Estimating frequency-dependent attenuation quality factors in pre-stack surface seismic data.

James Beckwith and Roger Clark, University of Leeds;

Summary

Estimation of a power-law frequency-dependent seismic quality factor is introduced into the pre-stack Q inversion (PSQI) method for estimating seismic attenuation from pre-stack data. The adapted method is tested with synthetic data, and found to estimate successfully the frequency dependence of the attenuation quality factor, within errors. Notably, though, if low frequencies (<20Hz) are excluded from the inversion, then frequency dependent estimates become inaccurate. The adapted PSQI method is applied to a CDP supergather over a North Sea oil field, and a slight frequency dependence on the attenuation quality factors is found, with a mean frequency exponent of 0.03±0.10. A previous study, based on available well log data, has found that the scattering attenuation quality factor value, in the range of 2.28s TWT and 2.68s TWT, shows a negative dependency on frequency, and can therefore account for much of the frequency dependence seen in the surface seismic results in this region.

Introduction

It is generally assumed in most attenuation estimation schemes (Tonn 1991) that attenuation varies linearly with frequency. That is to say, the attenuation quality factor value is independent of frequency over the bandwidth of surface seismic data. Attenuation which is not linearly dependent on frequency has been estimated by Bowles (1997) and Sams et al. (1997), although these measurements have been made over a frequency bandwidth which is much larger than that of surface seismic data. Reid et al (2001) estimated power-law frequency-dependent attenuation quality factor values (i.e. of the form $Q(f)=\alpha f^{\beta}$) from a North Sea vertical seismic profile (VSP) dataset. Jeng et al (1999) also found evidence that attenuation quality factor values in the near surface can be dependent upon frequency in the seismic bandwidth, using a technique that makes no assumption about the analytical form of the frequency dependence.

It is important to note that attenuation quality factor values estimated from surface seismic data are generally apparent attenuation values, and are thus a harmonic average of the intrinsic and scattering attenuation. The method of estimating scattering attenuation given by van der Baan (2001) highlights how scattering attenuation can be highly frequency dependent in the seismic frequency bandwidth and can have a non-trivial magnitude. Even if the intrinsic attenuation quality factor is in fact frequency-independent, the apparent attenuation quality factor value estimated from surface seismic could be frequency-dependent due to the influence of scattering attenuation.

Attenuation estimation schemes should, ideally, measure frequency-dependent attenuation quality factor values, but often do not. If the attenuation quality factor is frequency-independent, then attenuation is a linear function of frequency and we need only estimate the rate of loss of amplitude with frequency of a propagating wave. However, if the attenuation quality factor is frequency–dependent, then the acceleration of the loss of amplitude with frequency on the propagating wave needs to be accounted for, which is much more difficult. This requires having an estimate of the wavelet, or its amplitude spectrum, which is almost entirely free of interference due to other arrivals, noise or artefacts.

Jeng et al. (1999) found that, for unconsolidated sediments, the attenuation quality factor value was almost linearly dependent upon frequency. Herein lies a trade-off: attenuation preferentially cuts out higher frequencies but the frequency dependence of the attenuation quality factor is most readily observed at lower frequencies, where the change in the quality factor is greatest.

The estimation of frequency-dependent attenuation quality factor values will be introduced through an adaptation of the pre-stack Q inversion (PSQI) method (Reine et al. 2012). The method for estimating frequency dependent attenuation quality factor values is tested on synthetic data which is based upon blocked well log data in which scattering attenuation is minimal. The effect of altering the bandwidth used in estimating attenuation is investigated with a simple synthetic model. Finally the method is applied to a pre-stack CDP super gather from a North Sea seismic survey.

