Application of Visco-Acoustic Full Waveform Inversion to Shallow-Water, Shallow-Gas Data*

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Abstract

Successful imaging in geological environments with shallow gas infused overburden anomalies requires an Earth model and migration operator that provides the simultaneous corrections of the complex kinematics and the intrinsic attenuation that are present. In order to fully resolve the compartmentalized nature of the gas bodies, a wave equation-based method to derive the Earth model is required. Many current implementations of FWI are acoustic only, in this example we describe the use of a Q-FWI techniques.

Full waveform inversion (FWI) model building is applied in the data domain and is capable of creating a high-resolution Earth model through a wavefield-consistent solution. FWI derived velocity models have improved the imaging of marine and land datasets, with acquisitions ranging from narrow azimuth (NAZ) to wide azimuth (WAZ) to full azimuth (FAZ) to dual-coil and ocean-bottom cable (Sirgue and Barkved, 2009; Plessix et al., 2010; Vigh et al., 2011; Kapoor et al., 2013). In all cases, the uplift in reservoir-level imaging was facilitated through recovering a high-resolution velocity model within a heterogeneous overburden.

A kinematically precise velocity model combined with the appropriate migration algorithm can focus the recorded energy to its true subsurface locations. However, the anelastic nature of the real Earth can also significantly impact the amplitude and phase of the recorded seismic signal and the migrated image. To facilitate earth model building, improve imaging, and improve the fidelity of the amplitude versus offset/angle (AVO/A) responses, those anelastic effects must be characterized and compensated for. The first step in addressing the Earth's absorption effects is to derive a spatially and temporally variant interval 1/Q model in three dimensions, where the quality factor Q is used to characterize the anelastic effects. This is conventionally achieved using ray-based reflection tomography techniques (Cavalca et al., 2011; Hu et al., 2011). However, to overcome the limitations of the ray-based methods, two-way wave equation-based methods that derive a high-resolution

attenuation model should be implemented (Cheng et al., 2015). The second step in addressing the Earth's spatially variant absorption effects is to correct for these effects by embedding the amplitude and phase corrections within a migration operator.

Method and Theory

Under constant-Q assumption (i.e., linear attenuation with frequency), a set of second-order visco-acoustic isotropic wave equations describes the dispersion and attenuation effects of wave propagation reasonably well (Aki and Richards, 1980; Robertson et al., 1994; Carcione, 2007; Bai et al., 2014):

$$\begin{aligned} \frac{1}{\upsilon_r^2}\frac{\partial^2 P}{\partial t^2} &= (1+\tau)\rho\left[\nabla\left(\frac{1}{\rho}\nabla P\right)\right] + r + f, \\ \frac{\partial r}{\partial t} &= -\frac{\tau}{\tau_\sigma}\rho\left[\nabla\left(\frac{1}{\rho}\nabla P\right)\right] - \frac{1}{\tau_\sigma} r, \end{aligned} \qquad (1)$$

where P is for the pressure wavefield, ρ is the density, r is a memory variable, f is the source term, $\tau = \tau_e / \tau_\sigma - 1$, τ_e and τ_σ are the relaxation times of strain and stress:

$$\begin{aligned} \tau_\varepsilon &= \frac{1}{\omega_0}\left(\sqrt{1+\frac{1}{Q^2}} + \frac{1}{Q}\right), \\ \tau_\sigma &= \frac{1}{\omega_0}\left(\sqrt{1+\frac{1}{Q^2}} - \frac{1}{Q}\right), \end{aligned} \qquad (2)$$

v_r stands for the attenuated velocity, and refers to the dominant frequency of the source, and ω_0 refers to the dominant frequency of the source. It is well known that the higher the frequency, the more the impact of attenuation on seismic amplitude. However, this is not the case for phase dispersion. Under the same quality factor Q, the lower the frequency, the more the phase delay (i.e., dispersion effects). Figure 1 shows how the seismic amplitude and phase are distorted for different Q values for different frequencies. Thus although FWI, as a multi-scale iterative inversion method usually starting from low frequencies, will be impacted the least from the amplitude attenuation point of view, its convergence will be impacted the most by Q-induced phase dispersion if Q is not incorporated properly during inversion. The problem becomes more prominent if the objective function used in the low-frequency FWI is targeted to produce a kinematically correct model. These observations motivated us to develop a new method to focus on Q-induced phase dispersion for Q-FWI, especially under low-frequency considerations.

