Q estimation by a match-filter method

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Summary

A match-filter method for Q estimation using reflection data is proposed and evaluated using synthetic 1D, 2D data and field data in this paper. Testing results show that the proposed method is, compared to the spectral-ratio method, more robust to noise and more suitable for the Q estimation from reflection data, and has the potential to indentify a localized low Q zone of the subsurface, which can be used as a gas indicator.

Introduction

Conventionally, Q is estimated from transmission data. There are various methods for Q such as analytical signal method (Engelhard, 1996), spectral-ratio method (Bath, 1974), and the centroid frequency-shift method (Quan and Harris, 1997), and each method has its strength and limit. An extensive comparison between various methods for Q estimation was made by Tonn (1991) using VSP data; and a conclusion was made that the analytical signal method is superior if true amplitude recordings are available and otherwise the spectral-ratio method is optimal in the noise-free case. The estimation given by spectral-ratio method may deteriorate drastically with increasing noise (Patton, 1988; Tonn, 1991). Although transmission data (e.g. VSP) are ideal for Q estimation, they have limited areal coverage and are more expensive than surface data. Therefore, in practice, it is more useful to estimate Q from the surface reflection data. For reflection data, Q can be derived from the change in the spectra of reflections. The spectrum of the reflected wave is subjected to the tuning effect (Sheriff and Geldart, 1995) of local thin-bed formation, which makes spectrum smoothing necessary. Generally, estimating Q from noisy data or surface reflection data needs further investigation. The purpose of our work is to propose and evaluate a robust method for Q estimation that is suitable for application to reflection data.

Theory of match-filter method

Suppose that $|\mathrm{A}_1(f)|$ and $|\mathrm{A}_2(f)|$ are the two local amplitude spectra obtained from local waves near time t_1 and t_2 in a seismic record respectively. More often, there are spikes or notches in the spectrum caused by noise or the tuning effect of local reflectors, which cause problems for the Q estimation and can be mitigated by the multi-taper method (Thomson, 1982) for spectrum smoothing. So, rather than ratio the two spectra, we compute the minimum-phase equivalent wavelets (embedded wavelets) $\mathrm{w}_1(\mathrm{t})$ and $\mathrm{w}_2(\mathrm{t})$ from smoothed amplitude spectra, and then Q can be estimated by finding the forward Q filter that best matches the shallow wavelet to the deeper wavelet, which can be formulated as

$$\mathrm{Q}_{\mathrm{est}} = min_Q \|\mathrm{w}_1(\mathrm{t}) * \mathrm{I}(\mathrm{Q},\mathrm{t}) - \mu \mathrm{w}_2(\mathrm{t})\|^2,$$

where $*$ denotes convolution, the minimization is taken over the range of possible Q values; $\mathrm{I}(\mathrm{Q},\mathrm{t})$ is the forward Q filter for a quality factor value Q and travel time $(t_2 - t_1)$ and can be formulated as

$$\mathrm{I}(\mathrm{Q},\mathrm{t}) = F^{-1}(\exp\left(\frac{-\pi f(t_2-t_1)}{Q} - \mathrm{iH}(\frac{\pi f(t_2-t_1)}{Q})\right)),$$

where H denotes the Hilbert transform; and μ is a constant scaling factor and can be calculated as

$$\mu = \frac{\int_{-\infty}^{\infty}(\mathrm{w}_1(\mathrm{t}) * \mathrm{I}(\mathrm{Q},\mathrm{t}))\, \mathrm{w}_2(\mathrm{t})\mathrm{dt}}{\int_{-\infty}^{\infty} \mathrm{w}_2{}^2(\mathrm{t})\mathrm{dt}}.$$

The match-filter method described above is theoretically similar to the spectral-ratio method because the inverse Fourier transform of a spectral ratio is a matching filter. However, computing the match filter in the time domain is more robust in the presence of noise than direct spectral division in the frequency domain.

