Stratigraphic attenuation of seismic waves

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ABSTRACT

In this report we are investigating the role of stratigraphic attenuation (scattering) in Q-estimation. We find that 2D scattering shows offset dependent stratigraphic attenuation/amplification. Stratigraphic “amplification” is one possible explanation for the peaking of shallow depth Q-estimates from actual VSP data. Another possibility is the relative boost of high frequencies in shallow layers.

INTRODUCTION

Attenuation factors are of interest in seismic exploration because they can be useful for amplitude recovery, improving resolution, stabilizing wavelet phase, defining lithology and perhaps providing indications of hydrocarbon saturation. Thus, we seek robust and accurate ways to estimate attenuation or quality factors (Q) and applications for them. One technique we have employed for Q estimation is the analytic signal method (Haase and Stewart, 2004; *ibid*, 2005). However, when applying the analytical signal method to estimate Q in some actual VSP data from the Ross Lake heavy-oil field in Saskatchewan, we found an offset dependence in the results (Figure 1). Furthermore, our Q-factor estimates increase from about 500m towards shallower depths, and this trend is emphasized with increasing offset. What could be the cause for these over-estimated Q-values? It was also noted previously that the assumption of unity transmission coefficients could cause errors in Q-estimates (Haase and Stewart, 2005). Our list of potential error sources contains **Acquisition Issues** [1)seismic source variations, 2)borehole inconsistencies and 3)receiving sonde changes], **Analysis Problems** [1)moveout errors, 2)transmission loss errors, 3)ray bending approximations and 4)stratigraphic attenuation versus intrinsic Q] and a **Lithology Model Inadequacy** [Q-anisotropy]. The topic of Q-anisotropy has become increasingly popular at recent conventions. However, before invoking Q-anisotropy, the contributions of reflection and transmission effects (as predicted from modeling and the actual well-logs) to effective attenuation should be investigated. The Q-factors estimated here are effective Q, which is a combination of the desired intrinsic Q of the rock layers, the stratigraphic (apparent) Q caused by reverberations between layer interfaces, and a gain component. When comparing results from a 1D wave equation model to the running transmission coefficient product, a good match is observed. Because offset dependence is observed, a 2D model seems more appropriate in this case. We have adapted a 2D elastic wave equation method (Virieux, 1986) to the VSP case. Both P- and S_v - source VSP sections have been computed. P-source VSP sections are presented below.

1D WAVE-EQUATION MODEL

The Q-factors estimated in this study are really an effective Q, which is a combination of the desired intrinsic Q of the rock layers and stratigraphic (apparent) Q caused by reverberations between layer interfaces. The running transmission coefficient product employed previously only accounts for amplitude changes across interfaces on downward transmission. A first step beyond this simple transmission model is to consider all transmission and reflection coefficients of the stratigraphic column which includes reverberations (O'Doherty and Anstey, 1971). It is reported in the literature (see e.g., Richards and Menke, 1983; Mateeva, 2003) that stratigraphic filtering means low-pass filtering. Therefore, rejected higher frequencies could reverberate at shallow depths and mimic larger apparent Q-factors. Figure 2 gives the result of numerical wave equation modelling for a flat-layer earth with vertical incidence plane waves. A Ross Lake well log is employed to compute these plane wave amplitudes. Also shown is the cumulative transmission coefficient. When comparing the two curves in Figure 2, a reasonably good match is observed.

