Preliminary processing of the Chaparral-Farnsworth VSP data set with focus on attenuation

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ABSTRACT

In this report the Chaparral Farnsworth VSP data was investigated, with the aims of establishing an attenuation profile and identifying difficulties that may arise if anacoustic FWI were applied to the data. Q estimates were generated using both the spectral ratio method and the centroid frequency shift method. These yielded consistent results, prominently featuring nonphysical negative Q. Scattering effects were investigated as a potential cause for this error. Synthetic VSP data generated using the well logs demonstrated that scattering effects do provide effective negative Q forcing in the Q estimation methods, but not in the correct locations or to the necessary extent to cause the apparent negative Q in the measured data. Scattering effects on a smaller scale than the well log sampling could not be discarded as a potential cause for this behaviour however. A capacity to be able to account for both Q induced frequency shifts and sub seismic resolution scattering induced shifts is identified as a desirable property in any anacoustic FWI to be applied to this data.

INTRODUCTION

This report is a case study investigating the Chaparral Farnsworth vertical seismic profile (VSP) data. A later objective for these data is to perform a case study for anacoustic full waveform inversion. Zero offset VSP data features desirable attributes for experimenting with anacoustic FWI on a number of fronts. Importantly, anacoustic wave propagation is a much more accurate model for a VSP experiment than it is for surface seismic, where elastic and anisotropic effects can play a major role. Well logs provide a known true velocity structure, which is helpful in evaluating the quality of a recovered FWI model. Attenuation estimation is also much easier and more well established for VSP data than surface seismic data, which allows for a true Q model to be established by conventional processing techniques. Furthermore, a zero offset VSP experiment is essentially one dimensional, significantly lessening the computational burden incurred in performing FWI. This report is focused on applying conventional VSP processing techniques to recover a Q profile that can be used as a true model to compare against later FWI results, as well as to identify the problems faced in recovering Q on this data set.

Q ESTIMATION

Q is estimated from VSP data in a variety of ways. While one prominent effect of attenuation on seismic data is a decrease in amplitude of the seismic wave as it propagates, most Q estimation methods do not consider true amplitude information. This is largely due to the fact that it is difficult to accurately determine true amplitudes, given the wide variety of non-attenuative effects that change the measured wave amplitudes, as well as the fact that noise can easily contaminate amplitude information. Instead, most Q estimation techniques used on VSP data use changes in the frequency spectrum to estimate Q. These methods are much more robust than amplitude based techniques, as they are impacted only by frequency dependent effects in the seismic data. While there are a variety of techniques available, in this report only two are considered; the spectral ratio method (Gladwin and Stacey (1974)) and the centroid frequency shift method (Quan and Harris (1996)). Both of these methods assume a constant Q attenuation, that is, a Q independent of frequency.

Spectral Ratio Method

The spectral ratio method assumes a constant Q model, in which the amplitude at depth z_2 is given in terms of the amplitude at depth z_1 by

$$A(f, z_2) = \alpha A(f, z_1) e^{-\frac{\pi f \Delta t}{Q}} \quad , \tag{1}$$

where A is the amplitude of the seismic wave, f is the frequency, Δt is the time interval between the wave arriving at z_1 and its arrival at z_2, and α is a factor which encompasses all frequency independent amplitude changes which occur between z_1 and z_2. This equation can be rearranged to yield the form

$$\log\left[\frac{A(f, z_2)}{A(f, z_1)}\right] = -\frac{\pi \Delta t}{Q} f + c \quad , \tag{2}$$

where c is a frequency independent constant. This expression is a linear function of f, and the spectral ratio method determines Q by finding the slope of the best fit line, m, and solving

$$Q = -\frac{\pi \Delta t}{m} \quad . \tag{3}$$

This method is afforded greater reliability than amplitude based methods due to its invariance under changes in α, only frequency dependent effects alter the estimate of Q. An important consideration in this method, however, is the frequency band over which the best fit line is taken. If a linear least squares method is used to find the best fit line, then all frequencies will be weighted equally in the fit, both those which are prominent in the amplitude spectrum of the data, and those at which the signal to noise ratio is very low. Consequently, if too large a frequency band is taken, there is a risk that the frequencies at which there is low signal to noise will bias the result. Alternately, if too small a band is considered, the accuracy of the linear fit is reduced. Clearly, there are methods for dealing with these problems. One alternative is to apply a more sophisticated fit, such as weighted linear least squares with weights given by signal to noise ratio. Another is to choose an alternate algorithm inherently robust to the choice of frequency band, such as the centroid frequency shift method. The latter is the approach taken in this report.

Centroid Frequency Shift Method

The second method discussed here is based on changes in the centroid frequency of the propagating wave. The centroid frequency is a weighted average of the frequencies in the data, given by

$$f_c = \frac{\int_0^\infty f A(f) df}{\int_0^\infty A(f) df} \quad . \tag{4}$$

As seismic waves propagate in a constant Q medium, the higher frequencies decay faster than lower ones, leading to a down-shift in the centroid frequency. This can be quantified to determine the effective Q value. The expression for Q in the centroid frequency shift method is given by

$$Q = \frac{\pi\sigma^2\Delta t}{\Delta f_c} \quad , \tag{5}$$

(Quan and Harris (1996)) where Δf_c is the change in centroid frequency between measurements, and

$$\sigma^2 = \frac{\int_0^\infty (f - f_c)^2 A(f) df}{\int_0^\infty A(f) df} \quad . \tag{6}$$

The centroid frequency shift method, unlike the version of the spectral ratio method described earlier, is largely invariant under changes in the frequency band used due to the amplitude spectrum weighting in equation 4. It does face challenges, however, as the expression for Q in equation 5 is only strictly correct if the amplitude spectrum is Gaussian. If this is not the case, equation 5 will be incorrect by a positive scaling factor.

