VSP-based Q-estimation at Pike's Peak

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ABSTRACT

We estimate seismic attenuation (Q) from VSP data acquired in a 550m well of the Pike's Peak oilfield, Saskatchewan. The analytical signal method of Q-estimation is compared to two spectral-ratio methods for the 90m offset VSP data. The three Q-estimation methods compare quite well but the role of stratigraphic (apparent) Q in the estimated Q(z) remains unclear. Consistent with previous observations is an increase of estimated Q-values towards shallower depths.

INTRODUCTION

Seismic quality factors (Q) have been an active research topic for several decades now and interest appears to be increasing steadily as evidenced by the number of attenuation related publications and conference presentations. Our two-pronged approach involves theoretical studies with model data (see Haase and Stewart, 2007) and real data Q-estimation as described in this contribution. Haase and Stewart (2006) compared Q-estimation algorithms applied to different VSP data sets. In this paper we apply the analytical signal method (ASM) and the spectral ratio method (SRM) of Q-estimation to VSP-data acquired at Pike's Peak, Saskatchewan in 2000. In addition to SRM and ASM, we also apply a Q-estimation method suggested by Taner and Treitel (2003). Their method (TTM) is a modification of the standard SRM based on minimum-phase wavelets (see also Haase and Stewart, 2007). Data acquisition at Pike's Peak and the geological setting are reviewed by Watson (2004) and Soubotcheva (2006). Previous work at Pike's Peak also includes Q-factor estimation by Xu et al. (2001) applying a spectral ratio technique to VSP data.

Q ESTIMATION (Z-STACK)

Tonn (1991) states that in the case of true amplitude recordings the analytical signal method (ASM) seems to be the best technique. Because we want to apply ASM, a relative amplitude Z-stack with reasonable signal-to-noise ratio is selected from the available Pike's Peak data files. The display in Figure 1 reveals there are noise issues with some of the Z-stack traces. For Q-estimation these "bad" traces are exchanged with place holders computed from neighboring "good" traces. There are some reflections (up-going waves) visible in Figure 1. Note the decay of first arrival amplitudes with depth. Figure 2 shows normalized amplitude spectra of the traces in Figure 1 at selected depths. The increase of attenuation with depth and with frequency is clearly visible. Log spectral ratios, as required for application of spectral ratio methods (SRM), are given in Figure 3. There appears to be noise contamination at low frequencies and also at high frequencies in these ratios and we restrict Q-estimation to the midrange of 30Hz to 80Hz. The spectral ratios given in Figure 3 are computed for a depth interval of 158m (meaning for calculating Q(z) the depth range is z-158m/2 to z+158m/2). Depth dependent Q-factors [Q(z)] derived from these ratios can be seen in Figure 4 together with Q-factors estimated for depth intervals of 105m and 233m. Q(z) for the shortest estimation interval (105m) appears to be overwhelmed by noise or at least dominated by it. At the other extreme, Q(z) for the largest estimation interval of 233m is similar in appearance to the 158m equivalent but smaller in z-range because of depth averaging. SRM derived Q(z) for the 158m estimation interval is re-plotted in Figure 5 (black curve) and displayed together with an ASM derived Q-estimate (red curve) and a TTM derived Q-estimate (green curve). As common ground between the TTM technique and the SRM approach we find spectral ratios. Not surprisingly then, Q(z) for these two techniques is quite similar at depths larger than 300m. The general trend is similar for all three methods. Note also the Q-factor increase towards shallower depths for ASM and TTM.

Q ESTIMATION (P-DOWN)