ELASTIC WAVE-EQUATION MODEL WITH OFFSET SOURCES

Because offset dependence is observed in Q-estimates from actual VSP-data, a 2D model seems more appropriate than a 1D approach in this situation. When expanding to a 2D elastic wave equation model a completely different picture emerges, even for a 1D earth. A great richness of wave types and complications are generated. We have adapted Virieux's (1986) 2D elastic wave equation method to the VSP case. Horizontal and vertical particle velocities are computed on a staggered grid from P-velocities, S-velocities and densities for a given source type and a given source wavelet. The vertical particle velocity of a synthetic VSP generated for a source offset of 54m (P-wave source) is shown in Figure 3. Note that surface effects are ignored and that this model includes an offset dimension (2D wave propagation) but is based on well log data (flat-layer earth). The first arrival slope steepens with faster velocities at depth. Reflections and multiples are clearly visible. Instantaneous first arrival amplitude maxima for 54m source offset are plotted in Figure 4; they decay quite smoothly with depth. A Q-estimate derived from the maximum instantaneous amplitude curve of Figure 4 is shown in Figure 5. A 399m offset equivalent to Figure 3 is displayed in Figure 6. First arrival times are delayed when compared to Figure 3 because of increased travel distances. There is also clear evidence for energy converted on reflection as well as transmission. Instantaneous first arrival amplitude maxima for 399m source offset are displayed in Figure 7. There are significant instantaneous amplitude increases at certain depths. Furthermore, this effect is enhanced by a decrease in the V_p/V_s-value (which means by an increase in shear velocity V_s). The curves in Figures 4 and 7 appear to indicate the existence of an offset-controlled energy partitioning effect which could explain (at least in part) the peaking of shallow depth Q-estimates from actual VSP-data. The stratigraphic Q-factor estimated from the red curve in Figure 7 (following the smoothing demonstrated in Figure 8) is shown in Figure 9. Note that intrinsic attenuation is zero for this elastic model.

CONCLUSIONS

Q-estimates obtained by the analytical signal method do depend on VSP-source offset to some degree. A 2D elastic wave-equation method is adapted to the VSP case in this study to investigate the offset dependence of Q-estimates. At small source offsets, trace maxima of instantaneous amplitudes decay quite smoothly with depth. At large offsets, however, significant depth regions of instantaneous amplitude increases are observed. Q-factor estimates from these zero intrinsic attenuation models show a near surface increase. Offset dependent energy partitioning (stratigraphic "amplification"?) is one possible explanation for the peaking of shallow depth Q-estimates from actual VSP-data.

Another possibility is the relative boost of high frequencies in shallow layers. Our modelling approach is currently being extended to anelastic situations. Flat-layered earth 3d models are also planned.

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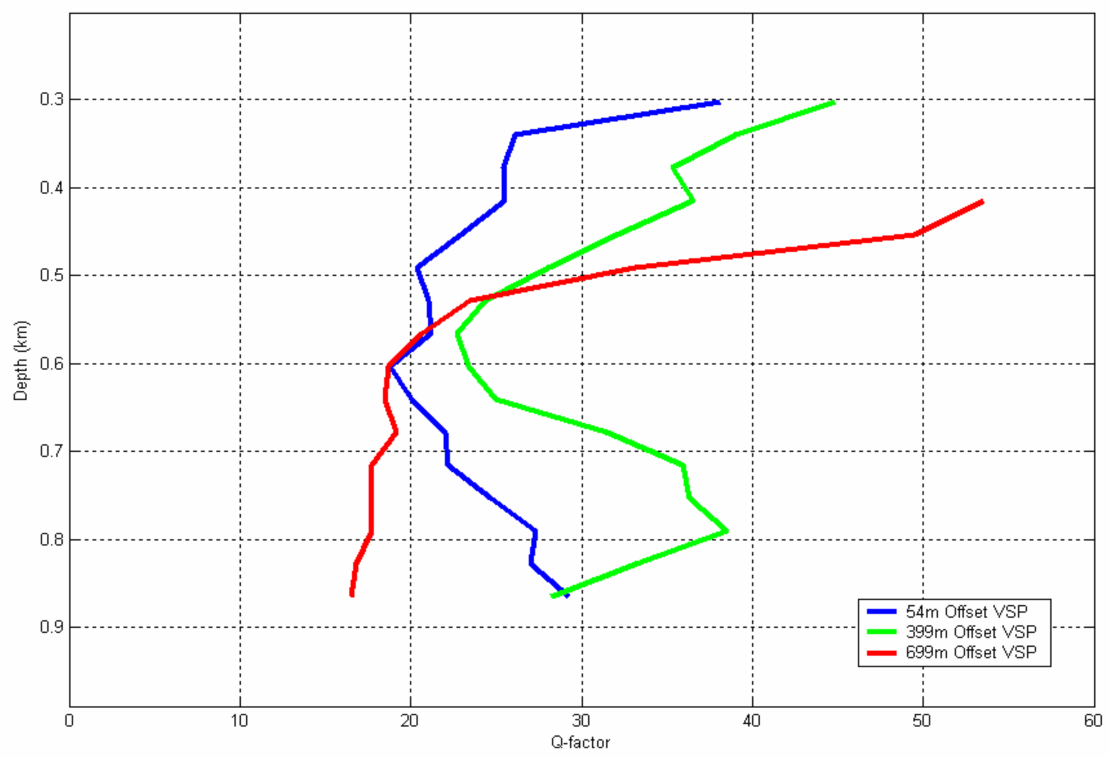

