Seismic attenuation estimation using ray-based and wave-equation-based Q tomography

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Abstract

Seismic attenuation poses a challenge for hydrocarbon exploration and development. In this paper, we present two methods to understand and quantify such attenuation and use them to estimate seismic attenuation models. These are ray-based and wave-equation-based Q tomography. In this study, we examine the advantages of the wave-equation-based method over the ray-based method in the case of Q tomography in a complex setting. We employ two synthetic models. The first model has an anomaly with strong attenuation and a strong velocity contrast (Figure 1). The second model has salt bodies with rugose salt boundaries. Two attenuation anomalies are included: One is above the top of salt; the other one is close to the steep salt flank (Figure 2). We measure the attenuation effects from the spectral loss of the seismic events. We then do a least-squares inversion of the same measurements to update our Q model using ray- and wave-equation based tomography. The results show that the wave-equation based method more effectively estimates seismic attenuation model than the ray-based method in a complex setting.

Introduction

Attenuation causes frequency dependent amplitude loss, i.e. reduced signal to noise, and phase distortions because of velocity dispersion. This presents challenges for velocity model building, structural interpretation, and quantitative amplitude interpretation. Seismic attenuation tomography can understand and quantify the attenuation effects and estimate a reliable attenuation model. Ray-based Q tomography and wave-based Q tomography are two methods for Q estimation. Ray methods are based on high frequency approximation. Those methods work well in a geological setting with smooth velocity variation in the subsurface. However, ray-based methods can fail in imaging in more complex media e.g., below or near salt, where wave-equation-based methods are known to be more robust for imaging.

In this study, we examine the advantages of the wave-equation-based method over the ray-based method in the case of Q tomography in a complex setting. We applied both methods to two synthetic models. Through numerical tests, we study how the complex overburden impacts Q inversion differently in ray- and wave-equation based tomography.

Theory

Both, the ray- and wave-equation-based tomography employ estimates of the attenuation effects derived from the spectral losses of the seismic events in the migrated gathers. For both methods we use the same estimated dissipation times using the Log *Spectral Ratio (LSR)* method (Tonn, 1991).

Ray-based tomography inverts the dissipation times ρ given by the integral of the inverse of Q along the ray path,

$$\rho = \int_{\text{ray}} \frac{1}{QV} dl,$$

where *V* is the velocity. Least-squares inversion minimizes the difference between the measured dissipation times and the dissipation times computed using the updated Q model.

Wave-equation-based tomography estimates Q models using *Wave-Equation Migration Q Analysis* (WEMQA) developed by Shen et al. (2013,2014, 2018a, b). We first convert the measured dissipation times into a perturbation in the migrated image using the conversion formula developed by Shen et al. (2018a, b). The conversion introduces some smoothing of the estimated dissipation times ρ along depth. The perturbed image represents the migrated events that are impacted by attenuation. The wave-equation-based tomography back projects the image perturbation to generate an update in the interval Q model. This method solves the least-squares inversion using a conjugate gradient scheme.

Numerical Examples

We compare the ray- and wave-equation-based tomography using a synthetic model that has an anomaly with strong velocity contrast and high attenuation, as shown in the top figures of Figure 1. The bottom figures of Figure 1 show the inverted results using ray-based method and wave-equation-based method respectively. The strong velocity contrast of the anomaly presents a difficulty for ray tracing at the anomaly boundary. When compared with ray-based method, the results using wave-equation based method better recovers the shape and location of the Q anomaly.

