Estimating seismic attenuation (Q) from VSP data at a heavy oilfield: Ross Lake, Saskatchewan

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ABSTRACT

The analytical signal method is used for seismic attenuation (Q) estimation from VSP data acquired at Husky Energy Inc.'s Ross Lake oilfield, Saskatchewan. Q estimation is conducted on downgoing P-wave and upgoing converted-wave data. The logarithm of the instantaneous-amplitude ratio versus time-increment plot is surprisingly smooth for downgoing P-waves and converted-waves. The resultant estimates are: $Q_p \approx 43$ at 300m depth and $Q_s \approx 28$ at 930m.

INTRODUCTION

Seismic quality (Q) or attenuation factors are not only useful for amplitude analysis and improving resolution, but for information on lithology, saturation, permeability and pore pressure (Calderón-Macias et al., 2004). The widening field of Q applications motivates revisiting Q-factor estimation. Previous efforts at Q estimation from the Ross Lake data (see Haase and Stewart, 2003) resulted in considerable error ranges. These results are in keeping with reports in the literature, but nonetheless disappointing. Some of this uncertainty must surely be caused by our 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 (also referred to as complex trace analysis) is superior. This report describes our efforts of applying the analytical signal method to the Ross Lake VSP data.

ANALYTICAL SIGNAL METHOD REVIEWED

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

$$u(t) = a(t)\cos\varphi(t) . \tag{1}$$

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

$$z(t) = u(t) + iv(t) = 2\int_0^{+\infty} U(\omega)e^{i\omega t}\,d\omega . \tag{2}$$

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

$$z'(t) = 2i \int_0^{+\infty} \omega U(\omega) e^{i\omega t} d\omega . \quad (3)$$

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

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

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

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

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 with $\omega = 2\pi f$, 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 METHOD

First, the enhanced downgoing P-waves from the Ross Lake offset VSP-data (Figure 1) are used to compute a trace-envelope (Figure 2) using Equation 2 and

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

Second, one trace at a time, we search for the maximum of $a(t)$ and take note of the time t_{max} of this envelope maximum. Third, from Equations 2, 3 and 4, instantaneous frequency $\omega(t)$ is determined.

Last, we assume a range of Q-factors, compute the corresponding range of log-spreading-factor-ratios from Equation 5 and plot the results (Figure 3). Note that, for each curve in Figure 3, $\Delta t = t_{max2} - t_{max1}$ 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 $\omega(t)$. The upgoing converted-waves are shown in Figure 4 and the computed trace envelopes are plotted in Figure 5 (400m-offset VSP). Applying the same procedure as in the P-wave case gives the $\ln[G_2/G_1]$ versus Q_s plots shown in Figure 6. The event followed starts just beyond 700ms at maximum depth.

DISCUSSION AND CONCLUSIONS

Equation 5 can be regarded as a linear equation with intercept $\ln[G_2/G_1]$ and slope $(\omega(t_1)+\omega(t_2))/4Q$. Figure 7 shows a plot of $\ln[a(t_2)/a(t_1)]$ versus Δt for P-waves 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 7. The $\ln[G_2/G_1]$ versus Q plot shown in Figure 3 gives the option of picking Q and intercept simultaneously. Here we estimate $Q_p \approx 43$. Plots like Figure 3 can be generated for a range of depth levels resulting in a Q versus depth display. Then Q for adjacent depth levels can be averaged, and the Q-scatter provides uncertainty information.

Converted waves are typically generated by P-waves impinging on a surface at non-normal incidence (e.g., from nonzero-offset VSP experiments). The upgoing converted or PS waves shown in Figure 4 have been isolated from the total wavefield of a 400m offset VSP. In contrast to the maximum instantaneous amplitude search for downgoing P-waves, here we need to pick and track one event out of many. Note the time scale difference between Figures 1 and 4. Because we are dealing with an upgoing event, we now take a "bottom up" approach. From Figure 6 we estimate $Q_s \approx 28$. The area of intersection in Figure 6 is not as concise as it is for the P-wave case in Figure 3, meaning uncertainty of Q_s-estimation is increased. The $\ln[a(t_2)/a(t_1)]$ versus Δt plot for C-waves given in Figure 8 shows the reason. Departure from straight lines is more severe for the C-wave case of Figure 8 when compared to the P-wave case in Figure 7. The two outliers in Figure 6 are probably caused by outliers in Figure 8. It will be interesting to correlate straight line departures with local reflectivity.

