Viscoacoustic reverse time migration in tilted TI media with attenuation compensation

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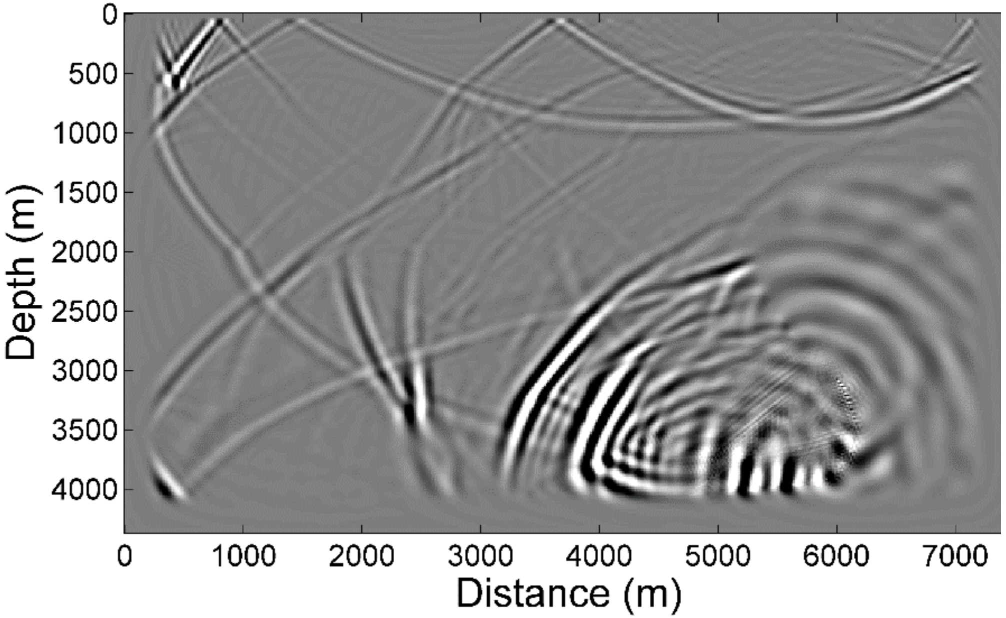
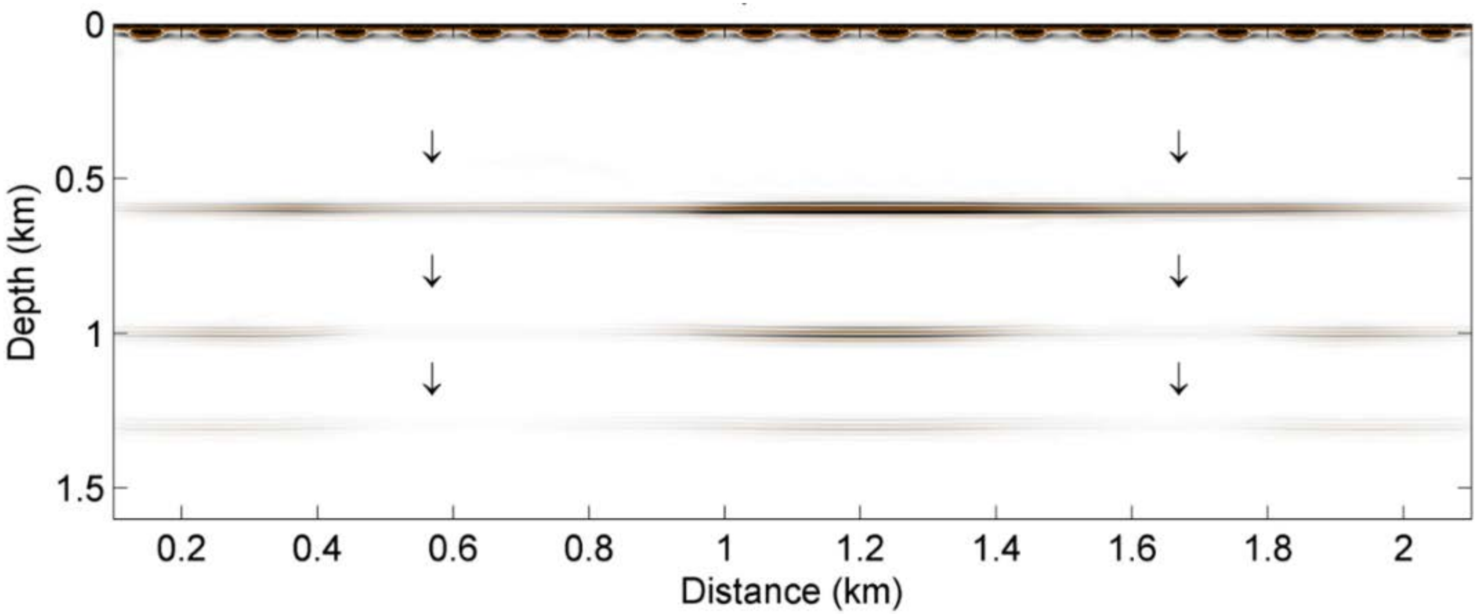
Motivation

Anisotropy



Viscosity



Fathalian and Innanen 2017

In real strata anisotropy and viscosity extensively exits. They degraded waveform in amplitude, resulting in which reducing of image resolution

Viscoacoustic wave equation in TTI media

2D viscoacoustic wave equations in TTI media(Alkhalifah, 2000)

$$\partial_t \sigma_H = \rho V_P^2 \left[(1+2\varepsilon) \left[\boxed{(\frac{\tau_\varepsilon}{\tau_\sigma})[(cos\theta cos\varphi \partial_x - sin\theta \partial_z)u_x] - r_H} \right] + \sqrt{1+2\delta}[(cos\varphi sin\theta \partial_x + cos\theta \partial_z)u_z] \right]$$

$$\partial_t \sigma_V = \rho V_P^2 \left[\sqrt{1+2\delta}[(cos\theta cos\varphi \partial_x - sin\theta \partial_z)u_x] + \boxed{(\frac{\tau_\varepsilon}{\tau_\sigma})[(cos\varphi sin\theta \partial_x + cos\theta \partial_z)u_z] \; - r_V} \right]$$

$$\partial_t r_H = -\frac{1}{\tau_\sigma} r_H + \rho V_P^2 ((cos\theta cos\varphi \partial_x - sin\theta \partial_z)u_x) \frac{1}{\tau_\sigma} \left(1 - \frac{\tau_\varepsilon}{\tau_\sigma} \right)$$

