by random noise. Large spikes in the IF occur when the denominator of equation 12 approaches zero more rapidly than the numerator suggested that the IF should be replaced by the damped IF when the large spikes are uninterested for our purpose. For stabilization in IF, the damped IF or weighted IF may be employed (Matheney and Nowack 1995). For noisy signals, IFs can also be extracted in the wavelet domain (Gao et al., 1999).
Quality factors estimation using wavelet’s envelope peak instantaneous frequency

Results

We examine the validity of our method using synthetic zero-offset VSP data. Figure 1a shows a 3-layer depth model. Based on this model, we calculate the synthetic seismogram using the method proposed by Ganley (1981). The source signature is a 50 Hz constant-phase wavelet with $\delta = 75$ located at the surface with zero-offset. There are 51 geophones; the interval between two successive geophones between 0 and 400 m is 10 m, while between 400 and 600 m, it is 20 m. The sampling interval in time is 2 ms. For the sake of comparison, we use the LSR, CFS, and WEPIF methods to estimate Q values as shown in Figure 1b. Each of these methods has a few depth ranges in which it can not work. The ranges are on the order of 160-210 and 350-420 m for the LSR method, 150-210 and 320-420 m for the CFS method, and 170-210 and 360-420 m for the WEPIF method. These methods all fail near interfaces due to serious overlapping of reflected waves, such as at 170-210 and 360-420 m, but the WEPIF method works well where direct waves are partially overlapped by reflection waves, such as at 150-170 and 320-360 m. Apparently, the Q values estimated by the WEPIF method are better than those of the LSR and CFS methods. This test shows that the WEPIF method is less sensitive to interference reflections and has a higher resolution.

We then test our method using one-shot zero-offset VSP records of 6-levels as shown in Figure 2a in which the depth range is 3380-3480 m, the sample interval is 1 ms, and the distance between two adjacent geophones is 20 m. The interpretation log shows that the well is drilled through 23.7-m gas sandstone at the target depth of 3395-3470 m. Figure 5b is the Q curve estimated by the LSR, CFS, and WEPIF methods. The depth ranges of target reservoirs are indicated by blue crosses in Figure 2b. Figure 2c shows the natural gamma ray (GR) and acoustic (AC) logs. In general, gas-bearing sandstone has a lower Q and more intensive absorption than other rocks. The lower Q values estimated by the LSR method are at depths of 3420-3480 m, and that estimated by the CFS method are at depths of 3400-3460 m. The intensive absorption zone estimated by our method is at the depth ranges of 3380-3400 and 3420-3440 m, which agrees primarily with the distribution of the gas reservoirs. This test shows that the intensive absorption zone relates to the productive gas reservoir.

We also use reflection seismic data to test the validity of our method. Figure 6a is a poststack seismic profile through wells in a gas field in which the sample rate is 1 ms. We get a $Q^1$-profile as shown in Figure 3b by the WEPIF method. For visualization, we also smooth the result in Figure 3b with a 2-D Gaussian function in the f-k domain and show it...
Quality factors estimation using wavelet’s envelope peak instantaneous frequency

in Figure 3c. Two wells shown in Figure 3b-6c, well 1 (the solid line in white) and well 2 (the dotted line in black), were drilled in this survey. Well 1 is drilled through 16.4 m of gas-bearing sandstone at the target reservoir (Shan 2 layer) and obtained 12.9815 m³/d industrial gas streams, yet well 2 is drilled through only 8 m of sandstone without a developed reservoir and proved to be a dry well. The GR logs and AC logs of wells 1 and 2 are given in Figures 3d and 3e, respectively. At the target depth (around 1.3 s) shown in Figures 3b-3c, well 1 corresponds to an intensive absorption zone, whereas well 2 corresponds to a weak absorption zone. The result also shows a relation between the intensive absorption zone and the well-developed gas reservoir. Based on this observation, we predict a gas well shown as well 3 denoted by a dashed line in purple. Fortunately, well 3 is drilled through 9.2 m of gas-bearing sandstone and obtained an open flow potential of 4.1481 m³/d at the gas test site. The GR logs and AC logs of well 3 are shown in Figure 3f. Although some unavoidable unphysical negative Q values appeared due to factors such as reflection/transmission coefficients and scattering of thin beds, this test shows the validity of our prediction of a gas reservoir based on the Q estimation.

Conclusions

We propose the WEPIF method for estimating $Q$. A test using synthetic VSP data shows that the WEPIF method is more stable, more convenient when selecting parameters, and less sensitive to interface reflections than the LSR and CFS methods. The results of zero-offset VSP data and poststack seismic data show that this method is valid for seismic attenuation estimation and gas reservoir characterization.

Acknowledgements

This work was supported by the NSFC (No. 40730424, and No. 40674074), and the HTRDPC (No. 2006AA09A102).

Figure 3 Q-value estimations of reflection seismic data by WEPIF method, (a) poststack seismic data of a certain gas-field, (b) the $Q^3$ profile, (c) smoothed $Q^3$ profile, and (d)-(f) are the GR logs and AC logs for wells 1-3 respectively. In (b) and (c), wells 1-3 are denoted by solid line in white, dotted line in black, and dashed line in purple, respectively.
EDITED REFERENCES
Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2009 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES
Kjartansson, E., 1979, Constant Q-wave propagation and attenuation: Journal of Geophysical Research, 84, 4737–4748.