Q-factor estimation from borehole seismic data: Ross Lake, Saskatchewan

Arnim B. Haase and Robert. R. Stewart

ABSTRACT

VSP data and well log information from the Ross Lake oilfield, Saskatchewan (Husky Energy Inc.) are used to estimate P-wave and S-wave quality-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, about 40 from drift curves, and 80 from convolutional model data matching. 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. Sonic velocities are measured at frequencies well above the seismic signal band, usually around 12 kHz. 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.

VSP and well-log data sets from the Ross Lake oilfield in Saskatchewan (Husky Energy Inc.) is used to demonstrate the spectral ratio method and the drift correction method of *Q*-estimation on downgoing P-waves and downgoing S-waves.

SPECTRAL RATIO METHOD FOR ESTIMATING Q

Figure 1 shows the downgoing P-wave of the zero offset Ross Lake VSP. Because of trace amplitude equalization, true amplitudes are lost. There is a visible stretch of the second peak (and trough) at deeper receivers, which is indicative of a narrowed spectral band. The spectral ratio method uses the changes in spectra at different depth levels to compute an attenuation factor (e.g. Tonn, 1991):

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

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.

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 150 Hz. This means no useful spectral ratio can be expected beyond about 150 Hz. Note that the P-wave source sweep went from 8 Hz up to 180 Hz. Figure 3 displays the ratio computed with a 5 Hz smoother from the amplitude spectra in Fig.2. As expected, the ratio is invalid beyond about 150 Hz. 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 53 m offset horizontal vibrator source. Again, true amplitudes are lost 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 40 Hz. Accordingly, the corresponding spectral ratio displayed in Figure 6 (computed with a 1 Hz smoother) is invalid beyond about 40 Hz. The S-wave source sweep went from 5 Hz up to 100 Hz. A straight line least squares fit of Figure 6 between about 10 Hz and 40 Hz gives a Q-estimate of approximately 23.

DRIFT CORRECTION METHOD FOR ESTIMATING Q

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

$$t_{delay} = \frac{d \ln(\omega_2 / \omega_1)}{V(\omega_2)\pi Q}, \tag{2}$$

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 (12 kHz).

Equation (2) can be rearranged for Q as

$$Q = \frac{t_P \ln(\omega_2 / \omega_1)}{\pi t_{delay}}. \tag{3}$$

The Ross Lake P-wave log was recorded between 340 m and 1180 m of depth. The average transit time is found to be in the range from 400 µs/m to 450 µs/m. From the supplied drift gradients, t_{delay} is calculated to be approximately 15 ms over the entire depth range. The corner frequency $f_1 = \omega_1 / 2\pi$ of the seismic wavelet is determined to be 70 Hz (from Figure 2). Introducing these numbers into Equation (3) gives the range of effective Q_P over the measured depth interval as $36.7 \le Q_P \le 41.3$.

No drift curve is available for the Ross Lake S-wave log. Note that the log analyst thought that the S-wave log was very poor to unacceptable (CREWES was not charged for it). The drift is estimated from snippets of energy in the shear log between 235 m and 355 m depth giving a transit time of 1.417 ms/m. From a geometry-corrected seismic S-wave travel time of about 179 ms for the same VSP depth interval (downgoing S-wave), drift is calculated to be about 9 ms. With a shear-wavelet corner frequency (f_1) of about 25 Hz (from Figure 5), Equation (3) yields a value of $Q_S = 37$.

A good signal area of the S-wave log exists between 630 m and 775 m 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 123 ms to 130 ms and the geometry-corrected seismic travel time is 124 ms. 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 25 Hz. When an empirical equation given by Udias (1999) is employed,

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

shear-Q is found to be $Q_S = 12$.