$$\partial_t r_V = -\frac{1}{\tau_\sigma} r_V + \rho V_P^2 ((cos\varphi sin\theta \partial_x + cos\theta \partial_z)u_z) \frac{1}{\tau_\sigma} \left(1 - \frac{\tau_\varepsilon}{\tau_\sigma} \right)$$

u: Particle velocity σ: Stress component r: Memory variable

Viscoacoustic wave equation in TTI media

Fourier transform to the frequency domain

Memory variable

$$\begin{cases} \tilde{r}_H=\rho V_P^2((cos\theta cos\varphi\partial_x - sin\theta\partial_z)\tilde{u}_x)\dfrac{\tau_\sigma^{-1}(1-\tau_\varepsilon\tau_\sigma^{-1})}{(i\omega+\tau_\sigma^{-1})} \\ \tilde{r}_V=\rho V_P^2((cos\varphi sin\theta\partial_x + cos\theta\partial_z)\tilde{u}_z)\dfrac{\tau_\sigma^{-1}(1-\tau_\varepsilon\tau_\sigma^{-1})}{(i\omega+\tau_\sigma^{-1})} \end{cases}$$

After removing memory variable equations and some algebra manipulation

$$i\omega\tilde{\sigma}_H = \rho V_P^2\left[(1+2\varepsilon)\left[\left(\frac{(\omega^2\tau_\varepsilon\tau_\sigma+1)}{\omega^2\tau_\sigma^2+1}+i\,\frac{(\omega\tau_{\varepsilon}-\omega\tau_\sigma)}{\omega^2\tau_\sigma^2+1}\right)[cos\theta cos\varphi\partial_x - sin\theta\partial_z)\tilde{u}_x]\right]+\sqrt{1+2\delta}[(cos\varphi sin\theta\partial_x + cos\theta\partial_z)\tilde{u}_z]\right]$$

$$i\omega\tilde{\sigma}_V = \rho V_P^2\left[\sqrt{1+2\delta}[cos\theta cos\varphi\partial_x - sin\theta\partial_z)\tilde{u}_x]+\left(\frac{(\omega^2\tau_\varepsilon\tau_\sigma+1)}{\omega^2\tau_\sigma^2+1}+i\,\frac{(\omega\tau_{\varepsilon}-\omega\tau_\sigma)}{\omega^2\tau_\sigma^2+1}\right)[(cos\varphi sin\theta\partial_x + cos\theta\partial_z)\tilde{u}_z]\right]$$

Viscoacoustic wave equation in TTI media

Transformed back to the time domain

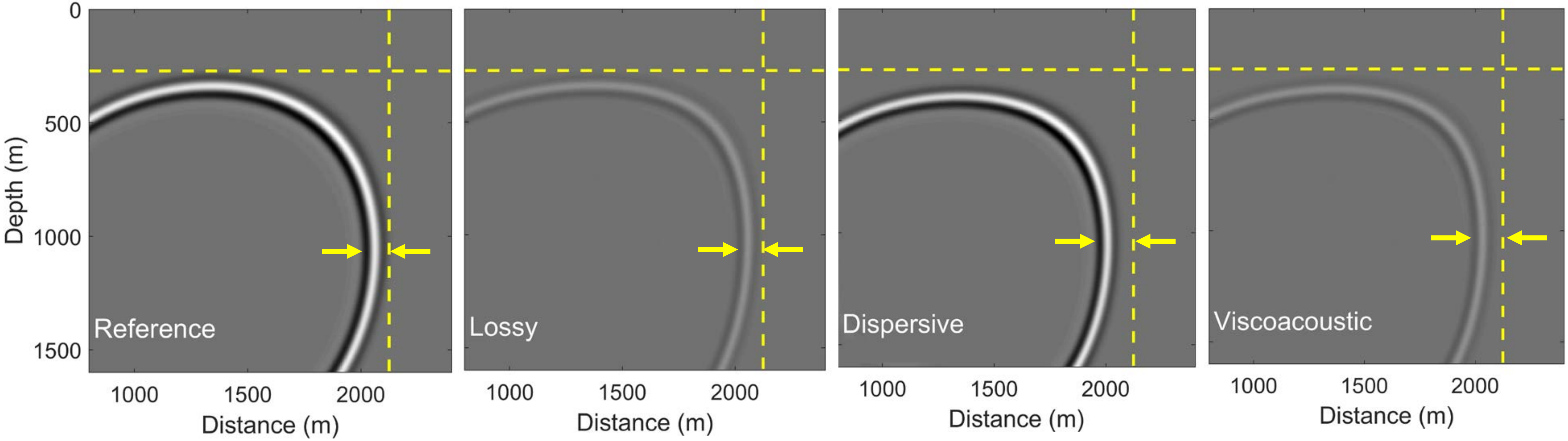
$$\partial_t \sigma_H = \rho V_P^2 \left[(1+2\varepsilon)[(a_1(2/A) + a_2(2/AQ))[cos\theta cos\varphi \partial_x - sin\theta \partial_z)u_x]] + \sqrt{1+2\delta}[(cos\varphi sin\theta \partial_x + cos\theta \partial_z)u_z\ ]\right]$$

$$\partial_t \sigma_V = \rho V_P^2 \left[\sqrt{1+2\delta}[cos\theta cos\varphi \partial_x - sin\theta \partial_z)u_x] + (a_1(2/A) + a_2(2/AQ))[(cos\varphi sin\theta \partial_x + cos\theta \partial_z)u_z]\right]$$

2/A: $Dispersion - dominated\ operator$

2/AQ: $Amplitude\ attenuation - dominated\ operator$

$$A = \left(\sqrt{1+\frac{1}{Q^2}} - \frac{1}{Q}\right)^2 +1$$



Viscoacoustic reverse time propagation

$$a_1, a_2 = \pm 1$$

- Positive sign of the a_2 constant refers to the reduction of the amplitude in extrapolating forward propagation.
- By reversing the sign of the amplitude attenuation term ($a_2 = -1$) in the viscoacoustic wave equation, we can compensate for the amplitude loss.
- To counteract the dispersion effects, we keep the sign of dispersion operator unchanged ($a_1 = 1$).