Examples

The ideal test for Q estimation is computing Q from noise free VSP data or reflection data with isolated events, which can be used to validate Q estimation methods theoretically. A synthetic attenuated seismic trace was created by a nonstationary convolution model proposed by Margrave (1998), using two isolated reflectors, a minimum phase wavelet with dominant frequency of 40 Hz and a constant Q value of 80, as shown in figure 1. Using the two local events in figure 1, Q estimation by the match-filter method is shown in figure 2. Figure 3 shows the fitting error of different Q values for the match-filter method. We can see that the match-filter method gives accurate estimation of Q=80.06. Then, random noise is added to the synthetic data to evaluate the Q estimation by spectral ratio method and match-filter method. 200 seismic traces are created by adding 200 difference random noise series of the same level (SNR=2) to the trace shown in figure 1. Then Q estimation is conducted using these noisy data. The histograms of the estimated Q values are shown in figure 4 and 5. We can see that the match-filter method gives good estimation with a closer mean value of 79.59 and a smaller standard deviation value of 12.03 while the spectral ratio method corrupts in presence of extensive noise.

Surface reflection data is the most common seismic data so that it is worthwhile to attempt to estimate Q from it. Figure 6 shows a synthetic seismic trace created using a random reflectivity series, a minimum phase source wavelet with dominant frequency of 40Hz and a constant Q of 80. To test the Q estimation method, 200 attenuated seismic traces are created from 200 random reflectivity series with noise of level SNR=2. Then, local waves are obtained by applying time gates of 100ms-500ms and 900ms-1300ms to the seismic traces, and used to conduct Q estimation. The histograms of the estimated Q values are shown in figure 7 and 8. Basically, the spectral ratio method does work this time. The match-filter method still gives good estimation with a mean value of 78.37 and a standard deviation value of 15.26.

An important application of Q estimation is that the result can be used as a gas indicator in conjunction with other observation such as flat spot, bright spots, and AVO anomalies. So, it will be very useful if the Q estimation method can identify the low Q zone of subsurface from seismic data. Synthetic 2D data for a layered earth model with a low Q zone is used to test the match-filter method, which is created from the seismic modeling using the Tiger software of SINTEF. To simplify the computation of travel time, we use an earth model with a constant velocity and layered density structure as shown in figure 9. The associated Q model is shown in figure10. The low Q zone has an extension of 1.2s – 1.26s in two-way travel time and 500m -750m in horizontal coordinate. Three shot records with source locations (x, z) = (650, 0), (750, 0) and (1000, 0) of the layered earth model are generated. The corresponding NMO applied CDP gathers (#1, #2 and #3) can be obtained from the shot records. To indentify the low Q zone, two time windows with a fixed small interval slide along a seismic trace to obtain pairs of localized reflected waves. For each pair of them, a Q value can be estimated and attributed to the time centered between the two time windows, and the Q estimation is applied to the entire 2D seismic gather trace by trace. Through this approach, a Q profile can be obtained corresponding to the 2D seismic gather. Three Q profiles are calculated from the CDP gathers and Figure 11 shows the Q profile of CDP gather #1, we can see the low magnitude area of the Q profile match well with the low Q zone of earth model. To refine the low amplitude areas of the Q profiles further, the variations of the mean value of Q with travel time or depth and horizontal position are derived. From figure 12 and figure 13, the estimated low Q zone should be the areas with a two-way travel time centered at 1.23s and horizontal extension from about 500m to 750m, which is a very good math to the Q model shown in figure 10.

Figure 14 shows the stacked CDP gather of Blackfoot field data, which was acquired over the Blackfoot field near Strathmore, Alberta in 1995. For the Blackfoot data the target zone is around 1050ms in two way time. In addition, there is a Well 14-09 about 200m away from it, which has nearly the same X coordinate with the trace CDP 36 The Q profile for the stacked CDP gather of Blackfoot field data is shown in figure 15. We can see that, there is measurable attenuation around 1050ms nearly across the entire line even a small interval time is employed, and the target zone of the well 14-09 locates within the low amplitude area of the estimated Q profile.