FIG. 1. Quality factor (Q) as determined by the analytical signal method from VSP data in the Ross Lake oil field, Saskatchewan.

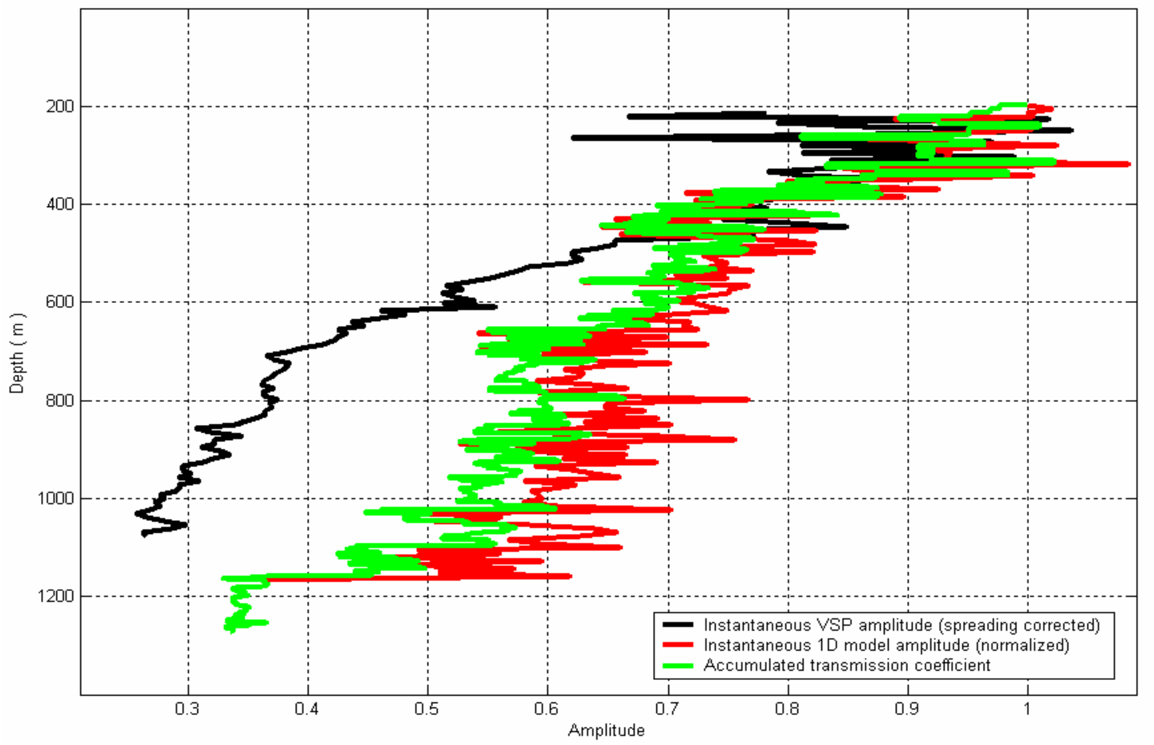

FIG. 2. Maximum instantaneous amplitudes compared to cumulative transmission coefficient.