Theory

Frequency-dependence of the seismic attenuation quality factor will be estimated via an adaptation of the pre-stack Q inversion (PSQI) technique of Reine et al. (2012). The PSQI method is a modified spectral ratio method which is designed to work on pre-stack data which has had a linear radon transform applied so that the data is in the intercept-time/horizontal-slowness (τ-p) domain. Each horizontal slowness trace corresponds to a common take-off angle in the overburden for two successive reflectors. By matching the ray paths in the overburden, it is possible to mitigate angle dependent effects such as directivity on the spectra used in the spectral ratio method. By also taking into account different take-off angles, then the effect of an increased path length within an interval of interest can also be observed.

$$\ln\left(\frac{A_2(f,\Delta t)}{A_1(f,\Delta t)}\right) = \ln(PG) - \frac{\pi f \Delta t}{Q_{i12}} \quad (1)$$

Equation 1 shows the general form of the spectral ratio equation used in the PSQI method where $A_i(f,\Delta t)$ is the amplitude spectrum of the i^{th} reflector at each horizontal slowness value analyzed (Δt is the travel time within the interval of interest). P is the energy partitioning term (corresponding to a ratio of amplitude versus slowness curves), G is a geometrical spreading term and Q_{i12} is the apparent interval attenuation between reflectors 1 and 2.

If the geometrical spreading is corrected for, the energy partitioning terms are assumed to be independent of frequency and the travel time with the interval (Δt) is known, then equation 1 can be solved through linear least squares inversion to obtain Q_{i12}. If Q_{i12} is now assumed to be frequency dependent in the form given in equation 2 then equation 1 cannot be solved with a least-squares linear inversion.

$$Q_{i12} = a_{12} f^{b_{12}} \quad (2)$$

$$\ln\left(\frac{A_2(f,\Delta t)}{A_1(f,\Delta t)}\right) = \ln(PG) - \frac{\pi f^{1-b_{12}} \Delta t}{a_{12}} \quad (3)$$

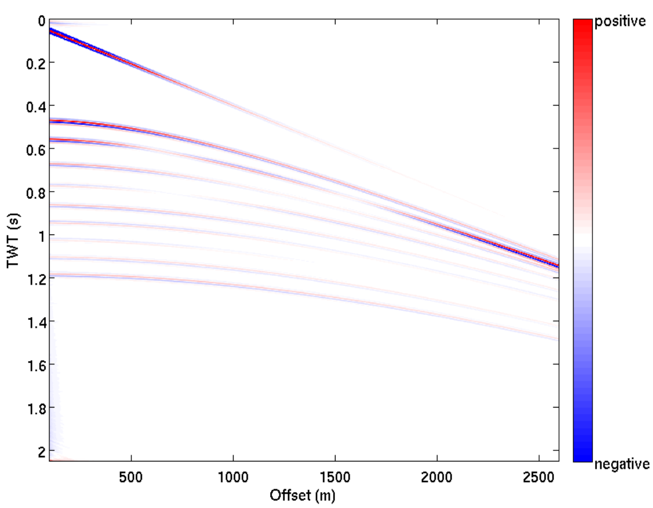

Figure 1: Synthetic shot gather based on well log North Sea well log data containing frequency dependent attenuation.

Here, a and b refer to the coefficient and exponent of the dependence of the attenuation quality factor on frequency. If the quality factor is frequency-independent then the exponent will be equal to zero.

Equation 3 can be solved by many different methods including but not limited to; non-linear inversion, Monte Carlo, directed Monte Carlo and grid search methods. If the energy partitioning terms are assumed to be independent of frequency, and equal to the energy partitioning terms estimated via equation 1, then a grid search method has been found to be the most computationally inexpensive