Q ESTIMATION ON THE CHAPARRAL FARNSWORTH VSP

This report is focused on the Chaparral Farnsworth VSP dataset. This consists of a zero offset stacked VSP shot and 150 down-hole receivers, spaced in 50 foot intervals from 319 feet to 7769 feet depth. This data is shown in figure 1. The well logs were also available.

Processing

Before the Q estimation methods described above can be applied to the measured data, several processing steps need to be undertaken. Most importantly, the downgoing wave needs to be isolated. If reflections are present, they will have a different frequency spectrum at the same receiver, having propagated through more of the medium and attenuated more than the direct wave. Two popular methods for separating the down and upgoing waves are f-k velocity filtering and median filtering. The f-k filtering strategy simply removes a chosen range of frequencies and wavenumbers. This approach was found to yield a noisy result on these data. In the median filtering approach, each trace is down-shifted by its first break time. This has the effect of flattening the reflection events. A median filter is then applied. This has the effect of smoothing the data along the depth direction, preserving the aligned upgoing events, but not the misaligned downgoing ones. After reversing the time shift, this provides an estimate of the upgoing wavefield, which can be subtracted from the data to obtain the downgoing wavefield. The reverse process can be applied to obtain the upgoing wavefield. The isolated downgoing wave is shown in figure 2.

After the downgoing wave has been isolated, it is necessary to remove any multiples present. This is due to the fact that the multiples will have traveled a longer distance and attenuated more than the direct wave when they reach a given receiver, and so will bias the Q estimate. The direct wave was isolated by applying a time windowing around the first break time, which excludes multiples. The time windowing used here was Gaussian. The downgoing wave after time windowing is shown in figure 3.

The isolated direct wave is the necessary input for the Q estimation methods employed

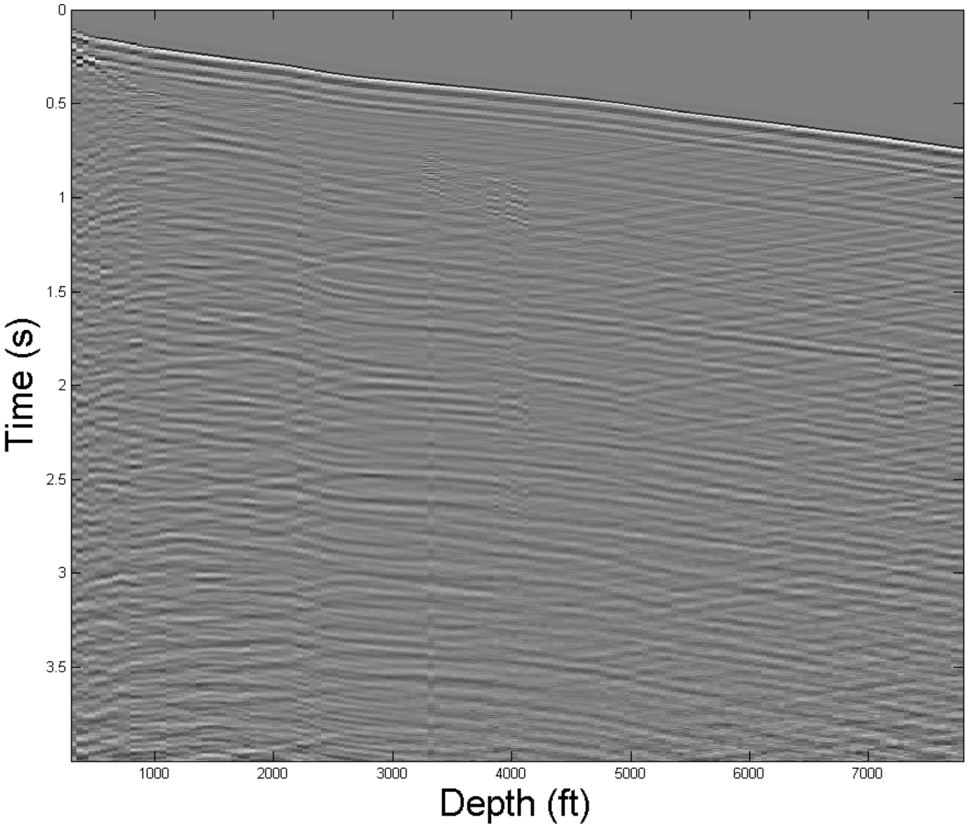
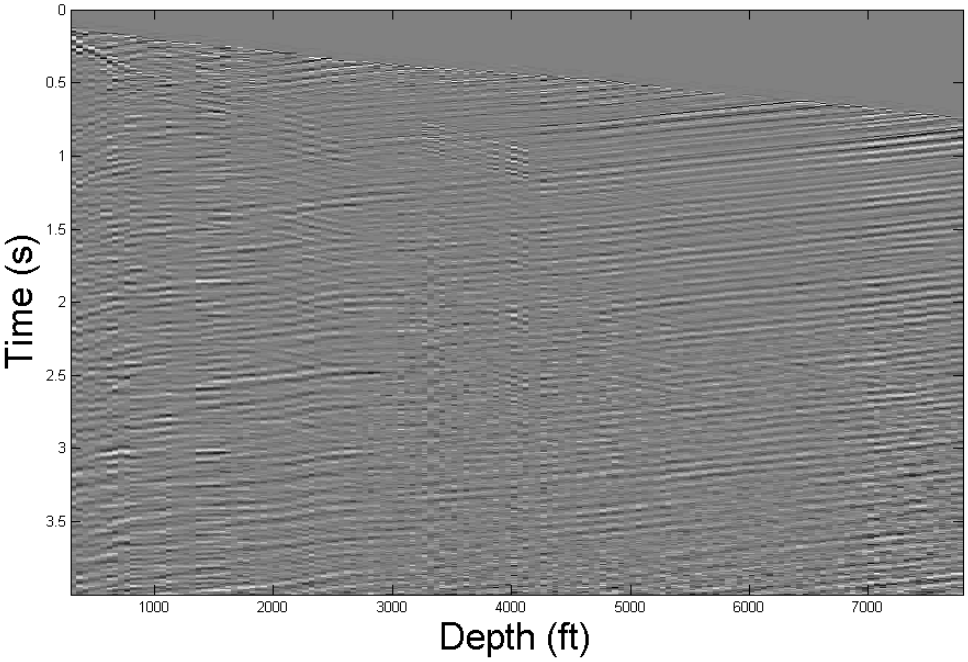