The above observations represent a first look at complex trace analysis. All results need to be verified by synthetic examples. However, even at a first glance, the curves in Figure 7 are much smoother than the log-spectral ratio method examples shown in a previous report (Haase and Stewart, 2003). The main difference is apparently caused by spectral notching. The ability to extract S-wave Q from offset VSP-data without a shear wave source appears promising.

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ACKNOWLEDGEMENTS

Thank you to Husky Energy Inc., in particular Mr. Larry Mewhort, for release of the VSP-data.

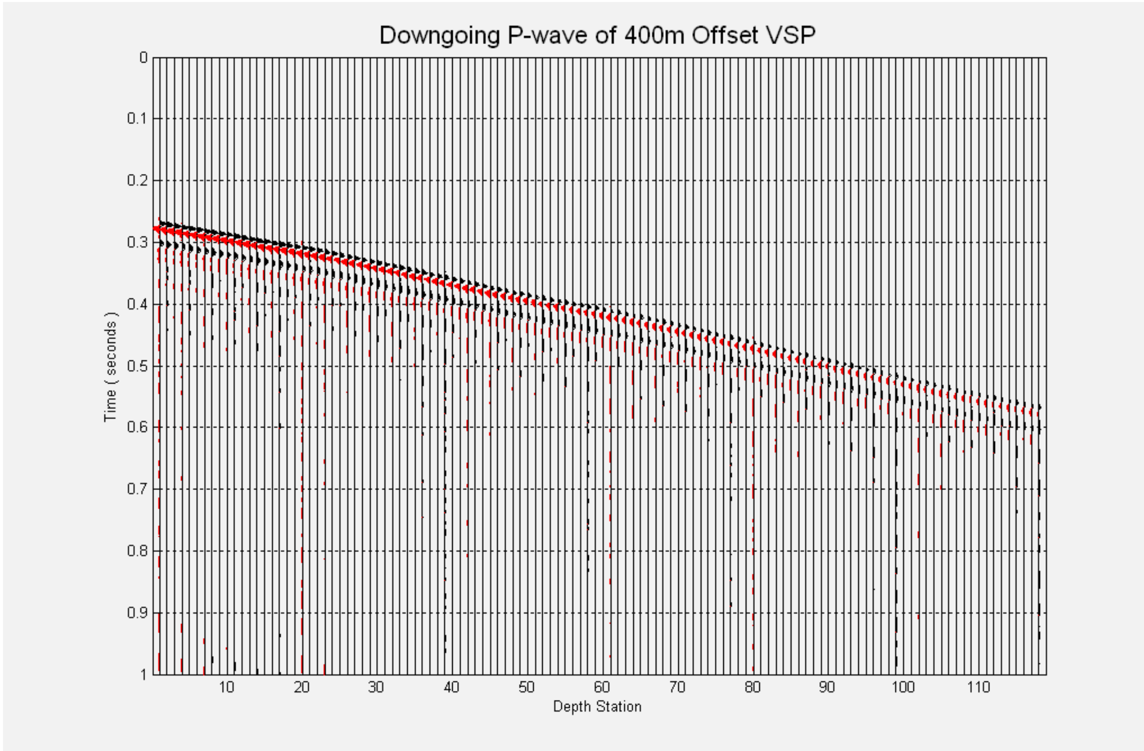

FIG. 1. Downgoing P-wave data from the Ross Lake offset VSP.