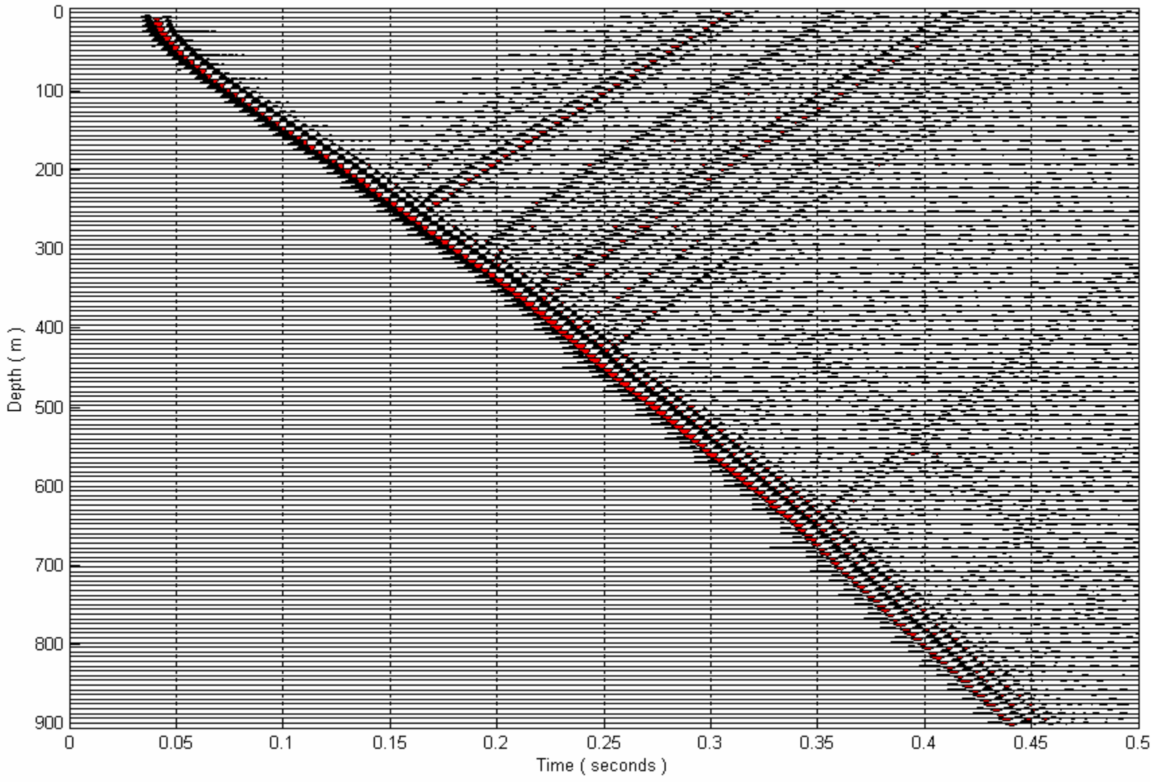

FIG. 3. 2D velocity-stress model VSP (vertical particle velocity, 54m offset).

