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# Viscoacoustic reverse time migration in tilted TI media with attenuation compensation

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## Summary

Simulation of wave propagation in an anisotropic viscoacoustic medium is an important problem, for instance within Q-compensated reverse-time migration. We present a new approach of the viscoacoustic wave equation in the time domain to explicitly separate amplitude attenuation with phase dispersion and develop a theory of viscoacoustic reverse time migration (Q-RTM) in tilted TI media. Because of this separation, we would be able to compensate the amplitude loss effect, the phase dispersion effect, or both effects. In the Q-RTM implementation, the attenuation-compensated operator was constructed by reversing the sign of amplitude attenuation. We validate and examine the response of this approach by using it within a reverse time migration scheme adjusted to compensate for attenuation. The amplitude loss in the wavefield at the source and receivers due to attenuation can be recovered by applying compensation operators on the measured receiver wavefield. After correcting for the effects of anisotropy and viscosity, numerical test on synthetic data illustrates the higher resolution images with improved amplitude and the correct locations of reflectors, particularly beneath high-attenuation layers.

## Introduction

Attenuation is an increasingly indispensable component of wavefield simulation in seismic exploration and monitoring applications. It is a key element in many recent instances of data modeling, reverse time migration (RTM). To consider the anisotropic media, the isotropic acoustic assumption for seismic processing and imaging method is not useful and affected the resolution and placed images of subsurface structures [1]. Therefore, it is necessary to focus on the anisotropy and viscosity for complex media to obtain a significant improvement in image resolution and positioning [2-5]. However, to investigate the RTM images in anisotropic viscoelastic medium, generally, the focus is on the anisotropy or viscosity. In this paper, we present a new approach of anisotropic viscoacoustic wave equation for attenuating media in the time domain based on SLS model. This equation describes the constant-Q wave propagation and contains independent terms for phase dispersion and amplitude attenuation.

## Viscoacoustic wave equation in TTI media

The simulation of wave propagation in attenuation media includes three cases, i.e., the amplitude loss effect, the phase dispersion effect, or both effects. In this paper, we present a new approach for the solution of the viscoacoustic wave equation in the time domain to explicitly separate phase dispersion and amplitude attenuation. We first apply the Fourier transform to the first-order linear differential equations [6] in the time domain to remove the memory variable and then transformed back to the time domain to derive the viscoacoustic TTI wave. To apply these equations on RTM, we write the viscoacoustic wave equation in TTI media for the forward and backward extrapolation as:

$$\partial_t\sigma_H = \rho V_P^2 \left[(1+2\varepsilon)\left[(a_1(2/A) + ia_2(2/AQ))\left[(\cos\theta\cos\varphi\partial_x - \sin\theta\partial_z)u_x\right]\right] + \sqrt{1+2\delta}\left[(\cos\varphi\sin\theta\partial_x + \cos\theta\partial_z)u_z\right]\right], \quad (1)$$

$$\partial_t\sigma_V = \rho V_P^2 \left[\sqrt{1+2\delta}\left[(\cos\theta\cos\varphi\partial_x - \sin\theta\partial_z)u_x\right] + (a_1(2/A) + ia_2(2/AQ))\left[(\cos\varphi\sin\theta\partial_x + \cos\theta\partial_z)u_z\right]\right], \quad (2)$$

where $A = (\sqrt{1+1/Q^2} - 1/Q)^2 + 1$. $2/A$ and $2/AQ$ are dispersion-dominated and amplitude-attenuation-dominated operators, respectively. $\sigma_H$ and $\sigma_V$ represent the horizontal and vertical stress components respectivel, $P(X,t)$ is pressure wavefield, $\rho$ is density, $\varepsilon$ and $\delta$ are Thomsen parameters, and $\theta$ represent the tilt angle and $\varphi$ represent the azimuth of tilt for TTI symmetry axis. The coefficients $a_1$ and $a_2$ are constants equal to 1. The sign of these coefficients is important for the forward and backward extrapolation.