Let $L(t)=\rho\left[\nabla\left(\frac{1}{\rho}\nabla P\right)\right]$ from the visco-acoustic wave equation (Equation 1), after Fourier transform to the frequency domain and some algebra manipulation, without the source term, we have:

$$-\frac{\omega^2}{\upsilon_r^2}\hat{P}(\omega)=D(Q)\hat{L}(\omega), \qquad (3)$$

In comparison with the acoustic wave equation, the only difference is an extra complex valued term *D* (*Q*), which is only a function of the quality factor Q. We noticed that the real and imaginary parts of the term *D* (*Q*) dominate the phase dispersion and amplitude attenuation, respectively. Thus, using the real part only, we obtained a new approximate phase-only visco-acoustic wave equation in the time domain as:

$$\frac{1}{\upsilon_r^2}\frac{\partial^2 P}{\partial t^2}=\Re\{D(Q)\}\rho\left[\nabla\left(\frac{1}{\rho}\nabla P\right)\right] \qquad (4)$$

In Equation 4, there is no need for the extra memory variables needed in the visco-acoustic wave equation (Equation 1), and the Q-induced phase dispersion is accounted for. The backpropagation of the wave fields will only include phase compensation without amplifying or further attenuating amplitude. For simplicity, we presented the derivation here using an isotropic example; to extend it to anisotropic is straight-forward.

To estimate the Q model, the gradient of Q can be easily obtained through chain rule from the gradient of *D* (*Q*) and velocity, which are given by the standard adjoint-state method (Plessix, 2006). The estimation of Q is then driven by phase mismatch between the observed and simulated seismic waveform, which are the dominant effects of Q at low frequencies. The sensitivity analysis reveals that compared with the Q fields, the velocity fields dominate the data misfit (Malinowski et al., 2011; Kurzmann et al., 2013). Thus, we propose to invert for velocity first while holding the background Q fields unchanged, provided that it is an appropriate representation of the background field, and only switch to the high-complexity Q estimation when velocity inversion is close to convergence. A strong preconditioner guided by the region of low-velocity anomaly could also be applied during Q estimation to accelerate inversion convergence.

Workflow

In this study, we present a proof-of-concept application of an approximate, phase-only, Visco-acoustic FWI algorithm to a shallow-water, shallow-gas offshore marine narrow azimuth (NAZ) data set from Myanmar. The FWI feasibility study involved a 77-km^2 target area of approximately 25,000 shots. The study area was selected based on the overburden complexities presented by shallow gas, incised channeling, and structural faulting. Since no wells were available for calibration or validation a simple anisotropy function was hung from the water bottom and fixed throughout the FWI velocity model updates.

Three frequency bands were used in the time-domain FWI iterations, progressing from low to higher frequencies. As the peak frequency and the range of frequencies included in the inversion increased, the resolution of the inverted model improved. Initially, the visco-acoustic FWI propagator was used to invert a high-resolution velocity model in the presence of a background Q-field. The model was primarily updated in the upper 1,000 m as inherently constrained by the penetration depth of the transmitted energy, recorded with a maximum streamer length of 4,500 m.

The details provided by FWI are clearly seen on the comparisons between the initial model and the Q-FWI model, as shown in Figure 2 and Figure 3. A Q-scan was then performed to estimate the Q-value in the low-velocity gas compartments. A relationship between velocity and Q was then derived and applied to the velocity field to derive a high-resolution Q-model. The use of the final FWI-derived velocity (Vp) and Q-models in a Q-compensated Kirchhoff prestack depth migration algorithm (Q-KPSDM), Figure 4, showed that the Q-FWI workflow could resolve the low P-wave velocities and high attenuation of shallow gas bodies, subsequently compensating for the complex kinematics and absorption during depth migration.

Conclusions

The presence of shallow gas presents challenges to seismic imaging due to the localized velocity variations and general Q effects (amplitude attenuation and phase dispersion). Due to the phase dispersion at low frequencies, Q needs to be incorporated into the propagation during multiscale FWI to derive a frequency-independent velocity model. Even with a simple background Q-model, a detailed velocity model can be retrieved using this approximate, phase-only, visco-acoustic approach for Q-FWI.