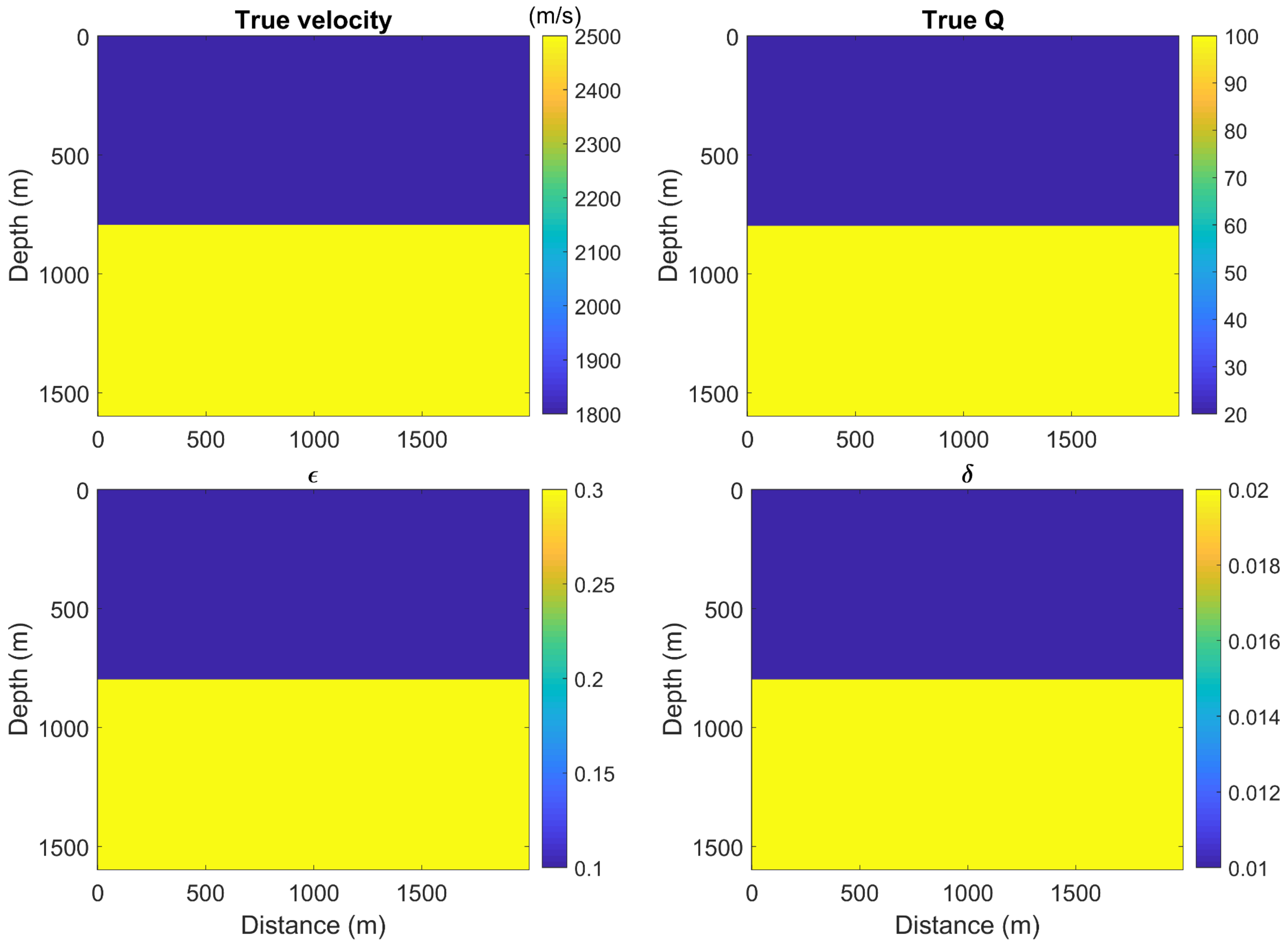
$$\partial_t \sigma_H = \rho V_P^2 \left[(1+2\varepsilon) \left[\left((2/A) - (2/AQ) \right) [cos\theta cos\varphi \partial_x - sin\theta \partial_z) u_x] \right] + \sqrt{1+2\delta} [(cos\varphi sin\theta \partial_x + cos\theta \partial_z) u_z] \right]$$

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

$$Dispersion - dominated\ wave\ equation\ for\ back - propagation$$

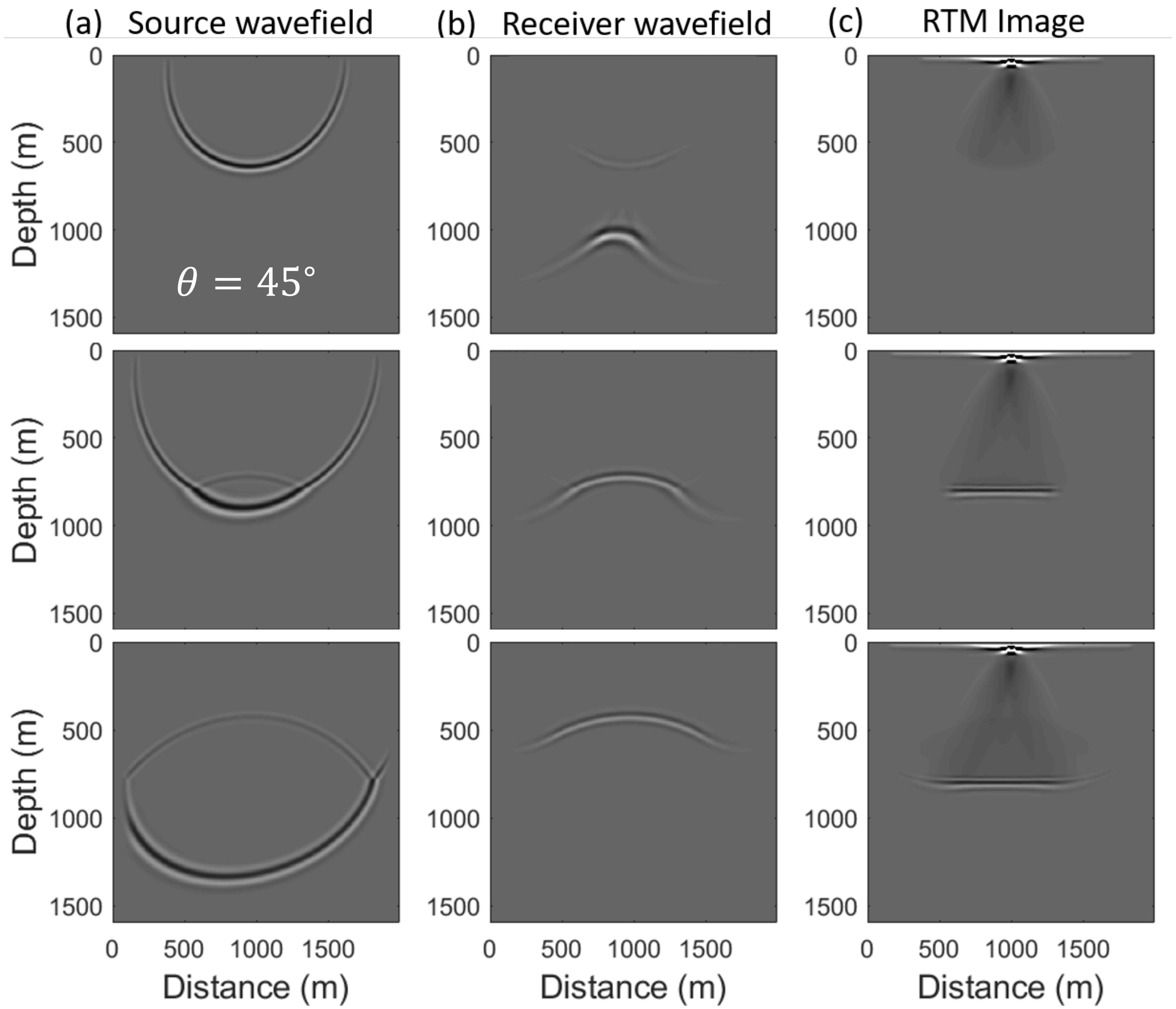
$$Loss - dominated\ wave\ equation\ for\ back - propagation$$