Q-ESTIMATES FROM MODELLING

Figure 7 shows synthetic traces computed from the P-wave sonic log and density log by invoking the convolutional model. A minimum-phase Butterworth wavelet is assumed (10 Hz to 95 Hz). The green trace represents $Q = 1000$ and the red trace was computed for a Q-factor of 90. The time shift between both traces (approximately 30 ms two way time) corresponds to15 ms 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 here. The frequency domain algorithm utilized in this modelling approach computes one synthetic seismogram for every frequency point. Note that internal multiples (or any multiples) are not modelled in Figure 7.

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. Delay time matching by convolutional modelling gives Q_P values somewhat above the spectral ratio results (by about 20%).

ACKNOWLEDGEMENTS

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

REFERENCES

Chopra, S., 2003, Enhancing seismic frequency bandwidth using VSPs-a case study: Oil & Gas Journal, Oct.20, 2003, 38-43.

Dasgupta, R., and Clark, R.A., 1998, Estimation of Q from surface seismic reflection data: Geophysics, **63**, 2120-2128.

Gretener, P.E.F., 1961, An analysis of the observed time discrepancies between continuous and conventional well velocity surveys: Geophysics, **26**, 1-11.

Jannsen, D., Voss, J., and Theilen, F., 1985, Comparison of methods to determine Q in shallow marine sediments from vertical reflection seismograms: Geophysical Prospecting, **23**, 479-497.

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

Stewart, R.R., Huddleston, P.D., and Tze Kong Kan, 1984, Seismic versus sonic velocities: A vertical seismic profiling study: Geophysics, **49**, 1153-1168.

Taner, M.T., and Treitel, S., 2003, A robust method for Q estimation: 73rd Ann. SEG Mtg., Expanded Abstracts, paper IT3.6.

Tonn, R., 1991, The determination of seismic quality factor Q from VSP data: A comparison of different computational methods: Geophys. Prosp., **39**, 1-27.

Udias, A., 1999, Principles of seismology: Cambridge University Press, page 260.

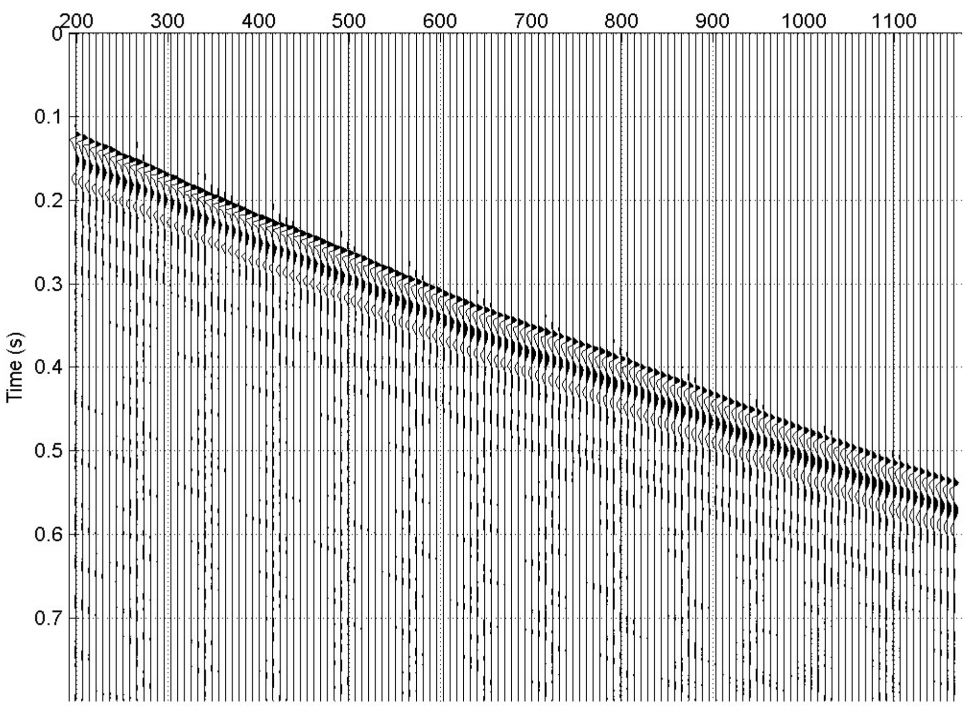

FIG. 1. Downgoing P-Wave, Ross Lake (depth (m) vs. time (s)).

