Attenuation (Q) from VSP and Log Data: Ross Lake, Saskatchewan

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Summary

VSP data and well log information from the Ross Lake oilfield, Saskatchewan (Husky Energy Inc.) are used to estimate P-wave and S-wave attenuation (Q-factors). We used both vertical and horizontal vibrators as sources and a downhole three-component tool. From the spectral ratio method, results are obtained for Q_P as well as Q_S. We estimate an average Q_P, over an interval of 200-1200m, to be 67 from the spectral ratio technique, and about 40 from drift curves. Q_S estimates over the same interval are 23 from the spectral ratio method and about 37 from "guesstimated" S-wave drift curves.

Introduction

Velocities are usually considered independent of frequency in seismic exploration, implying a purely elastic earth. However, discrepancies between seismic travel times and integrated sonic travel times had been observed early on (Gretener, 1961). Eventually, velocity dispersion was discovered to be a primary cause of the discrepancy (Stewart et al., 1984). This velocity dispersion is caused by anelasticity and its frequency dependence can be quantified by a frequency independent quality factor Q (Kjartansson, 1979). Q-factors are not only useful for improved resolution and amplitude analysis (Chopra, 2003) but can also be considered additional geophysical parameters (Dasgupta and Clark, 1998; Taner and Treitel, 2003). A variety of methods have been developed to estimate the Q-factor from VSP-data. Jannsen et al. (1985) and Tonn (1991) compare many of these methods and conclude that none of these approaches is significantly better than the others in all situations. Tonn (1991) states that, if true amplitude recordings are available, the analytical signal method is superior; otherwise, in noise-free cases, the spectral ratio method is optimal. If well-log information is available in addition to VSP-data, then other Q-estimation methods can be devised. VSP and well-log data sets from the Ross Lake oilfield in Saskatchewan (Husky Energy Inc.) are used to demonstrate the spectral ratio method and the drift correction method of Q-estimation on downgoing P-waves and downgoing S-waves.

Q-Estimation Methods Considered in This Study

Spectral Ratio Method

The spectral ratio method uses the changes in spectra at different depth levels to compute an attenuation factor (e.g. Tonn, 1991):

$$\ln\left[\frac{|A_2(\omega)|}{|A_1(\omega)|}\right] = (const.) - \omega\frac{d}{2cQ} \qquad (1)$$

where $A_1(\omega)$ and $A_2(\omega)$ are spectral amplitudes at different depths, $\omega = 2\pi f$ is the frequency, d is the travel distance, c is the travel velocity and Q is the quality factor. For frequency independent Q, Equation (1) represents a straight line as function of frequency. Q can be computed from Equation (1) when the slope of the log spectral ratio is determined from VSP-data.

Drift Correction Method

Stewart et al. (1984) derived an equation for the calculation of delay times (drift) from travel times, frequency ratios and Q:

$$t_{delay} = \frac{d\ln(\omega_2/\omega_1)}{V(\omega_2)\cdot\pi\cdot Q}, \quad \text{or} \quad Q = \frac{t_P\ln(\omega_2/\omega_1)}{\pi\cdot t_{delay}} \quad . \qquad (2)$$

where t_{delay} is the difference between seismic travel time and integrated sonic time, d is the travel distance, $V(\omega_2)$ is the sonic velocity {giving the sonic P-wave travel time as $t_P = d/V(\omega_2)$}, Q is the quality factor, ω_1 is the corner frequency of the seismic band and ω_2 is the frequency of the sonic measurement (12kHz).

Empirical Equation Method

Waters(1978) observes an empirical relationship between measured Q_P and velocities from a log-log plot of $1/Q_P$ versus velocity:

$$1/Q_P = \left(\frac{const.}{V_P}\right)^2 \tag{3}$$

where V_P is given in feet per second and the const. is approximately 10^3.