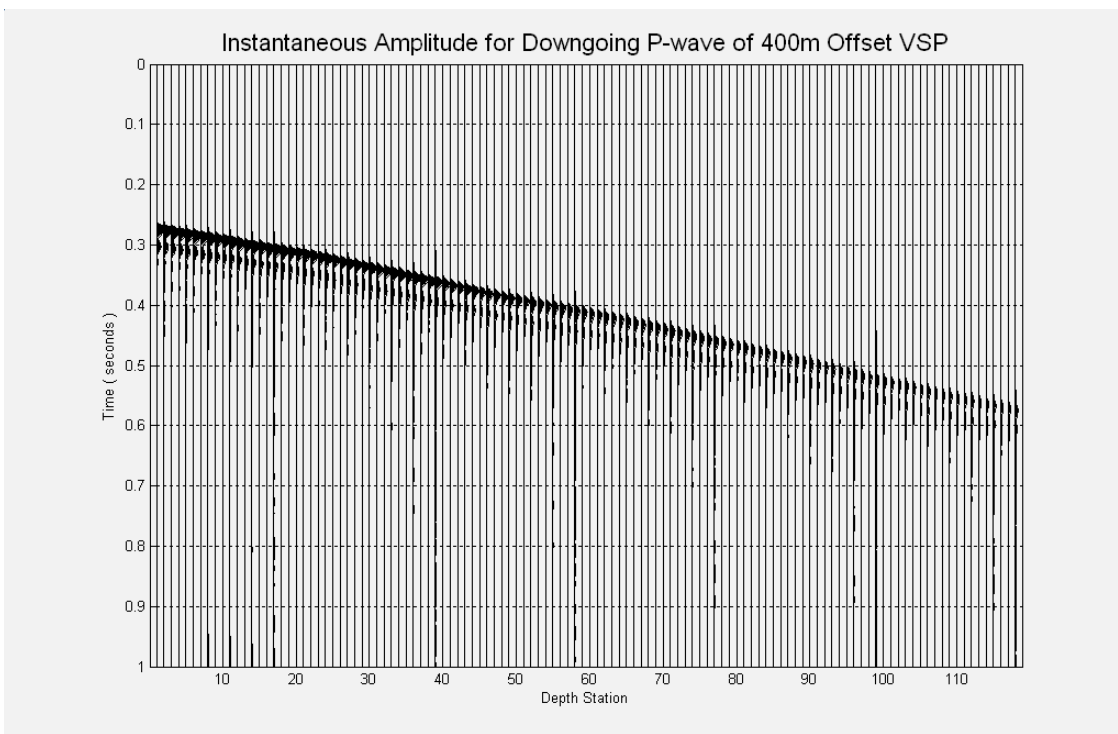

FIG. 2. Instantaneous amplitude of the Ross Lake VSP data shown in Figure 1.