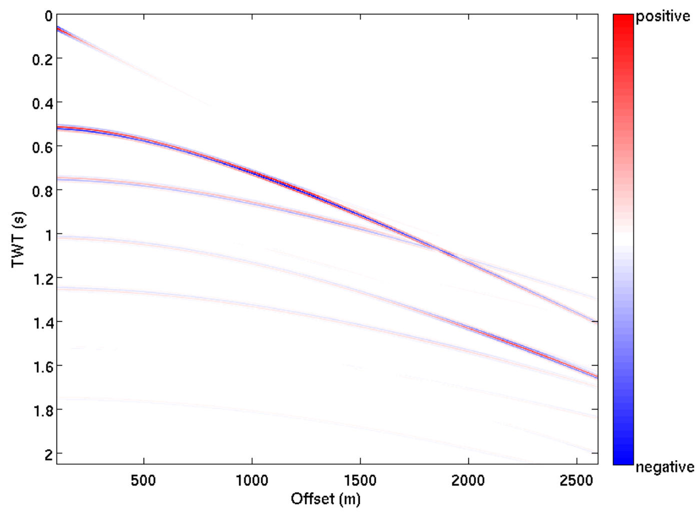

Figure 2: Synthetic shot gather used for testing the effect of frequency bandwidth choice on estimated attenuation.

whilst retaining accuracy.

Examples

Figure 1 shows the synthetic shot gather generated to test the accuracy of the adapted PSQI method in estimating a frequency dependent attenuation quality factor. The synthetic gather is generated using blocked density, compressional and shear wave sonic logs from a North Sea well. A homogeneous attenuation quality factor has been used in the synthetic model with a coefficient and exponent (a and b in equation 2) of 20 and 0.5 respectively.

The adapted PSQI method outlined by equation 3 is applied to 9 different reflector pairs in figure 1. The mean coefficient and exponent estimated from the 9 different intervals are 15±6 and 0.46±0.04 respectively. Within errors, the adapted PSQI method has returned the expected coefficient and exponent of the frequency dependence of the attenuation quality factor present in the synthetic gather.

Given the power-law form of frequency dependence of the attenuation quality factor shown in equation 2, then lower frequencies in the spectral ratio surface, defined by equation 3, will provide the most information about the frequency dependence of the attenuation quality factor. However, seismic signals are band limited and only contain information within a certain frequency range. It is prudent to therefore investigate how the frequency band which is used to estimate attenuation will affect the derived value of attenuation itself.

To assess this, a simple synthetic shot gather (figure 2) is generated which contains a homogeneous frequency dependent attenuation quality factor with coefficient and exponent of 20 and 0.5. The adapted PSQI method, using equation 3, is then used to determine the coefficient and exponent over the frequency bandwidths of 0Hz-80Hz and 20Hz-80Hz.

When using a regression bandwidth of 0Hz to 80Hz, the estimated coefficient and exponent are 20±4 and 0.46±0.05 respectively. These values are, within errors, equal to the input coefficient and exponent of 20 and 0.5. However, when estimating attenuation form the spectral ratio surface within the frequency band of 20Hz to 80Hz, the estimated coefficient and exponent are 15±3 and 0.52±0.05, which are not equal to the input coefficient and exponent of 20 and 0.5.

These results highlight how useful lower frequencies can be in identifying frequency dependent attenuation quality factors accurately.

The method outlined so far for estimating frequency dependent attenuation quality factor values has been proven to accurately estimate the coefficient and exponent which describe the frequency dependence on synthetic data. It has also been shown that it is important to include low frequencies into the attenuation estimation scheme in order to accurately estimate the degree of frequency dependence.

This knowledge is now applied to a CDP super gather located over a North Sea oil field. Figure 3 shows the transformation of the CDP super gather into the τ-p domain and also highlights 9 different geological horizons that will be used to estimate frequency-dependent attenuation quality factor values.

Figures 4 and 5 show the coefficient and exponent of the estimated frequency dependence of the attenuation quality factor estimated using a grid search method with equation 3. The coefficients of the frequency dependent attenuation are similar to the estimated frequency-independent attenuation quality values estimated using equation 1. The maximum correlation coefficient between the two sets of data is 0.7 at a sample lag of zero.

The range of exponent values in figure 5 is -0.25 and 0.32, showing only a very slight frequency dependence on the attenuation quality factor values. The mean exponent value is 0.03±0.10. There is however a general trend of positive exponent values between 1.3s and 2.1s TWT changing to a negative exponent value at two way times greater than 2.1s. This corresponds with a region of low coefficient values and thus high attenuation.