Spectral ratio methods are quite sensitive to noise according to Tonn (1991). However, they do not require relative amplitude recording. Figure 6 shows the downgoing P-wave isolated from a Pike's Peak VSP. The files do not specify which VSP this P-wave is isolated from and what process is used. Comparison with near-surface travel times of Figure 1 leads to the conclusion that the source offset for Figure 6 must be less than 90m. Indeed, Xu et al. (2001) mention a 23m offset VSP in their abstract. Because there is no amplitude decay with depth we conclude that trace balancing is applied and likely also a band pass filter (check first arrival wavelets). These traces are considerably less noisy when compared to the Z-stack plotted in Figure 1. Next we repeat SRM and TTM Q-estimation with the traces of Figure 6 in the hope of improving Q(z) results because of the improved input data signal-to-noise ratio. Normalized amplitude spectra of the traces in Figure 6 are displayed in Figure 7 for selected depths. There is considerably more variability (spectral notching) in these downgoing P-wave spectra than in the Z-stack amplitude spectra of Figure 2. Not unexpectedly so, spectral ratios computed from the amplitude spectra of Figure 7 also show similar spectral notching as can be seen in Figure 8. Spectral ratios like the ones shown in Figure 8 are input to the SRM Q-estimation. As part of TTM Q-estimation, minimum phase wavelets are derived from first arrival wavelets in Figure 6. Then spectral ratios are computed from the minimum phase wavelets. A few of the ratios for selected depths are plotted in Figure 9. There is a lot less spectral notching present in TTM spectral ratios (Figure 9) when compared to the equivalent SRM spectral ratios in Figure 8. Even when compared to the Z-stack SRM spectral ratios of Figure 3 there are fewer notches in Figure 9. According to Taner and Treitel (2003) their approach is less prone to the influence of zeros on or near the unit circle in the z-plane because minimum phase wavelets *cannot have* zeros on the unit circle. SRM and TTM Q-estimates of the isolated downgoing P-wave are shown in Figure 10 together with the ASM Q-estimate of Figure 5 (Z-stack derived). Comparing SRM and TTM quality factors in Figures 5 and 10 proves that indeed higher signal-to-noise ratio in the data analyzed results in smoother Q-estimates and with this data also gives good agreement in depth regions deeper than approximately 320m. Even the ASM estimate tracks quite well in this depth range. Again, note the Q-factor increase towards smaller depths.

CONCLUSIONS

Q versus depth in Figure 10, estimated by spectral ratios (SRM) and analytic signals (ASM), are again similar (but far from identical), as found in a previous study. There it is also mentioned that minima of Q(z) appear to occur at depth locations where reflections originate in the VSP trace display. In the Pike's Peak Z-stack (Figure 1) a reflection can be seen to travel upward from a depth of approximately 340m. Figure 5 shows Q(z) minima in that vicinity for all estimation methods. This seems to confirm the observations of the previous report on VSP-based Q(z) regarding stratigraphic (apparent) Q. Also consistent with previous observations is the increase of Q(z) values toward shallower depths. Current thinking on the cause for this increase is focused on the near field effect of spherical wave propagation.

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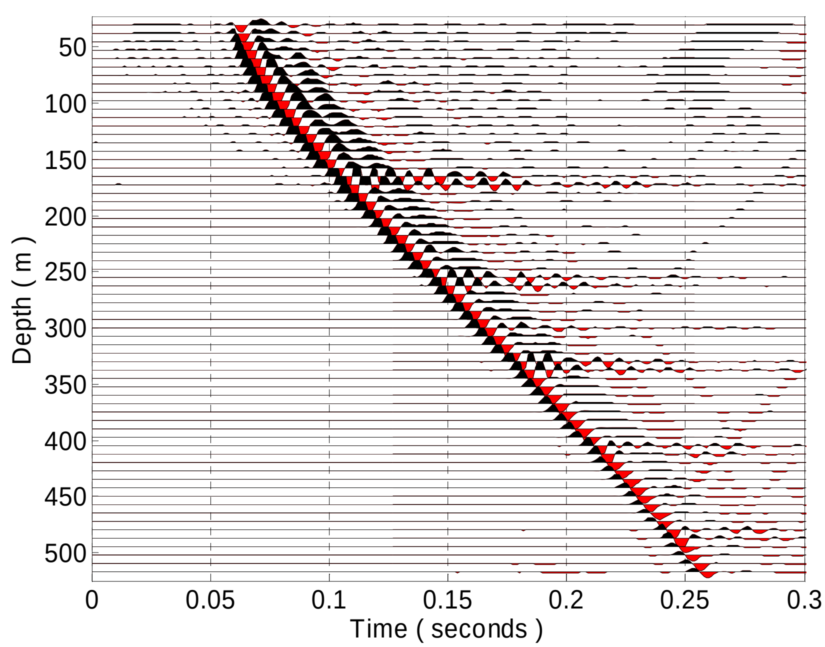

FIG. 1. Pike's Peak 90m offset VSP (true amplitude Z-stack). Note noisy traces and reflections. Peaks are plotted in black, troughs in red.