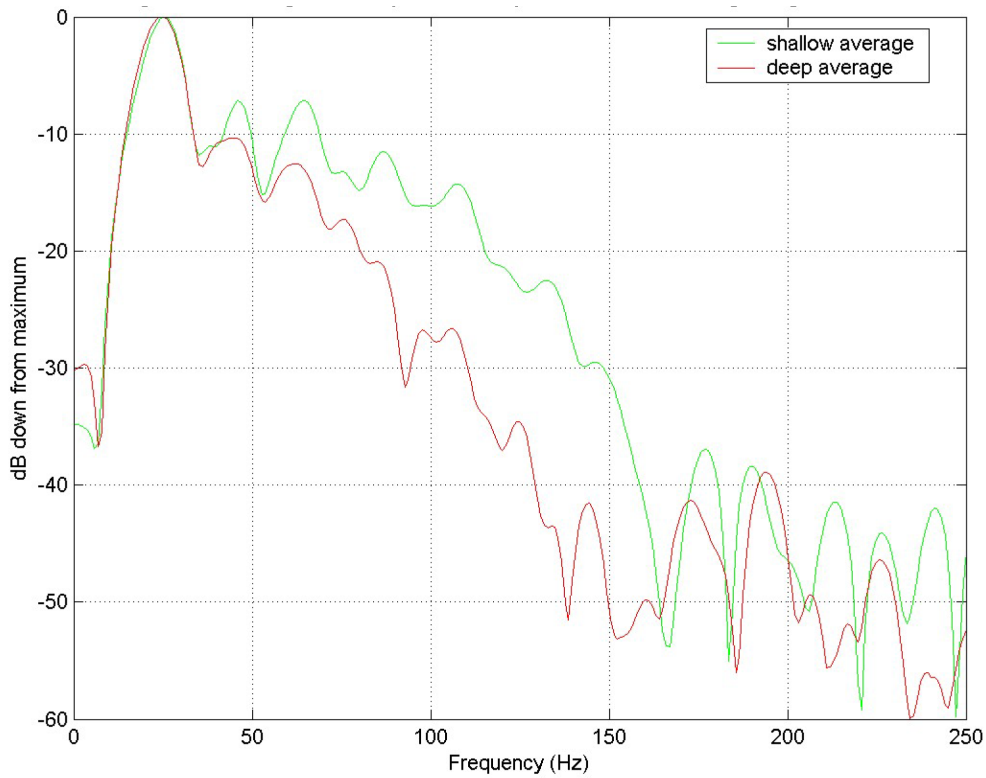

FIG. 2. Averaged amplitude spectra of the downgoing P-wave.