Waters(1978) and also Udias(1999) review a relationship between Q_P and Q_S which was derived assuming that there is no dissipation during a purely compressional cycle:

$$Q_S = Q_P \frac{4}{3}\left(\frac{V_S}{V_P}\right)^2 \tag{4}$$

Modelling Methods

Sonic velocities are measured at frequencies well above the seismic signal band, usually around 12kHz. When synthetic seismograms are computed with sonic velocities alone, a time shift or drift between "synthetic" events and actual seismic data events is observed. Q-factors can be estimated by adjusting this time shift to zero. We note that many logs are "calibrated" by applying a check-shot calculated drift curve to the raw integrated sonic times. The two methods chosen for this study are convolutional modelling (no multiples) and wave equation modelling (all orders of multiples). The frequency domain algorithms utilized in these modelling approaches compute one synthetic seismogram for every frequency point.

Results

Spectral Ratio Method

Figure 1 shows the downgoing P-wave of the 54m offset Ross Lake VSP. For plotting purposes the trace amplitudes are equalized. There is a visible stretch of the second peak (and trough) at deeper receivers, which is indicative of a narrowed spectral band. Averaged amplitude spectra of the five shallowest receivers (green) and the five deepest receivers (red) are plotted in Figure 2. These two amplitude spectra are input for the spectral ratio method. For the deeper signal (red) the background noise floor is reached at about 150Hz. This means no useful spectral ratio can be expected beyond about 150Hz. Note that the P-wave source sweep went from 8Hz up to 180Hz. Figure 3 displays the ratio computed with a 5Hz smoother from the amplitude spectra in Figure 2. As expected, the ratio is invalid beyond about 150Hz. The slope of the least squares fitted straight line results in a Q-factor of approximately 67.

Figure 4 gives the downgoing S-wave from a 54m offset horizontal vibrator source. Again, true amplitudes are not shown because of trace amplitude equalization. Similar to Figure 2, the averaged amplitude spectra of the downgoing S-wave are shown in Figure 5. The S-wave spectrum at depth reaches the noise floor around 40Hz. Accordingly, the corresponding spectral ratio displayed in Figure 6 (computed with a 1Hz smoother) is invalid beyond about 40Hz. The S-wave source sweep went from 5Hz up to 100Hz. A straight line least squares fit of Figure 6 between about 10Hz and 40Hz gives a Q-estimate of approximately 23.

Drift Correction Method

The Ross Lake P-wave log was recorded between 340m and 1180m of depth. The average transit time is found to be in the range from 400µs/m to 450µs/m. From the supplied drift gradients, t_{delay} is calculated to be approximately 15ms over the entire depth range. The corner frequency $f_1 = \omega_1 / 2\pi$ of the seismic wavelet is determined to be f_1 = 70 Hz (from Figure 2). Introducing these numbers into Equation (2) gives the range of effective Q_P over the measured depth interval as $36.7 < Q_P < 41.3$.

No drift curve is available for the Ross Lake S-wave log. Note that the log analyst thought that the S-wave log, which was conducted, was very poor to unacceptable. The drift is estimated from snippets of energy in the shear log between 235m and 355m depth giving a transit time of 1.417 ms/m. From a geometry-corrected seismic S-wave travel time of about 179ms for the same VSP depth interval (downgoing S-wave), drift is calculated to be about 9ms. With a shear-wavelet corner frequency $f_1 = \omega_1 / 2\pi$ of about 25Hz (from Figure 5), shear-Q is calculated by introducing these numbers into Equation (2) as $Q_S = 37$.

A good signal area of the S-wave log exists between 630m and 775m depth. This is the highest S-wave velocity area of the Ross Lake VSP-measurement. The range of sonic interval travel times here is found to be 123ms to 130ms and the geometry-corrected seismic travel time is 124ms. Calculated drift ranges from very small to negative, meaning the Q-factor must be large (exceeding 100) in this high velocity interval. Both depth intervals investigated span over three wavelengths each at 25Hz.

Empirical Equation Method

Velocities are obtained from the travel times in Figures 1 and 4 (and applying geometry corrections) as V_P = 2302 m/s and V_S = 888 m/s . Q_P is found to be 57 from Equation (3). Introducing these values into Equation (4) gives Q_S = 11.3 . This is well below the other estimates which casts doubt on the assumptions made in deriving Equation (4).