2D synthetic example (Layered model)



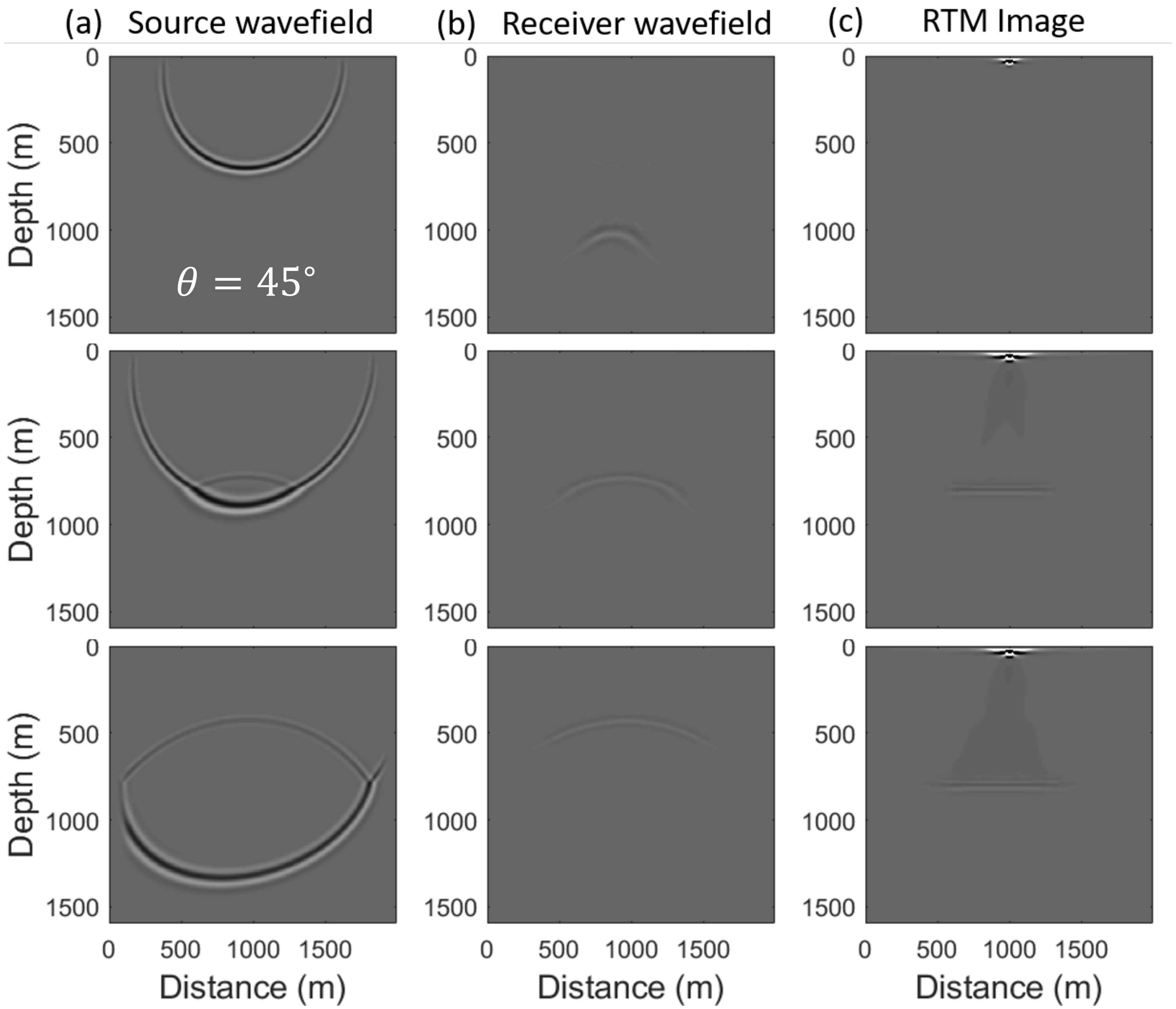
True and migration velocity models with a Q anomaly for the layered model

2D synthetic example (Layered model)



