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Using internal multiples for more accurate seismic Q estimation

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Summary

Seismic waves traveling through the subsurface experience several forms of attenuation, including geometric spreading, reflection, transmission, and earth attenuation (via the so-called quality factor Q). To achieve high-resolution sub-surface details, it is essential to tackle all types of attenuation resulting from the overburden. Attenuation is associated with dispersion, causing gradual changes in signal shape and strength, leading to a shift of energy towards lower frequencies and potential signal distortion over time. Precisely measuring Q in seismic data is challenging but crucial for accurate subsurface imaging. The primary objective of this study is to explore the role of internal multiples (reflections within subsurface layers) for more accurate Q estimation, although traditional methods remove multiples in advance. Therefore, we utilize the Full Wavefield Migration method, which make use of the Full Wavefield Modeling (FWMod) scheme as its forward engine. This approach encompasses not only geometric spreading, reflectivity and transmission effects but also includes multiple scattering. The FWMod process is structured in a modular manner, where wavefield operators describe propagation and reflection/transmission. Consequently, including Q is relatively straightforward by redefining the propagator. Based on a synthetic data example it is demonstrated that multiples, when integrated into the inversion process, enhance the Q estimation.

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Introduction

In seismic exploration, the transmission of waves through the Earth's subsurface is influenced by various attenuation mechanisms. One primary form of attenuation is geometric spreading, an effect that many migration algorithms inherently correct for. Another significant factor is the change in amplitude due to reflection and transmission across interfaces with different physical properties. These amplitude variations are attributed to the impedance discrepancies in the subsurface materials.

Furthermore, the intrinsic attenuation, quantified by the quality factor (Q), accounts for the energy loss of seismic waves as they travel over distance or with time. The specific quantitative model for this effect has yet to be fully established (Aki & Richards, 2002), but the frequency-dependence and exponential energy decay characteristics are well-recognized. Attenuation is also intricately linked with dispersion, which progressively changes the waveform, affecting its shape and energy content. Consequently, the peak energy of a seismic signal migrates towards lower frequencies over time, a phenomenon that can lead to signal broadening in the time domain and increased distortion with increased travel time. It is vital to comprehensively address all forms of attenuation caused by the overburden to obtain high-resolution details of the subsurface.

Measuring the quality factor (Q) precisely in seismic data analysis presents a challenging task, but it is essential for decoding the features beneath the surface. Every bit of information that can contribute to better estimating Q is crucial. In this work, we examined the role of multiples — the reflections within subsurface layers — to achieve a more accurate Q estimation. While conventional methods in seismic imaging often remove multiples to clear up the signal, we see them as a source of information. Multiples go up and down within a layer with a specific Q value, which causes them to weaken. However, this weakened state still provides just the right amount of response we need. In fact, they deliver additional information that aids in a more accurate estimation of the quality factor. Instead of eliminating multiples, our approach integrates them, enhancing the inversion process for better Q estimation.

Q model

In seismic analysis, it is commonly accepted that the quality factor Q does not change much within the range of seismic frequencies (Aki & Richards, 2002). Therefore, in our work, we use a nearly constant-Q model (Futterman, 1962) to estimate seismic wave attenuation during migration, which operates under the consideration that Q is almost frequency-independent. The one-way wave equation for viscoacoustic modeling, introduced by Futterman (1962), looks similar to the acoustic wave equation, but it uses a complex number to represent slowness, as follows:

$$s_c = s \left(1 - \frac{1}{\pi Q} \ln(\omega/\omega_0) \right) \left(1 + \frac{i}{2Q} \right), \quad (1)$$

Equation 1 involves the variables s_c , s , ω , ω_0 , Q , which are complex slowness, slowness without attenuation effect, angular frequency, central angular frequency, and the quality factor value, respectively. We can take the attenuation factor (A) as the inverse of the Q value, where A is defined as $1/Q$. This simplification facilitates the derivation process, and changes equation 1 as follows:

$$s_c = s \left(1 - \frac{A}{\pi} \ln(\omega/\omega_0) \right) \left(1 + \frac{iA}{2} \right). \quad (2)$$

Theory of FWM, including Q effects

The Full Wavefield Migration (FWM) (Berkhout, 2014b; Davydenko and Verschuur, 2017) technique utilizes the Full Wavefield Modeling (FWMoD) (FWMoD, Berkhout, 2014a) methodology to account for various wave propagation effects, including geometric spreading, reflectivity, and multiple scattering. This is achieved by recursively propagating wavefields up and down within the subsurface (Berkhout, 2014a). The basis of this approach is an inversion algorithm that updates the subsurface reflectivity model to match actual seismic data, employing a gradient descent method for this iterative

process. In FWM, data fitting is conducted by defining an objective function based on the residual energy, which is the difference between the observed seismic data and the predictions from the model.