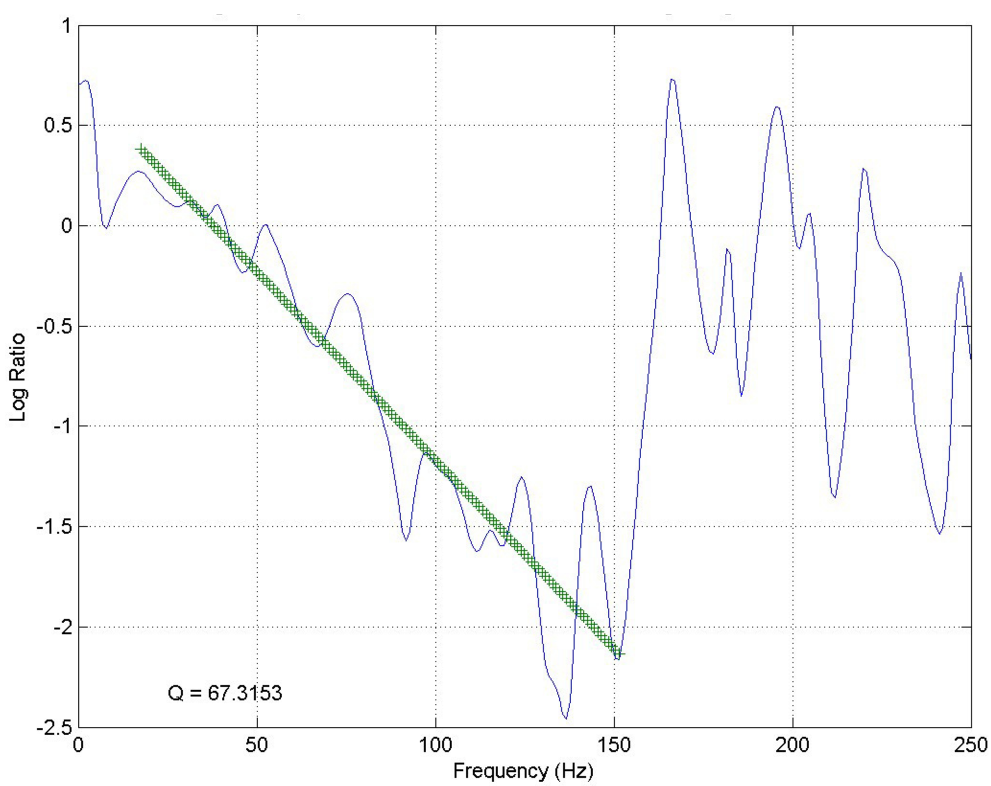

FIG. 3. Spectral ratio plot of the downgoing P-wave.

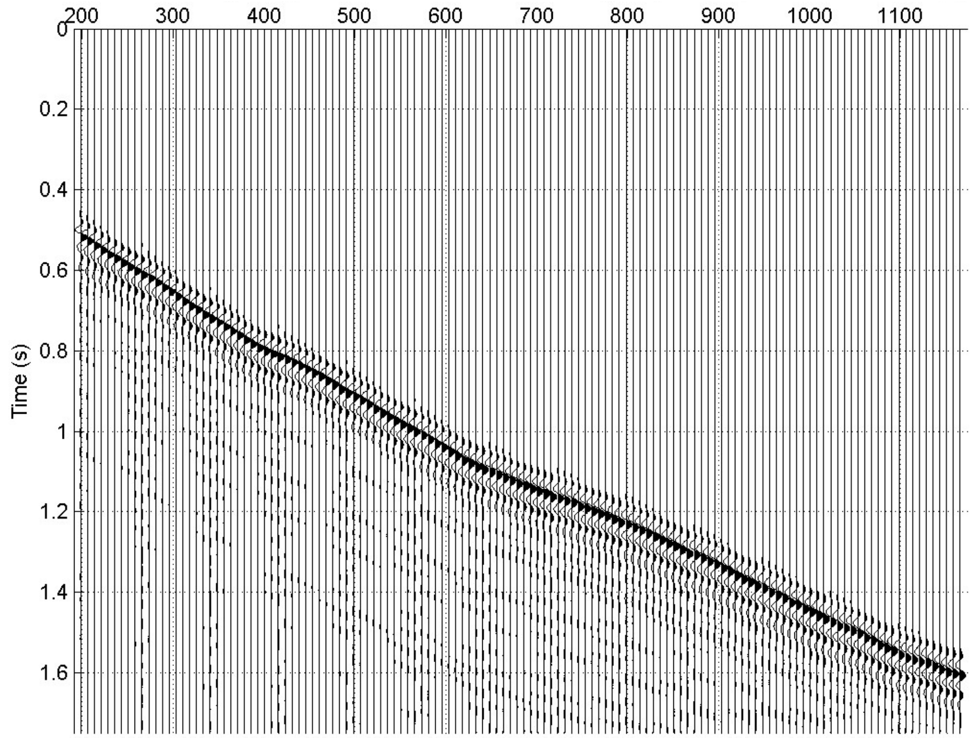

FIG. 4. Downgoing S-wave, Ross Lake (depth(m) vs. time (s)).