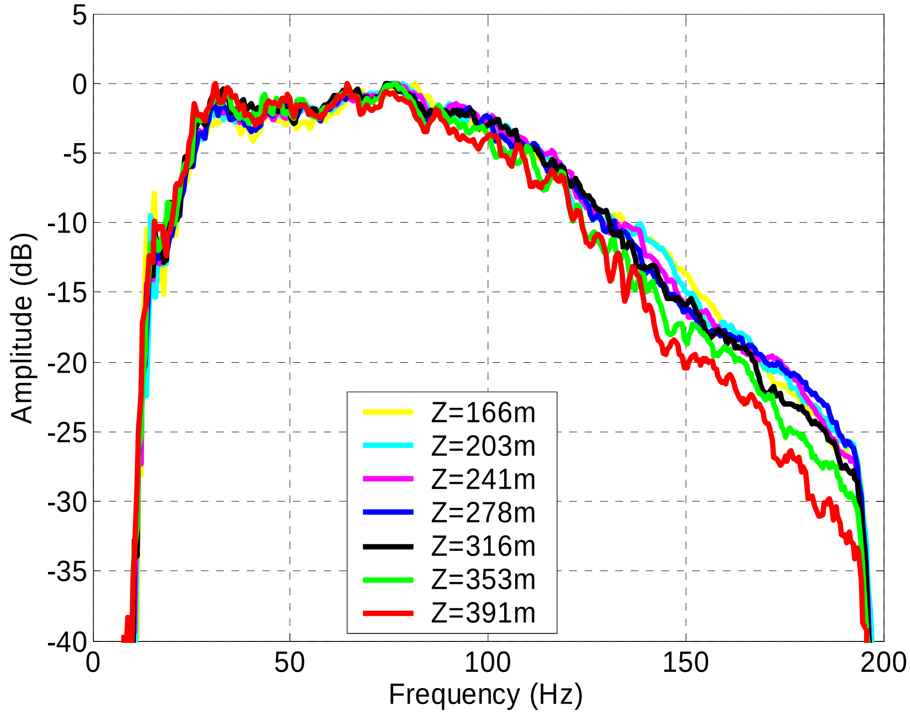

FIG. 2. Normalized trace spectra of Z-stack for selected depths from 166m to 391m (90m offset Pike's Peak VSP with sweep range from 8Hz to 200Hz).

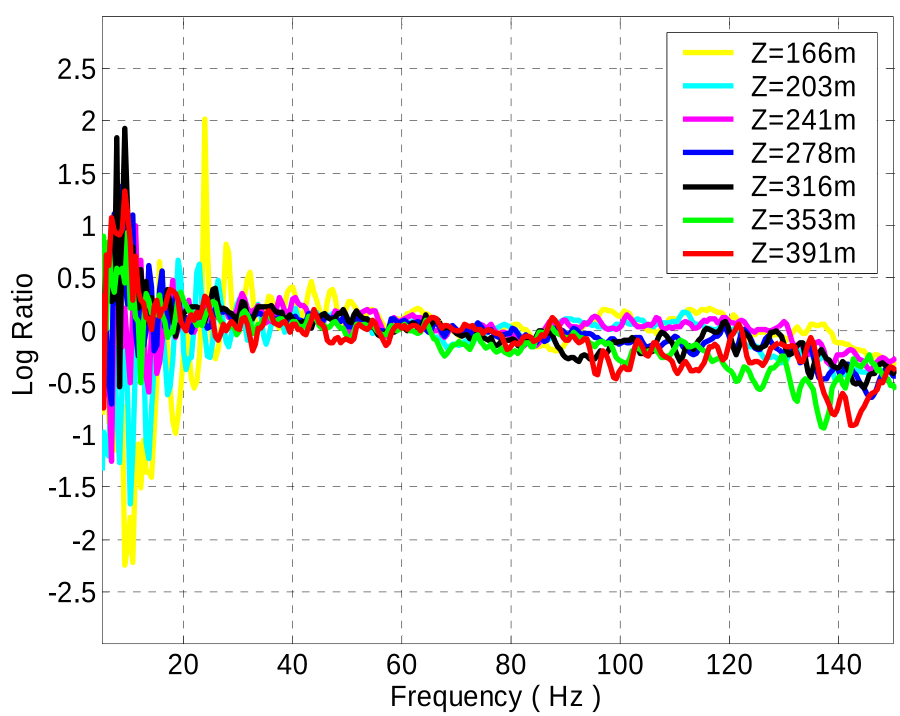

FIG. 3. Log spectral ratio of Z-stack (90m offset Pike's Peak VSP).