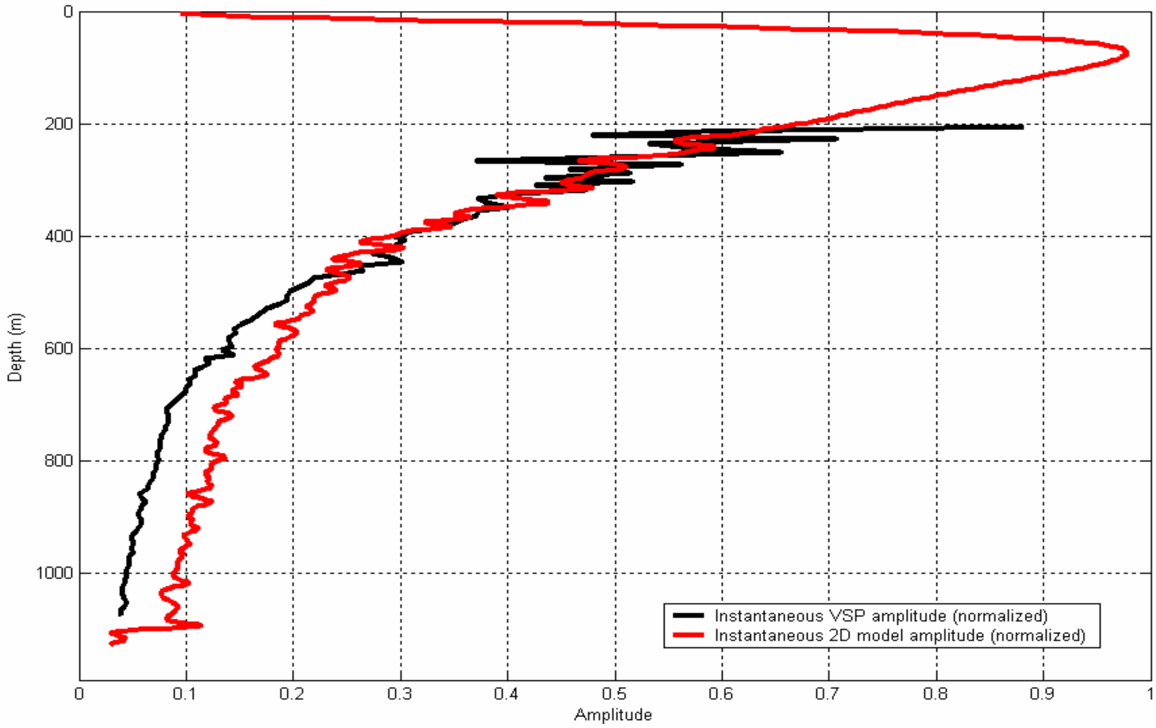

FIG. 4. Maximum instantaneous amplitudes for 54m offset.

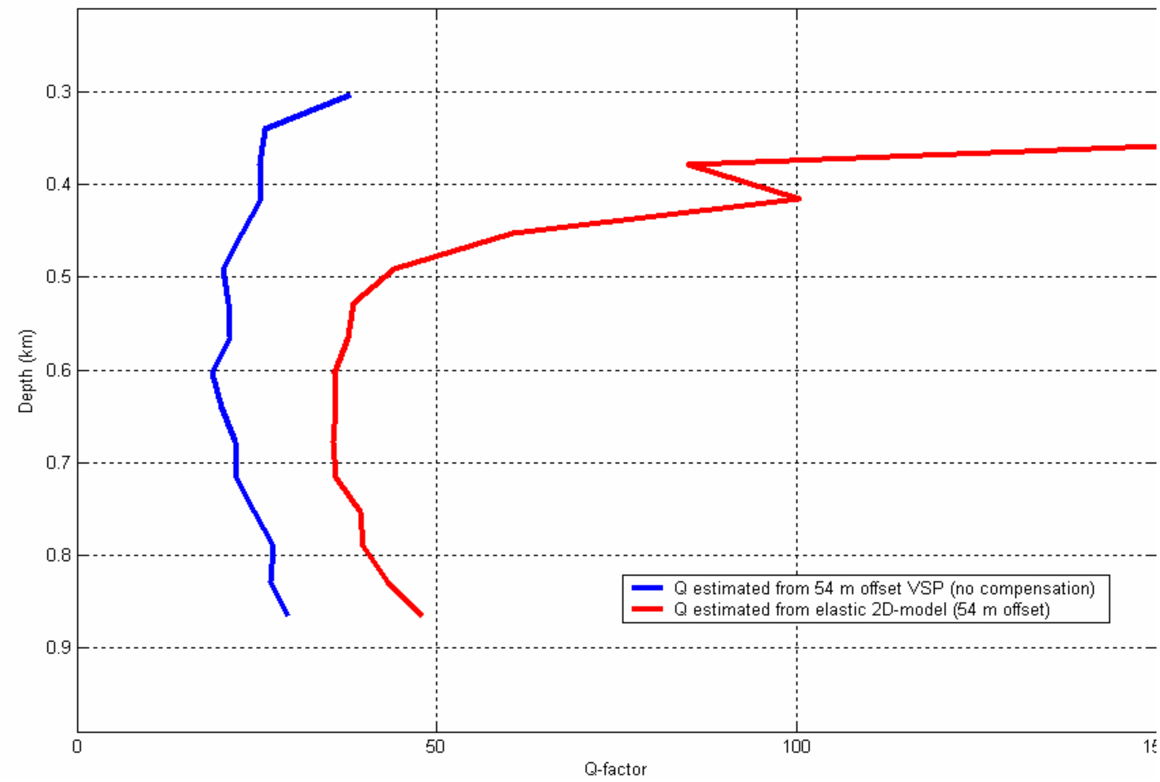

FIG. 5. Quality factor (Q) as determined from data and model (54 m offset VSP).