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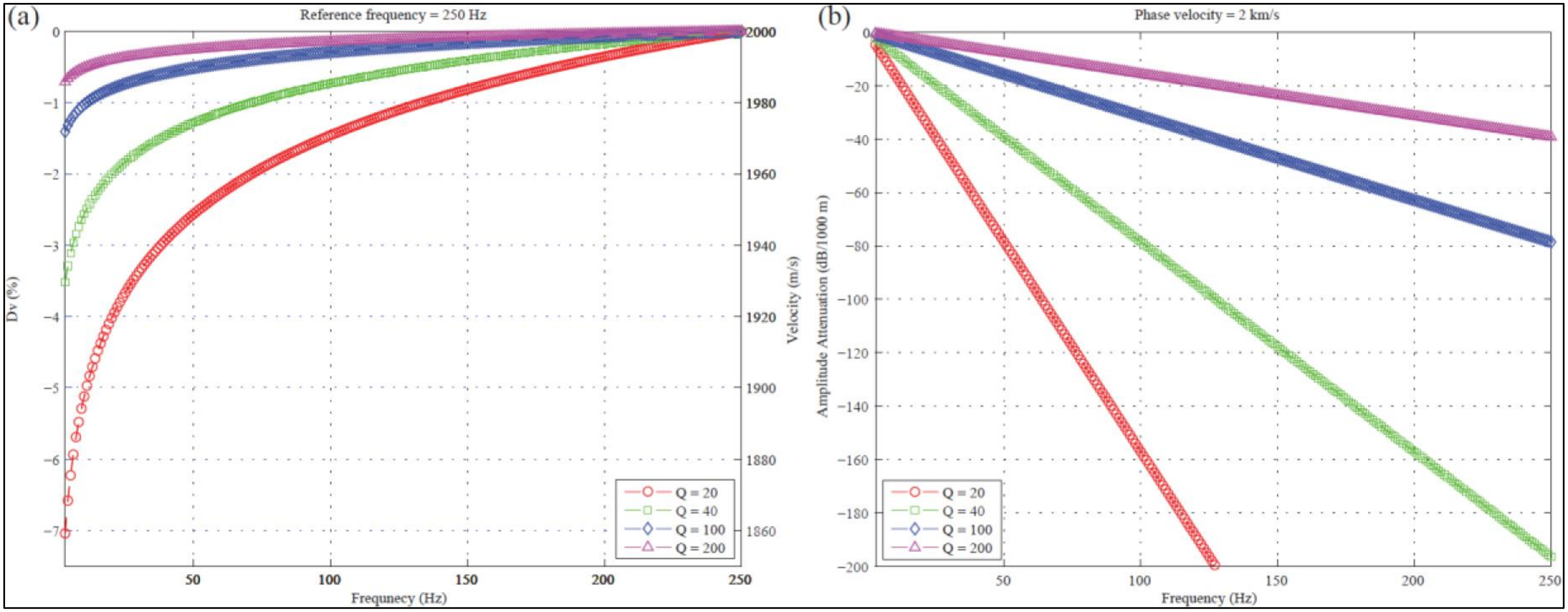

Figure 1. The (a) frequency dependent dispersion, and (b) attenuation of several different constant-Q models.