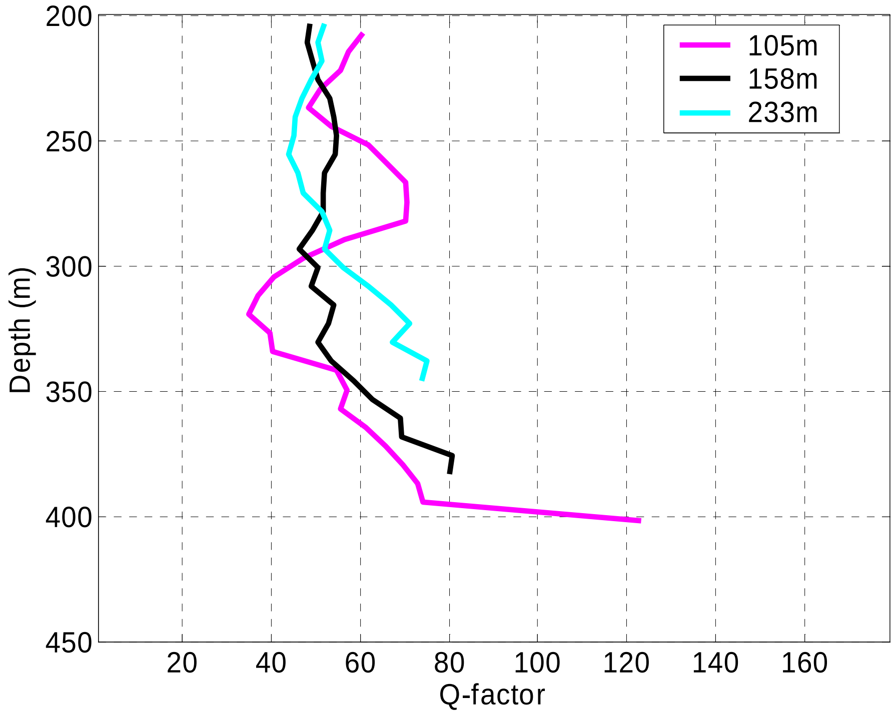

FIG. 4. SRM-Q versus depth as function of estimation interval (90m offset Pike's Peak VSP).

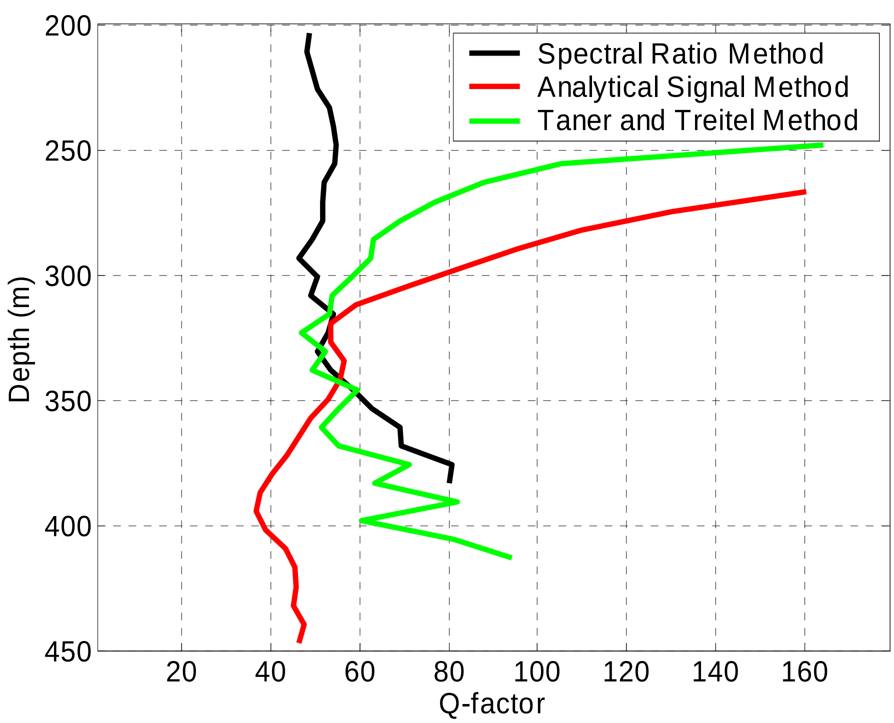

FIG. 5. Q versus depth for Z-stack (90m offset Pike's Peak VSP).