## Viscoacoustic reverse time propagation

The positive sign of the $a_2$ constant refers to the amplitude attenuation in extrapolating forward propagation. By reversing the sign of the amplitude attenuation term ($a_2 = -1$) in the viscoacoustic TTI wave equation, we can compensate for the amplitude loss. Also, the viscoacoustic wave equation contains the dispersion term that affects the phase during wave propagation, but the sign of this term ($a_1 = 1$) is not changed. For the backward modelling, the viscoacoustic TTI wave equations with compensation of attenuation effects ($a_1 = 1$ and $a_2 = -1$) can be written as

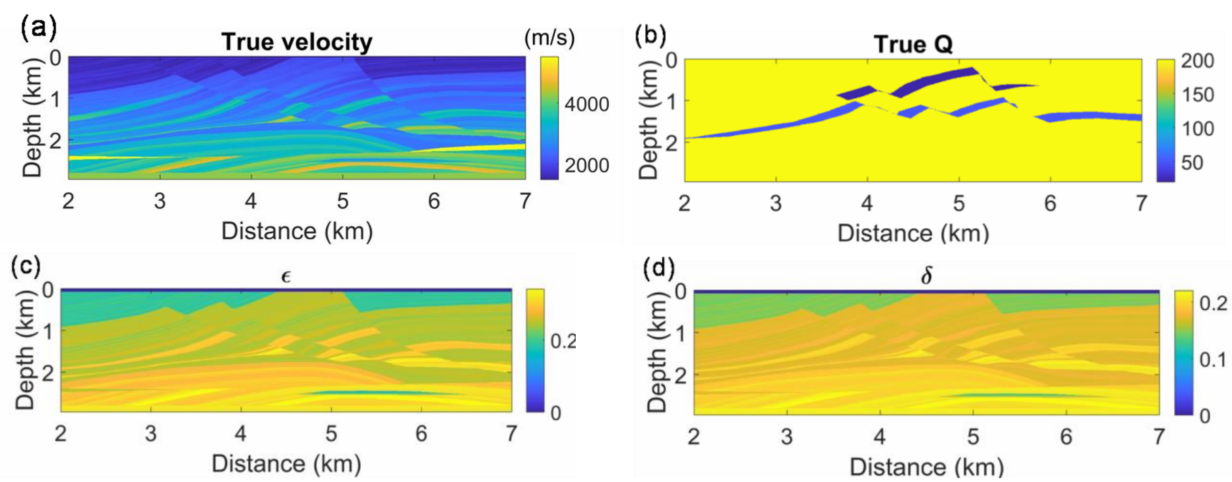



FIG. 1: The Marmousi models: (a) true velocity model, (b) true Q model, (c) Thomsen's $\varepsilon$ model, and (d) Thomsen's $\delta$ model.

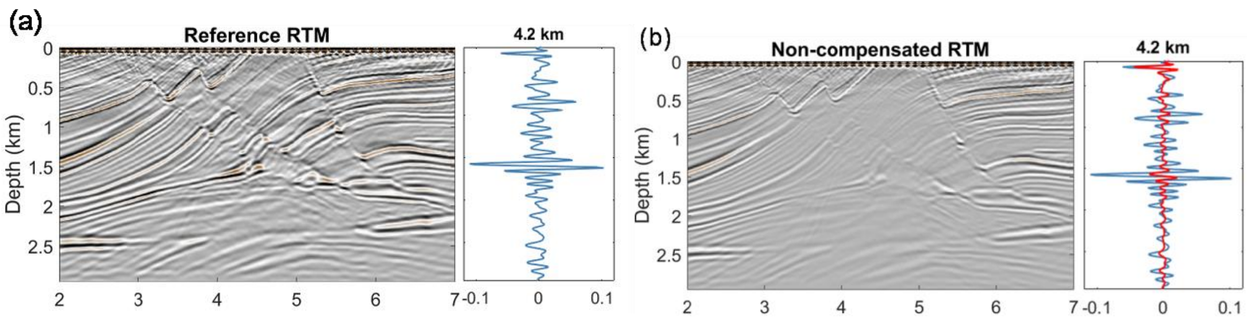
$$\partial_t \sigma_H = \rho V_P^2 \left[ (1+2\varepsilon) \left[ (a_1(2/A) - ia_2(2/AQ)) \left[ (\cos\theta\cos\varphi\partial_x - \sin\theta\partial_z)u_x \right] \right] + \sqrt{1+2\delta} \left[ (\cos\varphi\sin\theta\partial_x + \cos\theta\partial_z)u_z \right] \right], \quad (3)$$

$$\partial_t \sigma_V = \rho V_P^2 \left[ \sqrt{1+2\delta} \left[ (\cos\theta\cos\varphi\partial_x - \sin\theta\partial_z)u_x \right] + (a_1(2/A) - ia_2(2/AQ)) \left[ (\cos\varphi\sin\theta\partial_x + \cos\theta\partial_z)u_z \right] \right], \quad (4)$$