Conclusions

A match-filter method for Q estimation is proposed and evaluated in this paper. Testing on synthetic seismic trace shows that the proposed match-filter method, compared to the classic spectral-ratio method, is very robust to noise and more suitable to be applied to reflection data. In addition, numerical test using the 2D synthetic data and field data demonstrates that the match filter has the potential to identify the localized low Q zone of the subsurface from surface reflection data for a layered medium.

Acknowledgements

We would like to thank the sponsors of CREWES project for their financial support.

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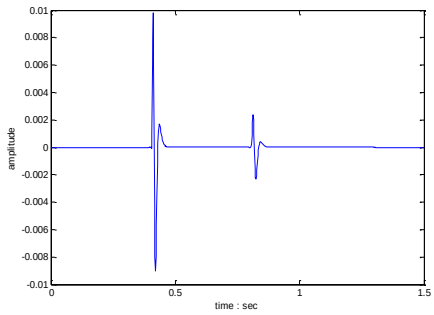


Figure 1. Synthetic attenuated seismic trace created with two isolated events

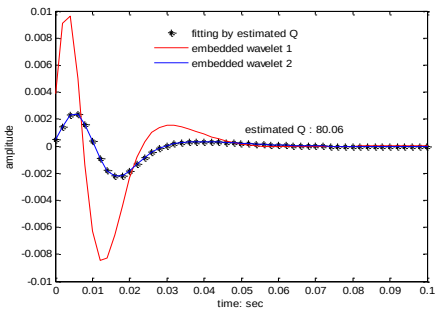


Figure 2. Q estimation by match-filter method using the isolated events shown in figure 1.

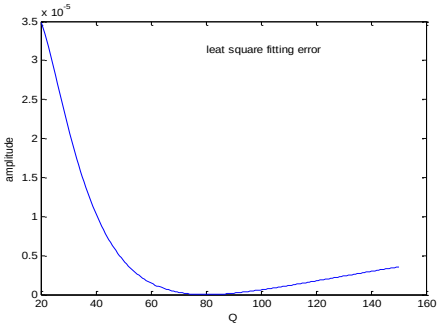


Figure 3. The fitting error curve for Q estimation by the match-filter method corresponding to figure 2

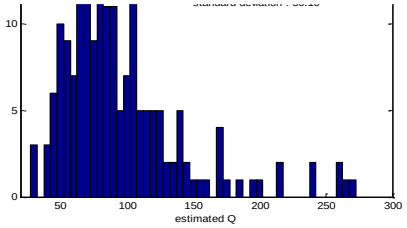


Figure 4. Histogram of estimated Q values by the spectral ratio method using 200 synthetic seismic traces with isolated events (SNR=2)

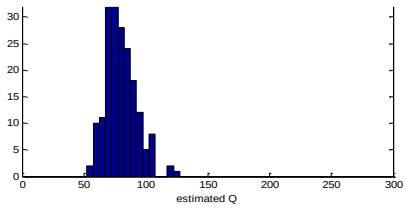


Figure 5. Histogram of estimated Q values by match-filter method using 200 synthetic seismic traces with isolated events (SNR=2)

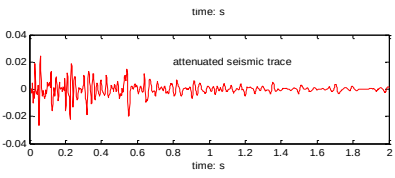


Figure 6. Synthetic attenuated seismic trace created using random reflectivity

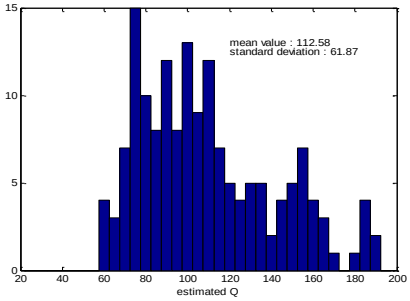


Figure 7. Histogram of estimated Q values by the spectral ratio method using 200 synthetic seismic traces (SNR=2)