Conclusions

An adaptation to the pre-stack Q inversion methodology to allow for the determination of frequency-dependent attenuation quality factor values has been outlined. Using synthetic data, we have provided evidence that the adapted PSQI method can accurately estimate an input frequency-dependent attenuation quality factor. Evidence has also been presented to suggest that low frequencies will play a crucial role in estimating frequency-dependent attenuation quality factors, as they will change most rapidly at lower frequencies.

The adapted PSQI method ahs been applied to a CDP super gather over a North Sea oil field and the coefficient and exponent of frequency-dependent attenuation quality factor has been estimated for 36 different intervals of interest. The estimated exponent values, with an average of 0.03±0.10, shows that there is little frequency dependence on the attenuation quality factor value in this dataset.

Beckwith and Clark (2014) found the scattering attenuation quality factor value in the region of 2.28s TWT to 2.68s TWT to have a negative frequency dependency. The negative frequency dependency of the scattering attenuation can account for the frequency dependency seen in the attenuation quality factor values estimated from surface seismic data. When scattering attenuation is corrected for, the frequency dependence of the surface seismic estimates is negligible and the coefficient remains constant.

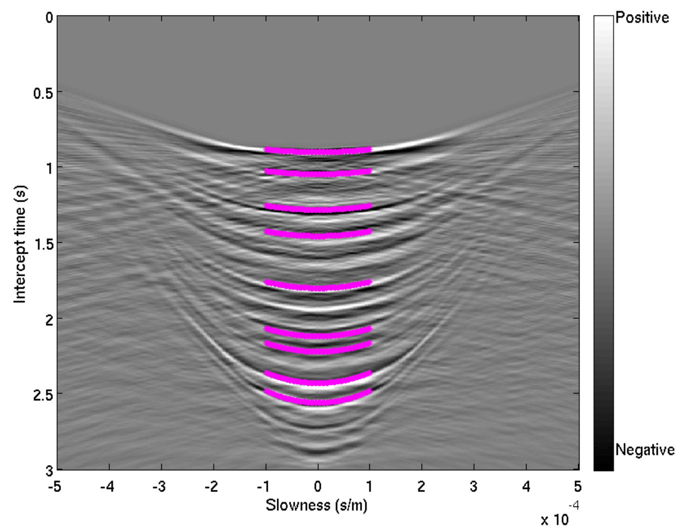

Figure 3: τ-p gather of a CDP super gather over a North Sea oil field. 9 different geological horizons which are used to determine attenuation quality factor values are highlighted.

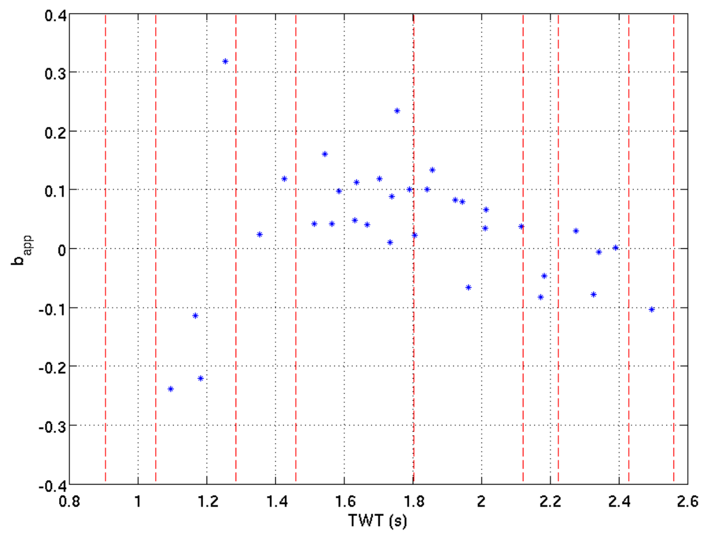

Figure 5: Exponents of frequency dependent attenuation quality factors estimated for a CDP super gather over a North Sea oil field. The geological horizons highlighted in figure 3 are also shown.

