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Logarithmic spectral simultaneous inversion for interval-attenuation estimation

Kai Xu, Sam Zandong Sun *, Ziqi Jin

Lab for the Integration of Geology and Geophysics, State Key Laboratory of Petroleum Resource and Prospecting, China University of Petroleum, Beijing, China

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ABSTRACT

Frequency domain Q estimation methods usually pick two reflections at different traveltimes, and estimate Q according to the variation of their amplitude spectra. However, the variation of the amplitude spectra is not only affected by the target layer, but also affected by the overburden, which lead to error of Q estimation results. In addition, this influence will become more obvious as the increase of offset, making the traces of large offset unusable for Q estimation. We have developed a novel Q estimation method, called logarithmic spectral simultaneous inversion (LSSI), to address this problem. This proposed method account for the effect of the overburden by picking another adjacent reflection, which is used as a constraint for the Q value estimation in the overburden, and separating attenuations from different layers according to the traveltime through the process of inversion. Q values of both target layer and overburden are estimated simultaneously. Model test and field data application indicate the validity of the method.

1. Introduction

Visco-elastic properties of subsurface media cause amplitude loss and phase distortion of seismic waves, thus decreases the quality of imaging profile. And it makes quantitative amplitude studies more difficult. An accurate estimate of attenuation is necessary for the improvement of quality of imaging profile through inverse Q-filtering (Wang, 2006) and Q compensation migration (Mittet et al., 1995). Q is also sensitive to parameters, such as lithology, porosity, and pore-fluid characteristics (Johnston et al., 1979; Winkler and Nur, 1982; Rao and Wang, 2009). Therefore, it is important to develop an accurate Q estimation method for compensation of energy loss and phase distortion, quantitative amplitude studies and reservoir characterization applications.

By transforming picked reflections at different traveltimes into the frequency domain, frequency-domain methods estimate Q according to the variation of their amplitude spectra. The best-known methods for Q-computation are probably the spectral ratio method (LSR) which is described in detail by Bath (1974) and Babbel (1984). Quan and Harris (1997) present the frequency shift method to estimate seismic attenuation using VSP data. Zhang and Ulrych (2002) computed the interval Q factor from the variation of the peak frequency of a spectrum, assuming that the source wavelet was Ricker-like. Nunes et al. (2011) compared these three methods and conclude that spectral ratio method is more appropriate to the other two regarding the robustness of the methods to the presence of dipping layers.

Considering that source wavelet is often unknown, frequency domain methods usually estimate the interval Q by picking two reflections at the top and bottom of the target layer (named reference and target) from the same source. However, these methods have neglected the effect from the overburden. Attenuation not only affected by the Q value, but also the travel path of the reflection. The two picked reflections, with different travel paths in the overburden (Reine et al., 2012), experience different attenuation. It is an approximation to attribute the variation of spectra to the attenuation in the target layer only. This approximation will become more unreliable as offset increase. Behura and Tsvankin (2009) combined the LSR and layer stripping method to address this problem by identifying the reflections from the top and bottom of the target layer that share the same ray paths in the overburden. Reine et al. (2012) picked reflections that share the same ray paths in the overburden by matching events with a constant horizontal slowness. The two methods both attempt to estimate Q value in the target layer, but actually there are not enough reflections that satisfy that requirement. In addition, it may introduce transform artifacts, which may result in error in Q estimation (Reine et al., 2012).

In this paper, we develop an effective interval Q estimation method (LSSI) using surface reflection data. We first calculate the traveltime of picked reflections by ray tracing, and then separate the attenuations from different layers according to the traveltime. Q values of both target layer and overburden can be estimated simultaneously. The advantages of this method are that there is no need to find reflections that share the same ray paths as the target reflections, and we just pick another adjacent reflection in the overburden for inversion. The accurate and reliable Q estimation results can be used as input for other Q inversion methods

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* Corresponding author.
E-mail address: szd@cup.edu.cn (S.Z. Sun).

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(e.g. FWI). The proposed method is designed for surface reflection data, which is the most available seismic data.

2. Theory and method

In this part, we first analyze the effect of overburden on the Log Spectral Ratio method, and derive an equation that quantifies the error of Q estimation results. Then our new method is introduced to account for these effects.

2.1. Effects from overburden on Log Spectral Ratio analysis

Considering only the variation of amplitude spectra and neglect phase change and velocity dispersion, amplitude spectra of seismic wave that propagate in the visco-elastic medium can be simplified as (Tonn, 1991):

$$A(\omega, s) = GS(\omega, s_0)\ \exp\left(-\frac{\omega t}{2Q}\right) \tag{1}$$

where A is the amplitude spectrum at travel distance s,G is the frequency-independent factor due to geometrical spreading, transmission/reflection loss, est., S is the amplitude spectra of source wavelet.