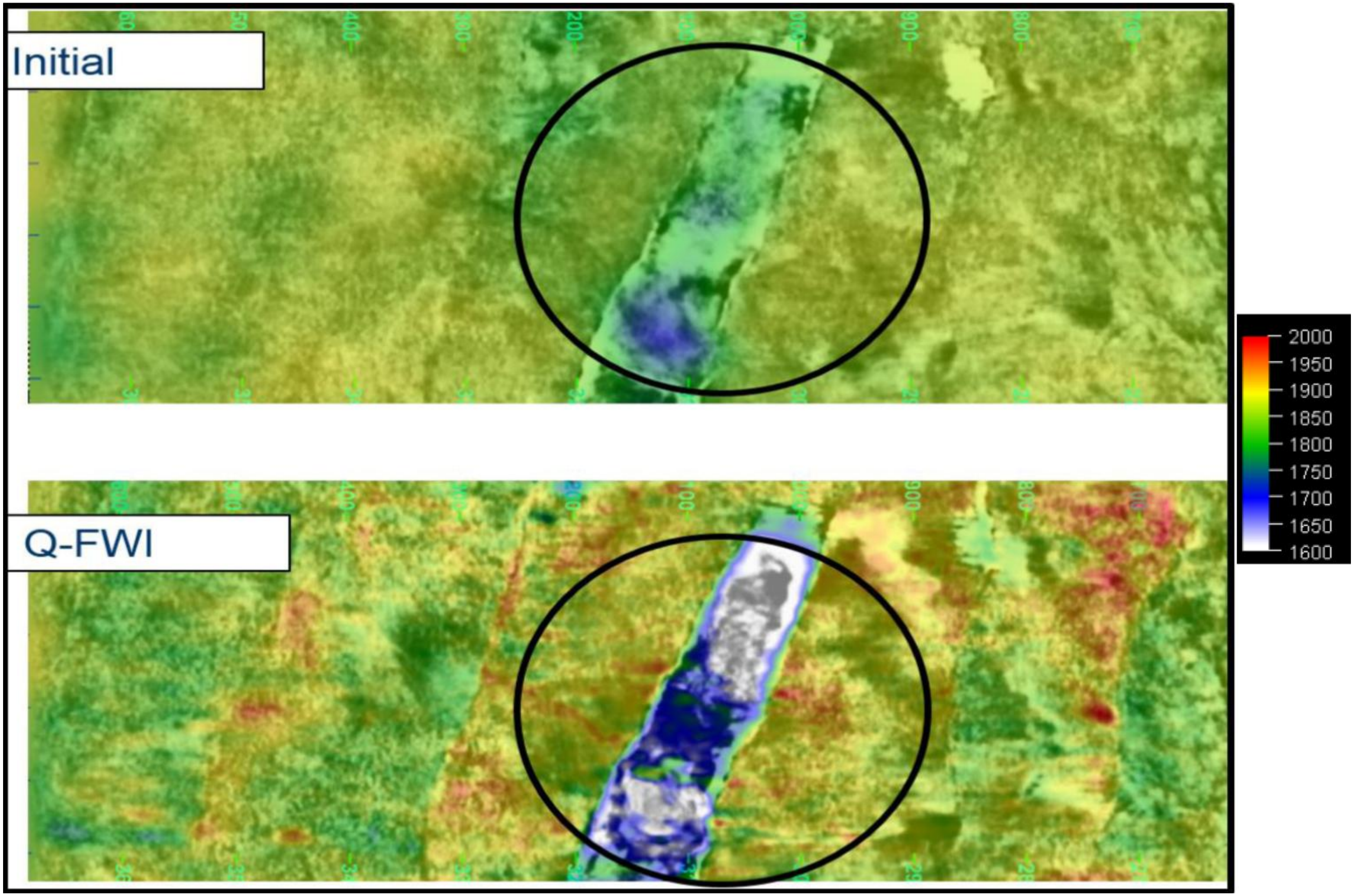

Figure 2. Comparison of (top) depth slice overlay of the initial velocity model, and (bottom) Q-FWI derived velocity model.