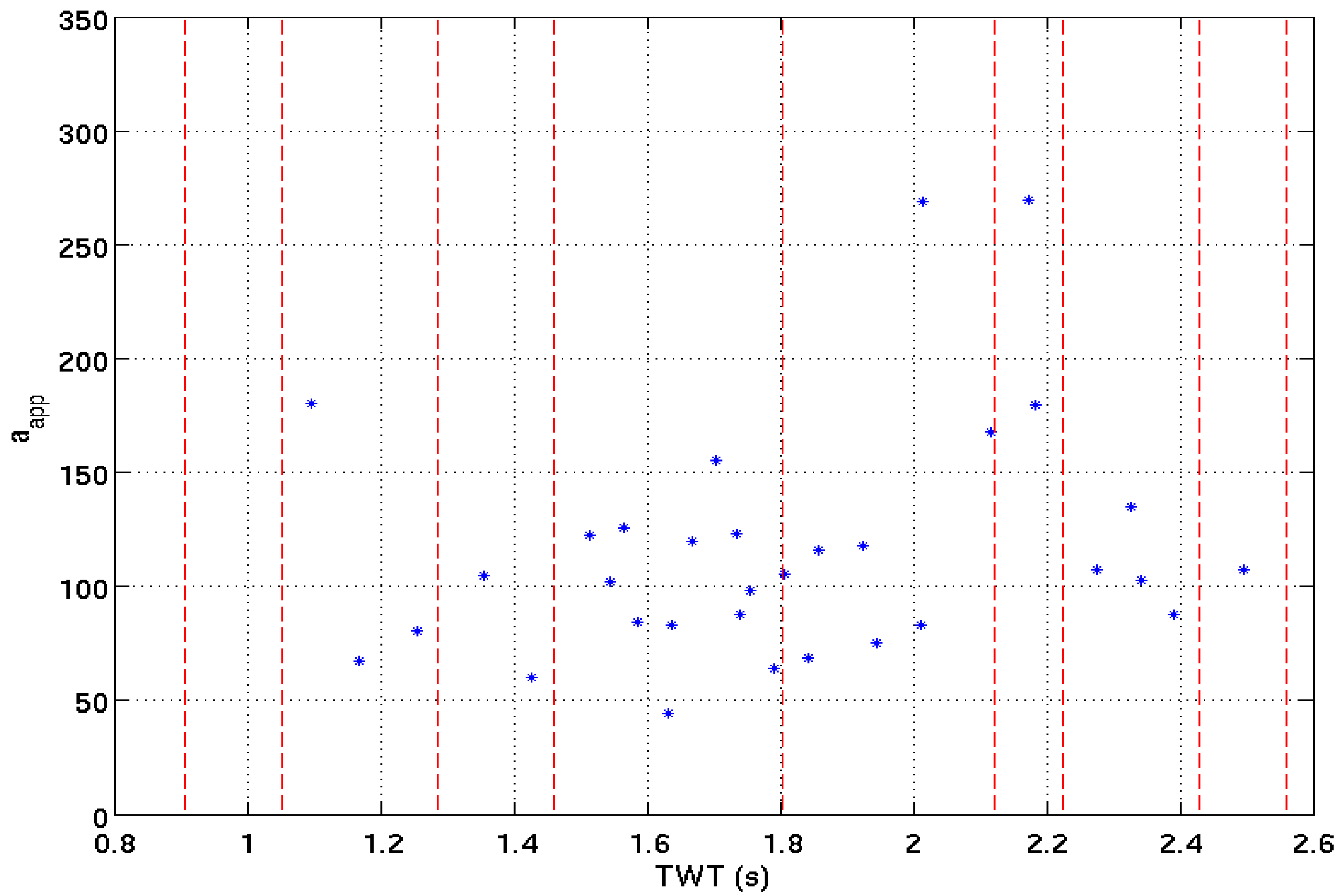

Figure 4: Coefficients of frequency dependent attenuation quality factors estimated for a CDP super gather over a North Sea oil field. The geological horizons highlighted in figure 3 are also shown.