Reference snapshot results using acoustic RTM at different time step

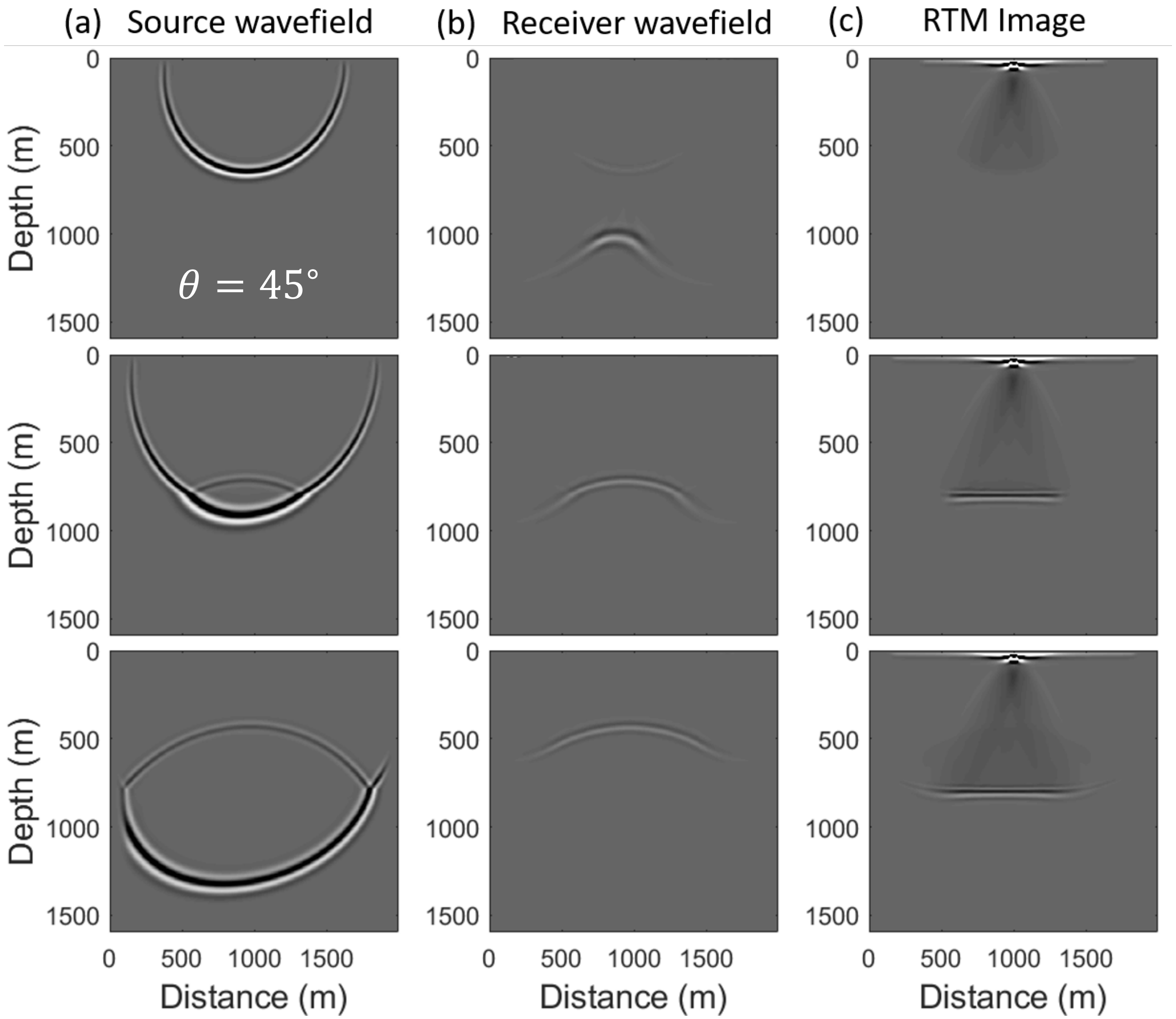
2D synthetic example (Layered model)



Non-compensated snapshot results using acoustic RTM with viscoacoustic data at different time step

- ✓ The receiver wavefield shows reduced wave amplitude while the source wavefield is comparable to the reference result
- ✓ Resulting images at three time slices are underestimated

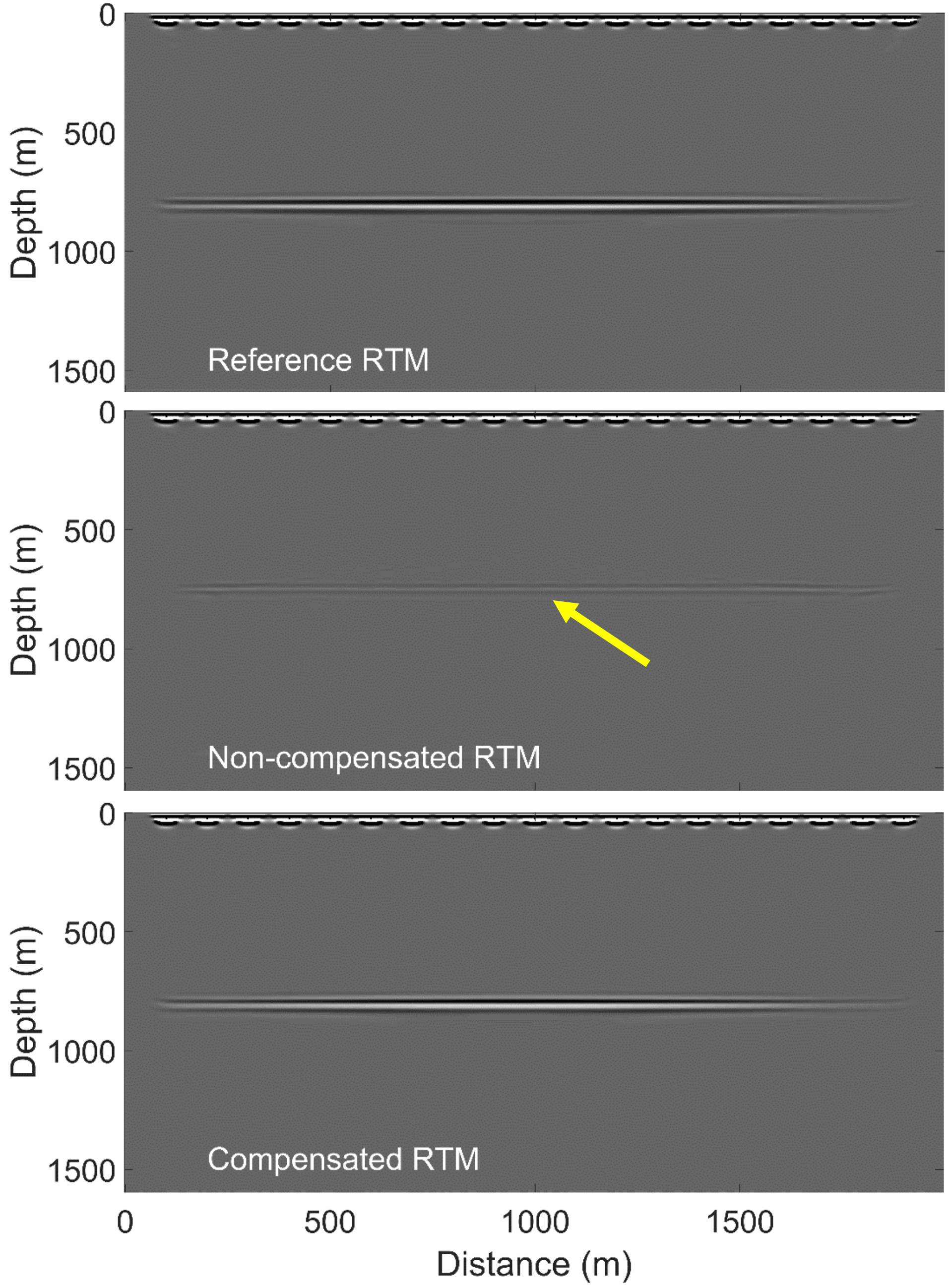
2D synthetic example (Layered model)