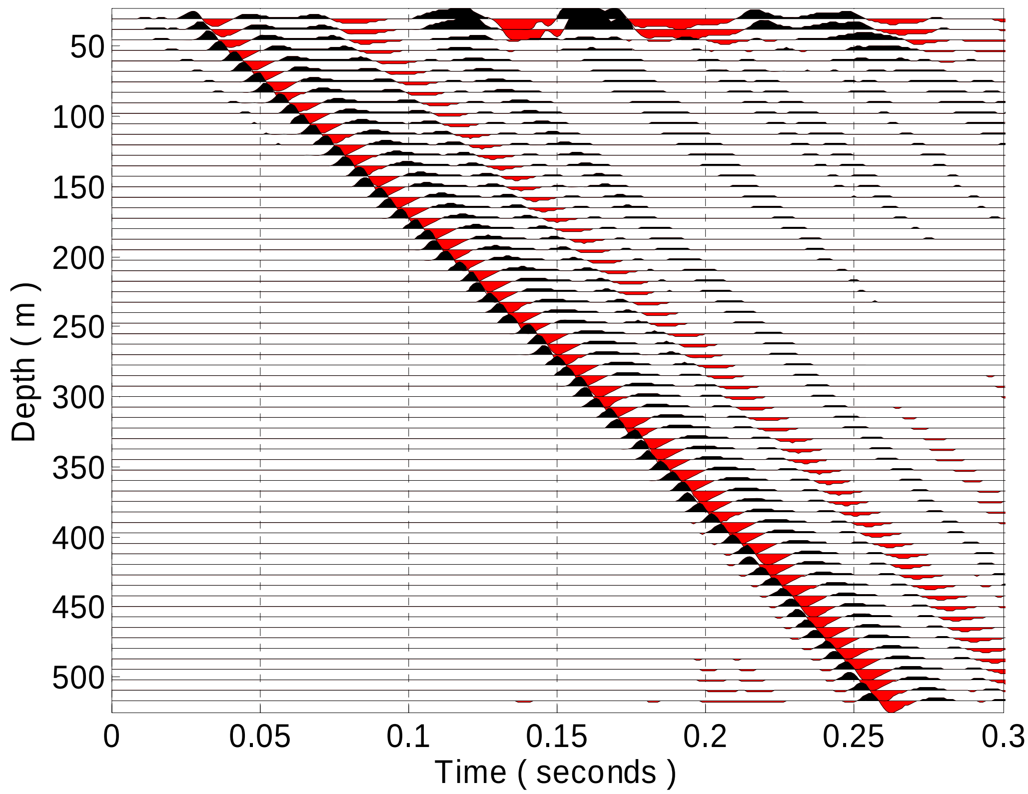

FIG. 6. Pike's Peak VSP (isolated downgoing P-wave). Note noisy shallow traces and the lack of depth-dependent amplitude decay because of trace balancing. There is also a noise built-up at larger travel times which is outside the plotting window at this time scale.