FIG. 1. Measured data for the Chaparral Farnsworth VSP data set.



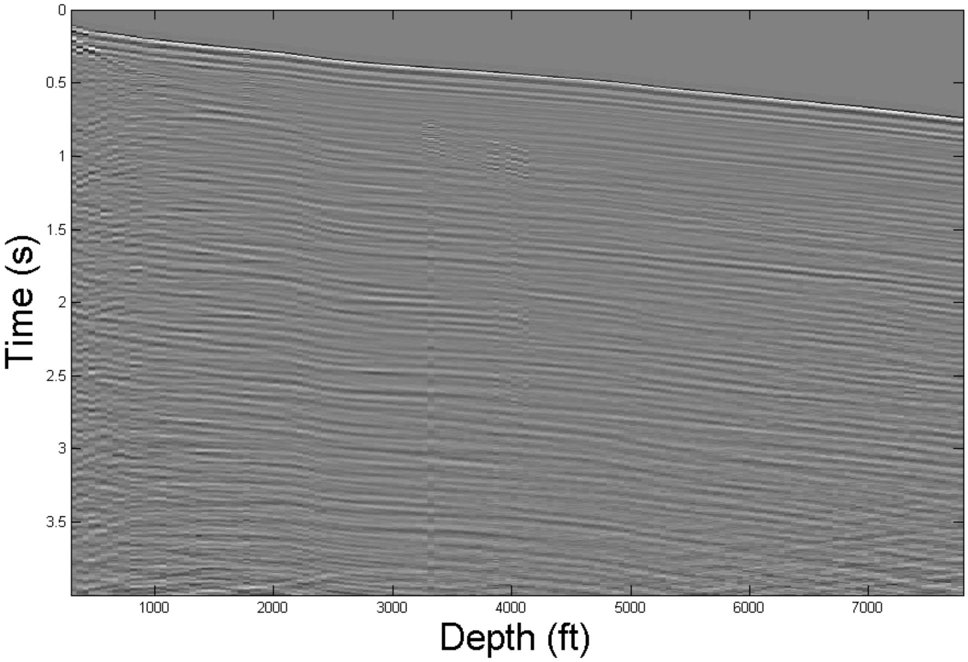


FIG. 2. Top: Upgoing wave field. Bottom: Downgoing wave field.