To improve image resolution, we test the new approach of Q-RTM on viscoacoustic data

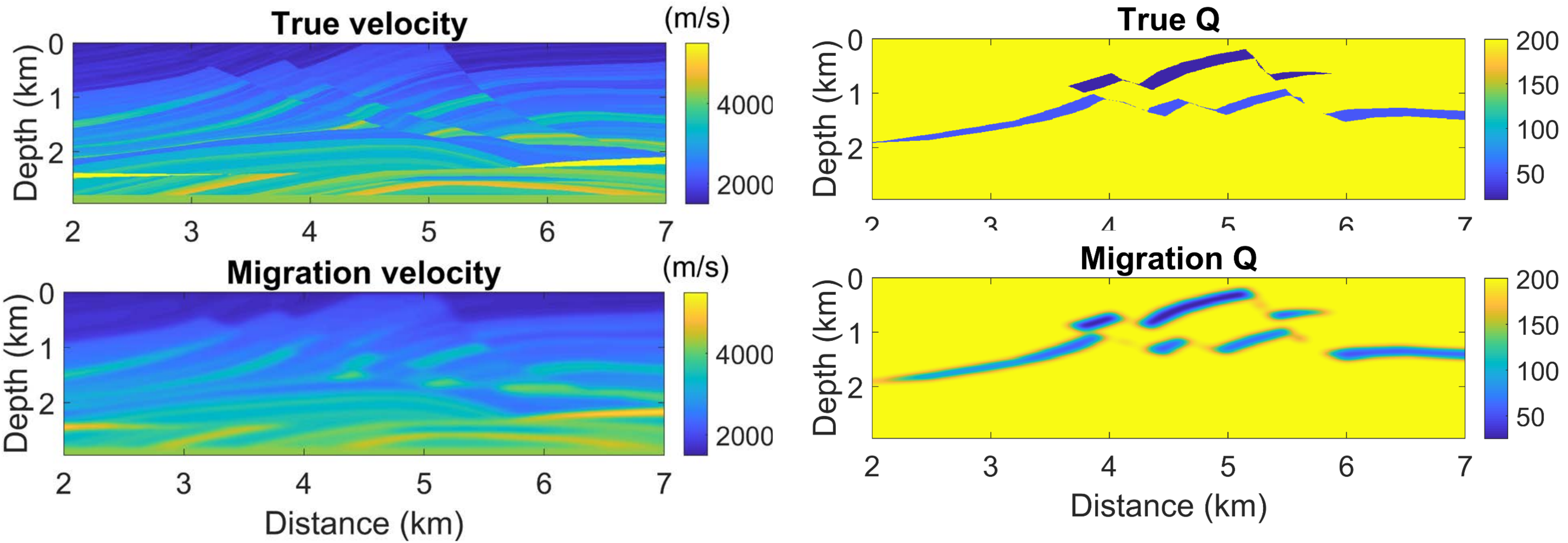
- ✓ Interestingly, such a balanced -attenuation compensation procedure leads to the crosscorrelated Q-RTM images that have comparable amplitude to the corresponding reference images

2D synthetic example (Layered model)



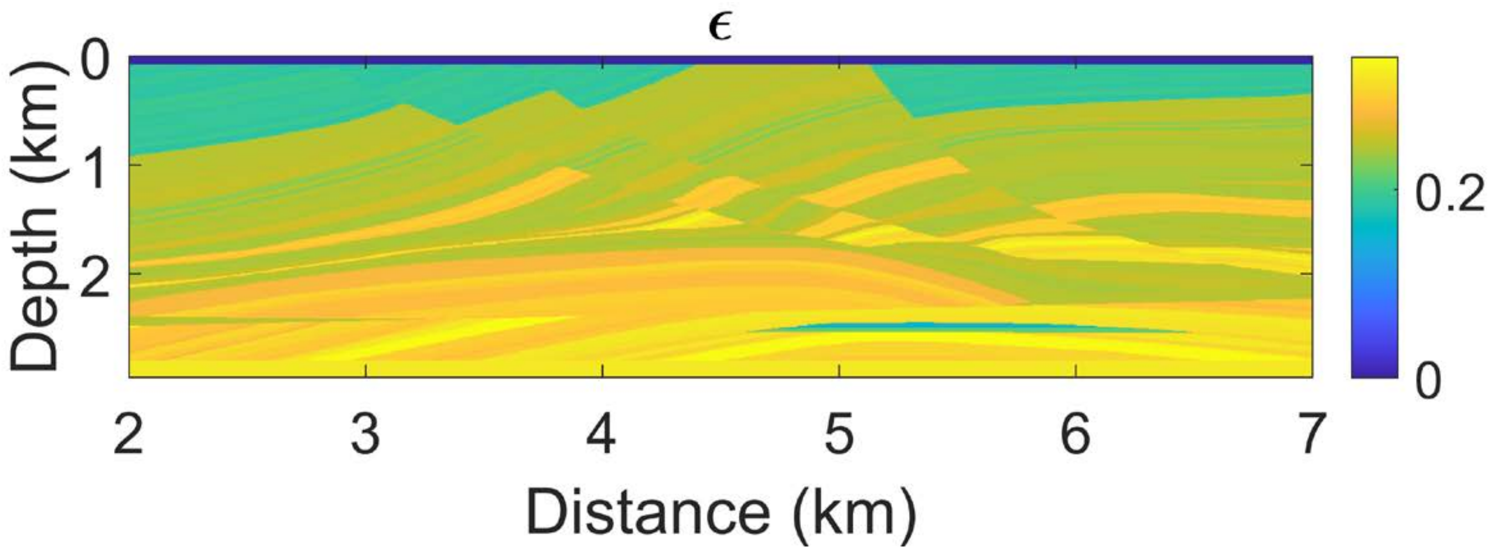
- ✓ In acoustic RTM with viscoacoustic data (non-compensated RTM), there is one reflector in the RTM-image with amplitude loss
- ✓ The result indicates improved RTM image with recovered amplitudes of the reflectors at the dip depths compared with the reference image