Modelling Methods

A synthetic trace is computed from the P-wave sonic log and density log by invoking the convolutional model and assuming Q=80 (not shown). The time shift of the deepest reflection when compared to the elastic case (Q>1000) corresponds to 15ms of P-wave drift, which is the total drift value derived from the well-log. Thus, from convolutional modelling, a Q-factor of about 80 is obtained. Lowering the Q-factor also diminishes amplitudes. This additional information is potentially useful but ignored thus far.
The wave equation modelling approach is work in progress. No results are available at the time of writing.

The results are summarized in the following Table.

Method	Spectral Ratio	Drift Correction	Empirical Equation	Convolutional Modelling
Q_P	67	37 to 41	57	80
Q_S	23	37	11.3	

Table 1. Summary of Q estimates for P-waves and S-waves for the methods under consideration.

Conclusions

Reasonable values of Q_P and Q_S are found when applying the spectral ratio method to downgoing P-waves and downgoing S-waves at different depth levels. Ideally, spectral ratios are straight lines as function of frequency. In reality, spectral smoothing must be applied to “noisy” spectral ratios. Q-factor estimation from drift corrections leads to lower (by about 40%), but still reasonable, P-wave values when compared to the spectral ratio method. A drift correction Q-estimation attempt for S-wave Q-factors gives values well above the spectral ratio results because of unreliable shear log information. S-wave Q-factors well below the spectral ratio results are obtained when an empirical equation is employed.

Acknowledgements

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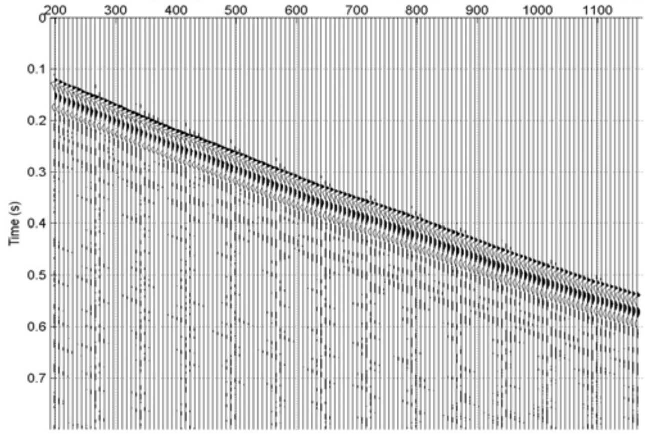

Figure 1. Downgoing P-Wave (depth(m) vs. time(s))