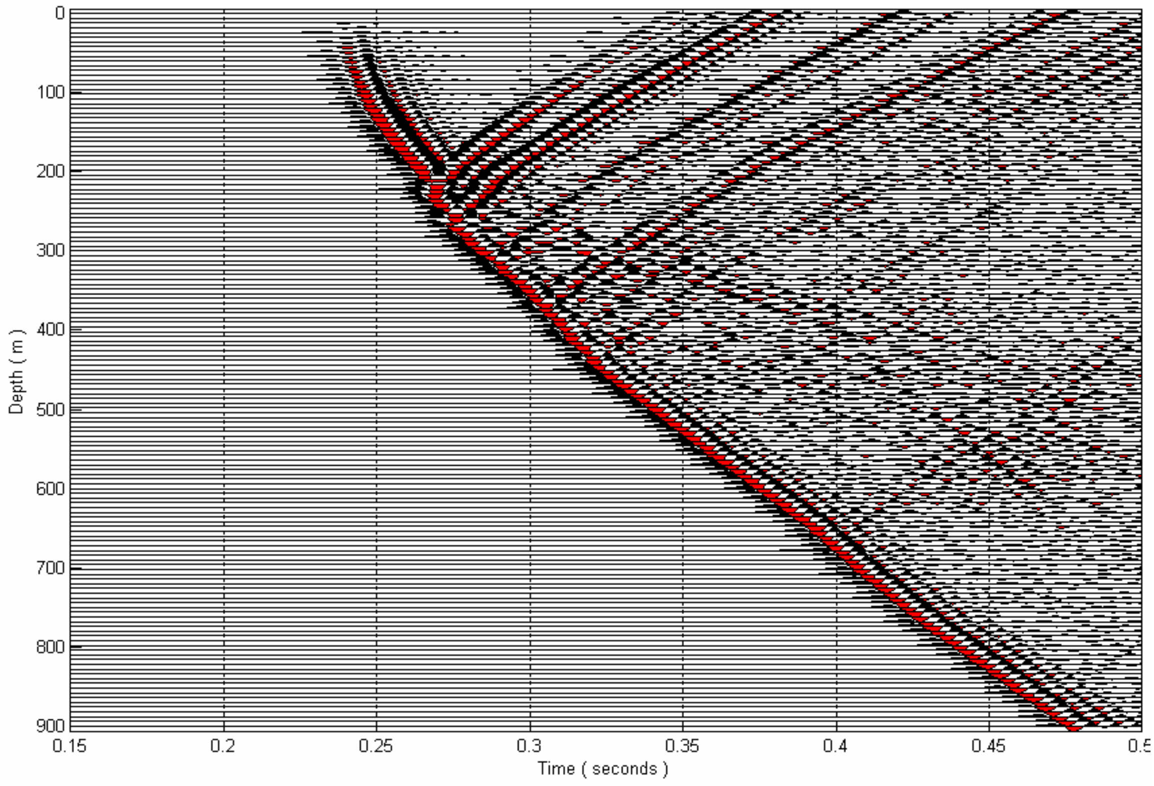

FIG. 6. 2D velocity-stress model VSP (vertical particle velocity, 399 m offset).