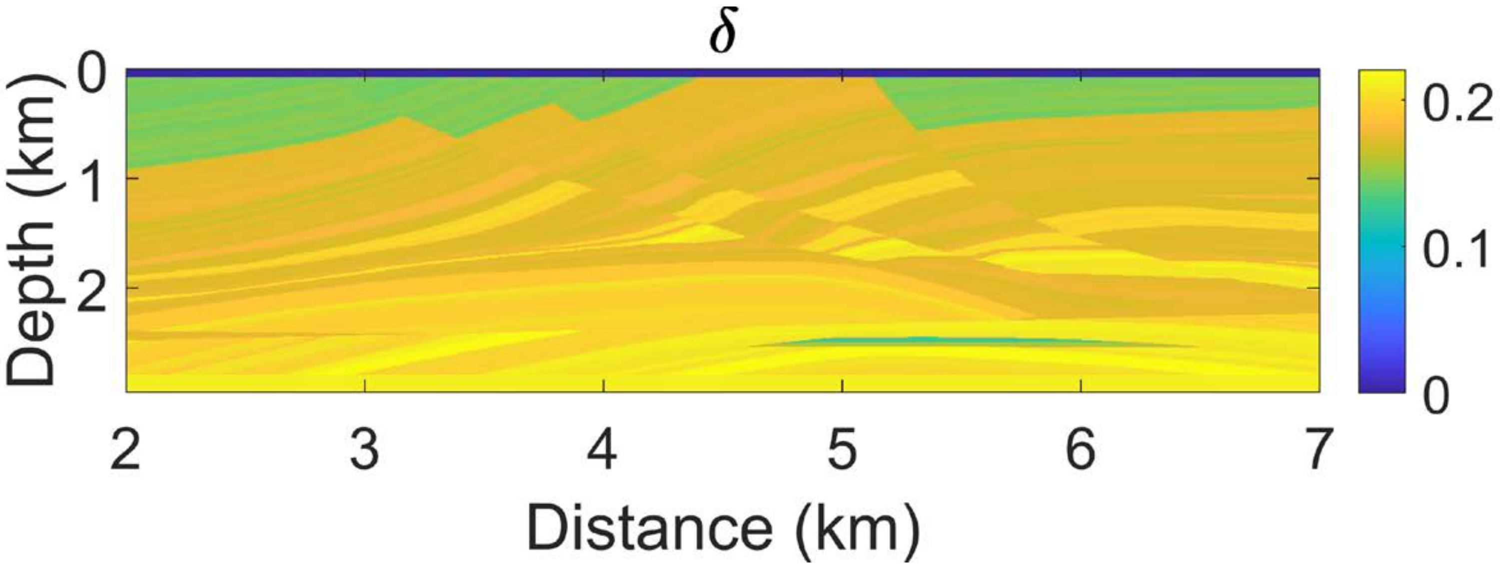
2D synthetic example (Marmousi model)



- ✓ Velocity and Q models are first smoothed from true models and then used for migration

2D synthetic example (Marmousi model)