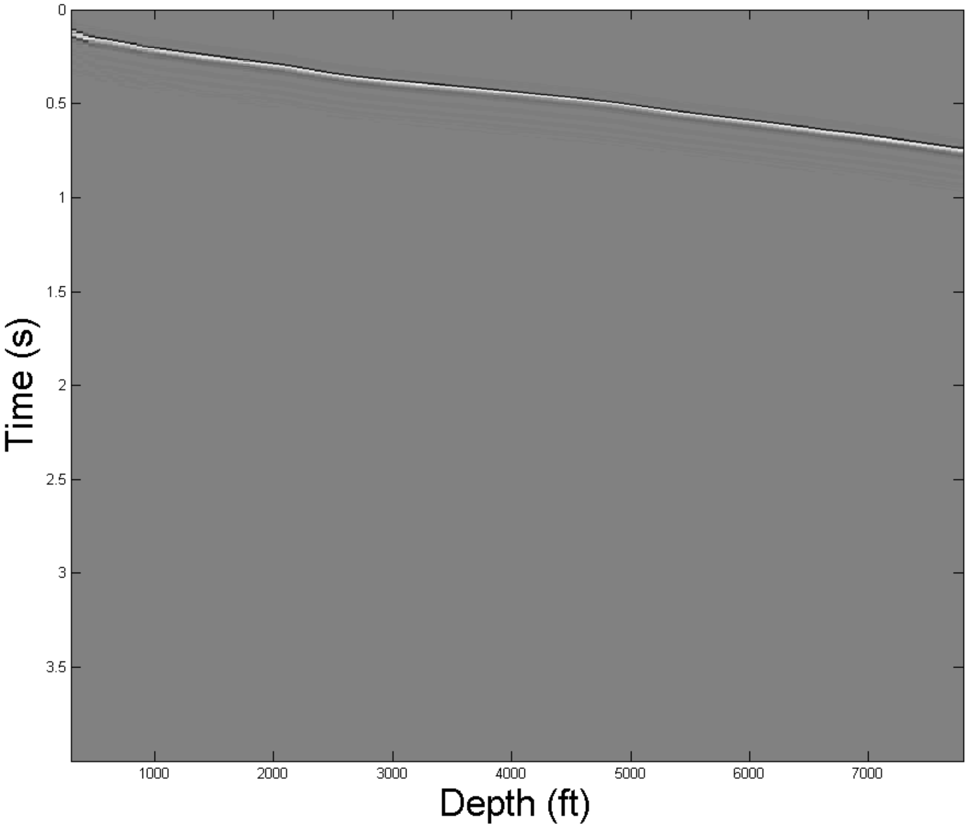


FIG. 3. Isolated direct wave.

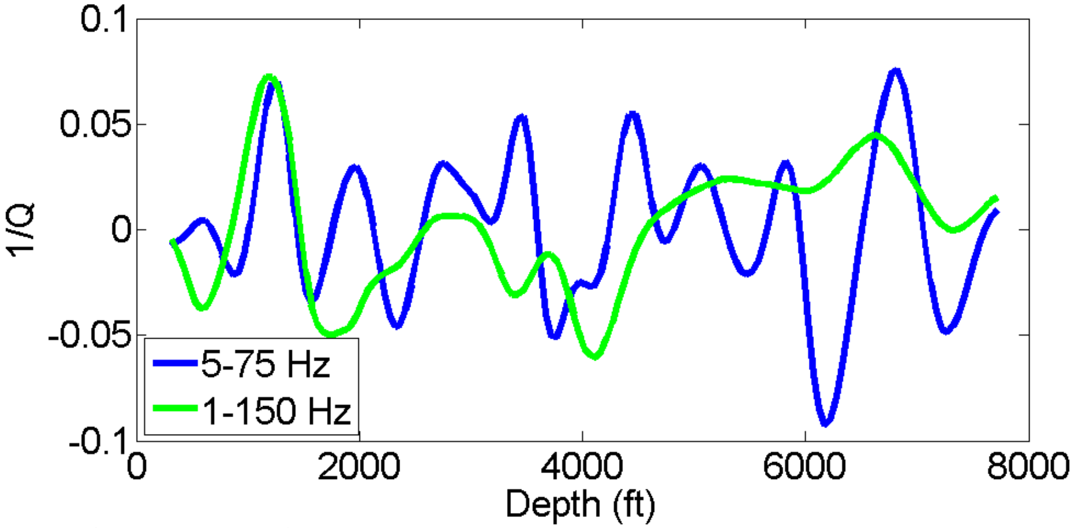


FIG. 4. Estimated Q with the spectral ratio method using bands 5-75Hz and 1-150Hz.

here. One additional step was taken once this was obtained, however. Both the spectral ratio and frequency shift methods can yield highly noisy results if applied to adjacent traces due to the relatively small changes observed. This can be mitigated by sacrificing some spatial resolution, either by comparing traces with greater separation, or by smoothing the amplitude spectra at each frequency one dimensionally in depth. The latter approach was taken here for its superior noise mitigation.

Q estimation

After the initial processing, the spectral ratio method was applied to the data. The resulting Q estimates from this method for two choices of frequency band are shown in figure 4. The significant differences evident highlight the importance of the choice of frequency band in the spectral ratio method. The amplitude spectrum of the isolated direct wave is shown in figure 5. This supports the choice of 5-75 Hz for the frequency band used, as the signal predominates in this range.

Concerningly, there are significant regions of negative Q estimated with either choice of frequency band. Negative Q is unphysical, and implies that spectral ratio method has failed to accurately recover the true attenuation behaviour of the subsurface. Given the significant changes seen in figure 4 when the frequency band used is altered, it is natural to wonder if these negative Q effects are simply a result of poorly chosen frequency bands. This leads to consideration of the frequency shift method.

The frequency shift method is largely invariant under changes in the choice of frequency band. This is demonstrated in figure 6, where the same two bands used in figure 4 are employed in the frequency shift method. Unfortunately, the negative Q previously observed remains in the frequency shift estimate. While the frequency shift method can be wrong by a scaling factor for non Gaussian amplitude spectra, this scaling factor will always be positive, and cannot give rise to such negative Q effects. Additionally, comparison of the results of the spectral ratio and centroid frequency methods demonstrates that both methods