Considering that source wavelet is often unknown and picking the reflection from different interface in the Fig. 1, their amplitude spectra can be expressed as:

$$A(\omega, s_1) = G_1 S(\omega, s_0)\ \exp\left[-\omega\left(\frac{t_{AF}+t_{FE}}{2Q_1}\right)\right] \tag{2}$$

$$A(\omega, s_2) = G_2 S(\omega, s_0)\ \exp\left[-\omega\left(\frac{t_{AB}+t_{DE}}{2Q_1}+\frac{t_{BC}+t_{CD}}{2Q_2}\right)\right] \tag{3}$$

where Q_1 is effective Q of the overburden, Q_2 is effective Q of the target layer. t_{AF},t_{FE},t_{AB},t_{DE},t_{BC},t_{CD} are the traveltimes respectively relate to ray paths AF,FE,AB,DE,BC,CD. Taking the logarithm ratio of amplitude spectra in Eqs. (2) and (3), we obtain:

$$b = \ \ln\left[\frac{A(\omega, s_2)}{A(\omega, s_1)}\right] = B - \frac{\omega(t_{AB}+t_{DE}-t_{AF}-t_{FE})}{2Q_1} - \frac{\omega(t_{BC}+t_{CD})}{2Q_2} \tag{4}$$

where the intercept term $B = \ln(G_2/G_1)$ is a frequency-independent constant. By assuming that Q is frequency independent in the selected frequency range, LSR method calculates the Q factor according to Eq. (9), neglecting the component proportional to $1/Q_1$. The Q value is estimated from the slope p of a straight line fit to b by $Q = -\pi\Delta t/p$.

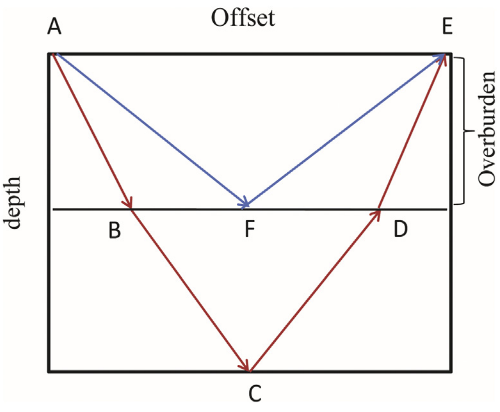

Fig. 1. Ray paths of reflections from different interfaces. The ray paths of the two reflections in the overburden are different, and the discrepancy is more obvious with thin overburden and large offset.

Unfortunately, the picked reflections travel through different paths in the overburden, $t_{AF} + t_{FE} \neq t_{AB} + t_{DE}$, which leads to error of Q estimation in the LSR. Eq. (4) can also be expressed as:

$$b = B - \frac{\omega(t_{BC}+t_{CD})}{2Q_2 u} \tag{5}$$

where error component u is expressed as:

$$u = 1/\left(1+\frac{\Delta t_1}{t_2}\cdot\frac{Q_2}{Q_1}\right) \tag{6}$$

where $\Delta t_1 = t_{AF} + t_{FE} - t_{AB} - t_{DE}$, $t_2 = t_{BC} + t_{CD}$. Thus the error of LSR comes from traveltime term $\Delta t_1/t_2$ and attenuation term Q_2/Q_1. The value of error affected by variation of offset, thickness of the overburden and the ratio of Q values in the overburden and target layer. Near surface, characterized by small Q value and shallow location, always attenuate seismic waves significantly due to the poor consolidation. Q estimation results of the near surface become more unreliable when traces of large offset are used.

2.2. Q estimation based on the logarithmic spectral simultaneous inversion

For accurate interval Q estimation, it is necessary to separate the effect of attenuation in the overburden form that in the target layer. We pick reference reflection A_1 and its adjacent reflection A_2 at traveltime t_1, target reflection A_3 at traveltime t_2. Taking the logarithm ratio of amplitude spectra respectively, we obtain:

$$b_1 = \ \ln\left(\frac{A_2}{A_1}\right) = B_1 - \frac{\omega\Delta t_{12}^1}{2Q_1} \tag{7}$$

$$b_2 = \ \ln\left(\frac{A_3}{A_1}\right) = B_2 - \frac{\omega\Delta t_{13}^1}{2Q_1} - \frac{\omega t_3^2}{2Q_2} \tag{8}$$

where Δt_{12}^1 (superscript stands for the number of layer) is the traveltime difference between reference reflection A_1 and A_2 in the overburden, Δt_{13}^2 is the traveltime difference between reference reflection A_1 and target reflection A_3 in the target layer. Eqs. (7) and (8) can be represented in a matrix form as:

$$d = \begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} x & y & -\pi\Delta t_{12}^1\Omega & y \\ y & x & -\pi\Delta t_{13}^1\Omega & -\pi t_3^2\Omega \end{pmatrix}\begin{pmatrix} B_1 \\ B_2 \\ Q_1^{-1} \\ Q_2^{-1} \end{pmatrix} = Fm \tag{9}$$

where $\boldsymbol{b}$ is a vector containing the logarithm ratio of amplitude spectra, $\boldsymbol{x} = (1\,1\cdots1)^T$, $\boldsymbol{\Omega} = (f_1\,f_2\cdots f_n)^T$ and $\boldsymbol{y} = (0\,0\cdots0)^T$. Vectors $\boldsymbol{y}$, $\boldsymbol{\Omega}$, and $\boldsymbol{x}$ are of length n, where n is the number of frequencies within the signal bandwidth. The components of $\boldsymbol{m}$ that we are estimating are the intercept terms B and Q^{-1}.

The introduction of adjacent reflection A_2 can be regarded as a constraint on Q_1^{-1}, which helps to improve the robustness of the inversion system. For calculating interval Q factors in an N layers model, we pick reflection A_{n+1} at traveltime t_n, and reflection A_n at traveltime t_{n-1}. Taking the logarithm ratio of amplitude spectra of A_{n+1} and A_n, we obtain:

$$b_n = \ \ln\left(\frac{A_{n+1}}{A_n}\right) = B_n - \frac{\omega}{2}\sum_{k=1}^{n-1}\frac{\Delta t_{n,n+1}^k}{Q_k} - \frac{\omega t_{n+1}^n}{2Q_n} \tag{10}$$

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