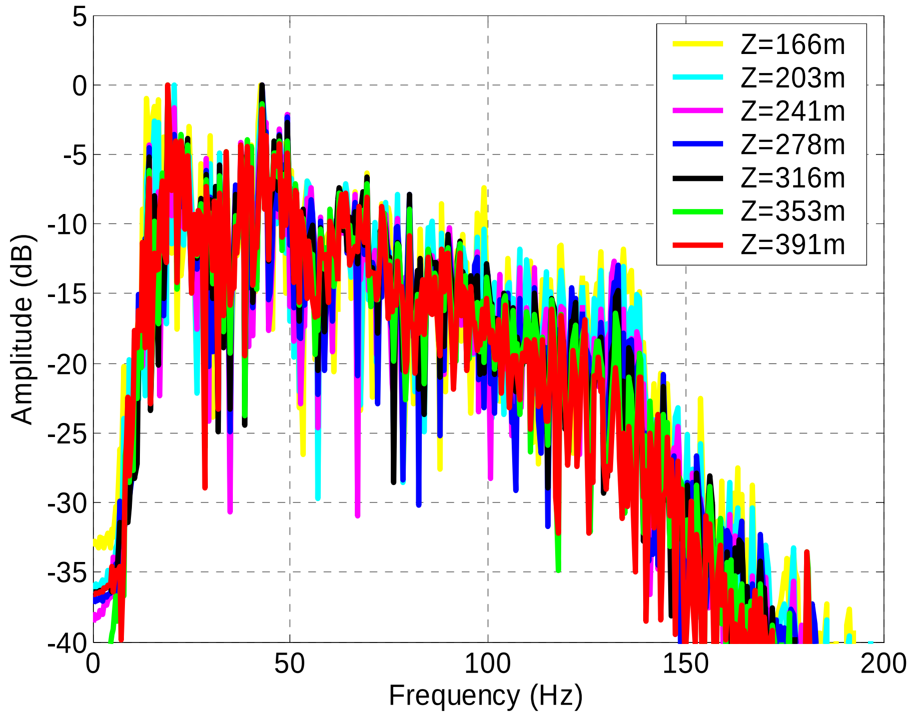

FIG. 7. Normalized trace spectra of isolated downgoing P-wave (90m offset Pike's Peak VSP).

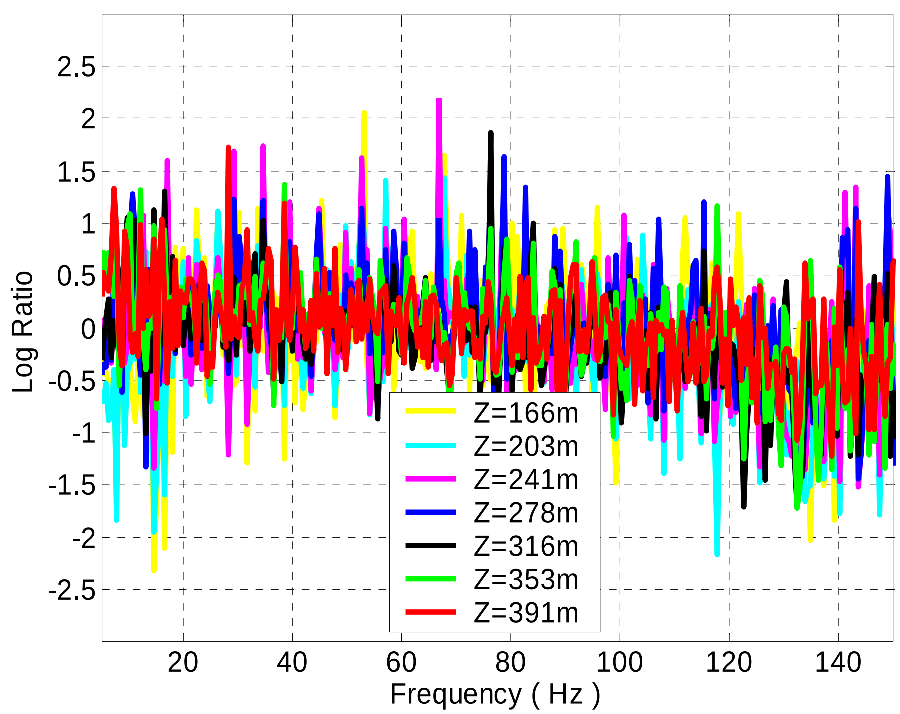

FIG. 8. Log spectral ratio of isolated downgoing P-wave (90m offset Pike's Peak VSP).