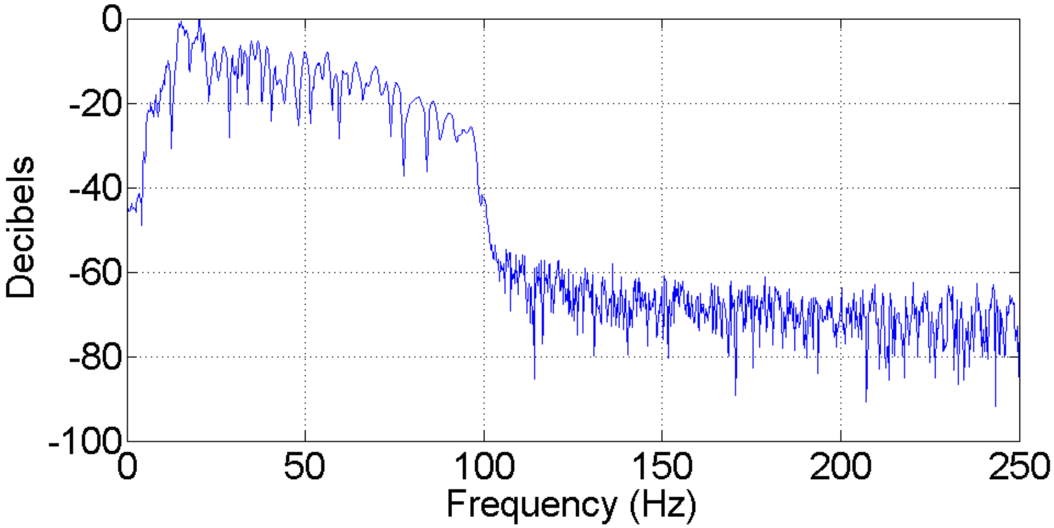


FIG. 5. Amplitude spectrum of receiver at 769 feet depth.

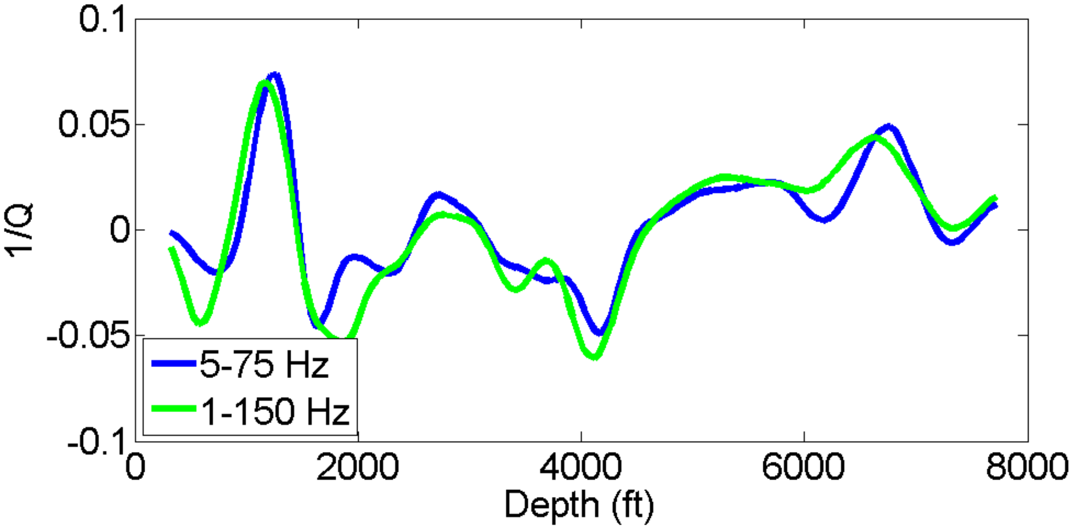


FIG. 6. Estimated Q with the centroid frequency shift method using bands 5-75Hz and 1-150Hz.

are recovering approximately the same model (figure 7). This implies that the negative Q effects are introduced either by an errant processing step, or by a failure in the common assumptions of the two methods.

Possible causes of negative Q estimates

Before investigating possible failures in the common assumptions of the methods used, it is important to ensure that the processing steps taken before Q estimation did not introduce significant problems into the amplitude spectra. The steps which significantly impacted the amplitude spectra were the time windowing to remove the downgoing multiples, and the smoothing of the amplitude spectra in depth. The time windowing should not affect the Q estimate, as the windowing effectively convolves each amplitude spectrum with a filter, and this filter is consistent between traces. Given that both Q estimation methods rely on differences in the spectrum with depth, this time windowing should have no effect.

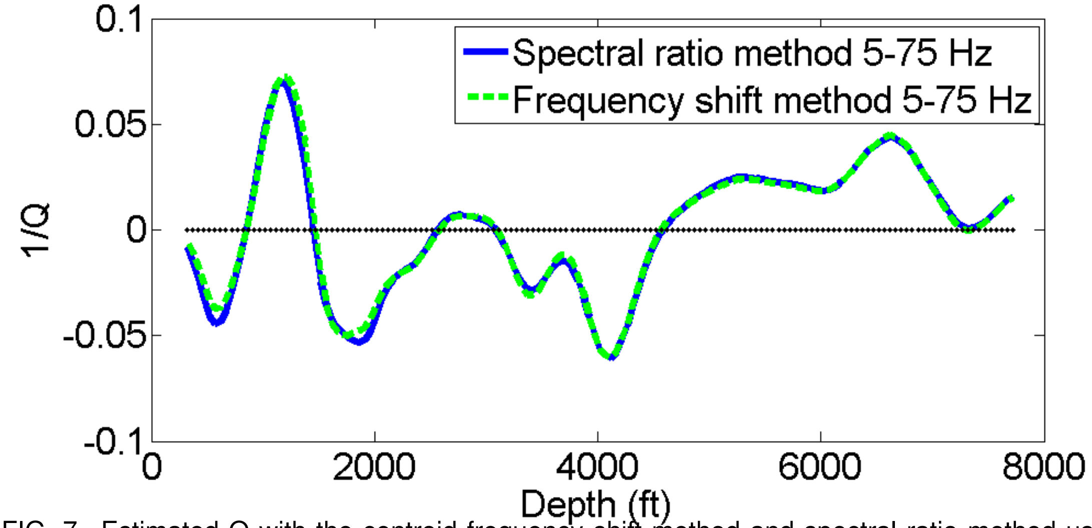


FIG. 7. Estimated Q with the centroid frequency shift method and spectral ratio method using a 5-75Hz band.