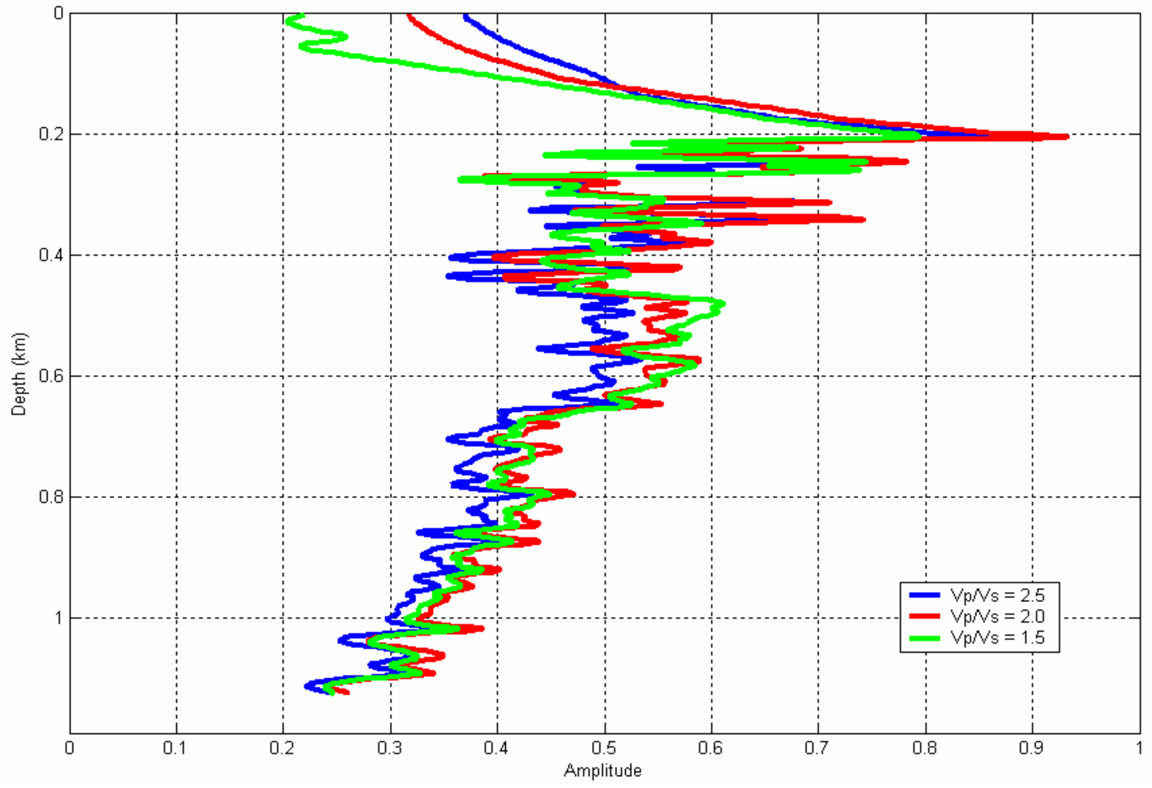

FIG. 7. Maximum instantaneous amplitudes picked from 2D model traces (399 m offset).