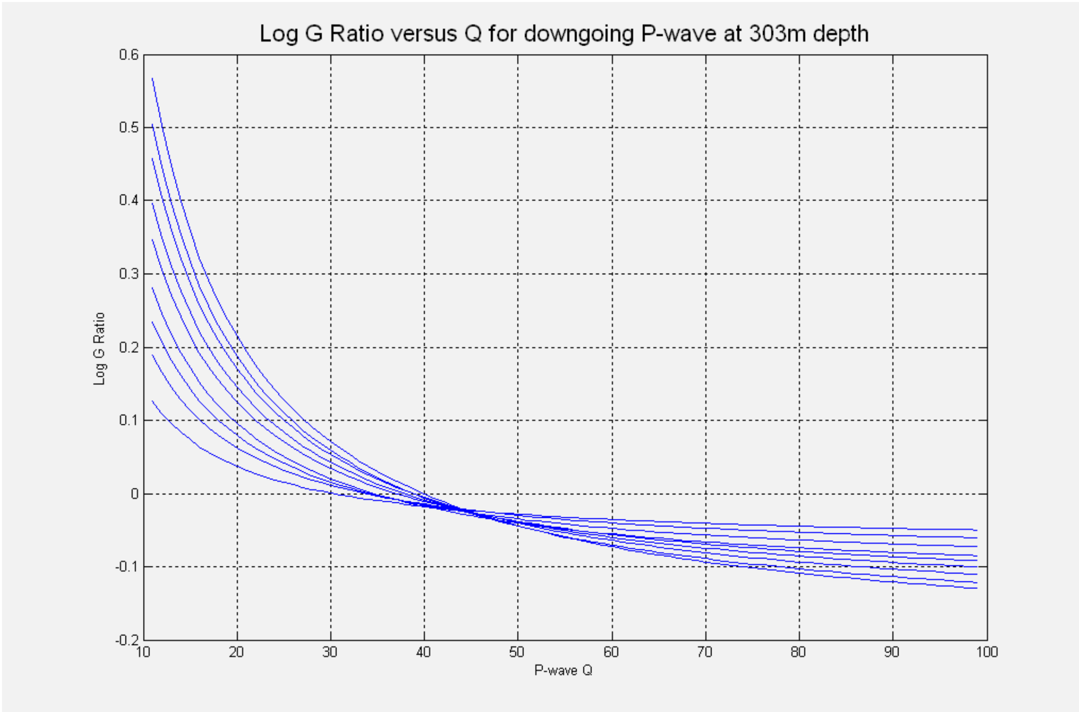

FIG. 3. Log spreading ratio versus Q for P-wave.

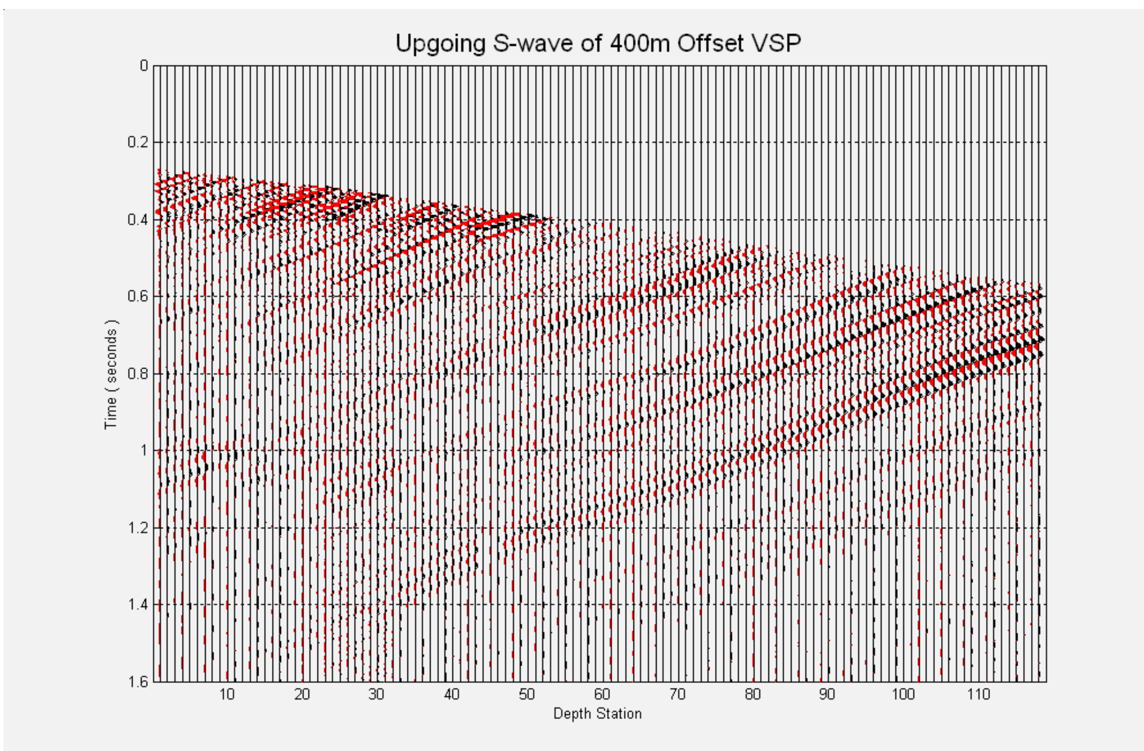

FIG. 4. Upgoing converted-waves.