The key parameters for inversion are the propagation velocity model and the seismic reflectivity model. With these parameters, FWMod can reconstruct seismic data to include primary reflections and internal multiples, thus refining the reflectivity model based on the imaging parameters. The modular nature of FWMod, which articulates propagation and reflection/transmission through wavefield operators, facilitates the integration of the Q-effect by simply adapting the propagation operator (Safari and Verschuur, 2023).

The FWMod uses one-way propagators that rely on phase-shift techniques, such as the phase-shift plus interpolation (PSPI) method (Gazdag and Sguazzero, 1984). The involved phase shift operators in the wavenumber-frequency domain for 2D are as follows:

$$W(k_x, \omega) = e^{-jk_z \Delta z}; k_z = \sqrt{\omega^2 s^2 - k_x^2}, \quad (3)$$

with Δz the extrapolation distance, can be easily extended to include the complex slowness as given by equation 2. For application in the 2D space-frequency domain, this propagation operator is inverse Fourier transformed from wavenumber to the lateral coordinate under the assumption of a locally invariant medium.

The method for updating the quality factor (Q) shares many similarities with the velocity update process in Joint Migration inversion (JMI) (Staal and Verschuur, 2013; Berkhout, 2014c; Verschuur et al., 2016), effectively constituting a tomographic problem where we combine wavefields that travel in the same direction. Initially, a linear relationship must be established between the propagation operators and the attenuation model by considering their respective perturbations. Unlike velocity, where derivatives are taken with respect to velocity or slowness, in this case, we take the derivative with respect to the Q value, or the absorption (A) value in my specific study. By substituting Equation 2 into Equation 3 and implementing their perturbations, we arrive at the following linearized equation, still in the wavenumber-frequency domain:

$$\begin{aligned} \Delta W &= W_{new} - W_{old} \approx \left[\frac{\partial W}{\partial A} \right]_{old} \Delta A \quad (4) \\ \Delta W &= -\frac{i\omega^2 s^2}{k_z} \left(\left(1 - \frac{A}{\pi} \ln(\omega/\omega_0) \right) \left(1 + \frac{iA}{2} \right)^2 \left(\frac{\ln(\omega/\omega_0)}{\pi} \right) \right. \\ &\quad \left. + \left(\frac{i}{2} \right) \left(1 + \frac{iA}{2} \right) \left(1 - \frac{A}{\pi} \ln(\omega/\omega_0) \right)^2 \right) W_{old} \Delta A \Delta z \end{aligned}$$

where W_{new} is the operator in an updated attenuation model, W_{old} is the operator in the current attenuation model, and ΔA is the attenuation update. Note that this linearization of phase-shift operators is very similar to the theory described by Shen et al. (2018), although here we have included all terms that may contribute without removing the ones with little impact. This expression can be inverse Fourier transformed to the space domain in order to get the operator to calculate spatially varying gradients from the propagation operators.

The foundation of our method is an inversion algorithm that iteratively updates the subsurface reflectivity model to align with the actual seismic data. This is achieved by employing a gradient descent method throughout the iterative process. During each iteration, the residual is back-propagated to each depth level and combined with the forward-modeled source field, which includes all multiple scattering. This combination serves to update the reflectivity or the attenuation, depending on which imaging condition is applied after back-propagation. To determine the step length for the gradient update—whether it affects the attenuation or reflectivity—a forward model of the gradient's linearized effect is computed and compared with the residual data. By iterating this procedure, the method fine-tunes the model parameters, ensuring that the forward-modeled data progressively reflects the measured data more accurately. Although not shown here, note that this approach also paves the road for including velocity updates as well, together with attenuation and reflectivity updates.

Numerical examples

We have chosen FWM for its inherent capability to account for multiple scattering, a feature we have utilized to enhance the accuracy of our attenuation measurements. By adapting FWM to estimate the attenuation parameter directly, we have improved its proficiency in providing higher seismic resolution within complex regions. Our study specifically addresses the challenges presented by gaseous formations, such as pockets and clouds, in delineating and interpreting reservoirs. In a synthetic test, we utilized a model with two lens-shaped anomalies characterized by varying attenuation properties. In seismic imaging, a Q value higher than 100 indicates very low attenuation. Often, for many practical purposes, the difference in attenuation for Q values above 100 is negligible. Therefore, for simplicity and practicality, we consider all Q values above 100 as equivalent to 100. Therefore, the default Q value for the model was set at 100, with the exception of a top-right lens-shaped anomaly, which was modelled with a high attenuation effect ($Q=20$), and a second lens-shaped anomaly with a moderate, but still noticeable, attenuation effect ($Q=50$). Beneath these anomalies, a reflector with higher Q values was also included. The frequency range spans from 5 to 40 Hz. For inversion purposes, the maximum data offset is 3000 m, with a depth of 1500 m, and sources and receivers are evenly spaced along the surface. The generated synthetic data include multiples up to the third order.

