Estimating Seismic Attenuation (Q) by an Analytical Signal Method

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Summary

The analytical signal method for seismic attenuation (Q) estimation is reviewed and investigated using a 1D surface data model and field VSP data. The error in Q-factor recovery from modelled data using the analytical signal method is better than 7 percent over a range of Q-factors from 25 to 100. The method is applied to the enhanced downgoing P-wave of an offset VSP-survey from Ross Lake, Saskatchewan. The logarithm of the instantaneous-amplitude ratio versus time-increment plot (an internal step in the method) is surprisingly smooth when compared to log spectral ratios of the same data. The depth average of Q is 34 for clastic rocks of the Ross Lake area. This compares to a Q range of 37 to 41 obtained from the drift correction method over a similar depth range in previous work, which is somewhat lower than a Q of 67 obtained from the spectral ratio method. Errors in Q-estimation by the analytical signal method appear to be caused by insufficient moveout compensation.

Introduction

Seismic quality (Q) or attenuation factors are not only useful for amplitude analysis and improving resolution, but also for information on lithology, saturation, permeability and pore pressure (Calderón-Macias et al., 2004). The motivation for revisiting Q-factor estimation comes from this ever widening field of Q applications. Previous efforts at Q estimation by the authors (Haase and Stewart, 2004) resulted in undesirable error ranges. These uncertainties are nonetheless consistent with other reports in the literature. Some of this uncertainty is likely caused by the use of simplified attenuation models. Lithology-controlled spectral notching, for example, impedes frequency domain methods of Q-factor estimation. All methods suffer when unity transmission coefficients are assumed. When ignoring reflection/transmission phenomena, effective quality factors as opposed to intrinsic Q are estimated. But, even with a simplified attenuation model, improvements are possible. Tonn (1991) points out that, when true amplitude recordings are available, the analytical signal method (which originates in complex trace analysis) is superior. This study describes our efforts of applying the analytical signal method to a surface data model and real VSP-data.

Analytical signal method reviewed

A measured seismic trace u(t) can be described by instantaneous amplitude a(t) and instantaneous phase φ(t) (Taner et al., 1979):

$$u(t) = a(t)\cos\varphi(t) \qquad (1)$$

With the aid of the Hilbert transform, a quadrature trace v(t) is generated from u(t) (Claerbout, 1976; Sheriff, 2002) giving the complex trace z(t) as

$$z(t) = u(t) + iv(t) = 2\int_{0}^{+\infty} U(\omega)e^{i\omega t}d\omega \qquad (2)$$

where $U(\omega)$ is the Fourier transform of $u(t)$.

Also required is the time derivative z'(t) of z(t), which is computed from

$$z'(t) = 2i\int_{0}^{+\infty} \omega U(\omega)e^{i\omega t}d\omega \qquad (3)$$

The instantaneous frequency ω(t) is the time derivative of the instantaneous phase φ(t) and can be computed from (Engelhard et al., 1986):

$$\omega(t) = \frac{d\varphi(t)}{dt} = \frac{z^* z' - zz'^*}{2izz^*} \tag{4}$$

Finally, Q-factors can be obtained from (Tonn, 1991):

$$\ln\left[\frac{a(t_2)}{a(t_1)}\right] = \ln\left[\frac{G_2}{G_1}\right] - \frac{\Delta t}{4Q}\left(\omega(t_1) + \omega(t_2)\right) \tag{5}$$

where $a(t_1)$ and $a(t_2)$ are instantaneous amplitudes at times t_1 and t_2, $\omega(t_1)$ and $\omega(t_2)$ are instantaneous frequencies at times t_1 and t_2, G_1 and G_2 are geometrical spreading factors at times t_1 and t_2, and $\Delta t = t_2 - t_1$.

Tonn (1991) describes three methods for computing Q from Equation 5. His first method is adopted here: Only the maxima of the instantaneous amplitudes are analyzed; Δt is the time difference between those maxima.

Application of the analytical signal method to a 1D surface data model

Dasgupta and Clark (1998) developed a procedure to estimate Q from offset dependent seismic data by applying the spectral ratio method. A similar approach, but using the analytical signal, is taken in this modelling study. 1D-model traces (no spherical spreading and a unity reflector) are generated for a reflector at 500 m depth, assuming a range of offsets (0 to 2000 m) and Q-factors (25, 50 and 100). The reference velocity is set to 3 km/s at 10 kHz and a zero phase 8/12-80\100 Hz Ormsby wavelet is assumed. Figure 1 shows model traces for Q=50 (in black) and their instantaneous amplitudes (in red) computed from Equation 2 and

$$a(t) = \sqrt{\left(u^2(t) + v^2(t)\right)} \quad . \tag{6}$$

Amplitude decay with offset and time delay with offset are apparent. For each instantaneous amplitude trace, the maximum a_{max} of a(t) and the time t_{max} of this envelope maximum are noted. Figure 2 shows these amplitude maxima as a function of offset for all three Q-factors considered. Equation 5, which can be regarded as a linear equation with intercept $\ln[G_2/G_1]$ and slope $(\omega(t_1)+\omega(t_2))/4Q$, is used next. From suitably selected values of Δt and the corresponding $(\omega(t_1)+\omega(t_2))$ as well as $\ln[a(t_2)/a(t_1)]$, Q can be computed. Table 1 compares Q-values thus determined and initial model Q's. The departure is thought to be caused by less than perfect fitting of amplitude maxima curves in Figure 2.