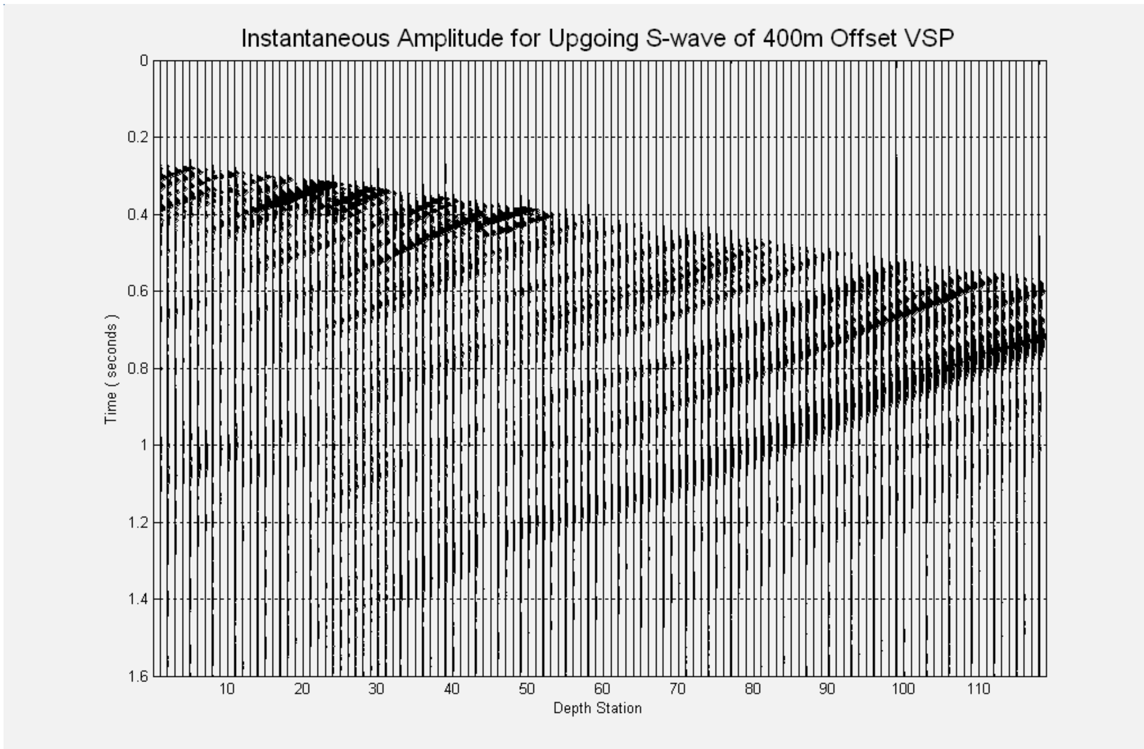

FIG. 5. Converted-wave instantaneous amplitude.