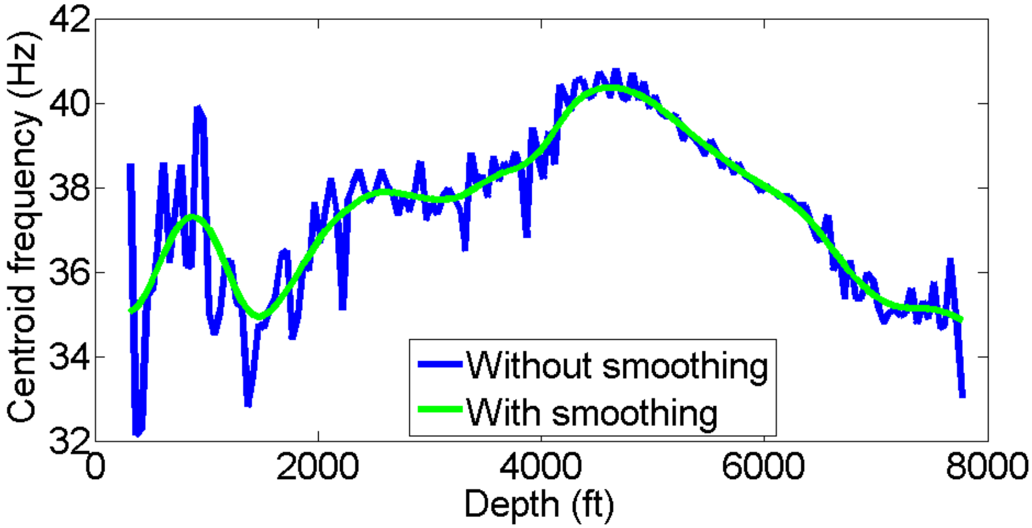


FIG. 8. Centroid frequency as a function of depth with and without amplitude spectra smoothing.

Tests done without the windowing yielded very similar Q estimates (presumably due to the downgoing multiples being too small of amplitude to have a large effect).

The smoothing of the amplitude spectra with depth should also have little effect. This is verified in figure 8, which shows the centroid frequency as a function of depth with and without this smoothing. As expected, without the smoothing the result is noisier, but the undesired increase in centroid frequency with depth that gives rise to negative Q remains prominent.

Negative Q estimates have been reported previously in both Jannsen et al. (1985) and Matsushima (2006). Numerous potential causes have also been suggested. Some are specific to the method used, and can be easily discounted here. Other suggestions include noise, geophone coupling and scattering effects (Matsushima (2006)). Noise and geophone coupling are unlikely candidates, as the negative Q estimate is sustained over a significant depth and both of these effects would be random. Scattering effects have been proposed by Mateeva (2002) to be a possible cause for negative apparent Q. This effect is caused by non-white reflectivities giving rise to short path multiples which reinforce certain frequencies in the direct arrival more than others. If the high frequencies are reinforced and low frequencies are not, there can be negative apparent Q. In order to evaluate the likelihood of scattering effects as a cause of the observed negative Q, synthetic VSP data generated from the well logs were investigated.

SYNTHETIC VSP TESTING

In order to evaluate the importance of scattering effects on the Q estimates recovered, synthetic tests were carried out. These were generated using the well logs, offering the advantage of the sub-wavelength velocity resolution that gives rise to spectral scattering effects. The synthetic VSP profiles were created using the $vspmodelq\_problem.m$ function from the CREWES toolbox. This function is largely an implementation of the algorithm described by Ganley (1981). Important inputs are the velocity, density and Q profile of the well, as well as a source wavelet. Two VSP models were generated, one with infinite Q to evaluate the effect that scattering alone has on the estimated Q, and another with uniform Q=30 to verify the effectiveness of the processing and estimation methods used. The attenuation free synthetic VSP data are shown in figure 9. The same processing and Q estimation as was used for the real data was applied to this synthetic. This resulted in the Q estimate shown in figure 10, where the logs used to generate the VSP and the recovered centroid frequency are also plotted. This result vindicates the idea that scattering effects have a negative Q forcing in some regions of the data, but the locations of this effective negative Q do not align with the negative Q estimates in the data. Additionally, the amplitude of the effective Q introduced by scattering is significantly less than that observed in the Q estimate from the measured data. This does not completely discount scattering effects as a possible cause for the observed effects in the measured data. Scattering effects are expected to have a more pronounced impact at smaller scales (O'Doherty and Anstey (1971)). This means that if the large negative effective Q observed were to be caused by scattering effects it would depend on scattering on scales smaller than the spatial resolution used in the synthetic VSPs (that of the well logging, 0.5 feet). It is possible that on these scales the effective negative Q is in better agreement with the recovered Q from the measured data. Three dimensional scattering effects are also a potential source of error.