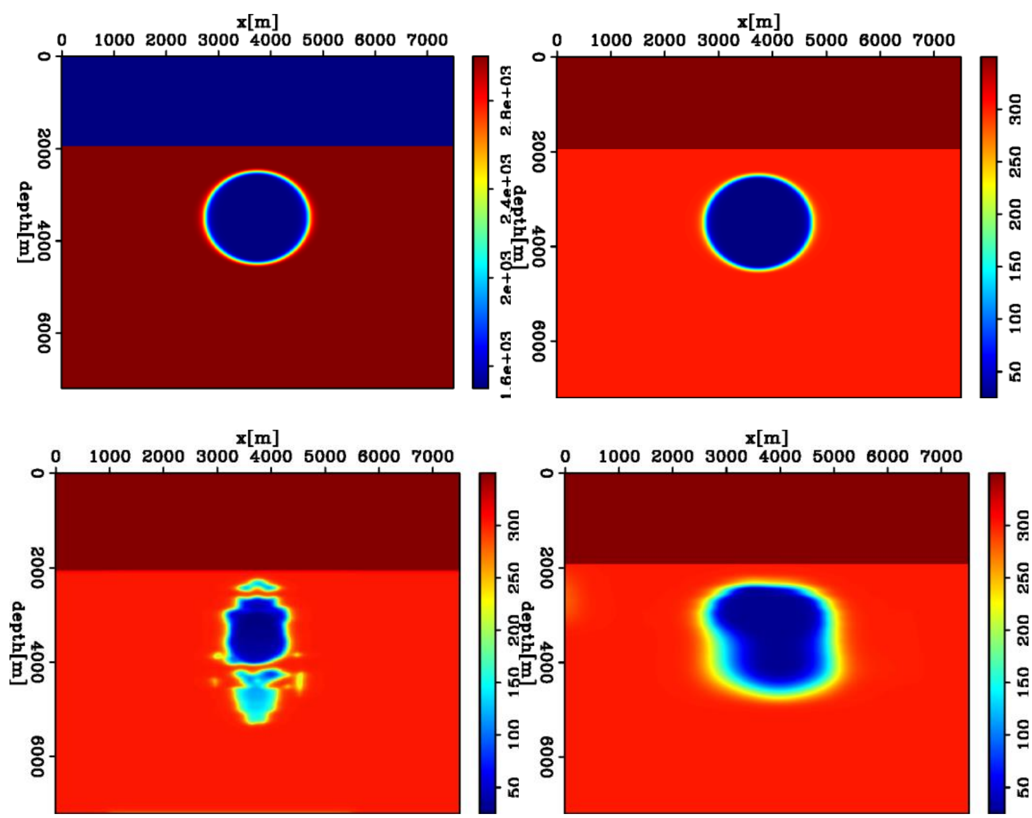

***Figure 1** True synthetic velocity model (top left), true synthetic Q model (top right), inverted Q using ray-based Q tomography (bottom left) and inverted Q using wave-based Q tomography (bottom right).*

The second synthetic example has salt bodies with rugose salt boundaries. The velocity model has three salt bodies as shown in the left image of Figure 2. Two Q anomalies are included as shown in the right image of Figure 2. One of the Q anomalies is above the salt; the other Q anomaly is close to the flank of the salt on the right. Both anomalies have Q values of 25. The sedimentary reflectivity model (not shown) for this test consists of flat reflectors.

We generated this synthetic seismic data using a one-way wave-equation propagator (Shen et al., 2013,2014, 2018a, b) for the described models. We then migrate the synthetic data using the same velocity model, without taking the Q model into account. The near-surface-offset (0 m – 600 m) migrated image and the mid-surface-offset (600 m – 1,200 m) migrated image are shown in the left and right images of Figure 3, respectively. Illumination compensation to these migrated images was not applied. The near and mid offsets provide limited imaging below the salt, which makes dissipation time measurements challenging in those areas.