We conducted the test under two conditions. Initially, we utilized only primaries in the modelling and exclusively primaries in the inversion, assuming that multiples were completely removed before starting the Q estimation. Subsequently, we performed the test by incorporating multiples in both the forward model and the inversion process. Figure 1a,d illustrates the configuration of the synthetic model. The results display the estimated reflectivity in the first iteration and the 30th iteration (Figure 1b,c), as well as the estimated Q with and without the inclusion of multiples (Figure 1e,f). It is evident that even in the first iteration, the estimated reflectivity is effective, and the accuracy of the estimated Q is enhanced with our new method compared to the scenario where multiples were not included in the inversion. This is because, in the absence of multiples, there is insufficient ray path coverage in certain areas, leading to misconceptions about the location of low Q zones. However, including multiples results in adequate ray path coverage in these regions, providing more information and enabling a more accurate localization of the attenuation anomaly.

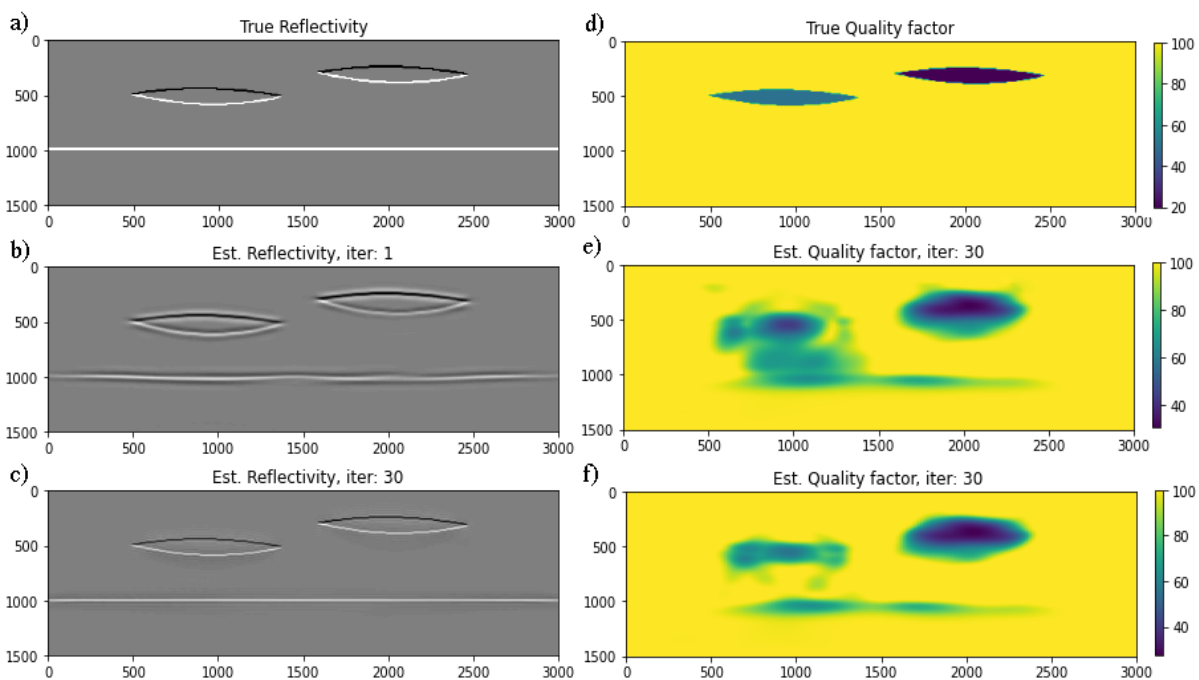


Figure 1 Figure 1: Comparative analysis of reflectivity and quality factor estimations. a) True reflectivity model. b) Estimated reflectivity after first iteration. c) Estimated reflectivity after 30 iterations. d) True quality factor (Q) model. e) Estimated Q result excluding multiples. f) Estimated Q result including multiples.

Conclusions

Incorporating attenuation into seismic imaging is a critical factor for optimally processing real seismic data. For the Full Waveform Migration (FWM) process, this integration can be effortlessly implemented within the forward modeling scheme, which is constructed from distinct propagation and scattering operators. The propagation operator, which utilizes laterally varying phase shift operators, can be readily adapted to encompass the Q-effect. Numerical examples have initially demonstrated that our proposed method is capable of retrieving an accurate image and attenuation model. Furthermore, it was shown that including multiples in the inversion process provides additional information, which assists in better Q estimation and precise localization of highly attenuative zones. The method proposed herein represents the initial stage of a sophisticated technique aimed at estimating and compensating for attenuation in seismic imaging. In this preliminary version, we deliberately chose not to apply any form of constraint or regularization to assess the unaltered behavior and performance of the model truly. This choice provides a baseline from which the efficacy of future enhancements can be measured. Moving forward, we plan to explore and implement constraint and regularization strategies to refine our model, targeting improvements in stability and accuracy of the attenuation compensation and potentially expanding the method's applicability to a broader range of seismic scenarios. Also, since we have already incorporated attenuation into the FWM engine, future work could enhance the Joint Migration Inversion (JMI) method to simultaneously estimate reflectivity, velocity, and attenuation models.

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