The Q estimate for the Q=30 case is shown in figure 11. In this synthetic case, the correct Q is approximately recovered, supporting the idea that the processing and Q estimation techniques used are not at fault for the negative Q estimates in the measured data.

IMPLICATIONS FOR FWI

The overall purpose of this analysis was to provide a true model for Q to compare against later FWI results, and to identify challenges that will be faced in applying anacoustic FWI to these data. The first of these goals has not been satisfactorily accomplished; unphysical negative Q is persistently predicted in both of the Q recovery methods used here. Several challenges to be faced by an eventual FWI formulation can be identified however. The negative recovered Q using the spectral ratio and frequency shift methods implies that

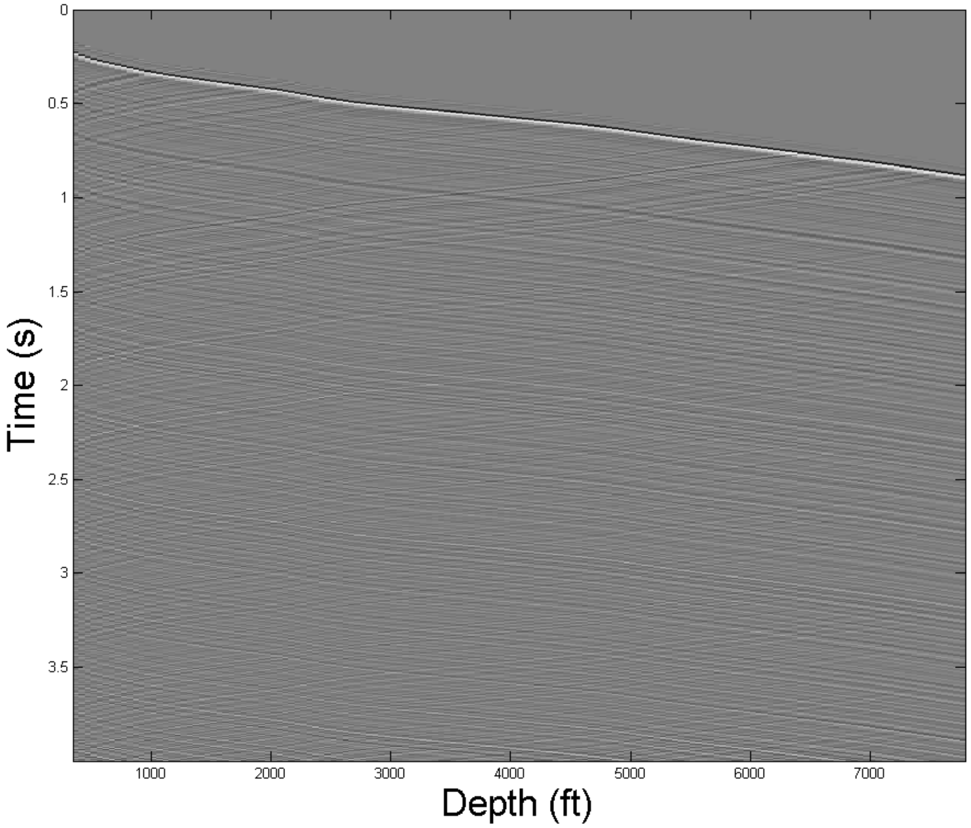


FIG. 9. Synthetic VSP generated from well log velocity and density. Q is treated as being infinite everywhere.