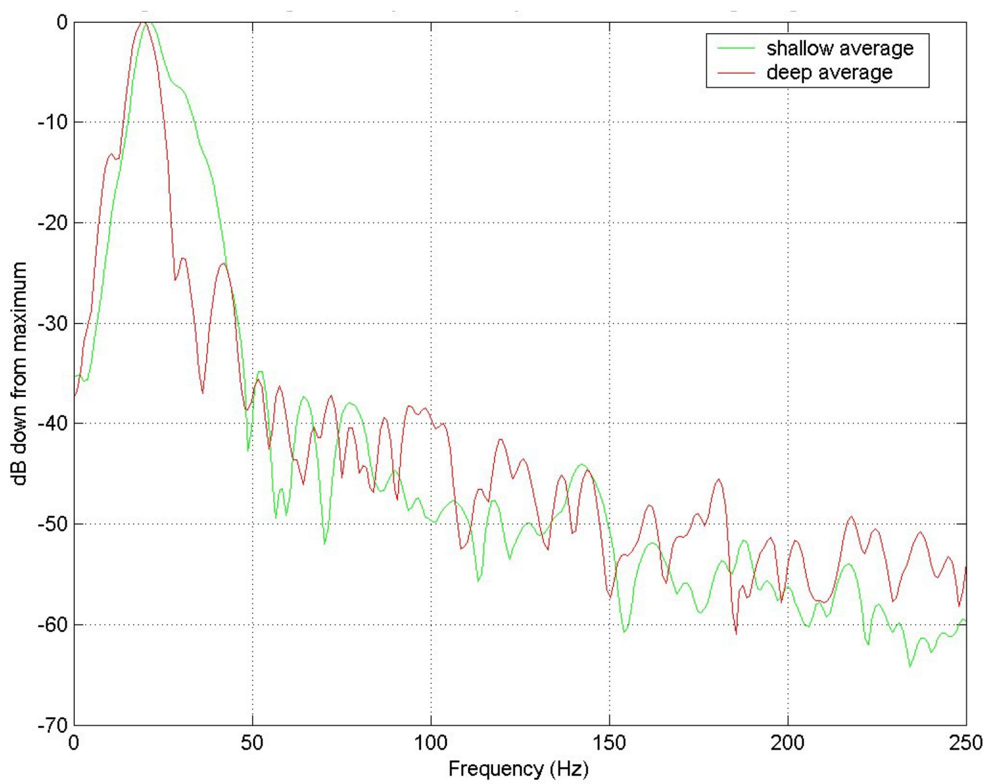

FIG. 5. Averaged amplitude spectra of the downgoing S-wave.