For the backward modeling, we solve equation 21 to extrapolate the receiver wavefield by flipping in time the measured data $R(X_r, t)$ at the receivers with a boundary condition.

## 2D synthetic example

We consider the more complex Marmousi model to verify the accuracy of the Q-RTM approach in TTI media. Figures 1 show the actual velocity, corresponding true Q models, and two anisotropy distributions. In the Q model, there are some regions that attenuate waves traveling through them and creating reflections with weaker amplitudes for the deeper layers, especially beneath strongly attenuating layers. By setting the tilt angle to be 45 degrees, the synthetic viscoacoustic TTI dataset is produced using equations 1 and 2. To avoid shear wave artifacts, we set a small smoothly tapered circular region with $\varepsilon = \delta$ around the source [7]. We set 50 sources positioned at a depth of 30 m and a zero-phase Ricker wavelet with a centre frequency of 15 Hz. The sampling interval rate is 0.4 ms, and the recording length is 3 s. The RTM images represented in Figure 2, which includes the acoustic RTM without attenuation (reference case), the acoustic RTM with viscoacoustic data (noncompensated case), and the compensated RTM using Q-RTM approach. The reference RTM image (Figure 2a) has similar artifacts and amplitudes in the shallow layers compared with the noncompensated RTM image, but the non-compensated case in Figure 10b has very weak amplitudes in the deeper layers especially beneath the layers with strong attenuation. The Q-compensated RTM image is shown in Figure 2c. The result indicates improved RTM image with recovered amplitudes of the reflectors at the dip depths compared with the reference image in Figure 10a. To verify that the reflectors migrated to the correct position we compare the image traces at the same offset. Right panels of Figure 2 show comparisons traces from the RTM images at offset 4.2 km. The non-compensated trace (solid red line) have a shifted phase and reduced amplitude. The compensated traces (solid green line) is more correct in amplitude and phase compared to the reference one (solid blue line). Both of these examples show that the proposed Q-RTM approach in TTI media is useful to compensate the amplitude loss and shifted phase due to attenuation effects.



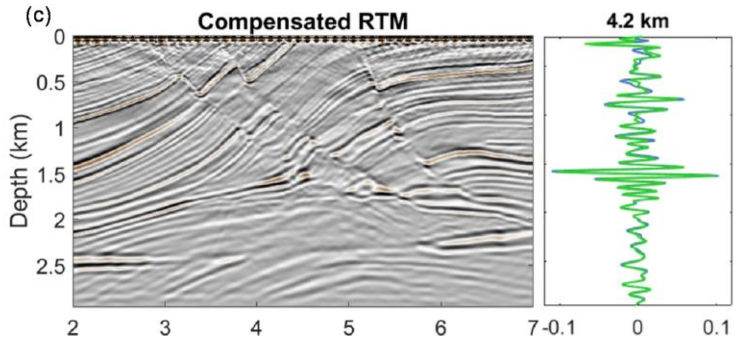



FIG. 2: Comparison among from (a) acoustic RTM (reference), (b) acoustic RTM with viscoacoustic data, and (c) Q-RTM with viscoacoustic data. The right panels show the reference trace (blue line), non-compensated trace (red line), and compensated trace (green line) at the horizontal 4.2 km. The compensated case agree with the reference image very well.

## Conclusions

The phase dispersion and amplitude attenuation operators in Q-RTM approach are separated, and the compensation operators are constructed by reversing the sign of the attenuation operator without changing the sign of the dispersion operator. It is clear that TTI Q-RTM can produce a more accurate image than isotropic RTM, especially in areas with anisotropy, attenuation and strong variations of dip angle.

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