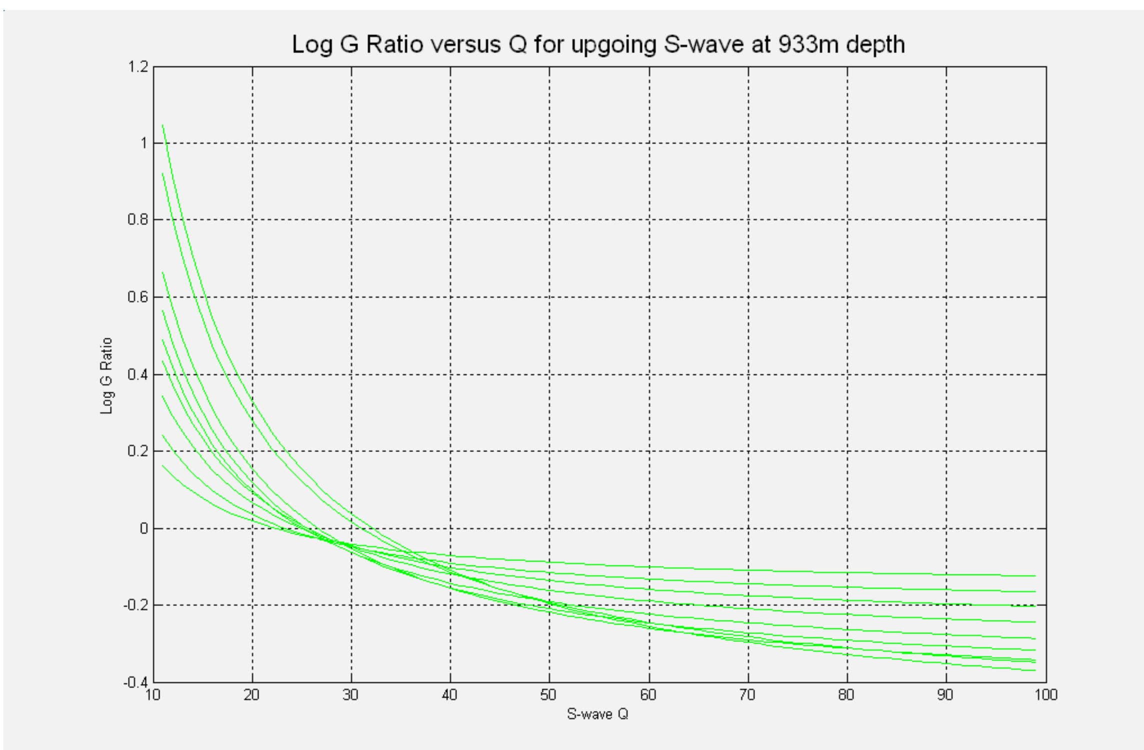

FIG. 6. Log spreading ratio versus Q for C-wave.