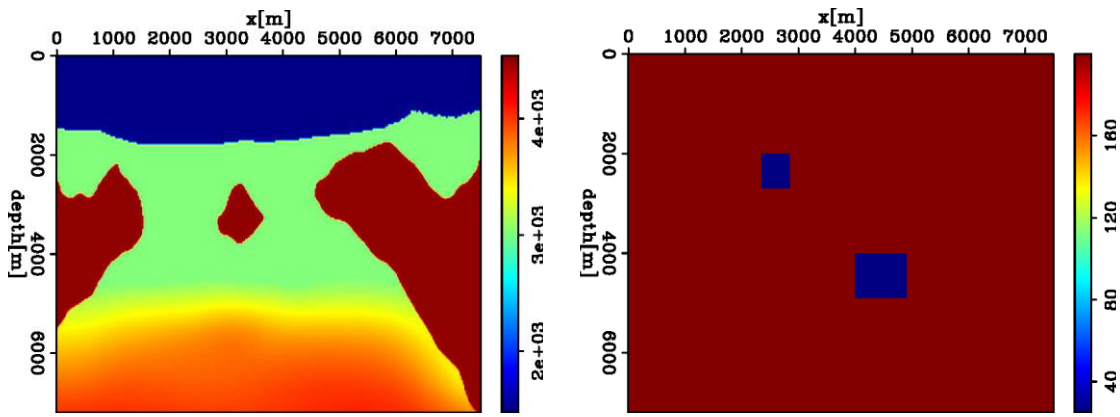

Figure 2 *Left: velocity model; Right: True Q model with two anomalies.*

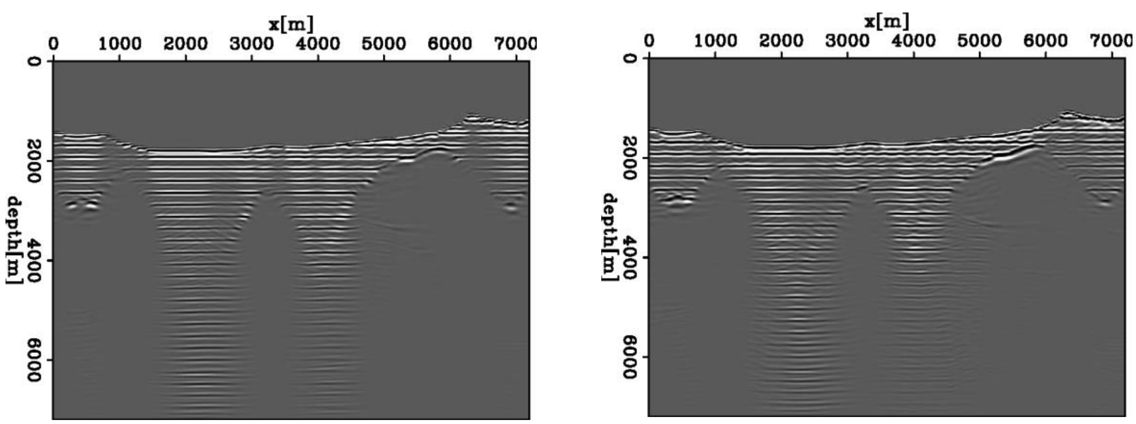

Figure 3 *Left: The near-offset (0 m – 600 m) migrated image; Right: The mid-offset (600 m – 1,200 m) migrated image.*

The left images of Figure 4 show the separately inverted Q model using ray-based tomography at near and mid offsets. The right figures of Figure 4 show the separately inverted Q model using wave-equation-based tomography at near and mid offsets.

The methods roughly retrieve the shape and location of the anomalies. However, we observe the following differences: 1) the wave-equation-based method retrieves a smoother model than the ray-based one; 2) the wave-equation-based method has lower Q values that are closer to the true model; 3) the ray-based method shows more additional artefacts.