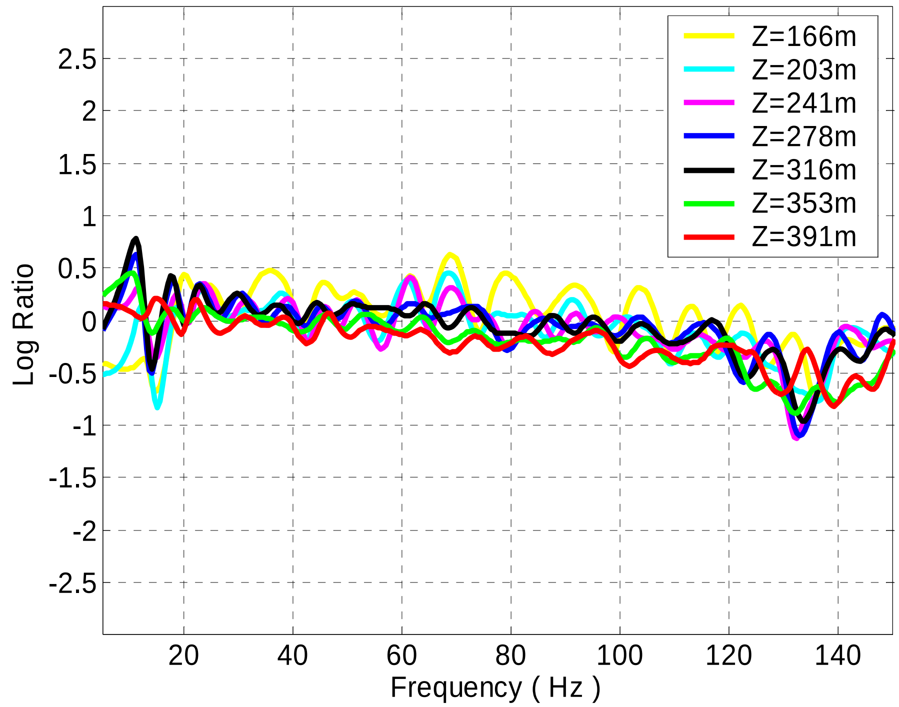

FIG. 9. Log spectral ratio of downgoing P-wave minimum phase wavelet (Taner and Treitel).

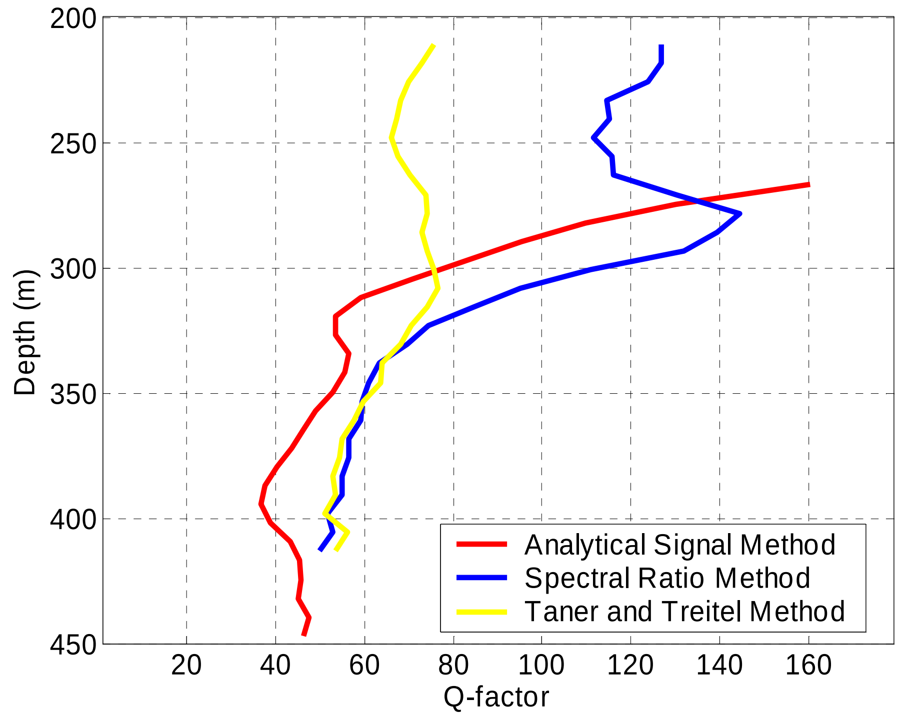

FIG. 10. Q versus depth computed with spectral ratios and Taner+Treitel for isolated downgoing P-wave, computed with analytical signal method for Z-stack (90m offset Pike's Peak VSP).