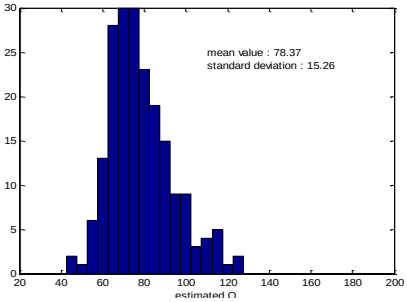


Figure 8. Histogram of estimated Q values by match-filter method using 200 synthetic seismic traces (SNR=2)

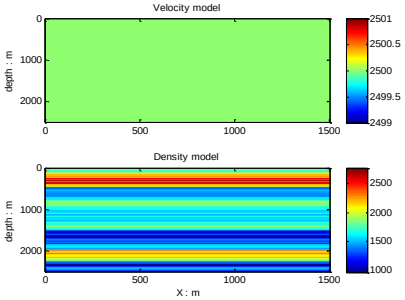
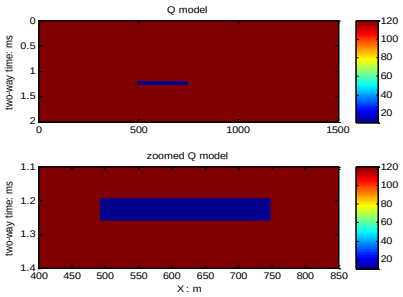
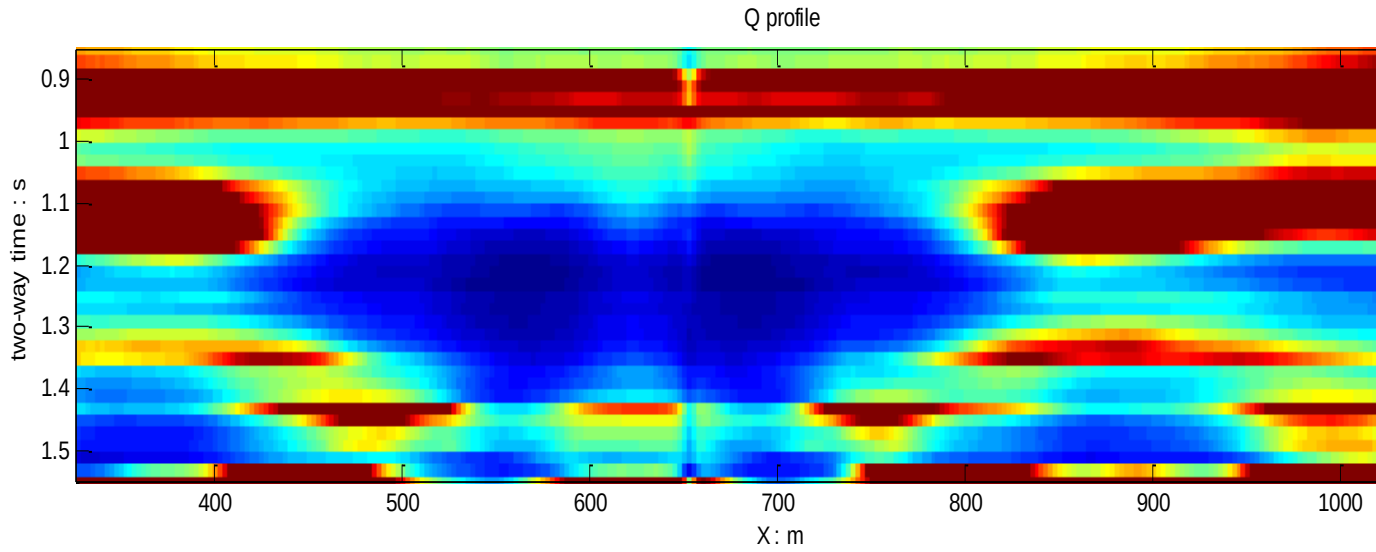
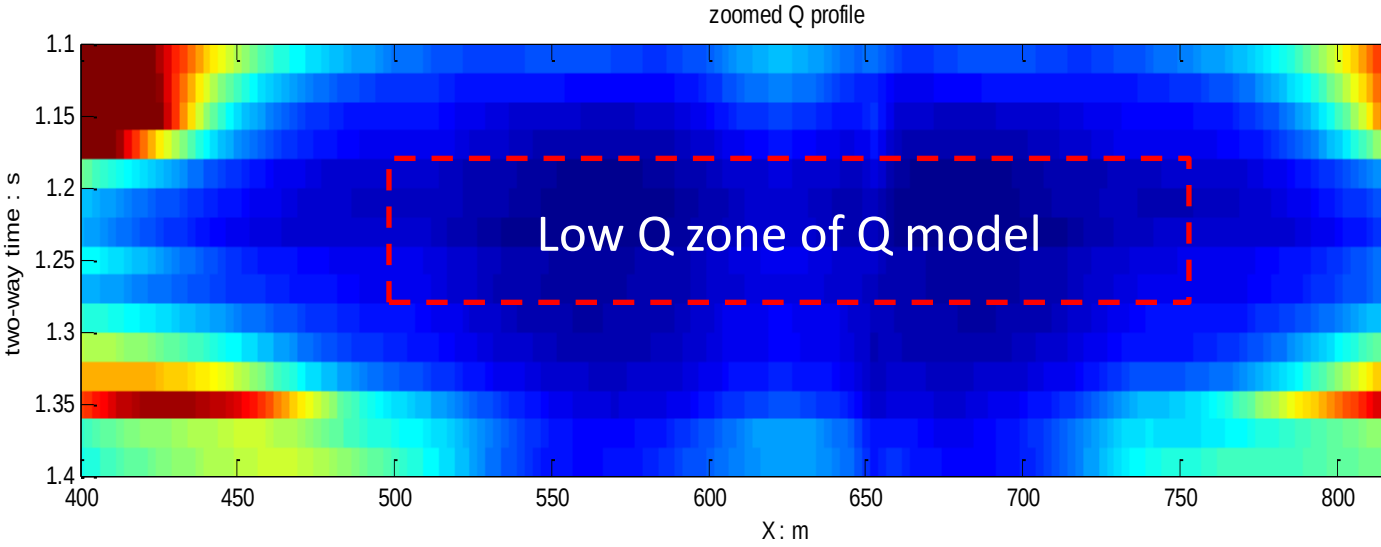