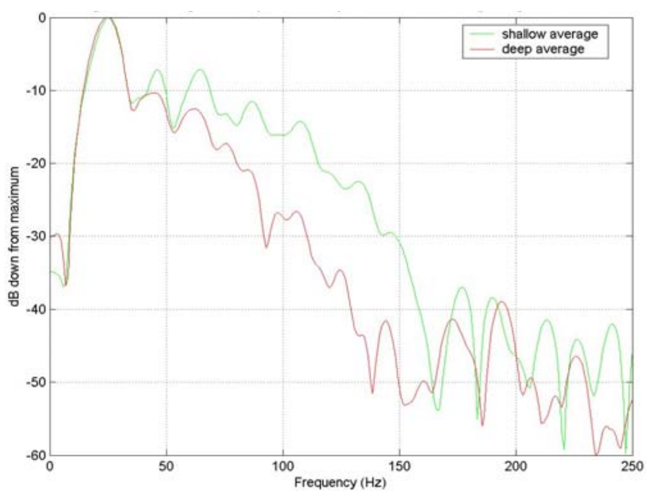

Figure 2. Averaged Amplitude Spectra of P-Wave

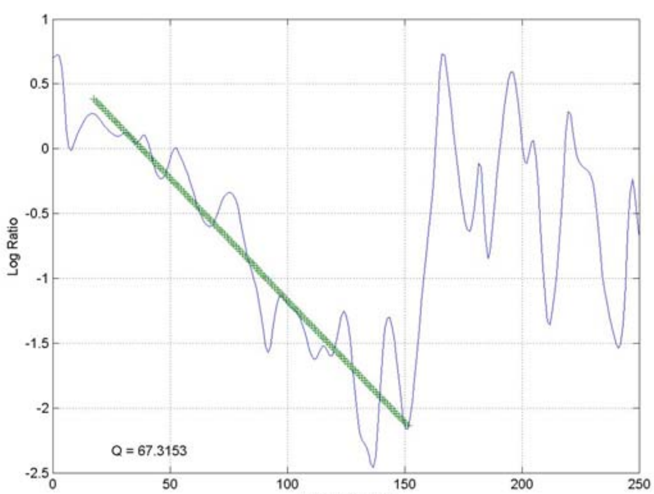

Figure 3. Spectral Ratio Plot of Downgoing P-Wave

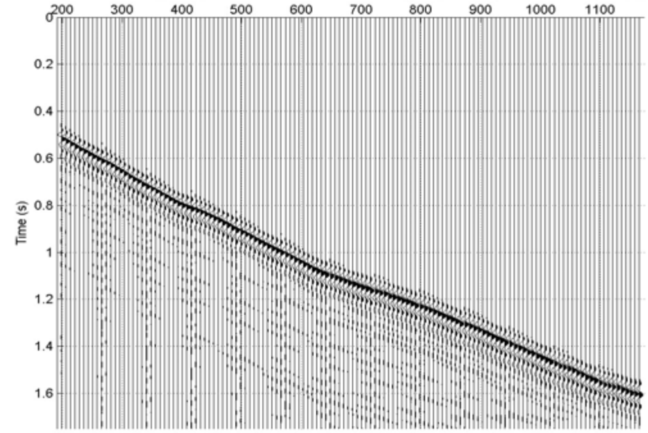

Figure 4. Downgoing S-Wave (depth(m) vs. time(s))

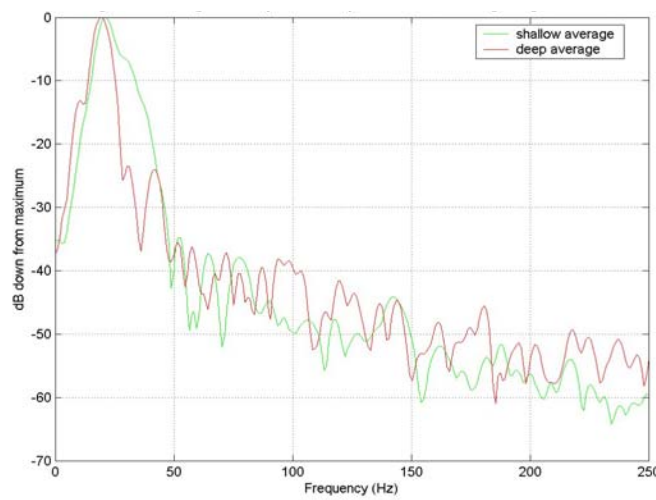

Figure 5. Averaged Amplitude Spectra of S-Wave

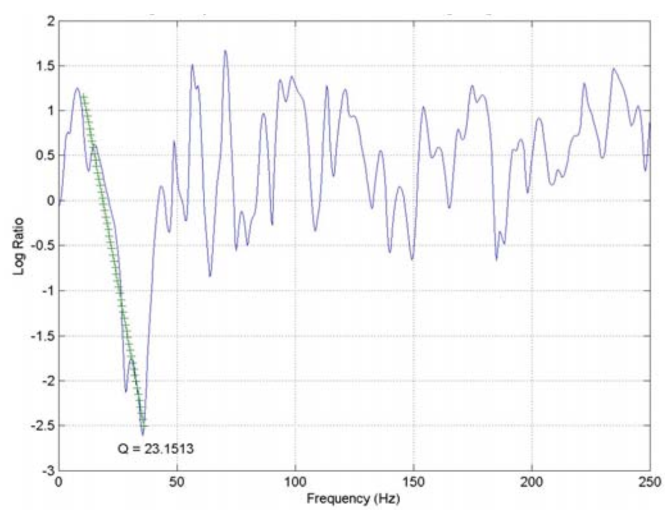

Figure 6. Spectral Ratio Plot of Downgoing S-Wave