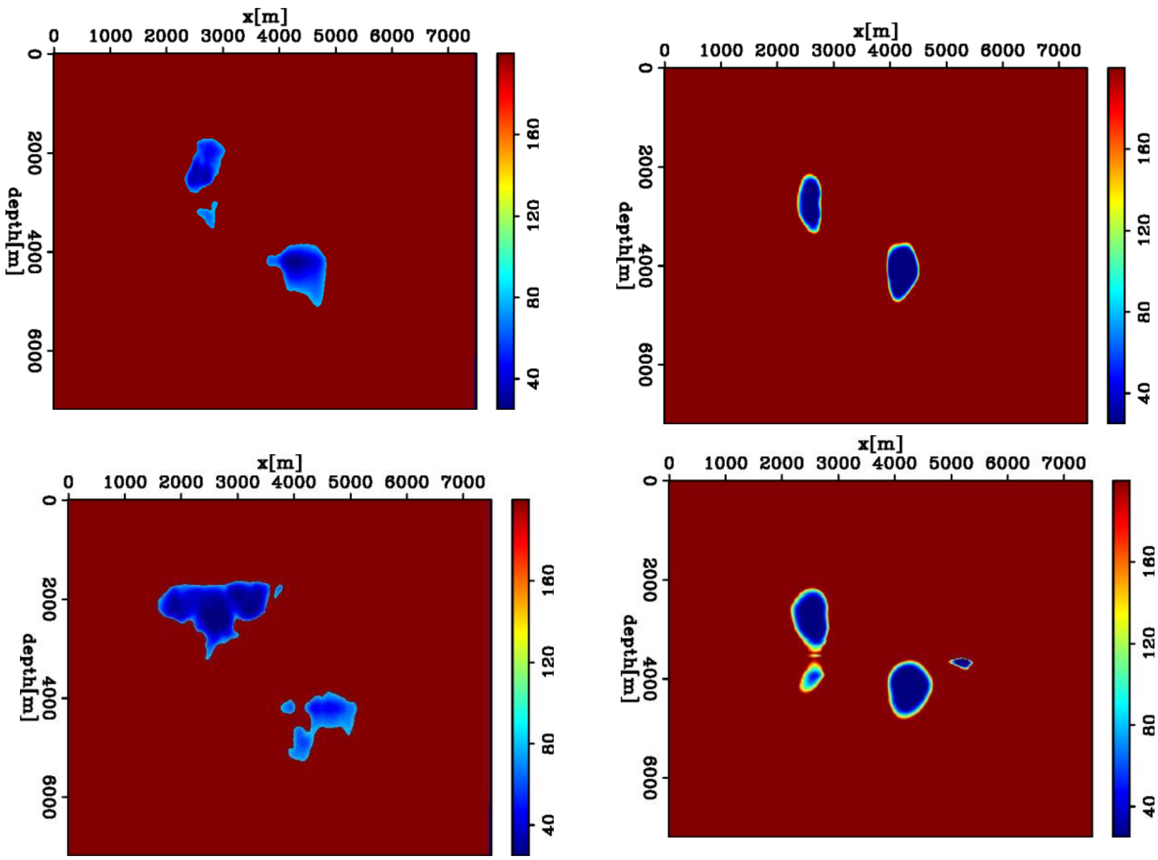

Figure 4 *Top Left: The inverted Q model using ray-based tomography at near offsets; Top right: The inverted Q model using wave-equation-based tomography at near offsets; Bottom Left: The inverted Q model using ray-based tomography at mid offsets; Bottom right: The inverted Q model using wave-equation-based tomography at mid offsets.*

Discussions and Conclusions

In this paper, we present two methods to reliably estimate Q model: ray-based Q tomography and wave-equation-based Q tomography. In this study, we examine the advantages of the wave-equation-based method over the ray -based method in the case of Q tomography in a complex setting through two synthetic examples. The results showed that the wave-equation-based method is more robust in highly complex geological settings, when compared with the ray-based method. Ray tracing can be unstable below and around high velocity contrasts (e.g., velocity anomaly and salt bodies). Also, the wave-equation-based method handles multi-pathing naturally. However, in the second example, neither method retrieves the exact shape and location. There is significant non-uniqueness in Q tomography, especially in the vertical directions. A joint multi-offset tomography should help to reduce non-uniqueness, and to improve the Q inversion.

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