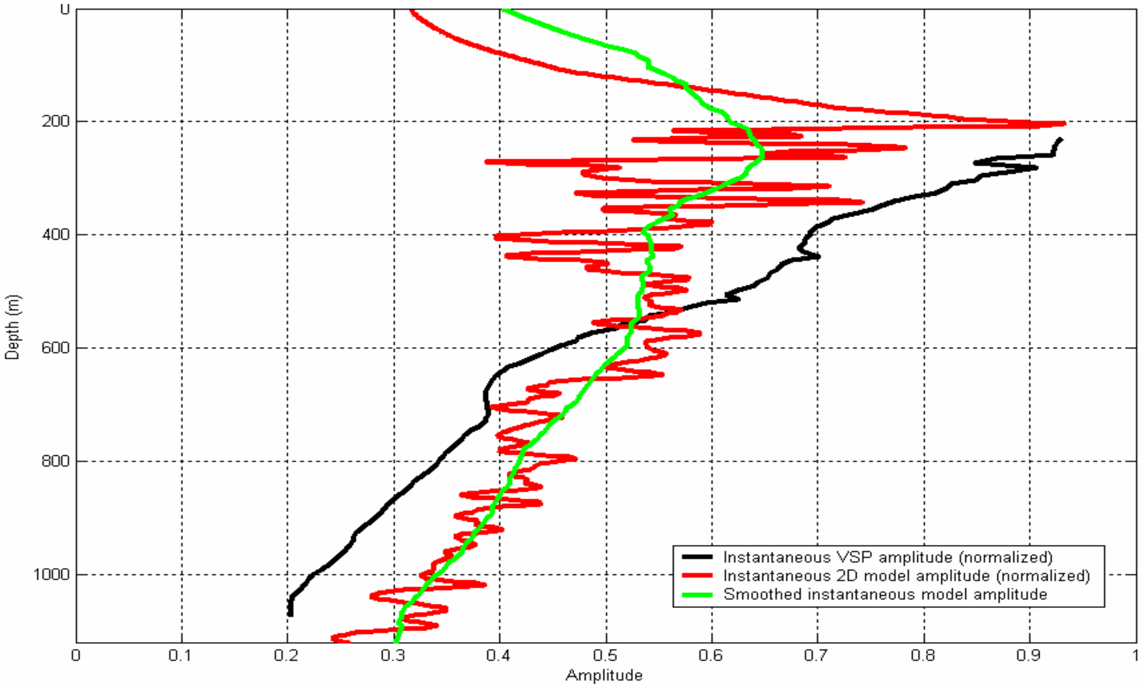

FIG. 8. Maximum instantaneous amplitudes for 399 m offset.

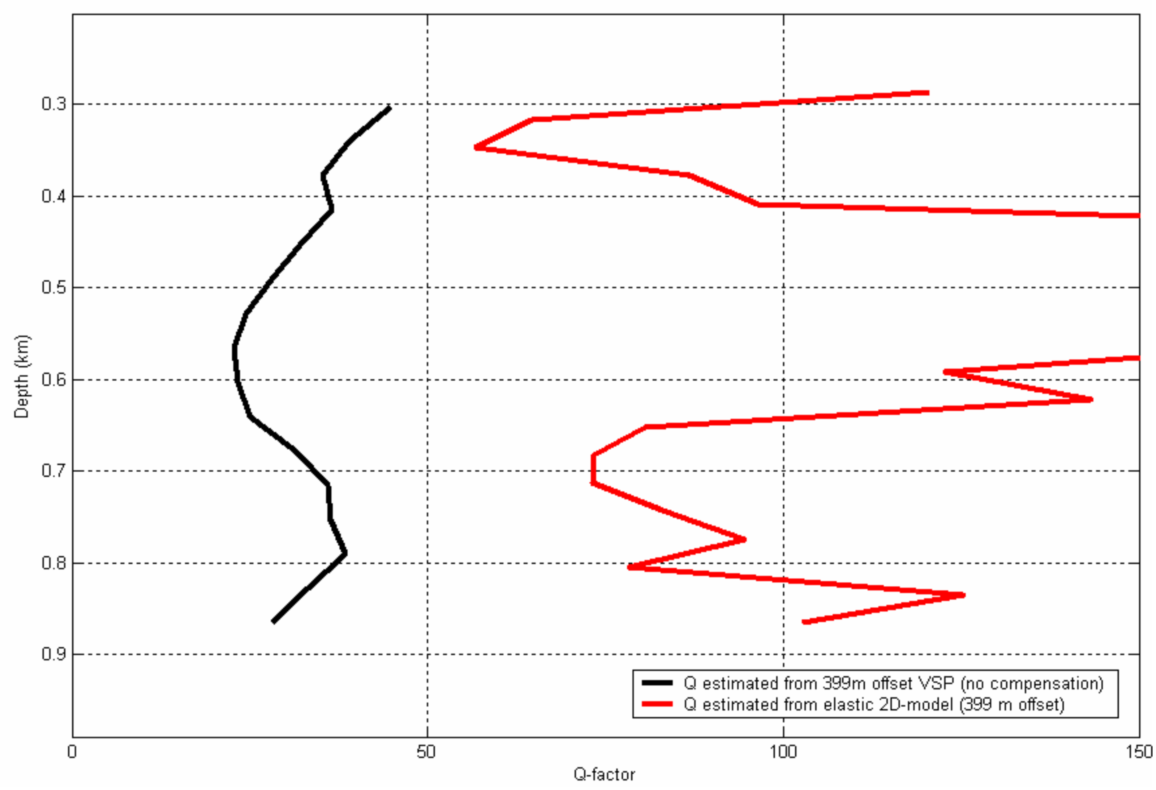

FIG. 9. Quality factor (Q) as determined from data and model (399 m offset VSP).