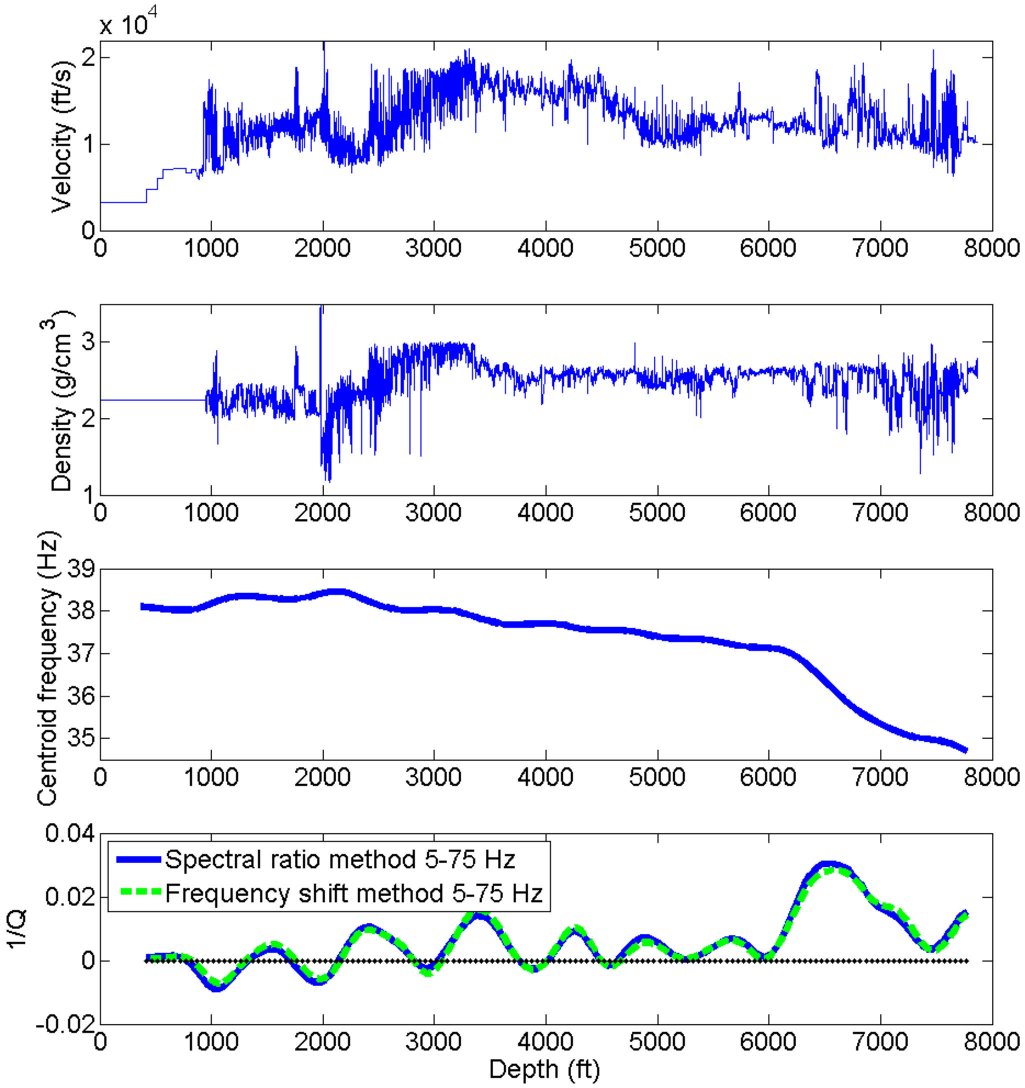


FIG. 10. Top: P-wave velocity from well logs used to generate synthetics. Mid top: Density from well logs used to generate synthetics. Mid bottom: Recovered centroid frequency estimate for attenuation free synthetic. Bottom: Estimated Q for attenuation free synthetic (figure 9).

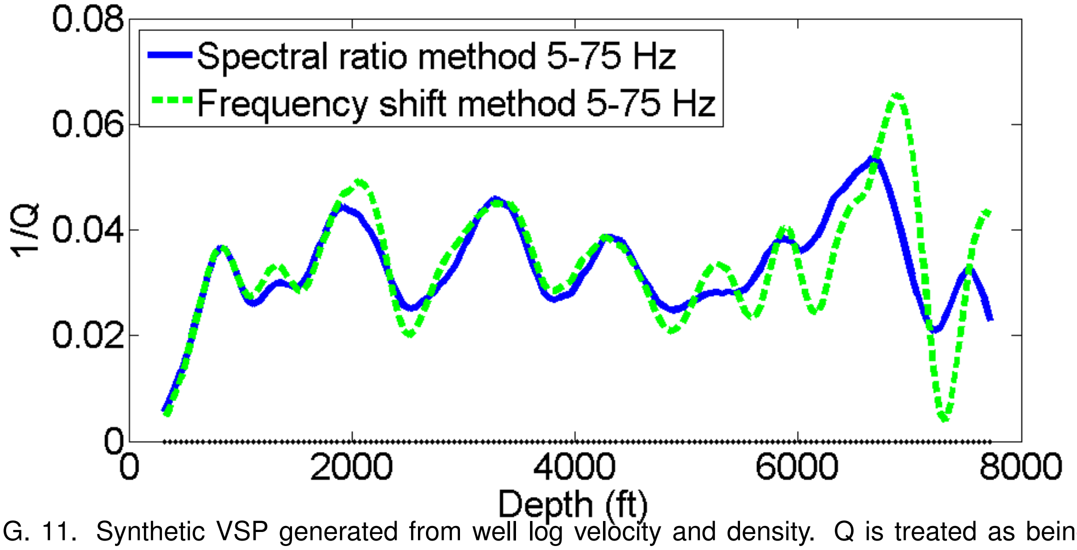


FIG. 11. Synthetic VSP generated from well log velocity and density. Q is treated as being 30 everywhere.

at some depths the low frequencies are losing amplitude faster than the high frequencies. There are no commonly used attenuation models which predict a decrease in attenuation as frequency increases. This means if an anacoustic FWI assumes a particular attenuation model, it will be incapable of reproducing the observed data, and may meet with significant problems. Additionally, regardless of whether scattering effects caused the observed negative recovered Q, it was demonstrated that they do impact the amplitude spectrum based Q estimation methods used here. These scattering effects likely do not also replicate Q effects in their impact on the amplitude or dispersion. In order to successfully match the data then, FWI will need to reproduce frequency shift effects independent of amplitude changes and dispersion effects.

CONCLUSIONS

The attenuation properties of the Chaparral Farnsworth VSP data set were investigated in this report. The spectral ratio and centroid frequency methods were used to obtain estimates of Q from the data. These estimates were consistent with one another, and featured prominent zones of negative Q, an unphysical phenomenon. Several potential causes for a negative Q estimate were considered. The likeliest of these were the frequency dependent changes caused by scattering effects. Further investigation with synthetic VSP profiles generated from the well logs demonstrated that although there are negative effective Q forcing effects introduced by scattering effects, they are not sufficient to explain the estimated Q profiles on the scale recovered by the well logs.

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