Figure 9. Velocity and density model for a layered earth medium.


Q model
two-way time: ms
zoomed Q model
two-way time: ms
X : m


Q profile
two-way time : s
X : m


zoomed Q profile
two-way time : s
Low Q zone of Q model
X : m

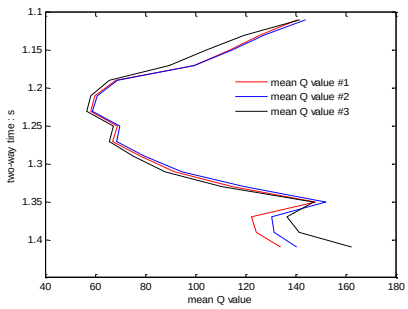

mean Q value #1
mean Q value #2
mean Q value #3
two-way time : s
mean Q value

Figure 10. Q model for a layered earth model.

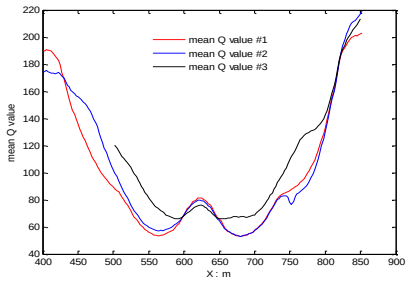
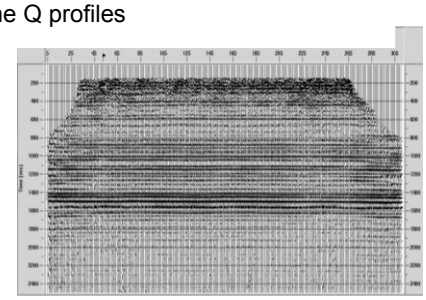


Figure 11. Q profile calculated from CDP gather #1

Figure 12. The variation of mean Q value with horizontal coordinates for the Q profiles