Table 1:

Q_{model}	25	50	100
$Q_{estimate}$	23.4	49.4	103.1
Percent Error	-6.4	-1.2	3.1

Application of the analytical signal method to VSP-data

The enhanced downgoing P-waves shown in Figure 3 (offset VSP data from Ross Lake, Saskatchewan) are used to compute instantaneous amplitude traces a(t) with the aid of Equations 2 and 6. Following that, one trace at a time, a search for the maximum of a(t) is conducted and the time t_{max} of this envelope maximum is noted. Next, from Equations 2, 3 and 4, instantaneous frequencies ω(t) are determined. Finally, a range of Q-factors is assumed, the corresponding range of log-spreading-factor-ratios is computed from Equation 5 and the results are plotted in Figure 4. Note that, for each curve in Figure 4, $\Delta t = t_{max2} - t_{max1}$ is different, but all Δt are centred on the same depth. The correct Q and the correct log-spreading-factor-ratio occur at the intersection point of the curves. It should also be noted that smoothing has been applied to a(t) and ω(t).

As in the modelling section above, Equation 5 is regarded as a linear equation with intercept $\ln[G_2/G_1]$ and slope $(\omega(t_1)+\omega(t_2))/4Q$. Figure 5 shows a plot of $\ln[a(t_2)/a(t_1)]$ versus Δt at various depth levels. These curves are the equivalent of the linear relationship between $\ln[A_2(\omega)/A_1(\omega)]$ and ω familiar from the log-spectral ratio method. Q-factors can be determined by least-squares error fitting of straight lines to the curves in Figure 5. The resulting Q-factors as a function of depth are shown in Figure 6. The range of P-wave Q-factors observed in Figure 6 is about $23 < Q_p < 45$ for depths from 300 m to 900 m, giving an average of 34. By comparison, $37 < Q_p < 41$ was found for a similar depth range from the drift correction method applied to Ross Lake VSP data in pevious work (Haase and Stewart, 2004), which is somewhat lower than a Q of 67 obtained from the spectral ratio method. Q-estimation errors of the analytical signal method appear to be caused by insufficient moveout compensation. This point needs to be addressed by sensitivity analysis.

Conclusions

This study revisits the analytical signal method for Q-factor extraction. The curves in Figure 5 are much smoother than the log-spectral ratio method examples shown in previous work (Haase and Stewart, 2004). Most of this difference is apparently caused by spectral notching. The possibility of averaging Q-factors computed for adjacent depth levels and deriving uncertainty information from Q-scatter appears promising for VSP data. The Q-factor determined from the VSP data is in the range expected for clastic sediments, although lower than that determined from the spectral ratio method.

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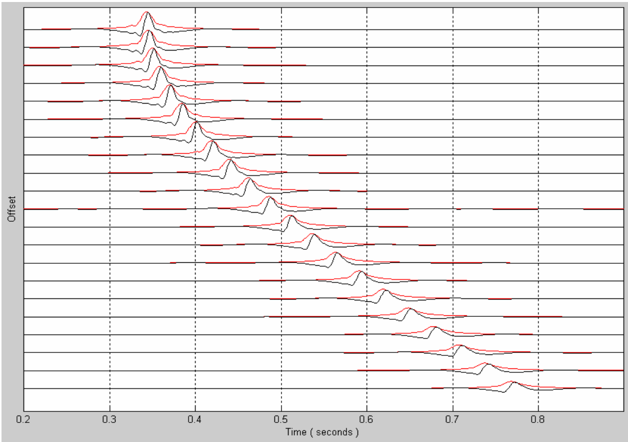

Fig.1: Offset dependent model traces for Q=50 and z=500 m using a 8/12-80\100 Hz zero phase Ormsby wavelet.

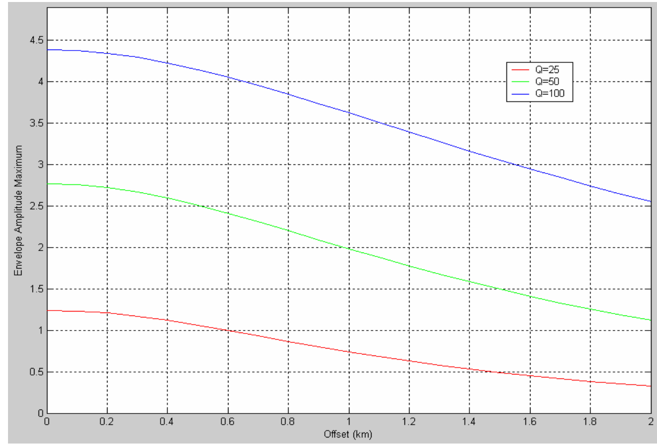

Fig.2: Trace envelope maxima for a range of Q-factors as a function of offset, same model parameters as Fig.1.