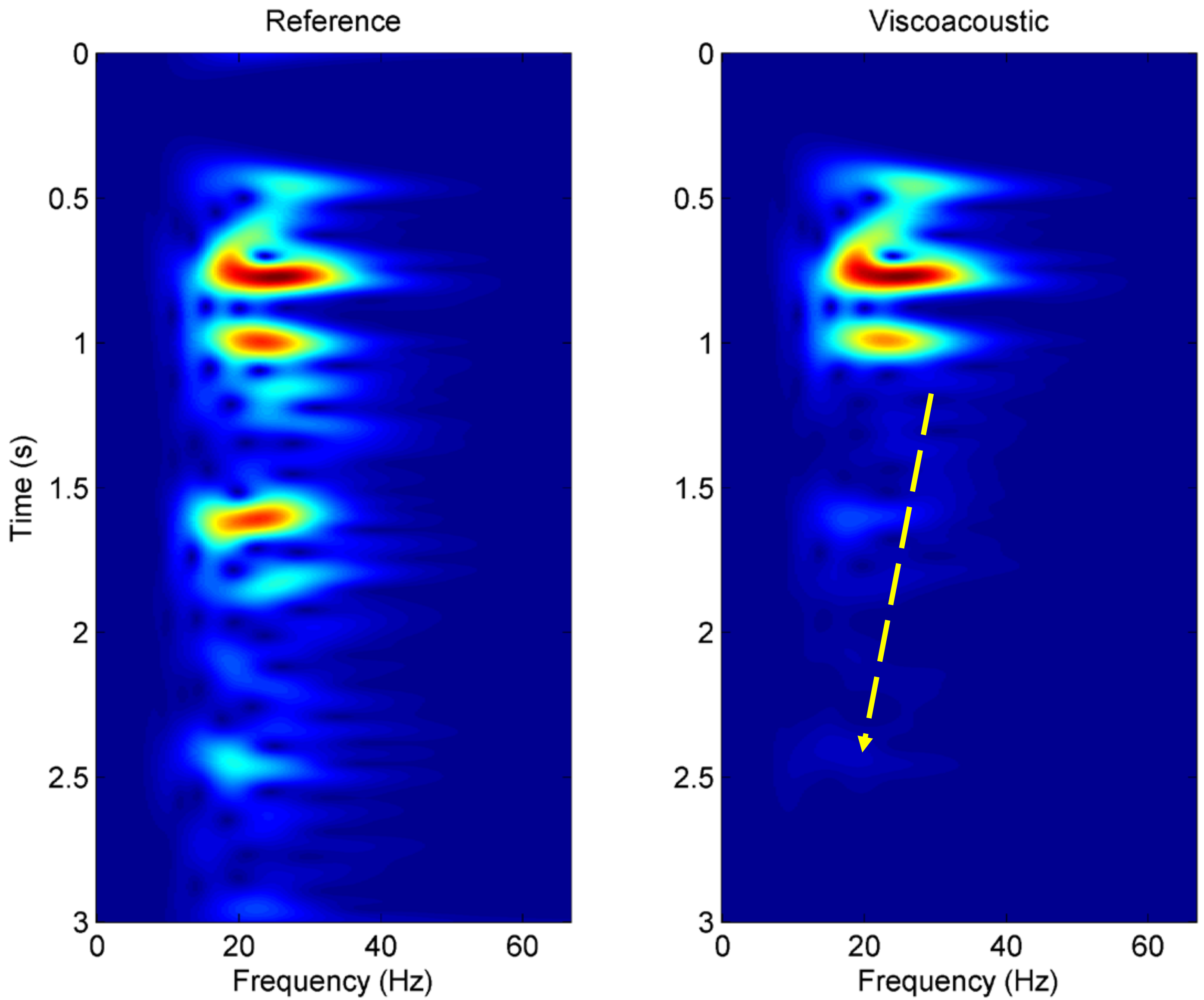


- ✓ some spots of high symmetry axis gradient produce large instabilities and blows up the amplitudes of the wavefield

- ✓ In area with instability, the anisotropy can be taken off around the selected high gradient points which set $\varepsilon = \delta$ to suppress artifacts from the source point in an anisotropic medium

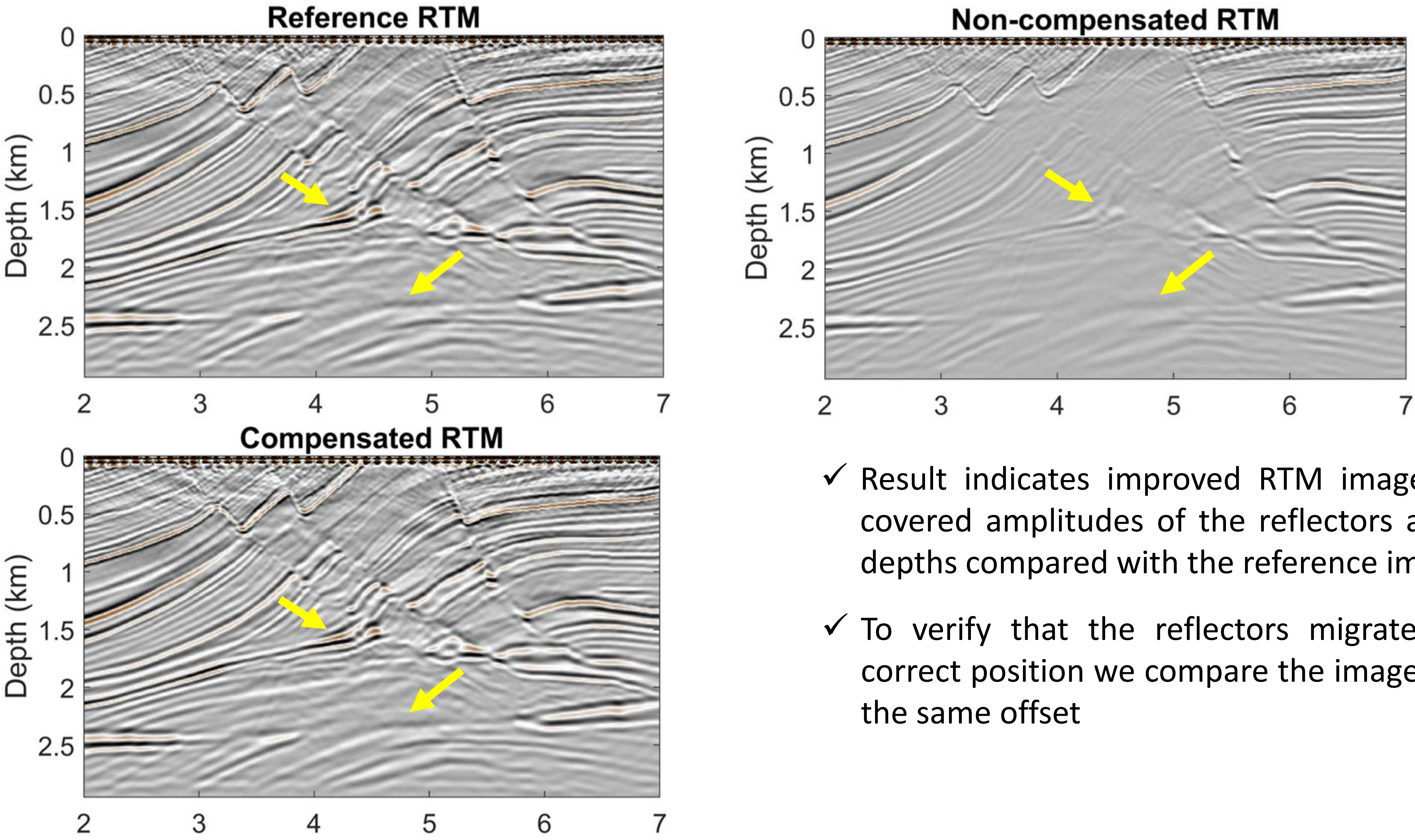
2D synthetic example (Marmousi model)

S spectra of the 240th trace of acoustic and viscoacoustic shot records



- ✓ Reflection wave energy in viscoacoustic medium is smaller than that in the acoustic medium, and with the increase of the depth, the gap become larger

2D synthetic example (Marmousi model)



- ✓ Result indicates improved RTM image with re covered amplitudes of the reflectors at the dip depths compared with the reference image
- ✓ To verify that the reflectors migrated to the correct position we compare the image traces at the same offset

Conclusions

- We have presented a viscoacoustic RTM imaging algorithm based on a decoupled viscoelastic wave equation that is able to mitigate attenuating and dispersion effects in the migrated images.
- 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.

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