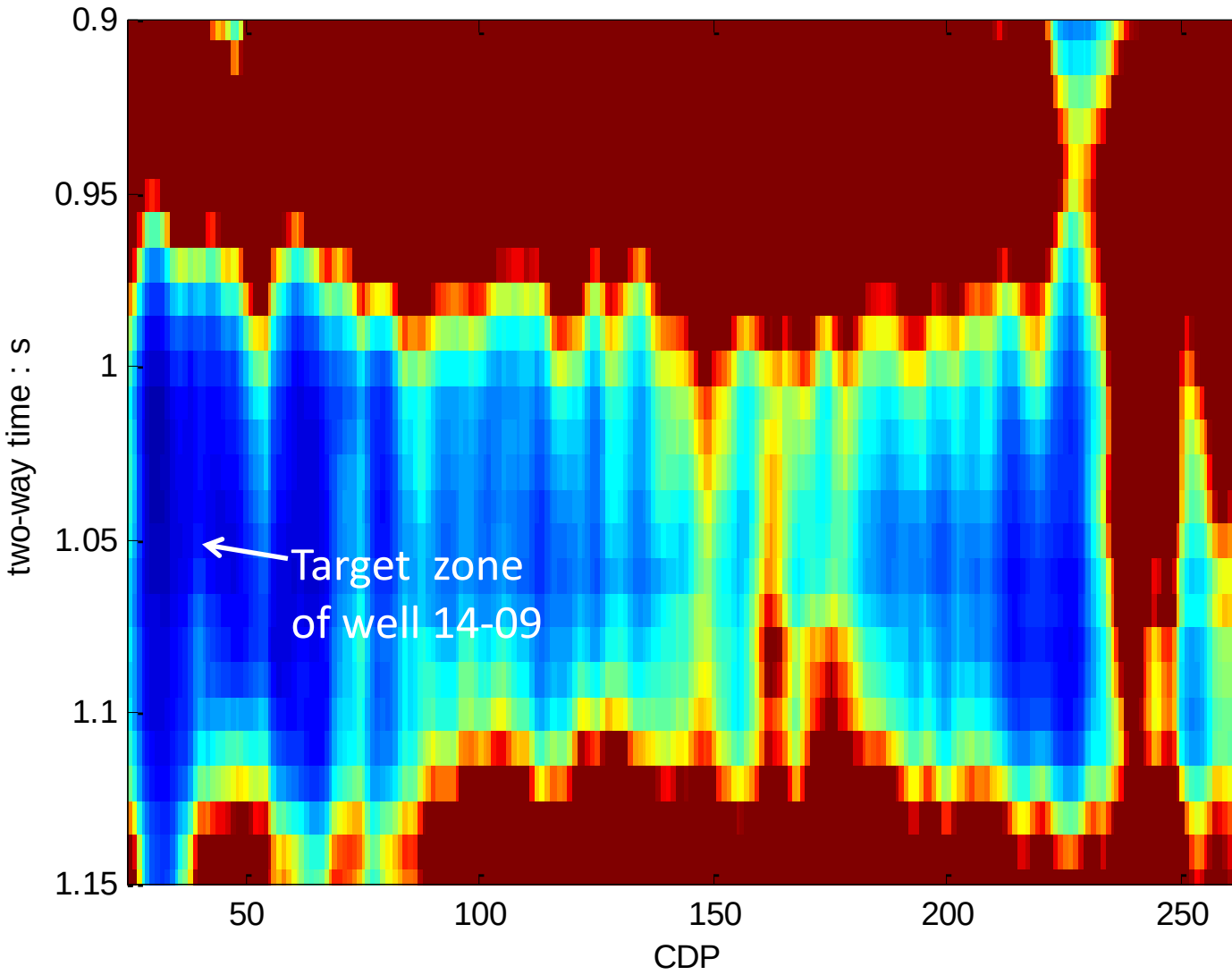


Figure 13. The variation of mean Q value with depth for the Q profiles

Figure 14. Stacked CDP gather of Blackfoot field data

Figure 15. Q profile for the stacked CDP gather of Blackfoot field data