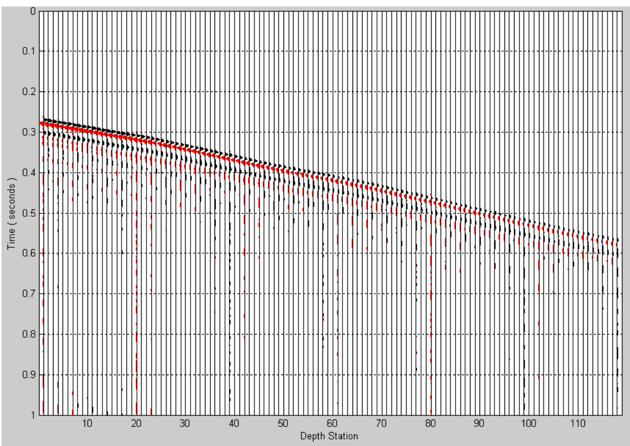

Fig.3: Enhanced downgoing P-wave from the 400 m offset VSP, Ross Lake, Saskatchewan (vertical vibe).

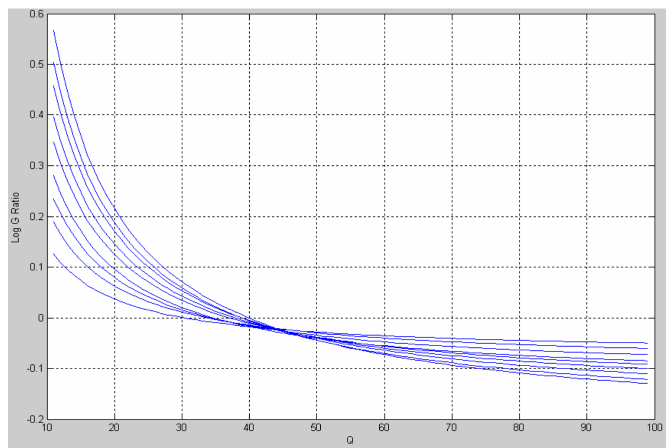

Fig.4: Log G ratio versus Q at 303 m depth. Each curve represents a single pair of points centred on 303 m depth.

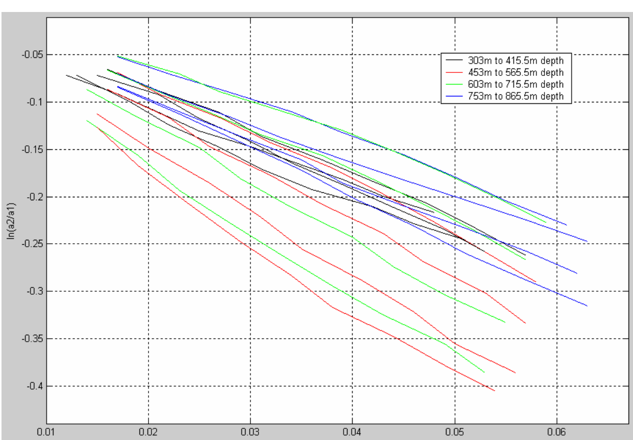

Fig.5: Log amplitude ratio $\ln(a_2/a_1)$ as function of Δt. Each curve represents a diagram like Fig.4 at a specific depth.

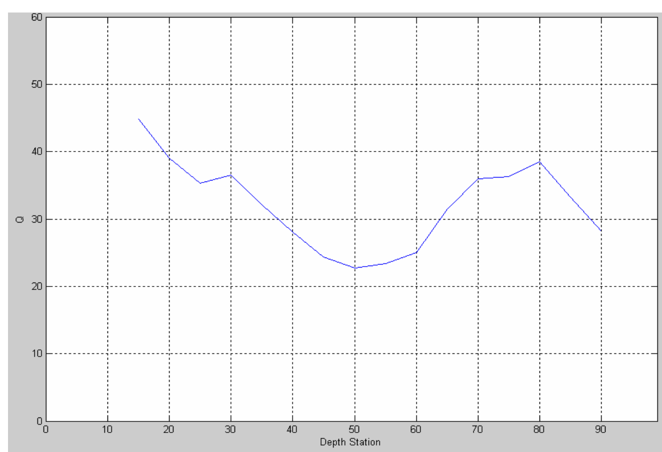

Fig.6: Q as a function of depth. These values are computed from the slope of straight lines fitted to curves in Fig.5.