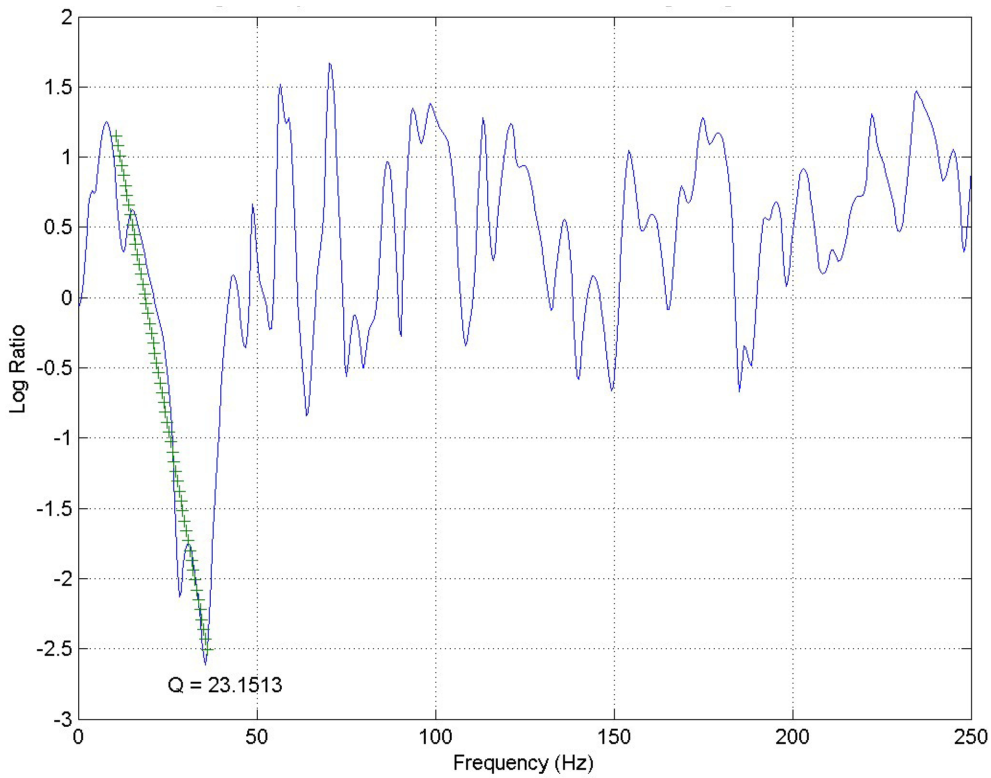

FIG. 6. Spectral ratio plot of the downgoing S-wave.

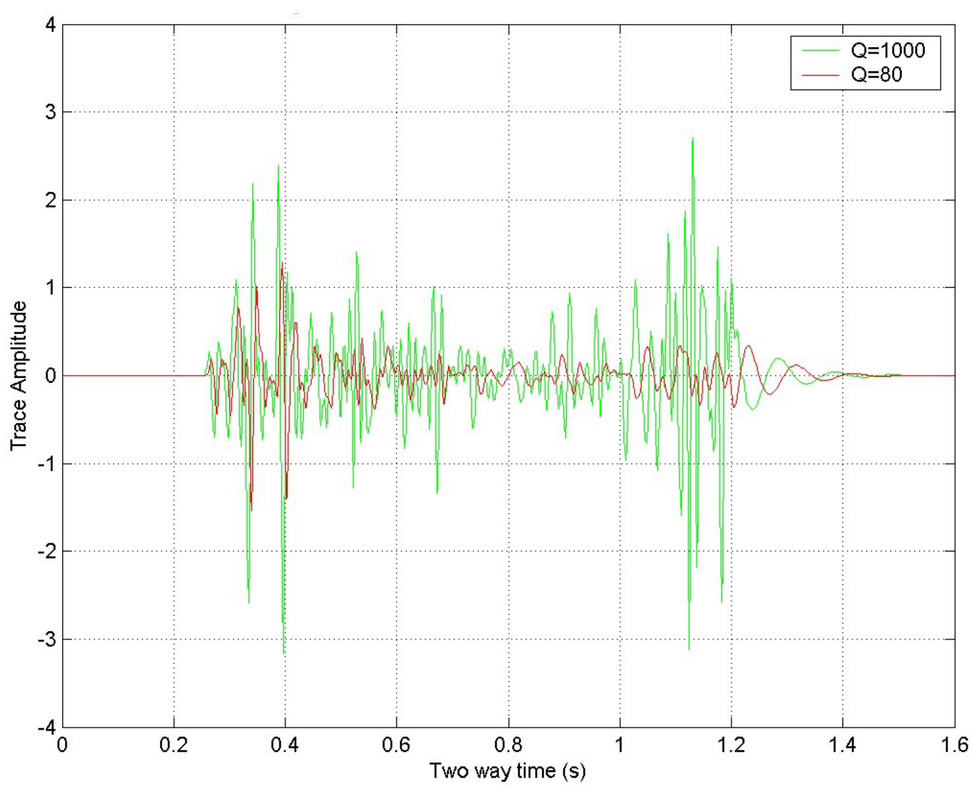

FIG. 7. CONMOD-trace, Ross Lake.