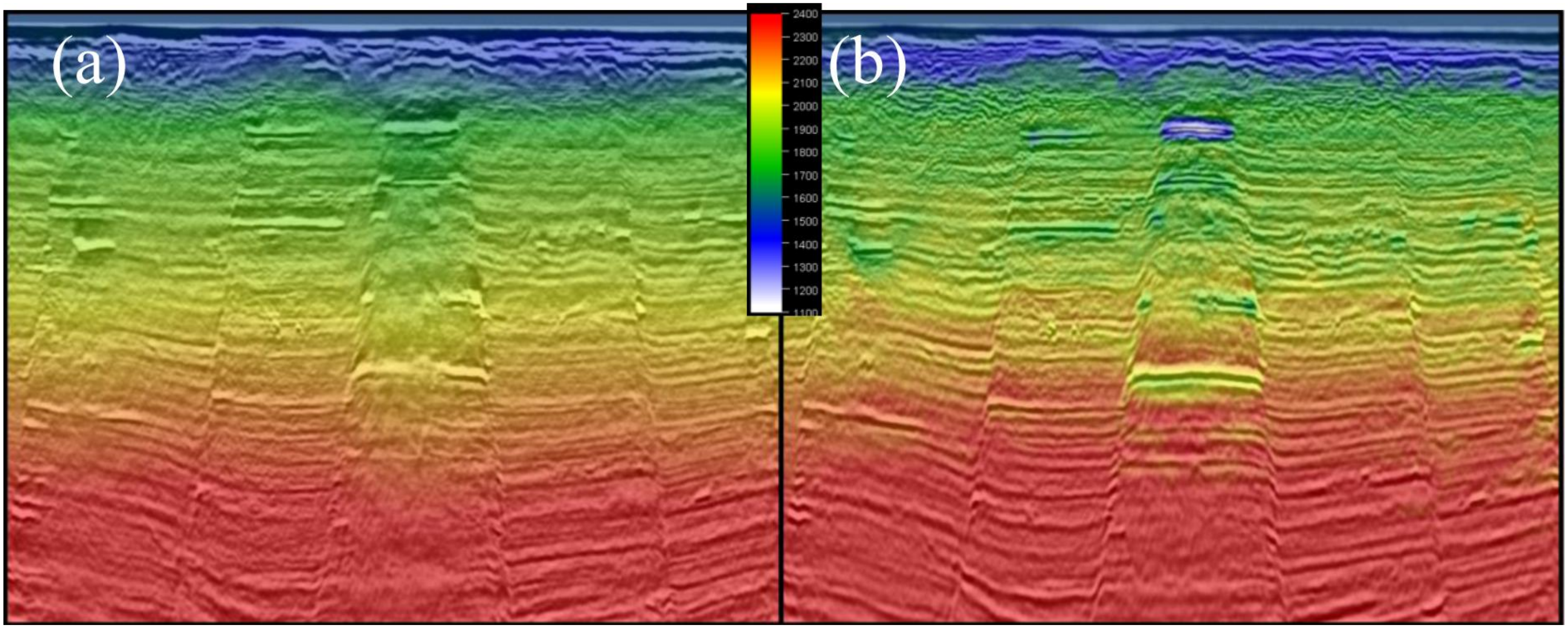

Figure 3. Comparison of Q-KPSDM stack sections with respective velocity model overlays showing (a) the initial velocity model, and (b) the Q-FWI-derived velocity model.

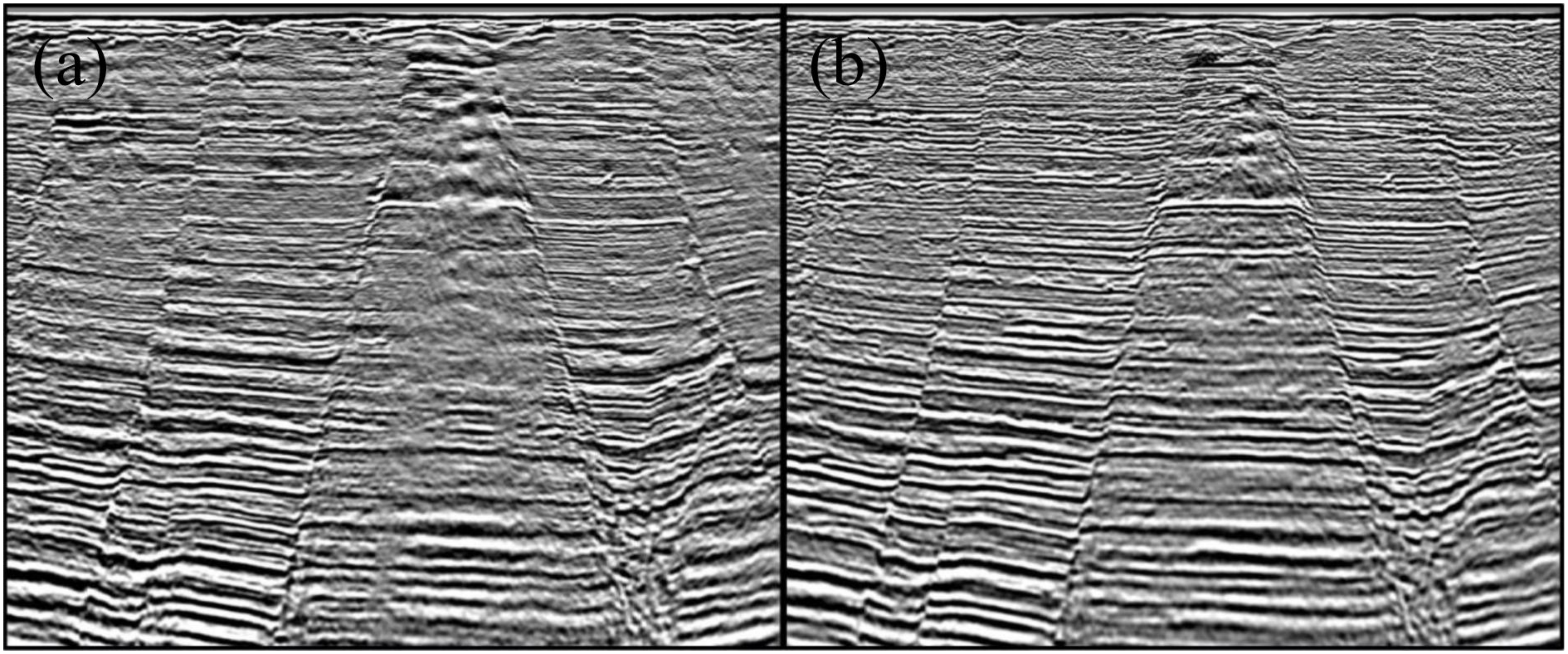

Figure 4. Comparison of Q-KPSDM stack section migrated with (a) the initial velocity model and background Q-model, and (b) the Q-FWI derived velocity model and Q-FWI Q model.