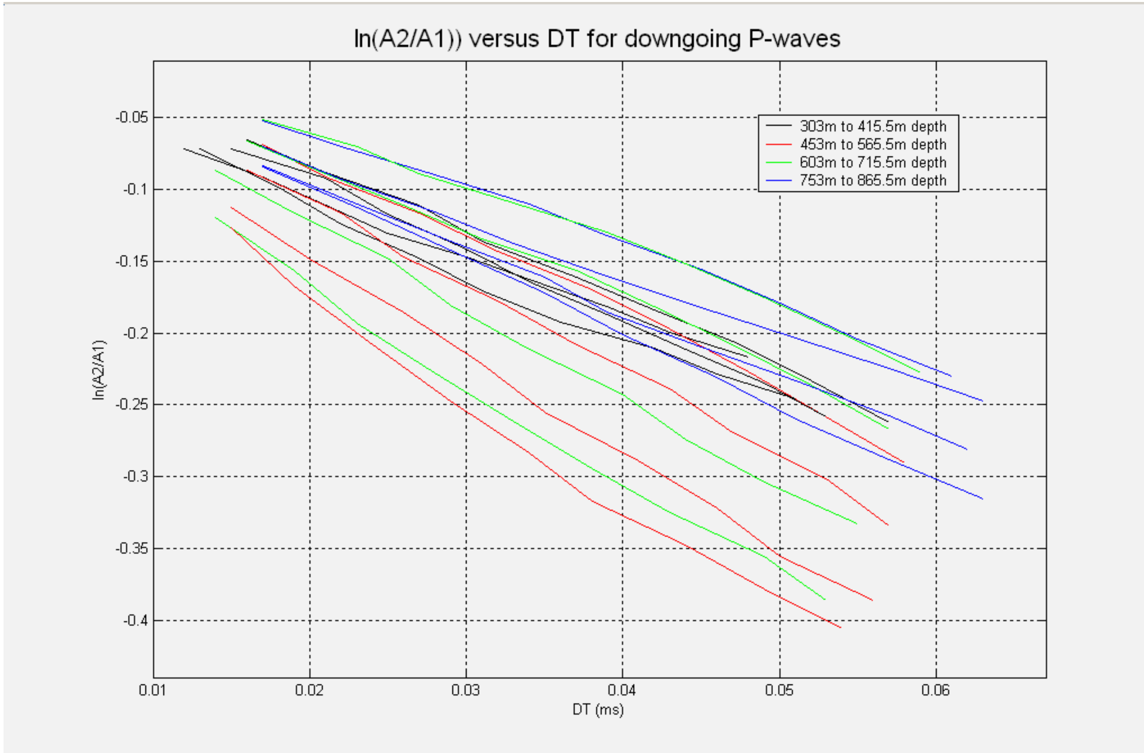

FIG. 7. Log amplitude ratio versus DT for P-wave.

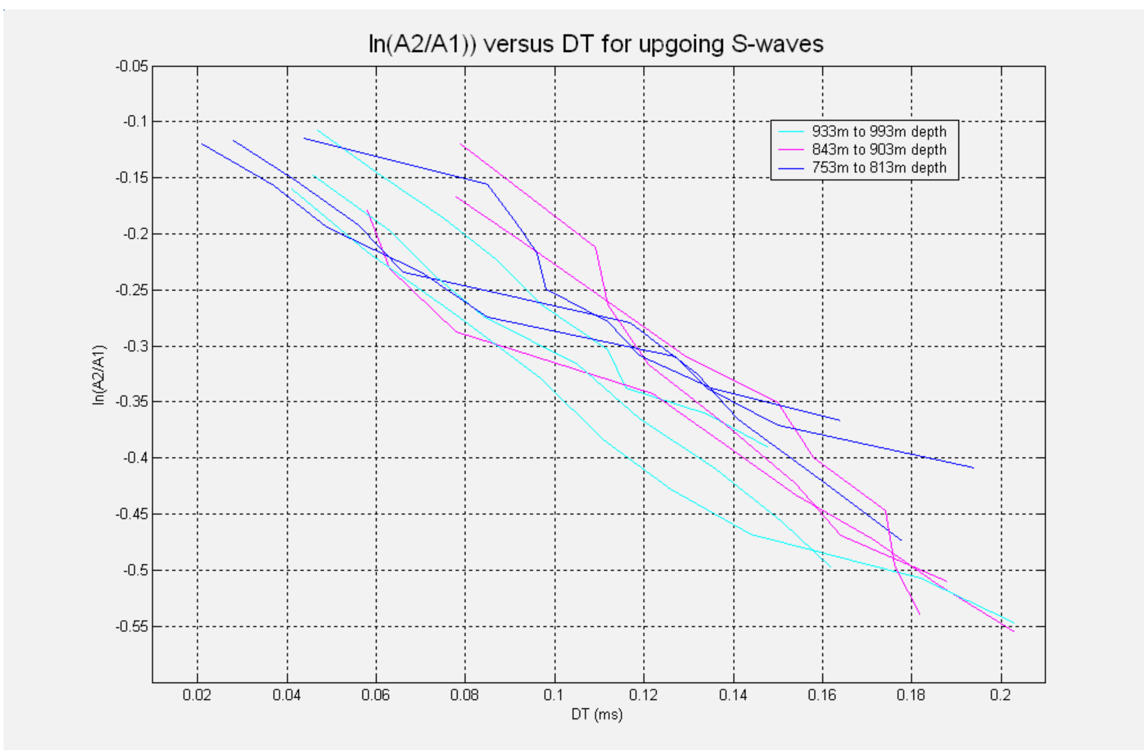

FIG. 8. Log amplitude ratio versus DT for PS-wave.